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PAST GLOBAL CHANGES

PAGES HORIZONS

Wet vs Dry

Picture the past

Change the future

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EDITORIAL
EXPLORING THE PAST FORCE OF WATER

By Juan A. Ballesteros-Cánovas, Gerardo Benito, Keely Mills, Ray Lombardi, Boris Vannière, Graciela Gil-Romera and Iván Hernández-Almeida

Dear Readers

Water, in all its forms, has the potential to shape the Earth's landscape over extended periods of time. For example, the formation of rivers which cut through the landscape, or larger (and rare) episodes such as the melting of ice sheets and mountain glaciers (which occurs over tens of thousands of years).

Water can also shape the landscape in the short term, following rare, extreme events (for example, from 100-year floods or droughts). These events can greatly impact the environment, including plants and animals (i.e. ecosystems), and people (such as farming and infrastructure). In recent decades it has become clear that global warming is changing the frequency and magnitude of heavy rainfall, flooding and drought events.

According to the latest Intergovernmental Report on Climate Change (Intergovernmental body of the United Nations; IPCC report, AR6), rising temperatures caused by climate change are intensifying wet and dry periods. Catastrophic floods are becoming more common, driven by changes in the frequency of extreme rainfall events, as well as by land degradation due to severe heatwaves and droughts, and/or deforestation by humans. Floods are also becoming more common in some regions because of increasing temperatures, which leads to the melting of glaciers and permafrost. Much of these changes in rainfall, flood and drought frequency, due to a warming climate, are particularly relevant in tropical regions, some of which are densely populated. There is an urgent need for people and communities to adapt to, and mitigate, such extreme climate events in the near future.

However, to do this, we need to understand the history of these extreme events, but our records are short – beginning only when people started measuring and recording them. In most world regions, instrumental measurements began less than 200 years ago. As such, we need a longer-term perspective, and this is where paleoscience – the study of climatic and environmental processes before there were instrumental records – can help us.

Paleoscience offers a better understanding of extreme floods by extending the instrumental record to hundreds, or even thousands, of years. When floods occur, rivers carry large amounts of sediment, move large boulders and cause land degradation. Extreme rainfall also infiltrates caves, flooding underground galleries. These sediments end up in the alluvial plains of the rivers and along rocky canyons, even reaching lakes and marine coastal areas. In the same way, droughts reduce infiltration into caves, and affect vegetation physiology. Every time an area is flooded or suffers a drought, a different kind of sediment layer, or ecological evidence, is produced. All this information forms the pages of a book that details the "history" of the past climate. The role of paleoscience is to help read the "pages" found in stratigraphic layers of sediments, tree rings, speleothems in caves, and sediments of lakes and marine basins.

We use paleorecords to learn how, for example, extreme wet and dry events have changed over time, and across the world. These long-term hydrologic histories help contextualize the magnitude of modern extreme events, their occurrence, impacts and trigger mechanisms. This information is essential to understanding the future trajectories of extreme wet and dry events under global warming, as well as to test hypotheses in hydrological sciences. What's more, we know that these rare but big events disrupted the functioning of past societies. Therefore, information from the paleosciences provide lessons from the past to help communities better prepare for extreme events and contribute to our sustainable development.

It is our pleasure to present this third volume of PAGES Horizons, dedicated to studying wet and dry using paleorecords. The volume contains a total of eight contributions which reveal, in a relaxed, fun, and visually appealing way, how scientists work with different archives, including speleothems, tree-rings, historical records, and sediments, and in various environments, such as volcanic, fluvial, cave and mountain regions. The research presented here covers the study of speleothems from caves in alpine and tropical environments; the impact of glacier retreat on the generation of massive floods in high mountain regions; the effect of volcanic eruptions triggering large floods due to changes in climatic and meteorological conditions; and changes in the precipitation and hurricane passages using isotopes and tree-ring records, among others. The value of paleoscience in analyzing hydrological-extreme events is illustrated using a variety of formats, including photo reports, comics and images.

We hope that readers will enjoy the stories told by different scientists and gain insight into how paleoscience can be used to inform a safe and sustainable future.

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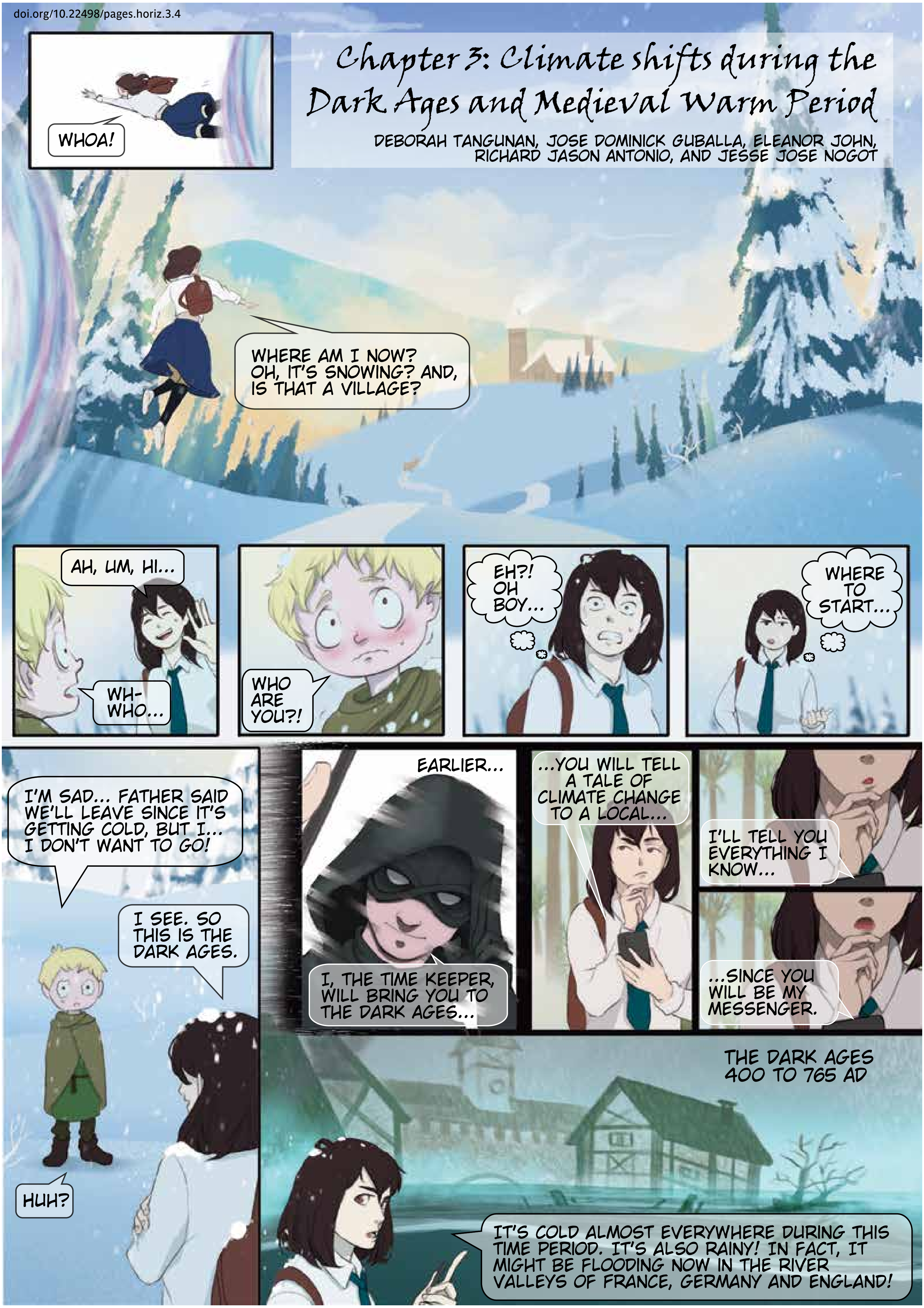
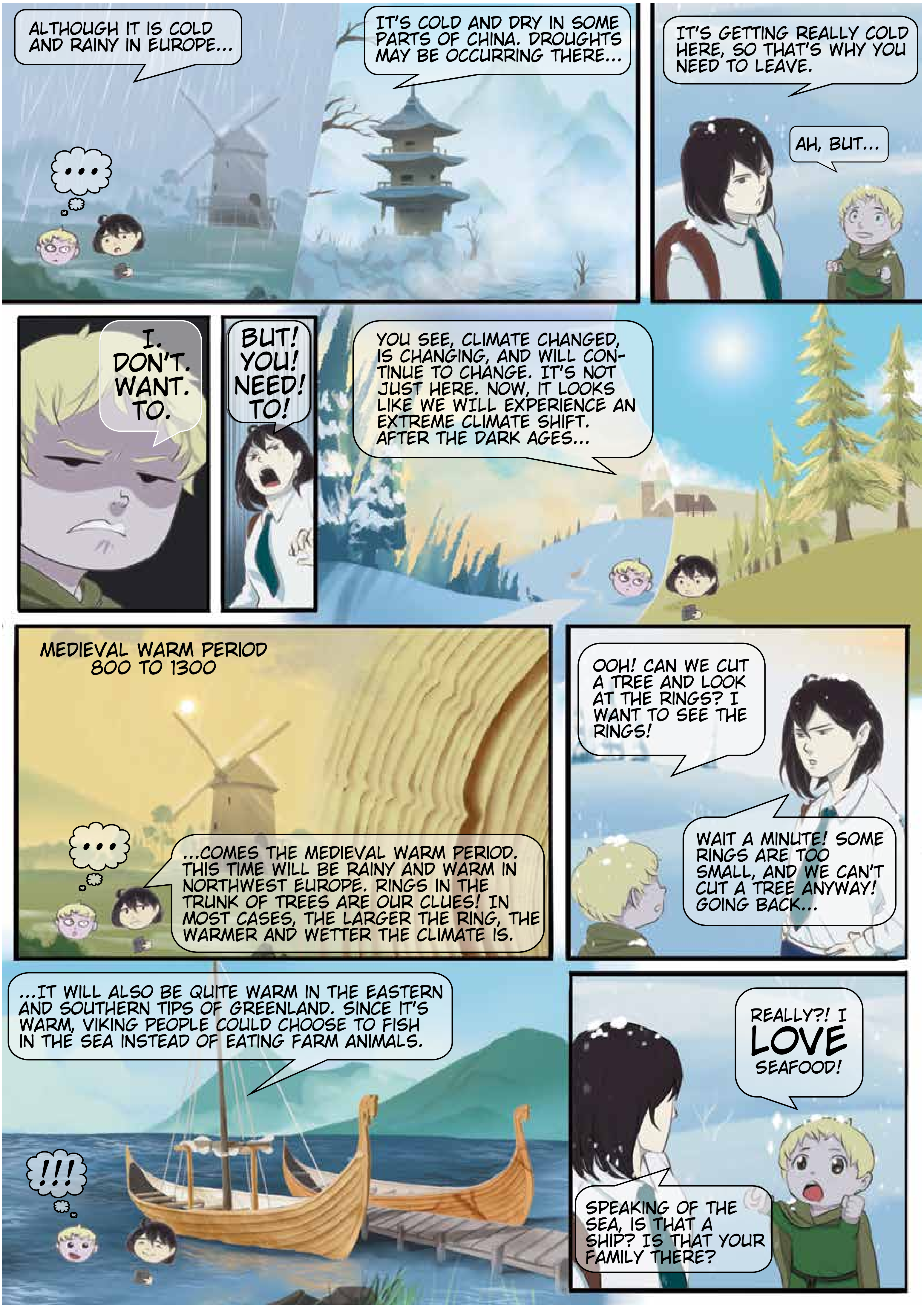
Chapter 3: Climate shifts during the Dark Ages and Medieval Warm Period

DEBORAH TANGUNAN, JOSE DOMINICK GUBALLA, ELEANOR JOHN, RICHARD JASON ANTONIO, AND JESSE JOSE NOGOT




ALTHOUGH IT IS COLD AND RAINY IN EUROPE...
...
IT'S COLD AND DRY IN SOME PARTS OF CHINA. DROUGHTS MAY BE OCCURRING THERE...
IT'S GETTING REALLY COLD HERE, SO THAT'S WHY YOU NEED TO LEAVE.
AH, BUT...
I. DON'T. WANT. TO.
BUT! YOU! NEED! TO!
YOU SEE, CLIMATE CHANGED, IS CHANGING, AND WILL CONTINUE TO CHANGE. IT'S NOT JUST HERE. NOW, IT LOOKS LIKE WE WILL EXPERIENCE AN EXTREME CLIMATE SHIFT. AFTER THE DARK AGES...
MEDIEVAL WARM PERIOD 800 TO 1300
...
...COMES THE MEDIEVAL WARM PERIOD. THIS TIME WILL BE RAINY AND WARM IN NORTHWEST EUROPE. RINGS IN THE TRUNK OF TREES ARE OUR CLUES! IN MOST CASES, THE LARGER THE RING, THE WARMER AND WETTER THE CLIMATE IS.
OOH! CAN WE CUT A TREE AND LOOK AT THE RINGS? I WANT TO SEE THE RINGS!
WAIT A MINUTE! SOME RINGS ARE TOO SMALL, AND WE CAN'T CUT A TREE ANYWAY! GOING BACK...
...IT WILL ALSO BE QUITE WARM IN THE EASTERN AND SOUTHERN TIPS OF GREENLAND. SINCE IT'S WARM, VIKING PEOPLE COULD CHOOSE TO FISH IN THE SEA INSTEAD OF EATING FARM ANIMALS.
!!!
REALLY?! I LOVE SEAFOOD!
SPEAKING OF THE SEA, IS THAT A SHIP? IS THAT YOUR FAMILY THERE?


YES! FATHER SAID THAT WE CAN'T GROW FOOD HERE BECAUSE IT IS TOO COLD NOW, SO WE WILL SAIL AND LOOK FOR ANOTHER PLACE TO CALL HOME...
OH, THE SHIP! THAT MEANS I HAVE TO GO BACK!
WAIT! BEFORE YOU GO...
REMEMBER THAT THE CLIMATE CAN CHANGE FROM ONE STATE TO ANOTHER. IT MIGHT BE COLD NOW, BUT CLIMATE MAY BECOME WARMER IN THE FUTURE.
...LIKE HOW A SHIP ROCKS AT SEA TO KEEP ITSELF STEADY, THE CLIMATE ALSO TRIES TO BALANCE ITSELF. EARTH'S CLIMATE WENT FROM WARM TO COLD TO WARM AGAIN... MANY, MANY TIMES IN THE PAST.
THIS IS WHY WE NEED TO LEARN ABOUT THE CLIMATE OF THE PAST, SO THAT WE CAN PREDICT WHAT THE FUTURE HAS IN STORE FOR US.
THANK YOU SO MUCH! I WON'T LET THIS BOTHER ME ANYMORE! THIS IS FOR YOU!
...NO WORRIES!
H-HEY, WAIT! NO, NOT YET!
YOU... TAKE ME BACK TO THE PAST, RIGHT NOW!
THE PAST, YOU SAY? BUT, I'M BORED OF IT ALREADY...
HEY... WANT TO SEE WHAT YOUR FUTURE MIGHT LOOK LIKE?
...TO BE CONTINUED!

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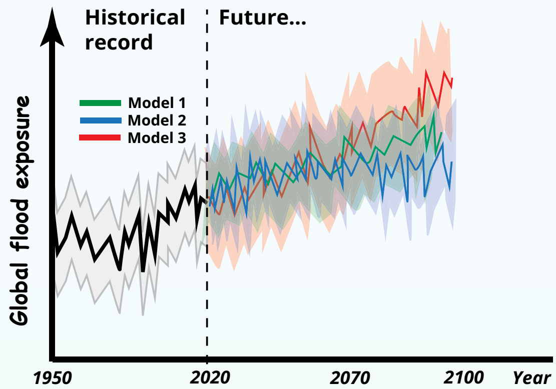
What do cave deposits tell us about *past floods?*

Miguel Bartolomé • Reyes Giménez
Guillermo Pérez-Villar • Marc Luetscher
Ana Moreno • Heather Stoll
Gerardo Benito • Art&Design by: Cooked Illustrations

Floods in a warm world

Addressing the consequences of current climate change represents one of the greatest challenges for our society. One fundamental and worrying outcome of global warming is the increase in frequency and intensity of river floods all over the world in relation to shifts in rainfall patterns [1]. A recent study reveals that the past three decades were the most flood-rich periods over the last 500 years in Europe [2].

Climate models show an intensification of extreme torrential events in the next decades as a result of climate change, which will affect social, ecological, and economic systems globally. However, there is still a high uncertainty with respect to projected changes at a regional scale since the trends are not yet robust.



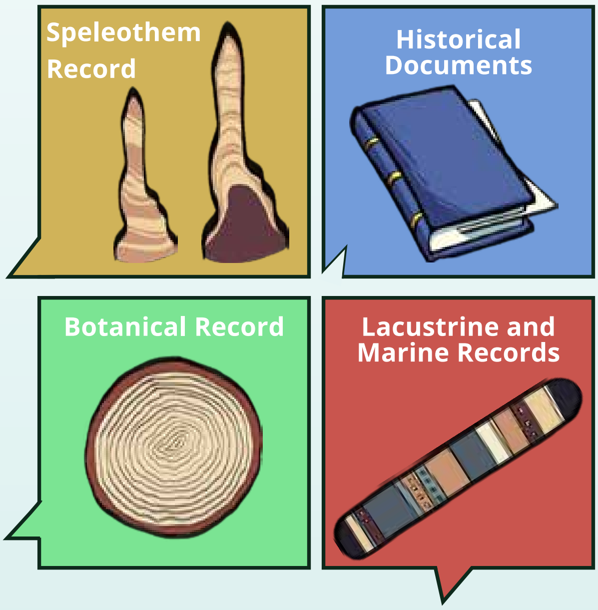
Historical record of global flood exposure and future flood trends using diferent climate models. Modified from reference [3]

Precipitation records, which are used to evaluate the return periods of floods, are too short or even absent in many regions. Moreover, most instrumental records are affected by land development, complicating the estimation of natural recurrence intervals of extreme floods.

Beyond the instrumental record...

Understanding the natural patterns of floods, in response to climate variability prior to the era of significant anthropogenic intervention in the climate system, is required. It is critical to extend records to understand the long-term flood variability at millennial to decadal scales to guide on future flood-risk adaptation.

Different paleoflood records such as riverine, lacustrine, marine, speleothem, botanical and historical documents can help us to understand the variability of past extreme events and improve future flood-risk assessments.



(1) IPCC (2021) Climate Change 2021: The Physical Science Basis.Cambridge University Press, 2391 pp
(2) Blöschl G et al. (2020) Nature 583: 560–566
(3) Hirabayashi Y et al. (2021) Sci Rep 11: 3740

Tracing the footprints of past floods

Rather than looking for clean caves to reconstruct past climate changes from stalagmites, the study of past floods using speleothems and detrital sequences require caves with some specific characteristics.

Caves with active rivers inside have intense and quick responses to rainfall events

Galleries with evidence of floods

Speleothems covered by sands / silts

Stalagmite with a thicker coat of sediments partially eroded by the impact of the dripping water.

Water-level marks in relation to floods

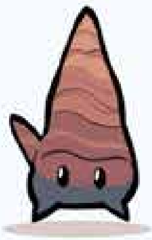
Visible **flood mark** along the cave after a flood event.

Sand and silt in elevated cave areas

Sand and silt deposited in higher cave passages, with respect to the cave streambed, inform about the karst water table during floods.

How are floods recorded?

Stalagmites & detrital deposits



During a flood event, sand and silt are transported through the **karst system.** The water can rise several meters from the streambed, flooding elevated areas of the cave. These sediments accumulate in protected areas from the main stream and/or blind cave passages, coating the surface of speleothems when the energy of the water decreases. The active precipitation of carbonate traps these detrital layers inside the speleothems.

Speleothems and detrital sequences situated next to a water stream can record ordinary floods. In contrast, those located far from the river or in the upper cave levels may only record extraordinary floods.

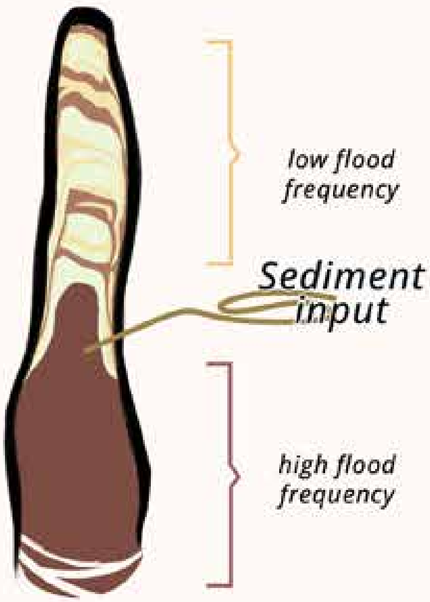
1 year Flood — *"Annual"*

100 year flood — *"Centennial"*

1000 year Flood — *"Millenial"*

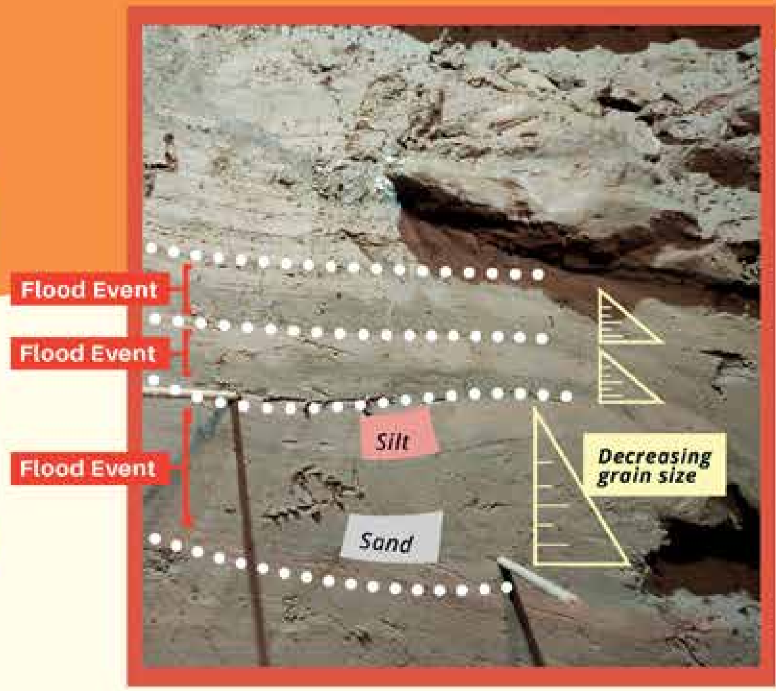
Flood events visible to the naked eye are recorded as detrital layers within the stalagmite.

The U-Th dating of the cleanest carbonate areas of the stalagmites provides robust age models. The location of the speleothem with respect to the streambed plays an important role in studying past floods, given that a balance between clean areas and flood layers should be found. Very dirty speleothems cannot be dated by U-Th but possibly by 14C.



The analysis of oxygen & carbon isotopes as well as trace elements in the carbonate inform about the climate conditions during the recorded flood periods.

The suspended sediment settles in low-energy basins, depositing the larger particles first followed by the silt and clay fractions. These sedimentary sequences accumulate for hundreds to thousands of years, forming distinguishable rythmites. These deposits are easily remobilised if they are not well protected from the main stream.



▲ *1 year Flood*

Sometimes an energetic flood can transport high amounts of sediment in suspension, which is suddenly deposited in a cave passage. In this situation, some passages can be completely blocked, generating an important change in the geometry of the gallery, affecting the water level during the next floods. This means that an ordinary flood (e.g. 1 year flood) can reach elevated areas (typically only affected by major floods) due to geomorphological changes caused by the sediment accumulation.

Dating detrital sequences

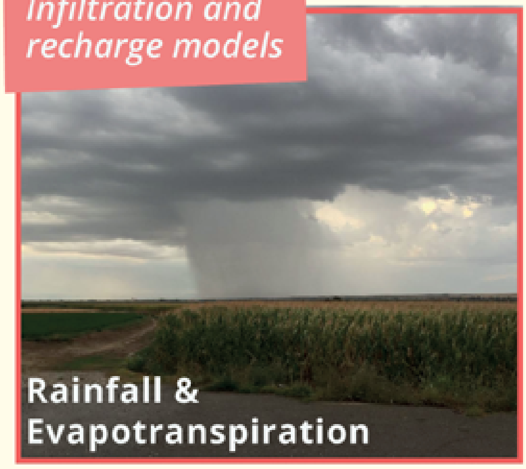
The chronology of clastic deposits can be determined by radiocarbon dating (^{14}C), which is applied to terrestrial plant macro-remains and charred organic matter found in sediments deposited during the flood. Alternatively, in the absence of organic matter, optically stimulated luminescence (OSL) dating can be used, provided the sandy layers are predominantly composed of quartz. This technique relies on the inherent ability of these minerals to accumulate environmental radiation after sedimentation.

Dating the detrital sequences is important not only for paleoflood reconstructions, but also to discern if coeval flood layers recorded in stalagmites correspond with extreme events or not.

The research on caves affected by floods

Karst systems have complex responses to rainfall, mostly based on hydrological thresholds and bypasses, and therefore show neither a linear nor gradual reaction. Although the floods in caves remain local and affect only marginally large populations, an abrupt increase in water levels inside the caves may threaten human lives, in particular when they are visited by tourists (e.g. show caves). As an example of a flood event in a cave, we all remember the rescue of children in Tham Luang cave in Thailand in 2018. Cave monitoring helps us to understand how the karst water table reacts to rainfall.

Infiltration and recharge models

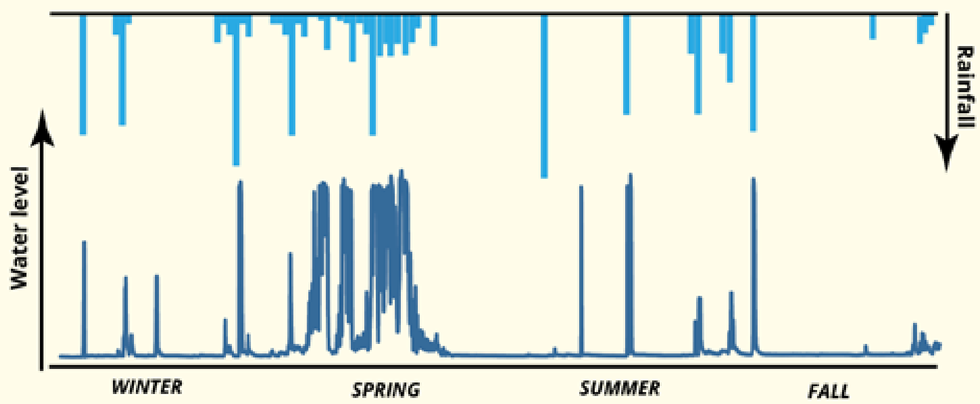


Cave hydrological monitoring

Quantification of paleofloods

Discerning the cave – flood magnitude is not straightforward since it may respond to different factors such as land use, changes in the sediment supply or changes in the cave geometry. For all these reasons, the cave hydraulic modeling, including the 3D structure of the conduits, as well as data from the water-level monitoring and discharge measurements, must be carried out to quantify flood magnitude recorded in the cave deposits.

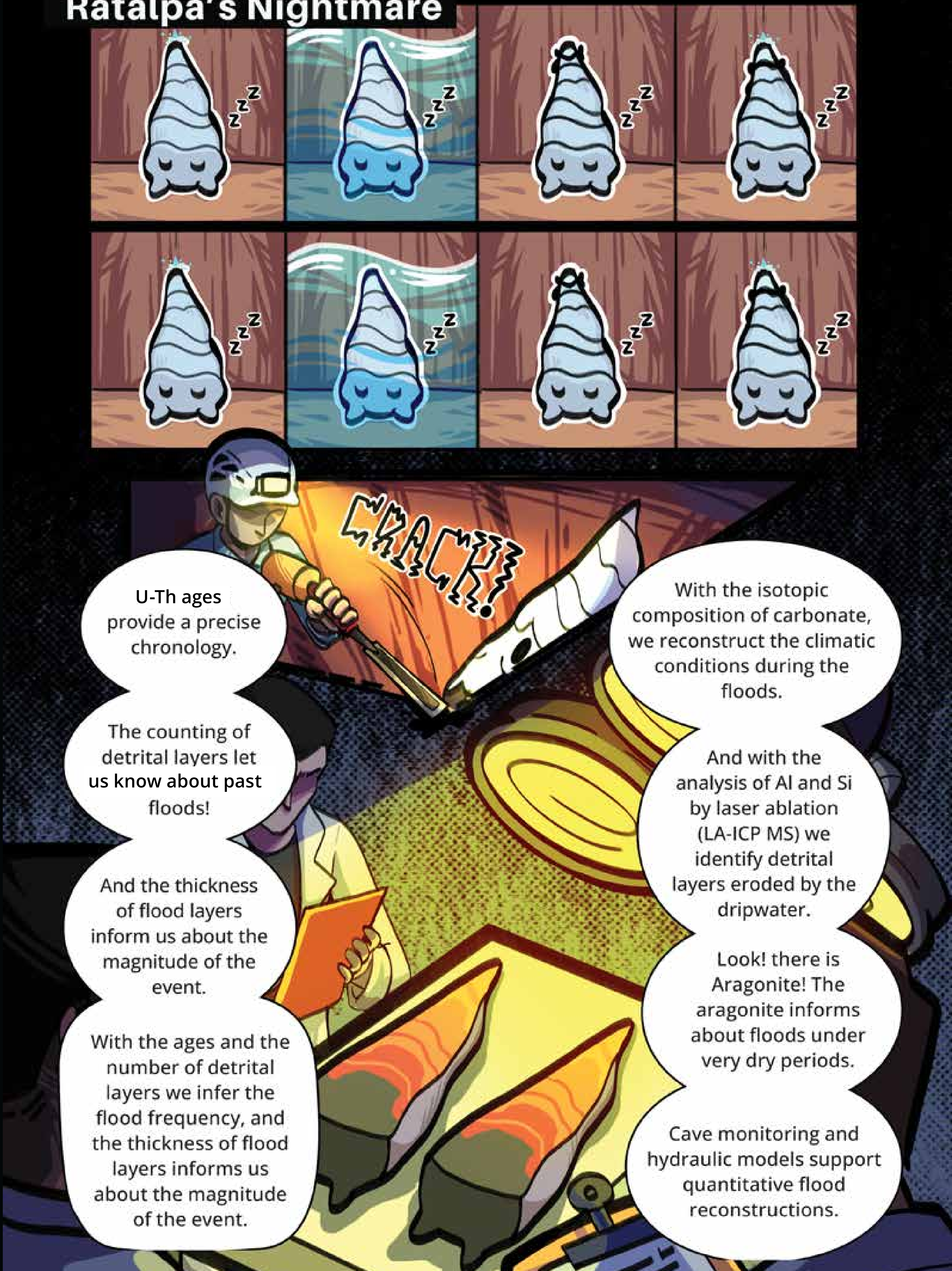
The infiltration and hydraulic models, the water level monitoring, and water – flow gauging allow us to establish an empirical relationship between the amount of rainfall, the aquifer recharge and the water flow in cave passages, to quantify the floods recorded in the cave.



Changes in the water level in response to rainfall events during the year. Different responses are observed depending on the amount of rainfall and the water stored previously in the karst system.

Funding: Miguel Bartolomé is supported by the HORIZON TMA MSCA Postdoctoral Fellowships Global 2022 MODKARST project (n° 101107943) funded by the European Union.

Ratalpa's Nightmare



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Tracking hydroclimate extremes from deep in the tropics

Natasha Sekhon[1,2,3], Celia Kong-Johnson[1], Annabelle Gao[1], Bryce K. Belanger[4], Sharon Tabujara[5], Jayrald V. Gatdula[6], Mart C. M. Geronia[7], Mónica Geraldes Vega[1,2], Justin Custado[1,2], Carlos C. P. David[7] and Daniel E. Ibarra[1,2]

Around 9% of the world population lives in southeast Asia, e.g. Philippines, Indonesia and Malaysia. The effects of climate change through severe typhoons, tropical droughts and extreme rainfall associated with the monsoon system and El Niño Southern Oscillation (ENSO) are expected to severely impact water resources, infrastructure, and the agrarian economy in southeast Asia.

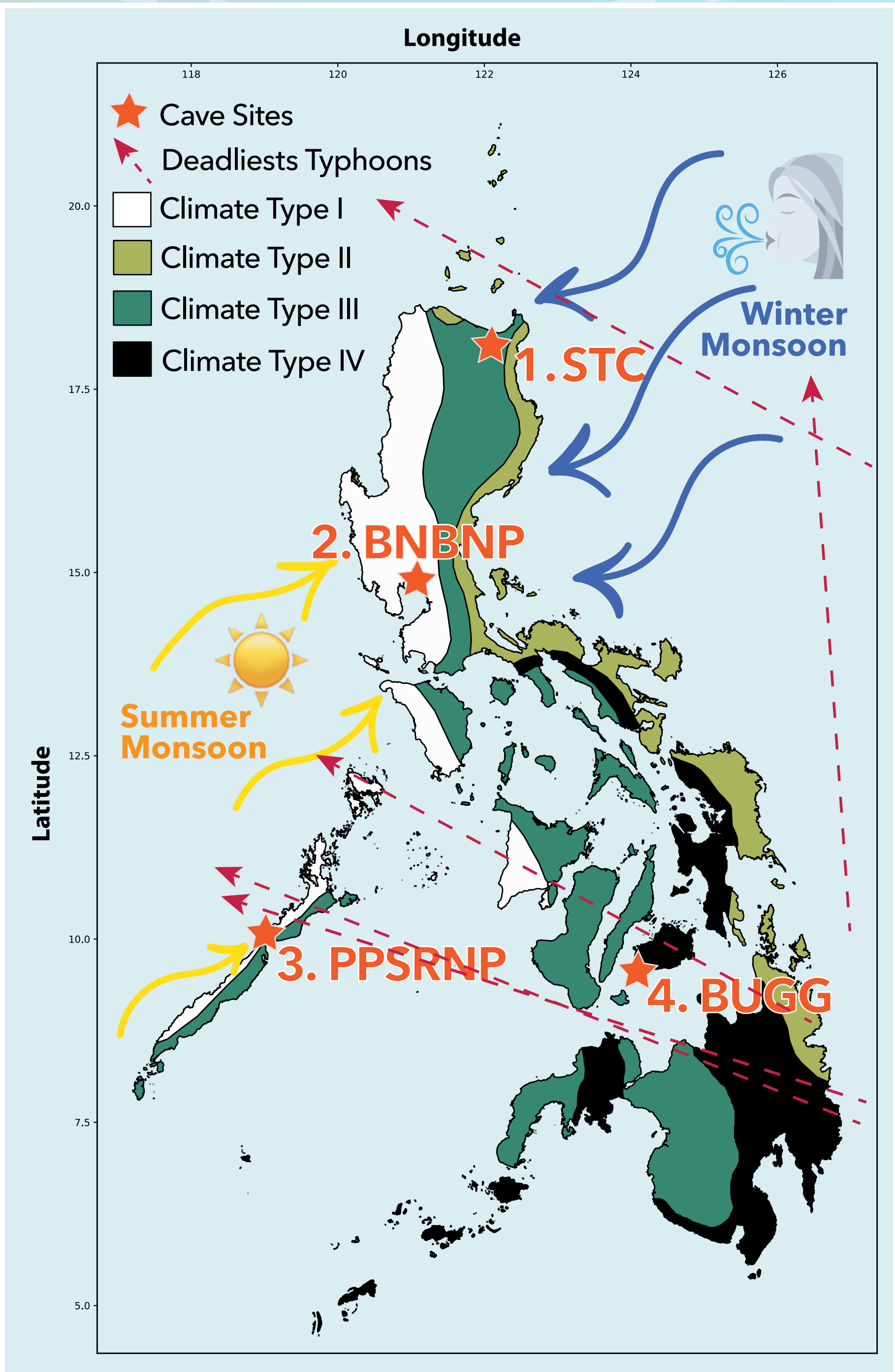


Figure 1: Map of the Philippines with the major climate types. The summer monsoon (Climate Type I) impacts the western seaboard and the winter monsoon (Climate Type II) impacts the eastern seaboard.

The orange stars and associated numbers indicate the location of cave systems that are being monitored:

1. Santa Teresita Cave (STC)
2. Biak Na Bato National Park (BNBNP)
3. Puerto Princessa Subterranean River National Park (PPSRNP)
4. Bohol UNESCO Global Geopark (BUGG)

The red dashed lines are typhoon tracks for the deadliest typhoons that have hit the Philippines over the last 10 years. Climate Type III and IV do no have distinct wet and dry seasons and are impacted by both the monsoon systems.

Cavers and researchers are checking the status of temperature and drip-rate loggers using a field computer.

From left to right: Edralin P. Orpilla, Bibem L. Jalam, Sharon Tabujara, Natasha Sekhon, Bryce K. Belanger

Sharon Tabujara takes notes while Natasha Sekhon prepares to change the plate sitting on top of an actively dripping stalagmite. Images are from PPSRNP, which is an 8-km-underground river system, and UNESCO World Heritage Site.

Our research team is investigating extreme wet and dry phases in southeast Asia to aid our understanding of the past in order to be better prepared for future flood and drought phases in the tropics.

A complex climate, characterized by seasonal change in wind circulation and precipitation driven by the winter monsoon and an anti-phased summer monsoon persists in the Philippines. El Niño and La Niña are phases of an ocean-atmosphere coupled system called El Niño Southern Oscillation (ENSO). In southeast Asia, the El Niño phase is characterized by cooler sea-surface temperature and a high pressure system that leads to drier climate.

Conversely, the La Niña phase is characterized by warmer sea-surface temperature and a low pressure system that leads to wetter climate. By analyzing the geochemistry of stalagmite growth layers, the chemistry of modern cave-drip water and modern calcium carbonate, we can quantify the hydroclimate history of the Philippines. We also install instruments to monitor changes in drip rate, temperature and CO_2 concentrations.

Data from these measurements help us assess the water-residence time in the bedrock, cave ventilation regimes and seasonality in calcite growth. This all ultimately dictates patterns in the ancient rainfall signal encoded in the stalagmites.

Figure 2:
(A) In northeastern Philippines, the dry season (pre-monsoon; April 2022) is highlighted with corn grains lying across the road for drying purposes.

(B) Flooded agricultural fields are a common sight during the wet season (peak monsoon; December 2022). Cave systems in this region (Location 1 in Fig. 1) sit under the karst hills seen in the background.

In April 2022, through close collaboration with the University of Philippines Diliman, Biak-Na-Bato National Park (BNBNP), Puerto Princesa Subterranean National Park (PPSNP; UNESCO World Heritage Site), and the Sierra Outdoor Club, we started our ongoing monitoring effort deep in the tropics.

By covering a large spatial distance of 10° in latitude, we target regions impacted by both the winter and summer monsoon, regions that are in the path of typhoons, and different types of karst (formed by calcium carbonate) landscapes.

Figure 3:
Two broken stalagmites (A, B) covering the Holocene period (last 11,700 years).

Stalagmite from Aries Cave (A) is influenced by the winter monsoon, and stalagmite from PPSRNP (B) is influenced by the summer monsoon. In addition, the two cave systems are very different.

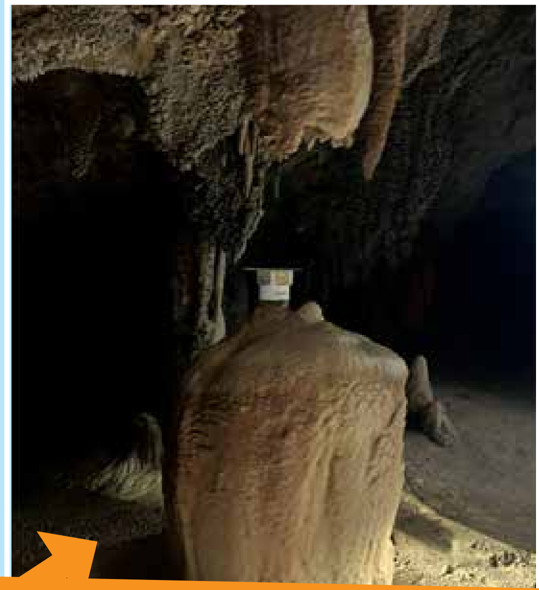
Aries Cave (C) sits under a karst hill with shallow soil and bedrock above the cave.

(D) PPSRNP is accessed via boat and an opening at the modern sea level sits under thick bedrock.

Our initial results demonstrate a relationship between rainfall above the cave to the drip rate in the cave. This is very exciting because it suggests that speleothems (mineral deposits formed from groundwater within underground caverns) that form in these cave systems would have responded to similar changes in rainfall in the past.

Initial stable isotope data of cave drip water points to a different moisture source between the caves in the eastern and western seaboard. Therefore, the growth of speleothems, which is sensitive to infiltrating rainfall, in the eastern cave systems will reflect the winter monsoons. Conversely, speleothems from the western seaboard will be impacted by the summer monsoon.

Monitoring data from instruments is downloaded every six months. Here, Sharon and Natasha investigate cave-air temperature and CO_2 measurements.



A drip-rate logger captures variation in drips through time. The data is then compared against surface-weather station data to discern correlations.

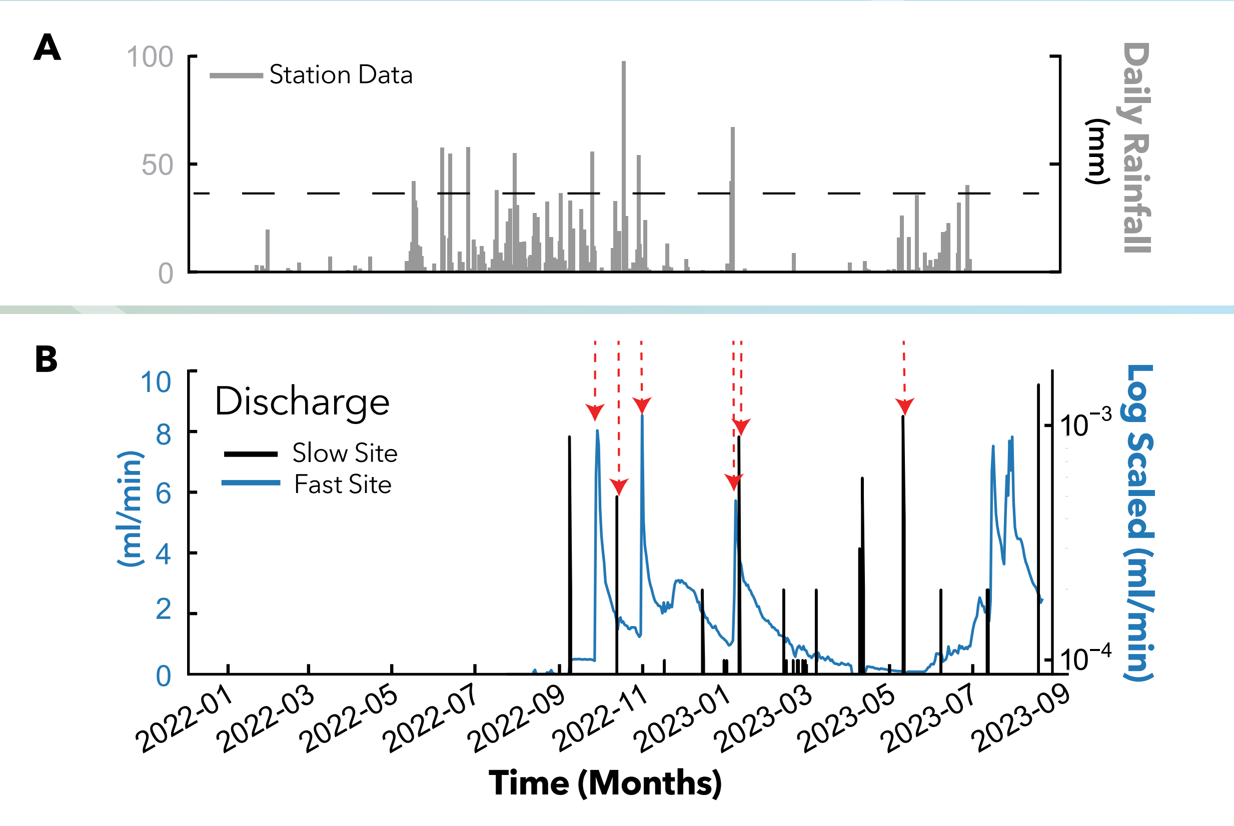
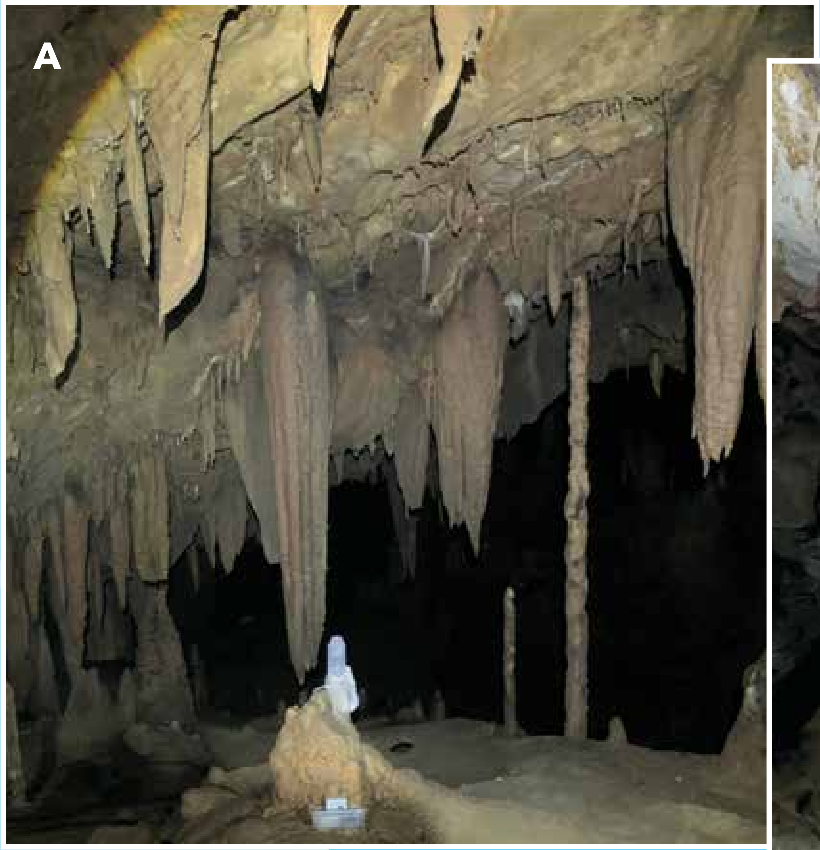


Figure 4:
(A) Daily rainfall data from weather-station data outside Manila, plotted against time. (B) Discharge/drip-rate time series for two (slow and fast) sites in BNBNP (Location 2 in Fig. 1). The red dashed arrows highlight spikes in the drip rate following heavy rainfall events at the surface.

This suggests that stalagmite growth layers will be sensitive to wet periods through time. Our goal is to continue this monitoring effort for multiple years to discern climate variability as opposed to weather conditions.



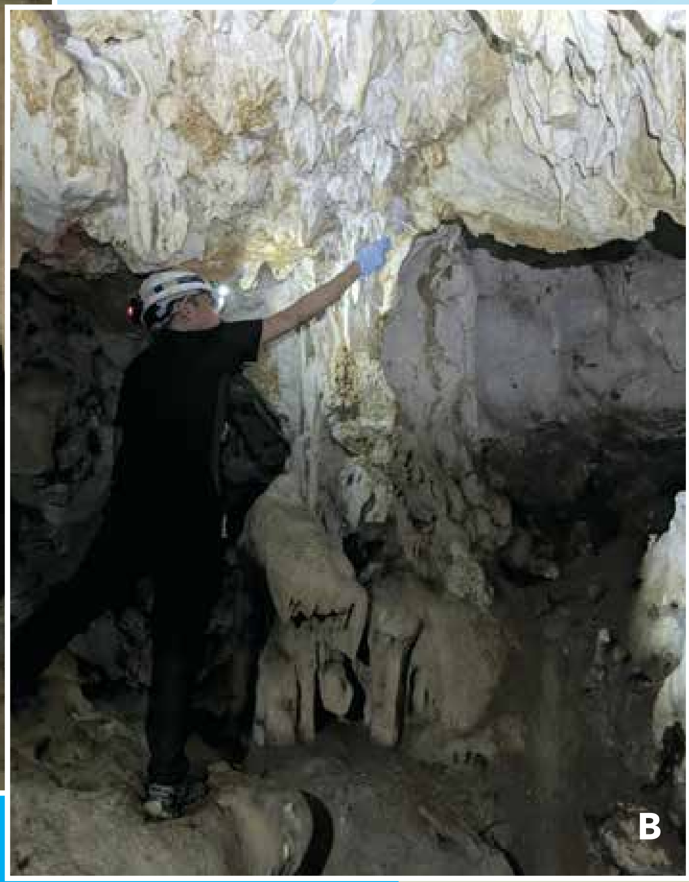
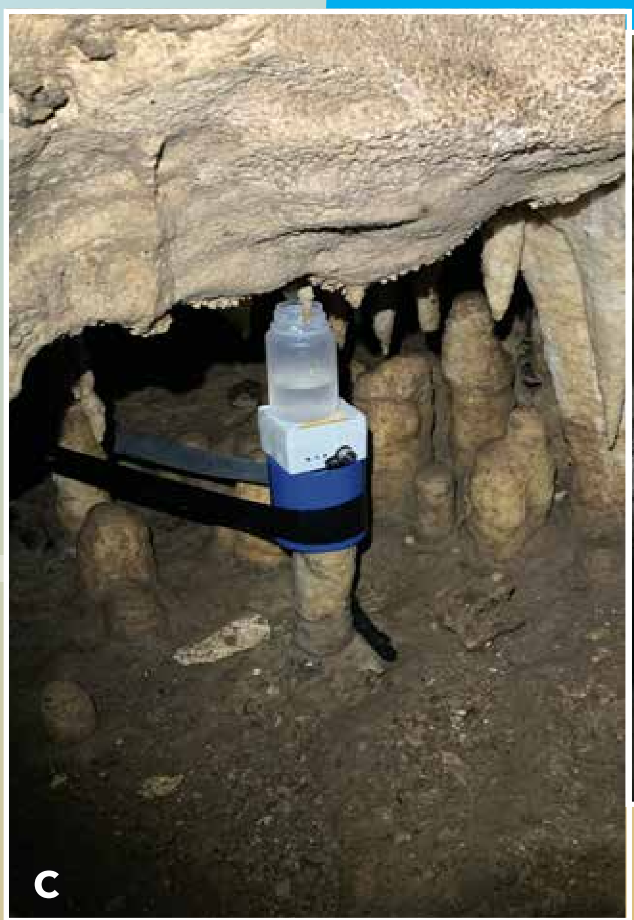


Figure 5:
(A–D) indicate different ways in which cave drip water is collected within different chambers of different cave systems.



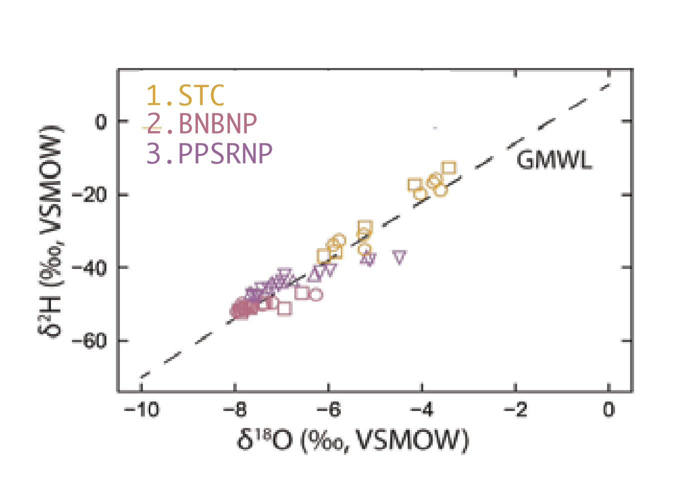


Figure 6:
A scatter plot with hydrogen and oxygen isotopes analyzed in dripping water (δ^2H and $\delta^{18}O$, respectively). The colored symbols correspond to three different locations (STC, BNBNP, PPSRNP). The different symbols indicate different sites within each cave with an aim of monitoring at least two sites within each cave.

With promising preliminary results and a continued collaborative effort to monitor cave systems deep in the tropics, we are well equipped to use various geochemical tools to investigate periods of past hydroclimate variability.

By looking at anti-phased patterns in the geochemistry extracted from speleothem layers and corroborated by the monitoring efforts, we aim to disentangle the range of natural variability in the climate system through the Holocene (last 11,700 years).

Acknowledgments
Many thanks to Elizabeth Maclang, Superintendent of Puerto Princesa Subterranean River National Park; board members of Protected Areas Management Bureau and Palawan Council for Sustainable Development. Field work in Santa Teresita would not have been possible without assistance, support and guidance from Nida Santos Dela Cruz and members of the Sierra Madre Outdoor Club. We also acknowledge seed grant funding from the National Cave and Karst Research Institute and Brown University. We would also like to thank Prof. Kim Cobb and Dr. Anna Waldeck at Brown University for guidance and assistance in analyzing cave drip water.

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Changing rainfall patterns over the Amazon rainforest

Gerbrand Koren; Illustrations: Cirenia Arias Baldrich

I have always been interested in tropical forests and I am now studying these ecosystems as a climate scientist. You have probably already heard about climate change and increasing temperatures in the news or at school. But what you have heard is not the complete story; climate change also leads to changes in rainfall patterns, which can result in droughts or floods in tropical forests. I find it exciting that we can learn about the past climate from tree rings. In this article, I will take you on a journey to the Amazon forest and share how we can use tree rings to improve projections of the future climate.

Gerbrand Koren in front of a tree cross-section with visible tree rings in the Ramon Margalef building (Barcelona).

Photo by Conscious Design, Unsplash

The Amazon in a changing climate

The Amazon forest is the largest tropical forest on our planet. It is home to many different plant and animal species that live together in this ecosystem. The trees and other plants in the Amazon forest contain a lot of carbon. All this carbon was once in the form of CO2 in the atmosphere and was then taken up via photosynthesis. Photosynthesis can be measured from space using satellite proxies. In the map in Figure 1, you can see the highly productive tropical forest regions.

Because of climate change, the conditions in the Amazon are changing. We are seeing more floods and droughts in the region. You can also detect more extreme dry and wet periods in river-flow measurements in Figure 1. The maximum monthly flow rate for each year shows an increase, whereas the minimum monthly flow rate shows a decreasing trend for the region.

During droughts, fires can ignite more easily, and the fires also tend to be more intense. Through these fires, the carbon that was stored in the plants is released back into the atmosphere. Dry conditions can also reduce the photosynthetic uptake of carbon. This happened in the Amazon during the severe 2015/2016 and 2023/24 droughts. The increased fires and reduction of photosynthesis during these droughts in the Amazon forest led to further increases of CO2 concentrations in the atmosphere.

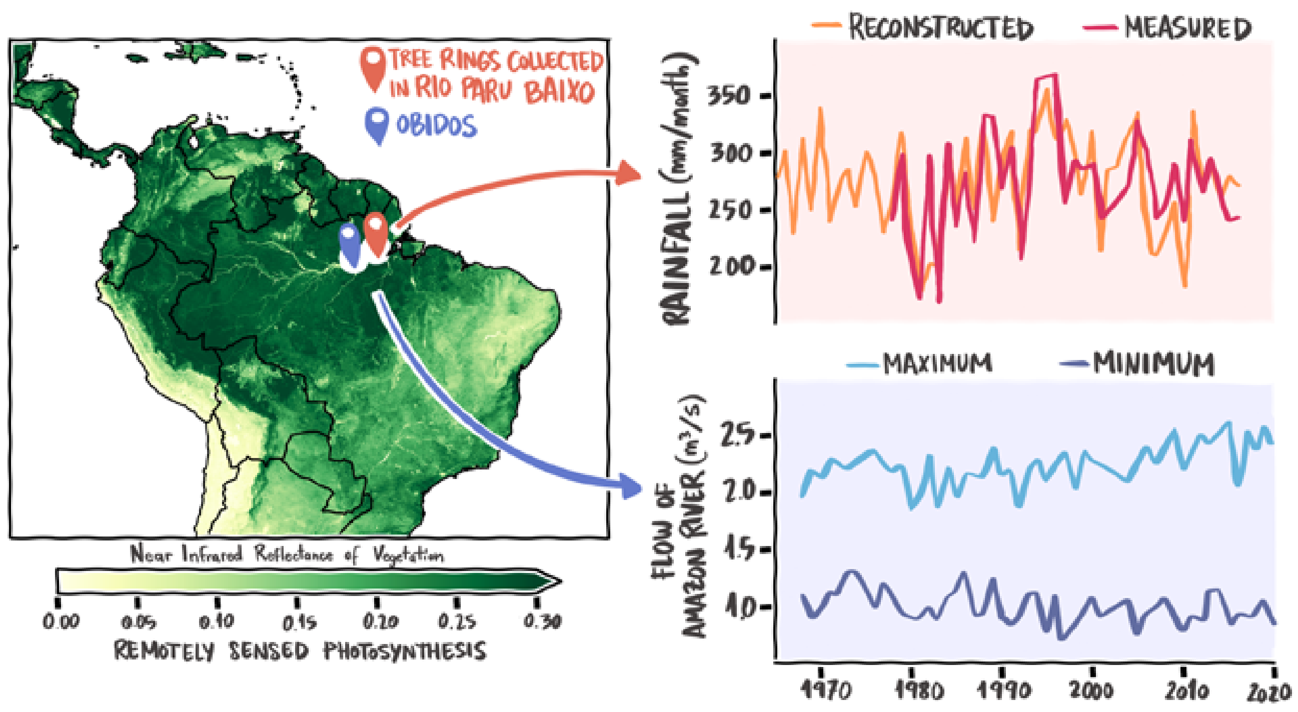

Figure 1:
Measurements of hydrology and vegetation activity in the Amazon forest. Left: Map of a remotely sensed photosynthesis proxy *(Data source: MODIS).*

Top right: Precipitation during the wet season (February to July) for the eastern Amazon, inferred from tree-ring growth ("reconstructed", orange line) and measured precipitation ("measured", red line) *(Data source: Granato-Souza et al. 2020).*

Bottom right: River-flow measurements from the Óbidos station along the Amazon river *(Data source: National Water and Sanitation Agency, ANA, Brazil).*

Tree-ring measurements from the Amazon

The width of tree rings tells us how much a tree has grown in a year. This also gives us information about the climate during those years. For instance, tree rings can be used to estimate how much the amount of rainfall varied from year to year. Figure 1 shows a comparison between precipitation reconstructed from tree-ring data and direct measurements made with instruments. The agreement between data sets for the overlapping years suggests that the reconstructed precipitation from tree rings, which covers ~250 years (not shown), is a reliable indicator of past precipitation.

Besides the width of the tree ring, we can also measure its isotopic composition. Measurements of oxygen isotopes in tree rings from the Amazon have indicated a decrease in dry season precipitation. This agrees with the negative trend in river flow rate for the driest months shown in figure 1.

However, isotopes in tree rings do not only record past rainfall, but can also reveal how vegetation responded to this changing rainfall. A strategy of vegetation to reduce its water loss during droughts is to close openings ("stomata") in their leaves. This can result in higher water-use efficiency (amount of carbon fixed divided by the amount of water lost via transpiration). This change can be detected from the ratio of carbon-13 and carbon-12 isotopes in the tree rings.

Figure 2: Conceptual overview of the main processes described in this article. The changing environmental conditions result in impacts on vegetation that are recorded in tree rings which can improve climate models, and therefore, the reliability of their projections. This illustrates how measurements of the past can improve our predictions for the future.

Improving vegetation models

What will the climate be like in 2050, or 2100? And will the Amazon forest still exist as we know it today? To answer these questions, researchers use climate models. These models are based on mathematical equations that describe the complex processes of the climate system. You can imagine that the more realistic these models are, the more reliable their output is. That is why a lot of time and energy is spent on further improving these climate models.

The tree-ring width and the isotopic (carbon and oxygen) composition of tree rings contain information about the past climate and the response of vegetation. Untangling this information is difficult, but will ultimately provide us with a better understanding of plant behavior. If we know how plants have responded to a changing climate in the past, we can use this information to improve vegetation models or climate models as summarized in figure 2, leading to more reliable climate projections.

Beyond tree rings

Besides tree rings, there are other records that can inform us on climate and vegetation, summarized in figure 3. Combining these different methods helps us to understand past climate changes and improve projections for future climate.

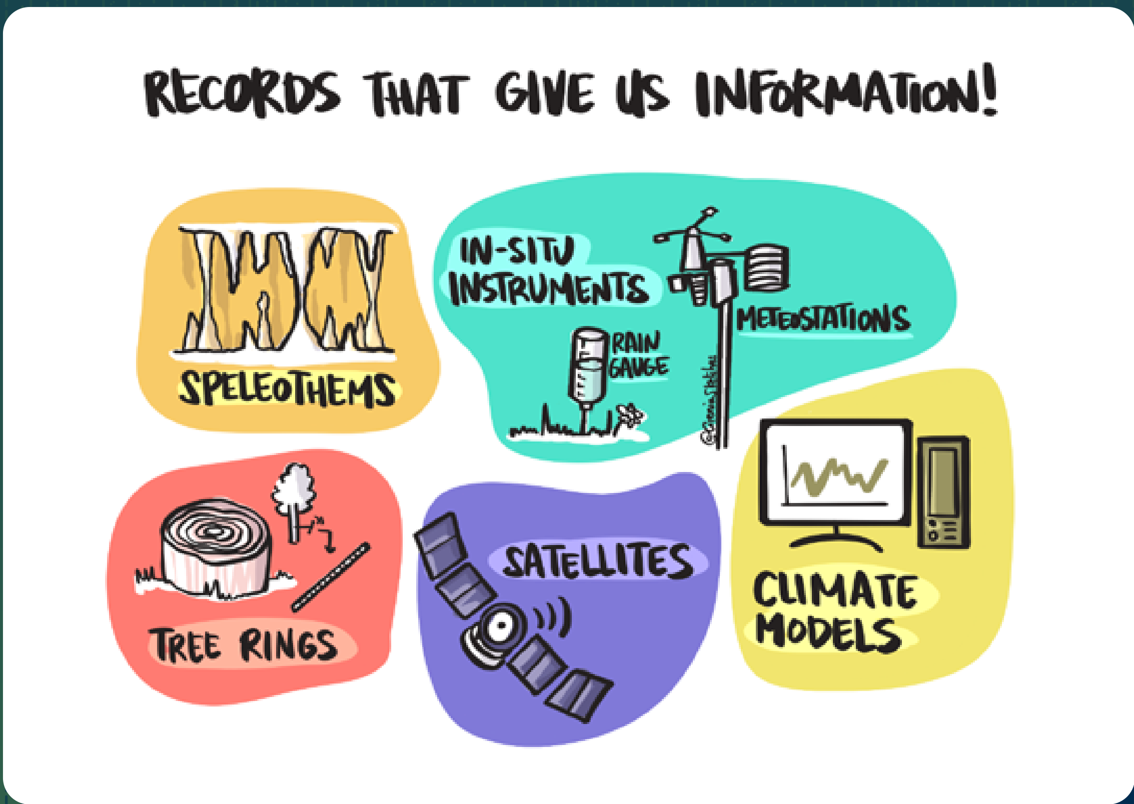

Figure 3: Overview of paleorecords, measurement instruments and models.

Further reading

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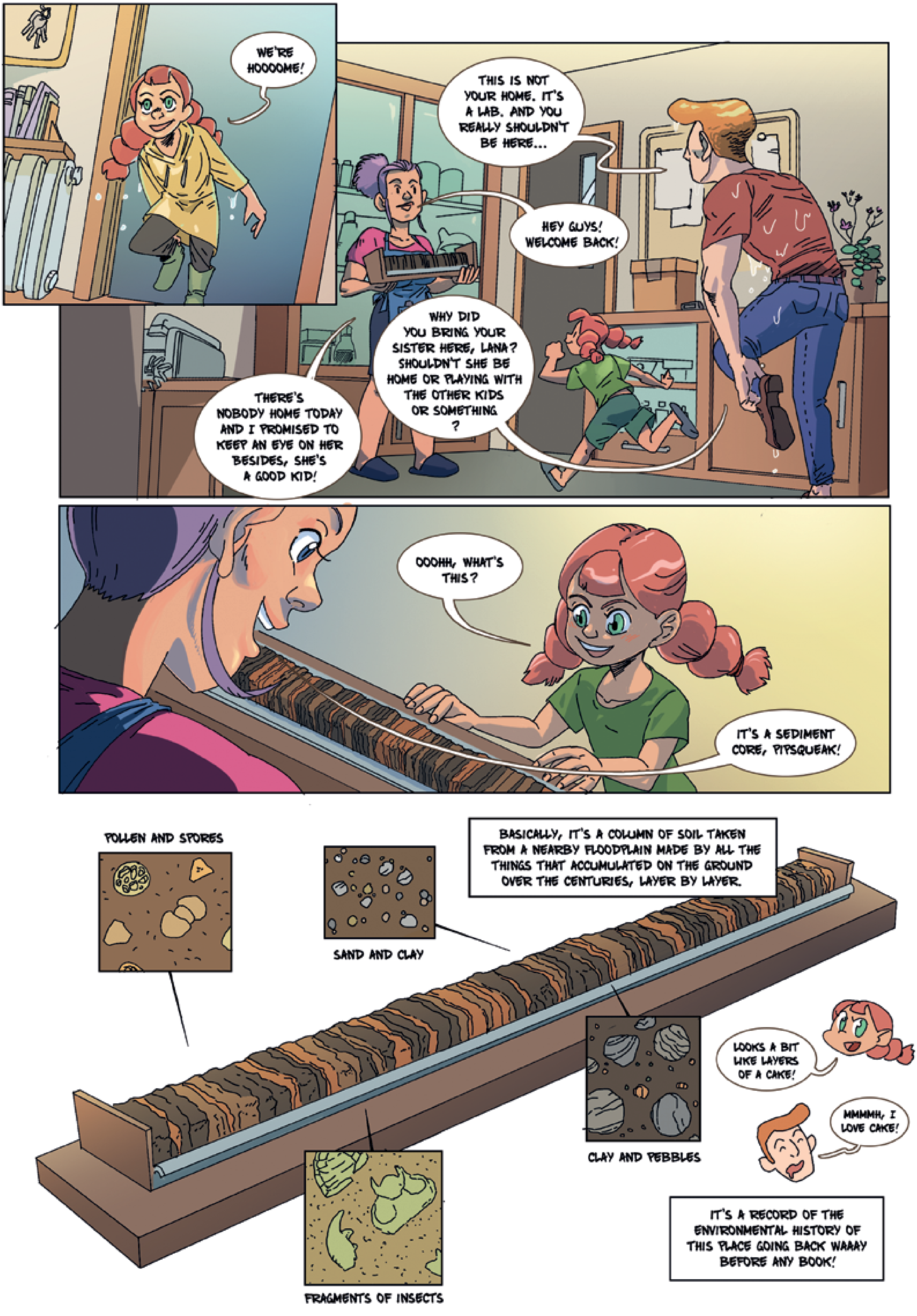
FUTURE MEMORIES OF A RIVER

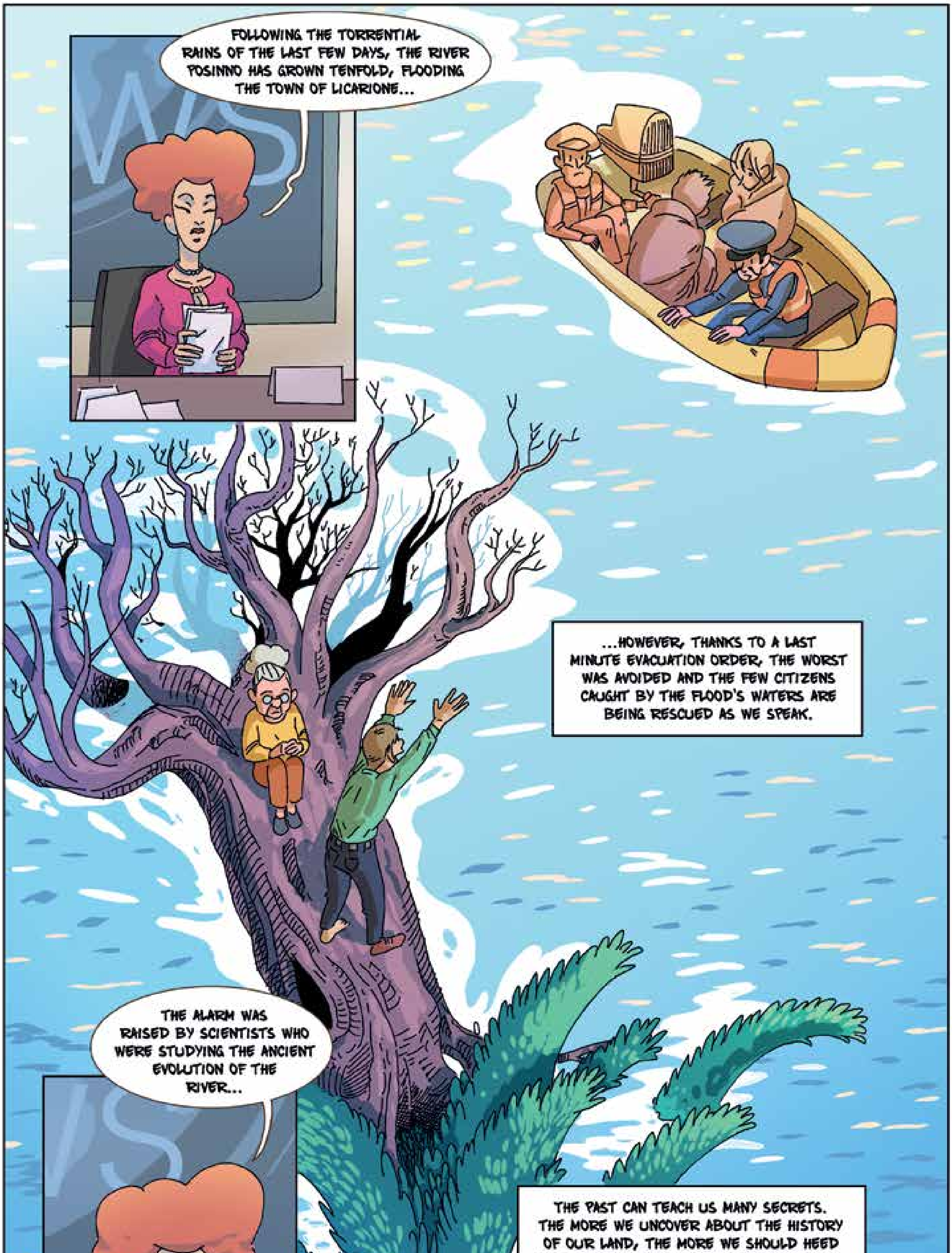
BY
MARCO PALOMBELLI
PETER GITAU


WE'RE HOOOOME!
THIS IS NOT YOUR HOME. IT'S A LAB. AND YOU REALLY SHOULDN'T BE HERE...
HEY GUYS! WELCOME BACK!
WHY DID YOU BRING YOUR SISTER HERE, LANA? SHOULDN'T SHE BE HOME OR PLAYING WITH THE OTHER KIDS OR SOMETHING ?
THERE'S NOBODY HOME TODAY AND I PROMISED TO KEEP AN EYE ON HER BESIDES, SHE'S A GOOD KID!
OOOHH, WHAT'S THIS?
IT'S A SEDIMENT CORE, PIPSQUEAK!
BASICALLY, IT'S A COLUMN OF SOIL TAKEN FROM A NEARBY FLOODPLAIN MADE BY ALL THE THINGS THAT ACCUMULATED ON THE GROUND OVER THE CENTURIES, LAYER BY LAYER.
POLLEN AND SPORES
SAND AND CLAY
CLAY AND PEBBLES
FRAGMENTS OF INSECTS
LOOKS A BIT LIKE LAYERS OF A CAKE!
MMMMH, I LOVE CAKE!
IT'S A RECORD OF THE ENVIRONMENTAL HISTORY OF THIS PLACE GOING BACK WAAAY BEFORE ANY BOOK!


BY LOOKING AT THE GRAIN SIZE OF SEDIMENTS IN THE VARIOUS LAYERS, WE CAN LEARN A LOT ABOUT PAST FLOODS...
THE LARGEST FLOODS CAN CARRY BIG SEDIMENTS LIKE COBBLE STONES, OR EVEN BOULDERS!
AND THE DEPTH IN THE CORE TELLS US HOW FAR IN THE PAST THEY HAPPENED...
TIPPITY TAPPITY
IF WE COMBINE THE TYPICAL GRAIN SIZE WITH STATISTICAL OR HYDROLOGICAL MODELS, WE CAN FIGURE OUT THE HIGHEST FLOW OF THE RIVER...
THIS IS WORRYING! THERE WERE SOME VERY LARGE FLOODS IN THE PAST!
LOOK AT THE TIME PERIOD... IT CORRESPONDS TO A TIME WHEN THE CLIMATE WAS VERY SIMILAR TO THE ONE WE ARE EXPERIENCING THESE DAYS!
CAPACITY OF THE DAM IS BASED ON DATA THAT ONLY GOES BACK AS FAR AS 50 YEARS AGO!
...AND IN THAT PERIOD THE RIVER NEVER GOT HIGHER THAN 7 METERS!
WE NEED TO WARN THE MAYOR!
FAST!!
THEY BOTH FORGOT THEIR UMBRELLA!
ADULTS...

WE ARE CLOSELY MONITORING THE SITUATION, MAYOR. THERE IS NOTHING TO WORRY ABOUT.
IF THE WATER LEVEL IN THE DAM REACHES 98% CAPACITY, I'LL GET A CALL...
....BUT I'M SURE IT WON'T HAPPEN.
MISS MAYOR! MISS MAYOR! WE ARE IN GRAVE DANGER!!
THE RAIN IS COMING DOWN AS HARD AS 140 YEARS AGO. THE LEVEL OF THE RIVER WILL RISE BY AT LEAST 10 METERS!!
RIIIIIIIIIIIIIINNGG
CAPTAIN, BEGIN THE EVACUATION PROCEDURES IMMEDIATELY! I WANT AS MANY PEOPLE SAFELY OUT OF TOWN AS SOON AS POSSIBLE.
YES MA'AM!


SPLOOOSH!!
YES, I WANT THE NEWS ON EVERY CHANNEL RIGHT NOW. I'M COMING TO THE TV STATION TO REPEAT THE ANNOUNCEMENT IN PERSON.
BRRRM
I'LL BE THERE IN TEN!
SPLASH
THANK YOU!
AND THANK YOU TOO, OLD FRIEND.


FOLLOWING THE TORRENTIAL RAINS OF THE LAST FEW DAYS, THE RIVER POSINNO HAS GROWN TENFOLD, FLOODING THE TOWN OF LICARIONE...
...HOWEVER, THANKS TO A LAST MINUTE EVACUATION ORDER, THE WORST WAS AVOIDED AND THE FEW CITIZENS CAUGHT BY THE FLOOD'S WATERS ARE BEING RESCUED AS WE SPEAK.
THE ALARM WAS RAISED BY SCIENTISTS WHO WERE STUDYING THE ANCIENT EVOLUTION OF THE RIVER...
THE PAST CAN TEACH US MANY SECRETS. THE MORE WE UNCOVER ABOUT THE HISTORY OF OUR LAND, THE MORE WE SHOULD HEED ITS TEACHINGS AND USE THE KNOWLEDGE WE, SOMETIMES QUITE LITERALLY, UNEARTH.
END

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After the storm:

How clues from past hurricanes help prepare us for our future

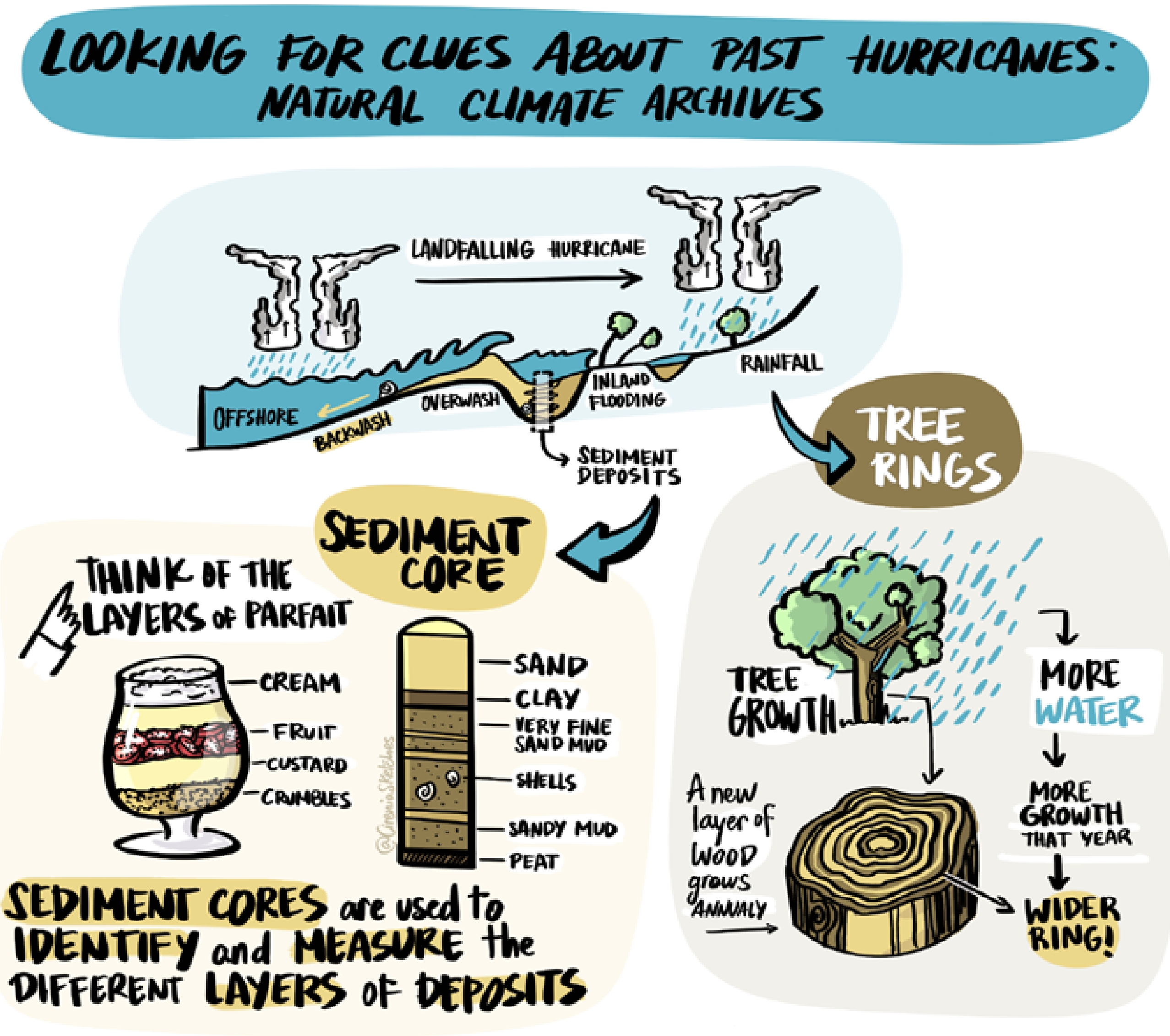
Joshua Bregy and Emily Elliott; Illustrations: Cirenia Arias Baldrich

If you were asked to think of devastating tropical cyclones (TCs), a few names likely come to mind: Mitch (1998), Katrina (2005), Haiyan (2013), Harvey (2017), Maria (2017), Dorian (2019), Goni (2020), Ian (2022), and the list continues. While the list seems to be densely populated by the names of infamous storms, the reality is that high-impact events are rare.

The more extreme the storm, the rarer it is. The current instrumental record extends to the 1850s in the North Atlantic, and while that may seem like a long time, the devastation wrought by these storms shows that our benchmark for the worst-case scenario is severely underestimated.

To illustrate this, look at Camille (1969) and Katrina (2005), which struck the same area in Mississippi, separated by only 36 years. If you ask anyone from the area, Camille was the storm that left a painful legacy. The storm surge was catastrophic, and Camille was used as the standard with which to compare subsequent storms for years. However, in 2005, Katrina—a storm that was less intense than Camille at landfall—produced a storm surge that far exceeded that of Camille. This storm scarred the coast and set a new standard for tropical cyclone extremes. This illustrates the point that even in two “extreme” events that share similar categories and locations of impact, no two storms are created equally, and we must do a better job of understanding the drivers of TCs if we want a chance to mitigate their impact.

To this end, the instrumental record has been invaluable in understanding these storms, especially with respect to the internal dynamics of a TC. Unfortunately, these data alone are not enough to fully capture that range of variability exhibited by these systems. This is particularly concerning as we continue experiencing the historically unprecedented ongoing warming trend,



which models indicate will lead to more intense TCs. In the face of climate change, how can we understand TCs and their associated hazards despite a relatively short (and sometime fragmented) instrumental record? The answer is that the best way to look forward is by looking back to extend our records in time using paleoclimate proxies to reconstruct paleohurricanes. This subdiscipline of paleoclimatology, where we use natural climate archives (i.e. proxies) to reconstruct past storm events, is called paleotempestology.

When a TC roars ashore, it brings with it an onslaught of water by both sea and sky. Water is the leading cause of fatalities in a storm, and directly on the coast storm surge is the primary threat. Waves of water rush forward, pummeling the shore as the sea claims everything in its way, a problem only exacerbated by sea-level rise. From the sky comes torrents of rainfall, which brings the effects of a TC inland and can lead to a host of cascading hazards: areal flooding, landslides, sediment and contaminant laden waters, nutrient overloading, eutrophication and even outbreaks of disease. Modeled data indicate that TC rainfall intensity will continue increasing as a consequence of warming. Despite the danger these two hazards (TC surge and precipitation) pose to people, they are the key to understanding prehistoric hurricanes.

TCs are architects of the coast, using storm surge to transport sand, according to the storm's beachside blueprints. If you have ever seen aerial photographs or videos of the beach following a TC, you may have noticed areas where sand has spilled behind the beach, forming a splay of sand that breaches into the vegetated, marshy, or lagoonal area behind. As the storm approaches, the sand is picked up and transported inland by increased wave energy as the ocean churns. The larger the storm surge, the greater the capacity for sand movement as it washes up and over the shoreline, and moves inland. When the wave energy subsides, that sand is deposited inland, essentially leaving a geologic fingerprint of the storm. If we are lucky, the sand transported by the surge will be deposited in a coastal lake, lagoon, estuary or marsh, where it will be buried by the fine-grained background sedimentation of the relatively quiescent environment. Think of it like a parfait: the yogurt or custard acts as the primary feature of the dish (background sediment like mud) with crumbled coarse bits of fruit or granola in different, defined layers interspersed throughout (sand deposits). We can then take a sediment core to identify and measure the different layers, similar to the way you can identify the layering of the parfait when it is in a glass. The observations that we obtain from these sediment deposits provide important information regarding the frequency of TCs. Moreover, if the sediment core contains a deposit from a modern TC, like Camille or Katrina, we can use that storm as a metric with which to compare previous events. By analyzing both the sediment from the paleohurricane and the modern storm, we can estimate storm surge height that would be required to deposit both layers of sediment, which can then help us understand how intense TCs were in the past. We can then use this information to assess the pre-industrial and pre-anthropogenic influence of TCs along our coastal zone to truly assess how storm intensity is increasing with warming temperatures and overall climate change. This information is critical for understanding the frequency and intensity of future storms and how we can prepare for such events.

The effects of a TC, however, are not restricted to the coast. Farther inland, rainfall from TCs can bring a host of other hazards, especially flooding. While the risks associated with TC rainfall will continue to increase in response to warming, it remains a critical part of regional hydroclimates and is an important water source for ecosystems. Unlike storm surge, which reworks sediment and makes a deposit, identifying the signature left by rainfall is much more subtle. TCs are an important source of water for trees, especially in areas where the soil properties allow water to drain quickly. The large volume of water produced over a period of 2–3 days raises the water table, which trees are then able to readily access and grow. As trees produce a ring every year, thereby providing an absolute date, it is possible to reconstruct the amount of TC rainfall for a year by measuring the width of a ring. Just like people, trees need water to live. More water means more growth, i.e. wider rings, so scientists studying tree rings, or dendrochronologists, can see past hurricanes by looking for thicker rings. Essentially, tree rings can act as a weather station that can exclusively capture TCs. Measuring ring width is just one way to reconstruct TCs using trees; the presence of unusual growths in the ring, like false rings, and the chemical signals in the wood has also been shown to indicate the occurrence of a TC in the past. Because we can correlate different trees in the study area expanding through different age ranges, like different pieces of a puzzle, this technique can be incredibly useful for understanding the larger picture of regional storm patterns. Presently, longleaf pine and baldcypress have been important species for TC reconstructions, though other tree species are under examination for their use as paleohurricane archives.

These two environmental indicators, or proxies, have have been invaluable for extending the storm record and understanding TCs and their response to climate change. However, there are several important caveats that must be addressed if we want to have a full understanding of the TC climate. Both sediment cores and tree rings have their strengths and weaknesses that make it difficult to connect them with one another. Two particular issues come to mind: First, there is an issue of temporal resolution. Tree rings produce a ring every year, and depending on the species, it is possible to sample at seasonal timescales. Conversely, sediment cores typically have a much coarser resolution, with annually resolved records being rare. Further, tree-ring records are shorter than sediment records, largely due to logging practices and the low preservation potential for fallen trees. While some of this can be resolved by relying on wood samples from historical structures, it remains difficult to reach the same record length as sediment cores. Second, the proxies are responding to different components of a TC, which have different thresholds at which they are recorded. For example, a particularly intense storm may be required to create an overwash deposit, whereas a tree will generally respond to TC rainfall regardless of storm intensity. Conversely, it is typically easier to identify individual events in sediment records, whereas trees may amalgamate multiple TCs into a single ring.

While challenging, with an appropriate understanding of what each proxy archive is recording (e.g. TC precipitation in trees vs. TC surge from storms) and statistical rigor, modeled reconstructions of past TCs using both sediments and trees has remained an area of active research in paleotempestology and shows promise in the development of more well-rounded records of TC frequency and intensity through time. Furthermore, with new records coming out every year, we are another step closer to better understanding how TCs change with the climate system. Of course, this work is meaningless if we do not use our results to help shape policies and develop infrastructure designed to create resilient communities and address social and environmental justice issues in the face of climate change. **So, while paleotempestology provides a critical role in looking to the past to contextualize present storms, we must integrate this work into the larger context of working with coastal managers, engineers, policy makers, social and environmental advocates, and most importantly, coastal communities, to build an equitable, sustainable future for our coastlines in the midst of a rapidly changing world.**

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Global warming impacts on floods in high mountain regions

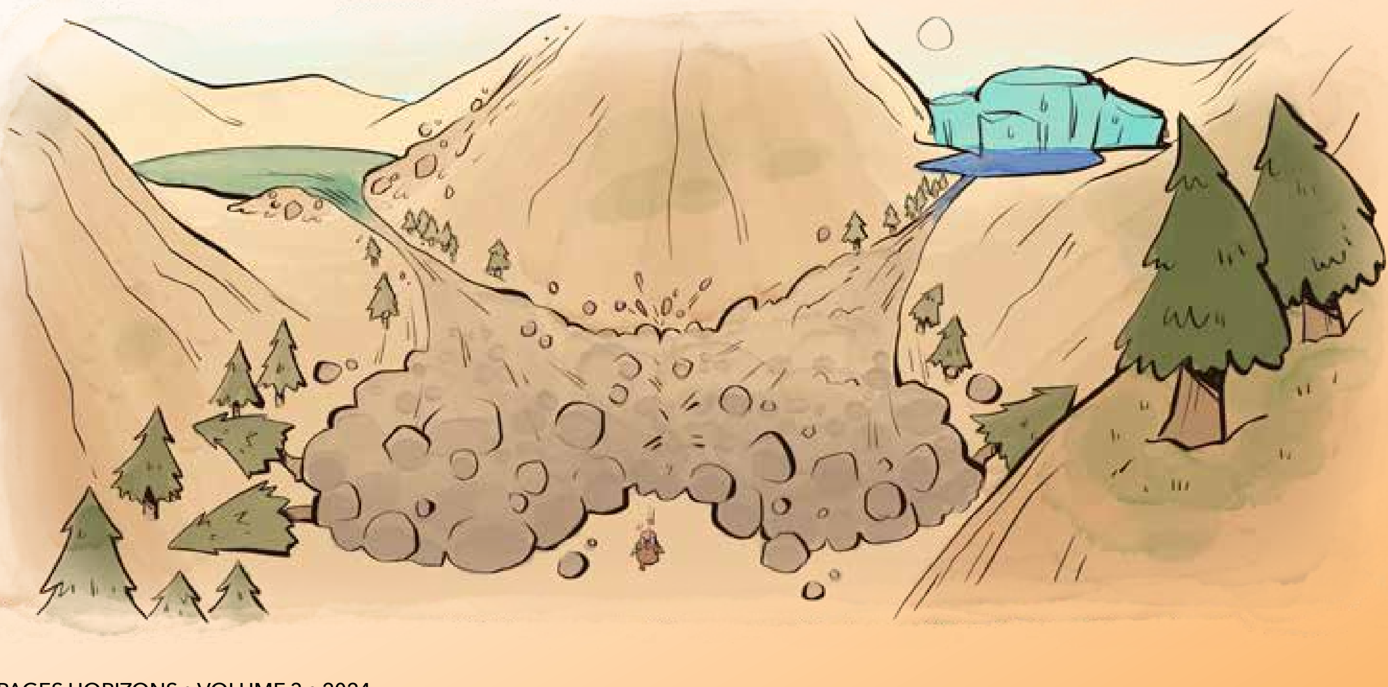
Juan A. Ballesteros-Cánovas[1], Ray Lombardi[2] and Gerardo Benito[1]; Illustrations: Ian Cooke-Tapia

Mountains are formidable ecosystems that hold unique resources for human well-being. Climate change is more pronounced in mountain regions where high elevation amplifies the rate of warming, impacting glaciers and the cryosphere. Some mountain regions are even heating up twice as fast as the mean global temperature. At the same time, mountains are highly sensitive to direct human impacts, mainly in forest cover and land uses. The frequency and magnitude of extreme hydrological events could increase in response to these changes, jeopardizing the sustainable development of communities. We must understand how climate warming is affecting extreme floods impacting mountain communities to facilitate adaption and mitigation of future disasters.

Sustainable development in the face of climate change requires us to anticipate how the magnitude or timing of floods may change. Accurate prediction requires an understanding of what triggers a flood and what elements are involved. First, we need to know what the specific mechanisms are that generate a flood event with extreme discharges (how fast a volume of water moves) and whether these mechanisms change in a warmer climate. To identify a mechanism, we consider: 1) what the source of the water is, and 2) how it moves through a river system.

In colder climate periods, glaciers hold much of the water sources in mountain regions. But in recent decades, rising temperatures are responsible for melting glaciers. As glaciers recede, they form new lakes trapped behind unstable moraines (sedimentary mounds deposited at the front of the glacier) that act as dams. When these moraines are subject to certain conditions, the glacial lakes burst from their natural dams, causing a high volume of water to rapidly move through the river valley. This type of flood mechanism, called a glacial-lake outburst flood (GLOF), results in large disasters for human settlements and infrastructure in mountain river valleys. A comparable flooding process takes place when higher temperatures unsettle mountain slopes by reducing the coverage of frozen ground and intensifying rainfall. Landslides and destabilized rock glaciers fall down hillslopes and intercept rivers, causing a natural dam to capture streamflow. Like the moraine, these natural dams often fail and produce extreme floods in a mechanism called a landslide-lake outburst flood (LLOF).

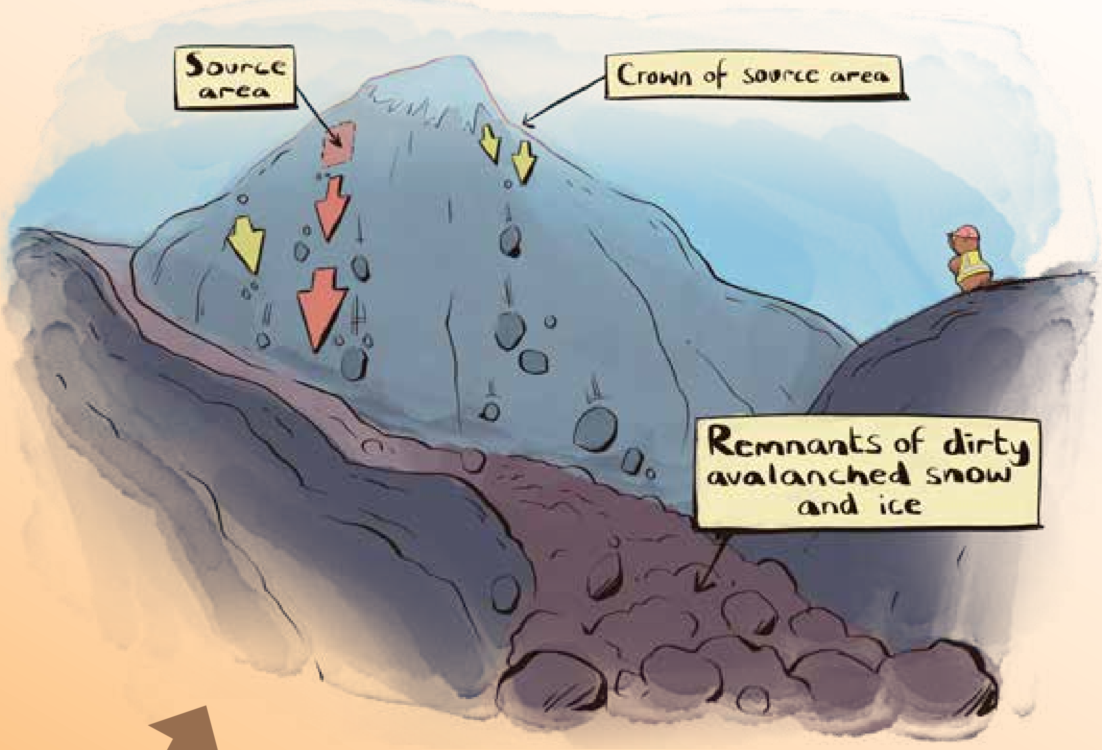
Other mechanisms for extreme flows include increased rainfall intensity and deforestation driven by people. Warmer air can hold more water, so mountains in our warming climate are experiencing bigger storms. Deforestation means less water is captured by soil. As a result, rainfall from larger storms runs off the slopes more quickly, generating larger flows in mountain streams. These mountain flood mechanisms illustrate the complex ways in which warmer temperatures create favorable conditions for extreme flows.



Unprecedented disasters?

Once the flood mechanisms are known, we need to find out the biggest floods (discharges) to be prepared for, and how often they occur for a particular river or region. This is a challenging task in mountain regions. In general, mountains have been isolated regions where life, and processes, have gone unobserved. Moreover, it is very difficult and challenging to record hydrological events in these harsh environments. The recent development of remote sensing and satellite imagery has improved our knowledge of mountain processes, but it is limited to the last decades.

In 2013, a massive GLOF event in Kedarnath (north India) resulted in the loss of more than 6000 lives. It was caused by a combination of anomalous precipitation associated with the early onset of heavy monsoon rains and immediate snowmelt. The event was massive, causing extensive damage to populations and infrastructure.



Examples of recent massive floods linked to climate warming have occurred in the Indian state of Uttarakhand, including the events of Kedarnath in 2013 and Chamoli in 2021 (Shugar et al. 2021). Such events in recent decades appear to be unprecedented. But do these flows really represent the worst-case scenario for their river systems? If so, how often can we expect such floods in the future? We can't answer these questions with one or two observations. We need longer records with more observations of extreme flows to contextualize these events and prepare for future hazards.

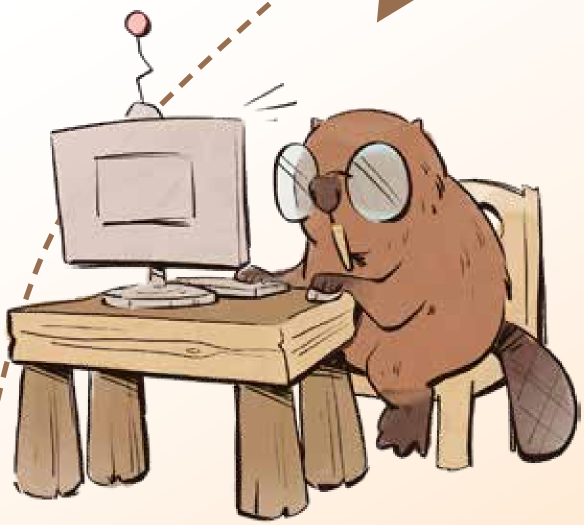
In 2021, in Chamoli (northern India), a large rockslide occurred in the upper part of the Rishiganga catchment, evolving into massive debris flow downstream. The event caused at least 200 deaths and extensive damage to road infrastructure. The slope instabilities associated with climate warming and long-term changes in cryospheric conditions appear to have played a role in triggering this disaster.

Searching for evidence of past flood disasters

Hello, I am Sandy, and I like to study the history of rivers. My job is to look for evidence of catastrophic events in the past.

There was a recent flood in a fantastic mountain valley, and the energy of the flood destroyed all the houses of a beaver community. The beavers are worried because they have never seen such an intense flood. Now, they have to build new houses, but they are afraid of experiencing similar disasters. Sandy is a geoscientist beaver who wants to help her friends. She decides to do research to find the best place for houses in the valley. First, Sandy examines the existing data and the entire aerial and satellite imagery to see what is happening in the headwaters. She sees a major glacier retreat and the formation of new lakes.

Um, this is interesting... The glacier has retreated 253 meters in the last 10 years and a new lake has formed on the glacier front...

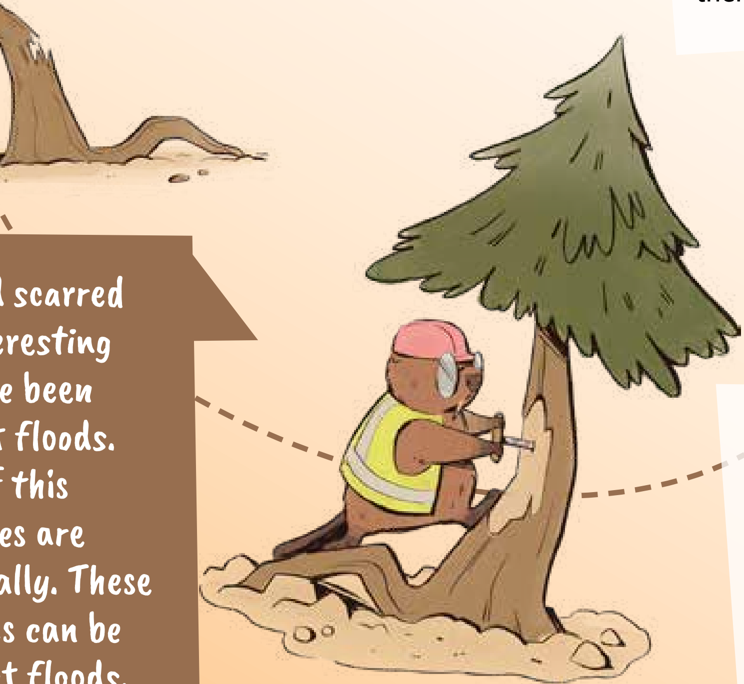


Sandy starts looking for paleoflood deposits along the river channel below the lake and finds a nice outcrop with nice layers of fine sand. She explains to her friends what a slack-water flood deposit (SWD) means.

These sand and silt sediments have been transported in suspension by flood waters, and are later deposited on high areas of valley sides, and upstream of tributaries. The height of the flood sediment layer tells us that the flood reached that location, so we can infer the depth of the flow. And multiple flood deposition layers represent different flood events whose ages can be determined in the laboratory by isotope and luminescence analysis.

As she analyzes the sediment, she begins to measure the size of the boulders that she finds in the higher terraces. Flood waters flow faster as the volume of water increases with flood depth. As the water flows faster, it can carry larger and larger sediment particles. Therefore, Sandy knows that she can estimate the minimum flood depth needed to create enough fast-moving water to carry boulders of this size. In addition, she and a colleague begin to measure the cross-section (topography) of a critical section (change in channel slope) in order to estimate the peak discharge.

These topographic measurements of this cross-section will allow us to accurately estimate the maximum discharge. In these slope changes, the flow is critical, and by measuring the height of the deposits, we can easily estimate the flow velocity and, therefore the peak discharge.



When she is finished, she notices that there are many trees that are growing abnormally, with tilted trees and scars. She decides to check the tree-ring records and start to sample some trees.

How do we reconstruct past floods?

We can model the event by quantifying the age and discharge of past floods using evidence preserved in the river landscape for centuries. Dating past floods requires an exhaustive field survey to find evidence of past floods. We need to determine the age of each flood event. There are several age-dating techniques, depending on the nature of the evidence. Relative methods only allow us to determine whether a particular flood is older or younger than another. Therefore, relative dating provides the sequence of events that occurred, but not their dates or the number of years between events. Absolute dating allows us to define the time of the event in a calendar, which helps to determine the rate of occurrence, or the relationship to climatic conditions.

On the other hand, estimating the magnitude of a flood requires a combination of information from the field and the use of numerical equations. In general, these equations require knowledge of the topography of the channels and moraines and bathymetry (underwater topography) or lakes, which is often difficult to obtain. Depending on the availability of data, researchers use empirical equations to estimate the magnitude (peak discharge or volume) based on parameters that can be easily obtained (moraine geometry, lake area, etc.). Or, they use complex numerical models able to simulate the process chain, including the generation of a wave caused by the impact of a landslide into the lake, and how this wave erodes the terminal moraine and generates the outburst flood downstream.

How can we prevent future flood disasters?

A recent study suggests that the occurrence of GLOFs may increase in the future, especially in vulnerable countries (Zheng et al. 2021). Preventing future disasters will be challenging, but necessary to ensure a sustainable and more equitable world. Researchers around the world agree that quality urban planning with reliable hazard maps is the most cost-effective option for adapting to, and mitigating, future disasters. In areas where vulnerable elements (i.e. population and infrastructure) are located, the implementation of an Early Warning System (EWS) has become an alternative. However, this option has some problems related to: 1) the need to rely on measurements that could fail in harsh mountain environments, 2) the need to implement exhaustive maintenance of the systems, and 3) the problems, or false alarms, that could lead to misperception of the population i.e. "crying wolves". In addition, some EWS' have been designed to adapt to rapid socioeconomic development in the mountains, without a proper understanding of the flood processes. Therefore, EWS' should be a complement to hazard zoning and, in any case, an exclusive element for mitigation and adaptation.

Further reading

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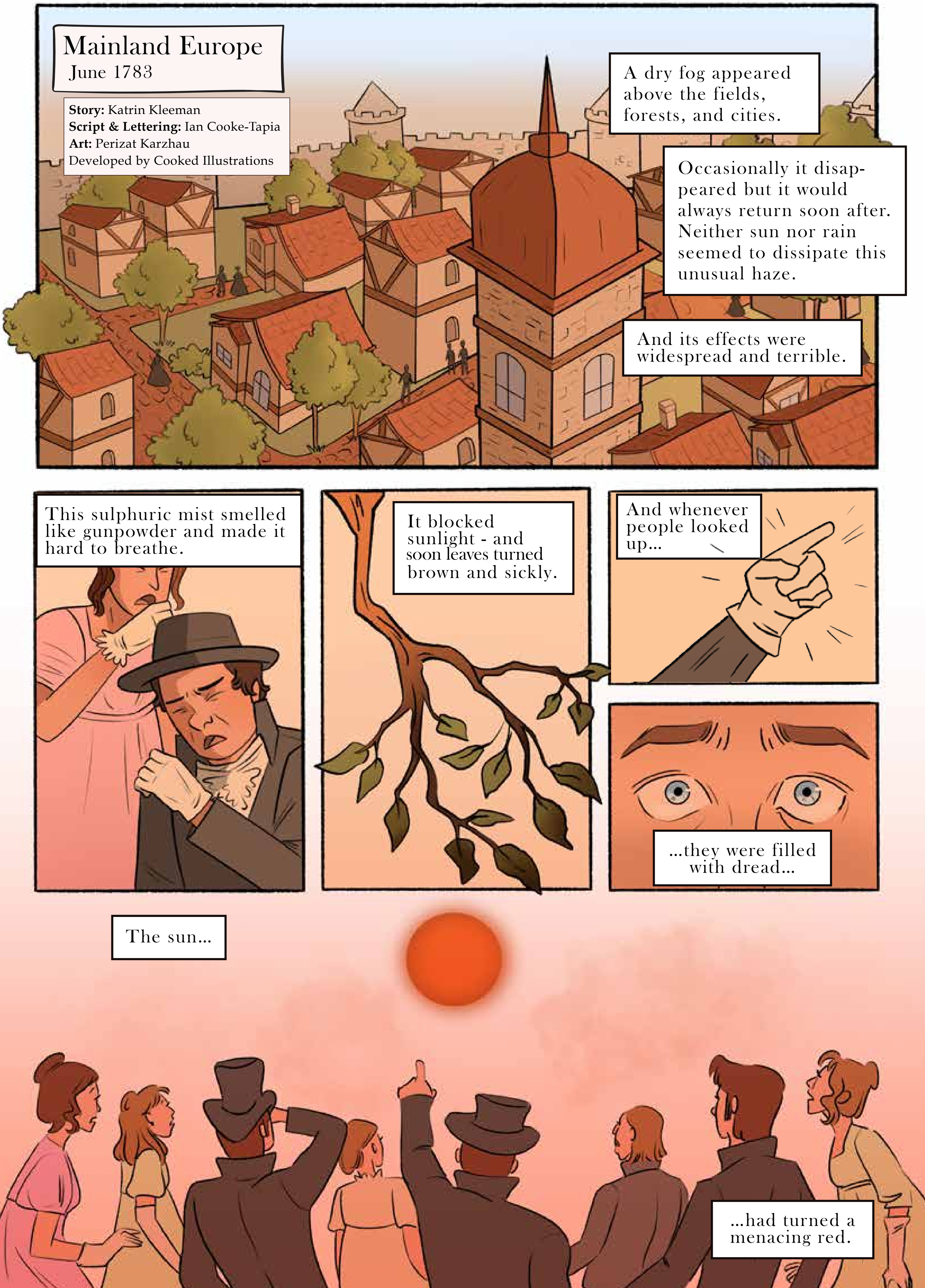
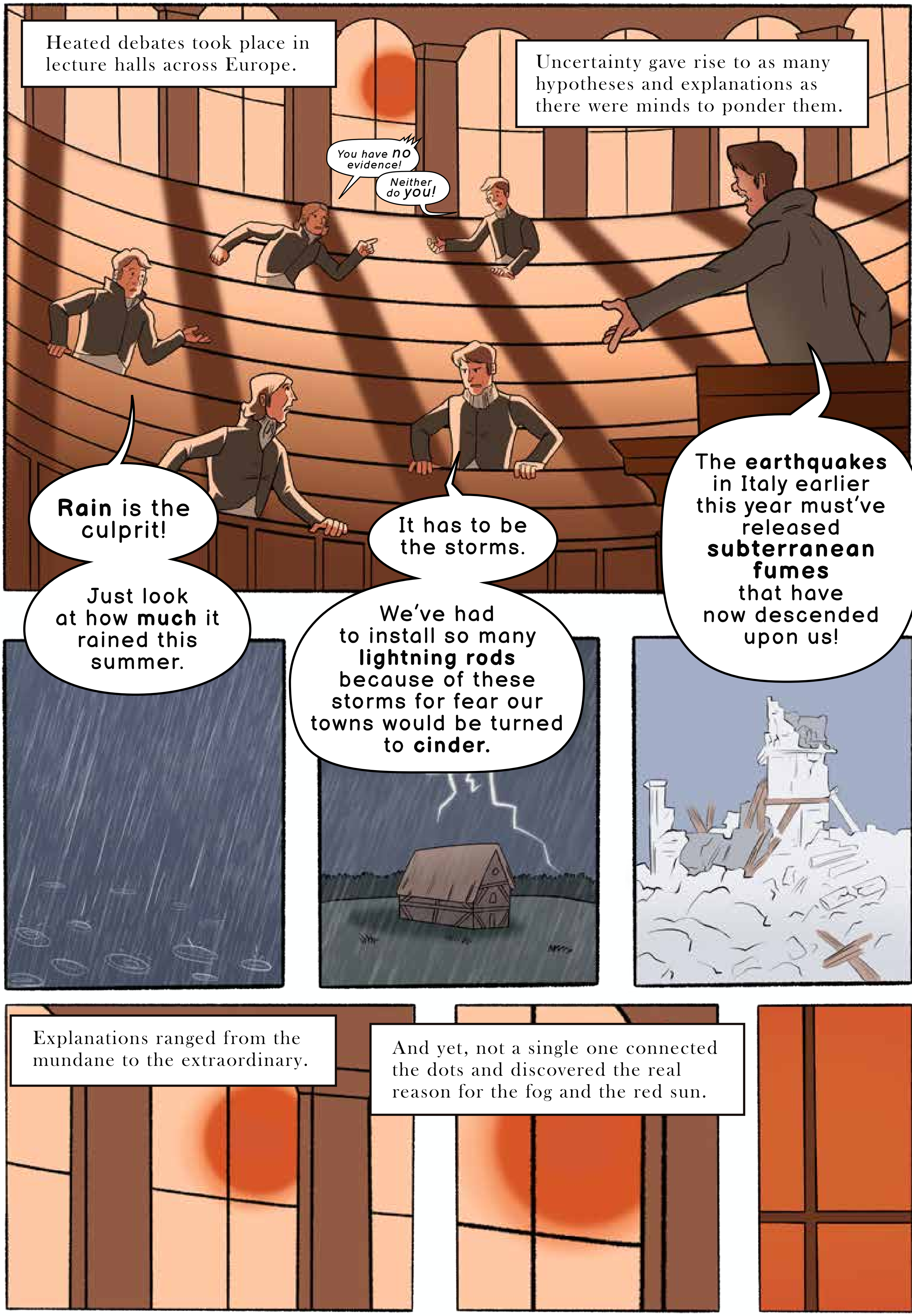
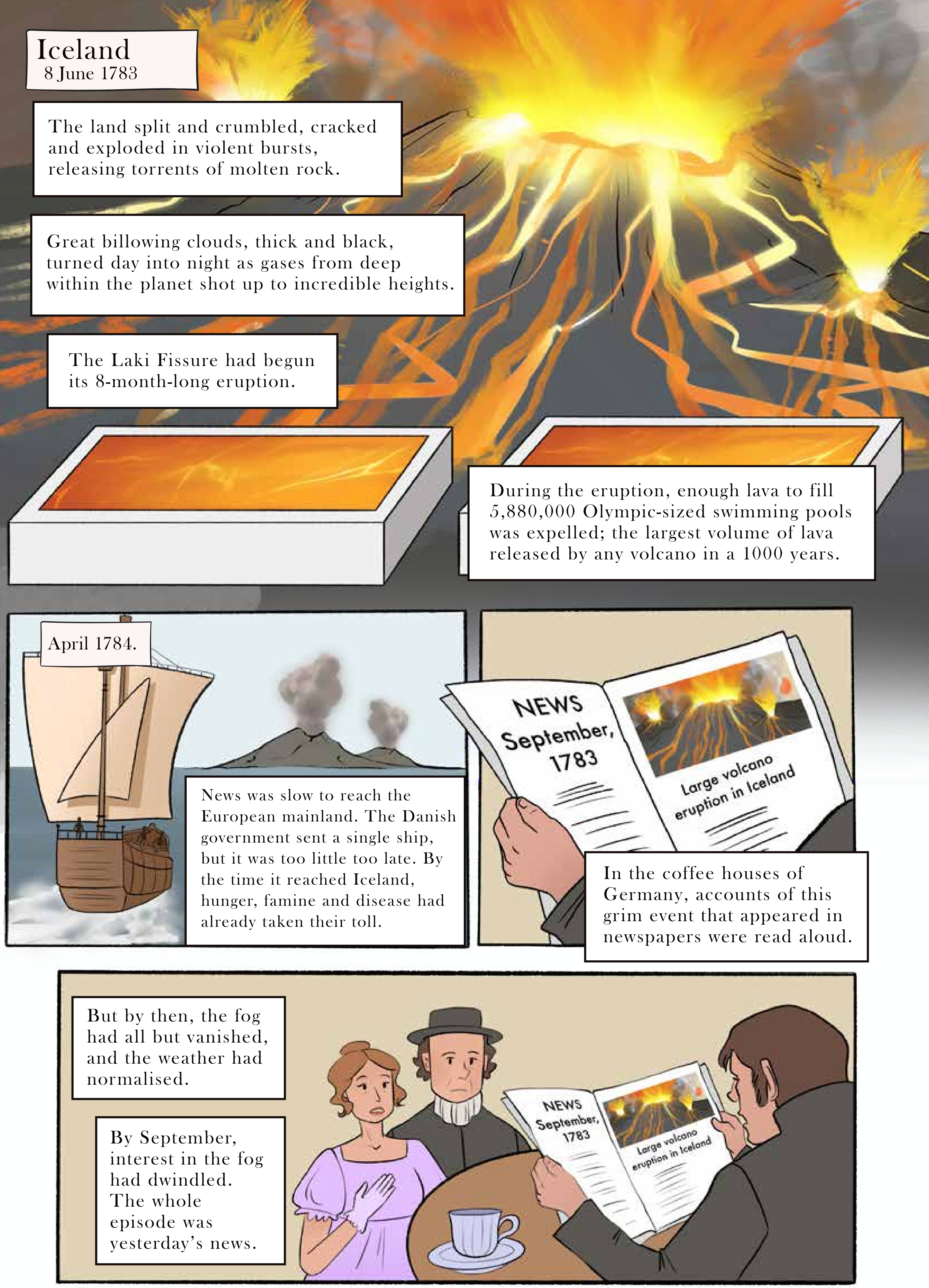
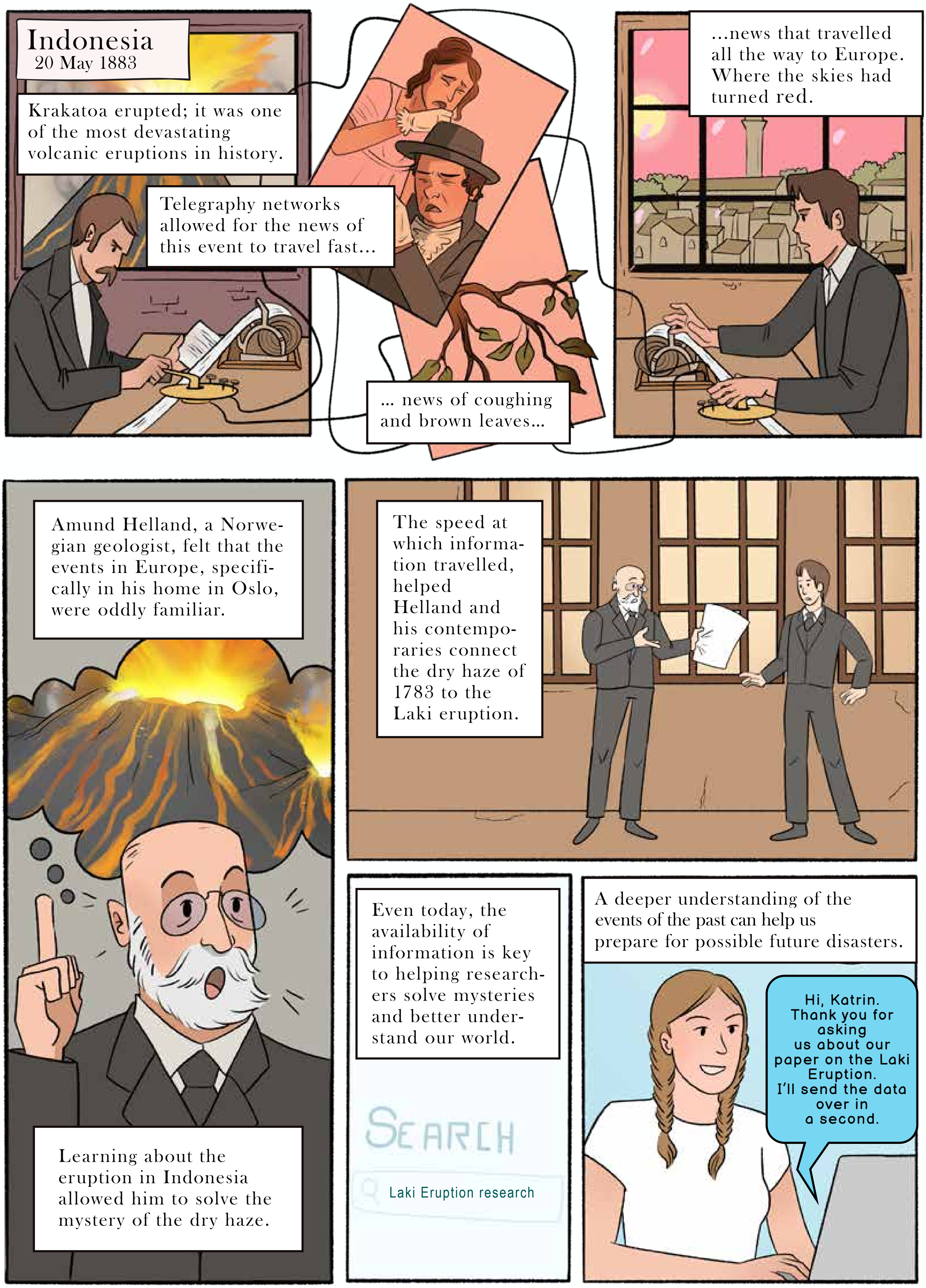




Heated debates took place in lecture halls across Europe.
Uncertainty gave rise to as many hypotheses and explanations as there were minds to ponder them.
You have no evidence!
Neither do you!
Rain is the culprit!
Just look at how much it rained this summer.
It has to be the storms.
We've had to install so many lightning rods because of these storms for fear our towns would be turned to cinder.
The earthquakes in Italy earlier this year must've released subterranean fumes that have now descended upon us!
Explanations ranged from the mundane to the extraordinary.
And yet, not a single one connected the dots and discovered the real reason for the fog and the red sun.


Iceland
8 June 1783
The land split and crumbled, cracked and exploded in violent bursts, releasing torrents of molten rock.
Great billowing clouds, thick and black, turned day into night as gases from deep within the planet shot up to incredible heights.
The Laki Fissure had begun its 8-month-long eruption.
During the eruption, enough lava to fill 5,880,000 Olympic-sized swimming pools was expelled; the largest volume of lava released by any volcano in a 1000 years.
April 1784.
News was slow to reach the European mainland. The Danish government sent a single ship, but it was too little too late. By the time it reached Iceland, hunger, famine and disease had already taken their toll.
NEWS
September, 1783
Large volcano eruption in Iceland
In the coffee houses of Germany, accounts of this grim event that appeared in newspapers were read aloud.
But by then, the fog had all but vanished, and the weather had normalised.
By September, interest in the fog had dwindled. The whole episode was yesterday's news.
NEWS
September, 1783
Large volcano eruption in Iceland


Indonesia
20 May 1883
Krakatoa erupted; it was one of the most devastating volcanic eruptions in history.
Telegraphy networks allowed for the news of this event to travel fast...
... news of coughing and brown leaves...
...news that travelled all the way to Europe. Where the skies had turned red.
Amund Helland, a Norwegian geologist, felt that the events in Europe, specifically in his home in Oslo, were oddly familiar.
Learning about the eruption in Indonesia allowed him to solve the mystery of the dry haze.
The speed at which information travelled, helped Helland and his contemporaries connect the dry haze of 1783 to the Laki eruption.
Even today, the availability of information is key to helping researchers solve mysteries and better understand our world.
SEARCH
Laki Eruption research
A deeper understanding of the events of the past can help us prepare for possible future disasters.
Hi, Katrin. Thank you for asking us about our paper on the Laki Eruption. I'll send the data over in a second.

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GLOSSARY

Hydrological extremes

Water moves continuously in all its phases (ice, liquid and vapor) above and below Earth's surface, including the atmosphere, oceans, glaciers, rivers, vegetation, soils, and groundwater. The study of the distribution and movement of Earth's water is **hydrology**. Energy, measured in temperature, drives the movement of water through its many pathways. The hydrologic cycle always changes, but sometimes, water abundance in a single location can intensely change in a short time, referred to as **hydrological extremes**. For example, heavy rainfall during storms can quickly overwhelm a soil's capacity to store water. This causes water to flow over the ground as runoff and rapidly fills local lakes or stream channels, leading to flooding. Hydrological extremes cause floods and drought hazards that impact society and ecosystems worldwide. Warming temperatures in our atmosphere and oceans intensify the rate and magnitude of water movement in the hydrologic cycle, leading to more hydrological extremes.

Paleohydrology proxies

We can't measure pre-instrumental precipitation or river flow directly, as we do today. Instead, we use indirect indicators of past environmental changes called **paleoproxies** to determine how hydrology varied in the past (so called "paleohydrology"). Changes in hydrology affect our natural environment in measurable ways. By comparing direct hydrologic measurements to the environmental responses that we see today, we can understand and reconstruct past hydrologic conditions based on indicators found in the natural landscape. Below, we briefly discuss three commonly used paleohydrology proxies in this magazine, and the broader scientific community.

Speleothems: Water dissolves and transports minerals from soil and rocks in solution. When groundwater carrying calcium carbonate ($CaCO_3$) enters a cave with low carbon dioxide (CO_2) concentrations in the air, the calcium carbonate will fall out of its water solution in a chemical process called precipitation (not to be confused with rainfall). Carbonate cave rocks (**speleothems**) form as water drips in low CO_2 concentration cave air, leaving behind the precipitated calcium carbonate minerals. Water drops, leaving behind minerals that repeatedly "grow" the speleothem rocks. Generally, rapid speleothem growth means more moisture, and little or no growth means drought. Scientists also look at the oxygen isotopes from the oxygen portion of the $CaCO_3$ mineral. The relative proportions of the "light" oxygen (^{16}O) and less abundant "heavy" oxygen (^{18}O) gives us insight into the intensity of rainfall generating the groundwater, or the source of the moisture. These ratios vary by cave, so dripping water monitoring is needed for accurate interpretation of the proxy records.

Tree rings: Trees grow annual rings that tell us how old the tree is and the environmental conditions the tree experiences year to year. Trees respond to various environmental variables, including temperature, rainfall, soil moisture and physical damage from fires and boulders. Additionally, trees grow in two distinct phases during the year after their dormant period: earlywood is a lighter, spongier ring that forms in the cool season, and latewood is the darker, denser ring that forms in the warm season. Therefore, tree rings provide highly detailed paleoproxies at the seasonal scale for thousands of years in some regions. By selecting tree species and locations highly sensitive to hydrological changes, we can use ring width and isotope measurements calibrated to modern records to reconstruct seasonal precipitation, soil moisture and streamflow. In some studies, damage to trees or tree rings can even provide flood stages or coastal storm surges.

Sediments: Sediment is organic or inorganic loose material that can be described by size, mineral composition and transportation process. The depositional record in landforms preserves sediment transported to a given location from other locations in response to various mechanisms (e.g. water, wind or ice). Sediment records from lakes, rivers and coastal landforms contain numerous and unique paleoproxies of wet or dry periods. We core these landforms to pull out intact sediment samples from a site. These sediment "cores" may represent hundreds to thousands of years of periodic deposition. Some sediment deposits are indicative of hydrological extremes as they are only transportable at high water levels, such as flood deposits in high-elevation rock shelters, or coarse sand in floodplains.

Hydrological risk

Paleohydrology studies are often conducted to improve our understanding of drought or flood risk. **Risk** is the exposure to an undesirable hazard. Often city planners and water-resource managers reduce risk with strategies such as damming rivers to reduce flood heights in very wet years, and retain water in very dry years. Understanding the full range of a natural hazard in a particular region is essential to quantifying risk. Paleohydrology studies are well suited to answer this important question.

A key measurement of risk is the **probability**, or likelihood, of a hazard in any given year. Probabilities (between 0 and 1) are estimated using a frequency distribution of real-life measurements. In hydrology, these measurements may be precipitation or streamflow. Generally, the higher the probability of an event (closer to 1), the more frequently this event occurs in nature. Low probability events (0.01 or smaller) are rare but would expose the largest amount of people to severe impacts and can, therefore, still be high risk. The availability of hydrological measurements can impact the accuracy of these probability estimates. If we have measured streamflow for 100 years, then the number of observations of the low probability events is likely one observed extreme flood, which is a very poor sample size. Also, it's not likely that these 100 years creating our sample of events have the same distribution as events occurring under warmer climates. This is where paleohydrologists come in! By adding thousands of years into the known event record, we obtain a greater sample size of extreme events, especially those occurring during warmer climates than those of last the 100 years. A large sample size means more certainty in probability estimates, and reduced uncertainty when evaluating risk.

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What do cave deposits tell us about past floods? (p. 7)

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Tracking hydroclimate extremes from deep in the tropics (p. 13)

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What do cave deposits tell us about past floods? (p. 7)

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Changing rainfall patterns over the Amazon rainforest (p. 20)

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Future memories of a river (p. 24)

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Future memories of a river (p. 24)

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After the storm: How clues from past hurricanes help prepare us for our future (p. 30)

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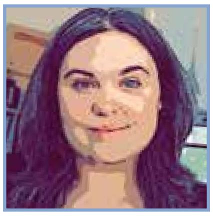
After the storm: How clues from past hurricanes help prepare us for our future (p. 30)



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Editor, Global warming impacts on floods in high mountain regions (p. 34)

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Editor, Global warming impacts on floods in high mountain regions (p. 24), What do cave deposits tell us about past floods? (p. 37)

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Changing rainfall patterns over the Amazon rainforest (p. 20), After the storm: How clues from past hurricanes help prepare us for our future (p. 30), Paleotherapy (p. 48)

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Laki eruption (p. 40)

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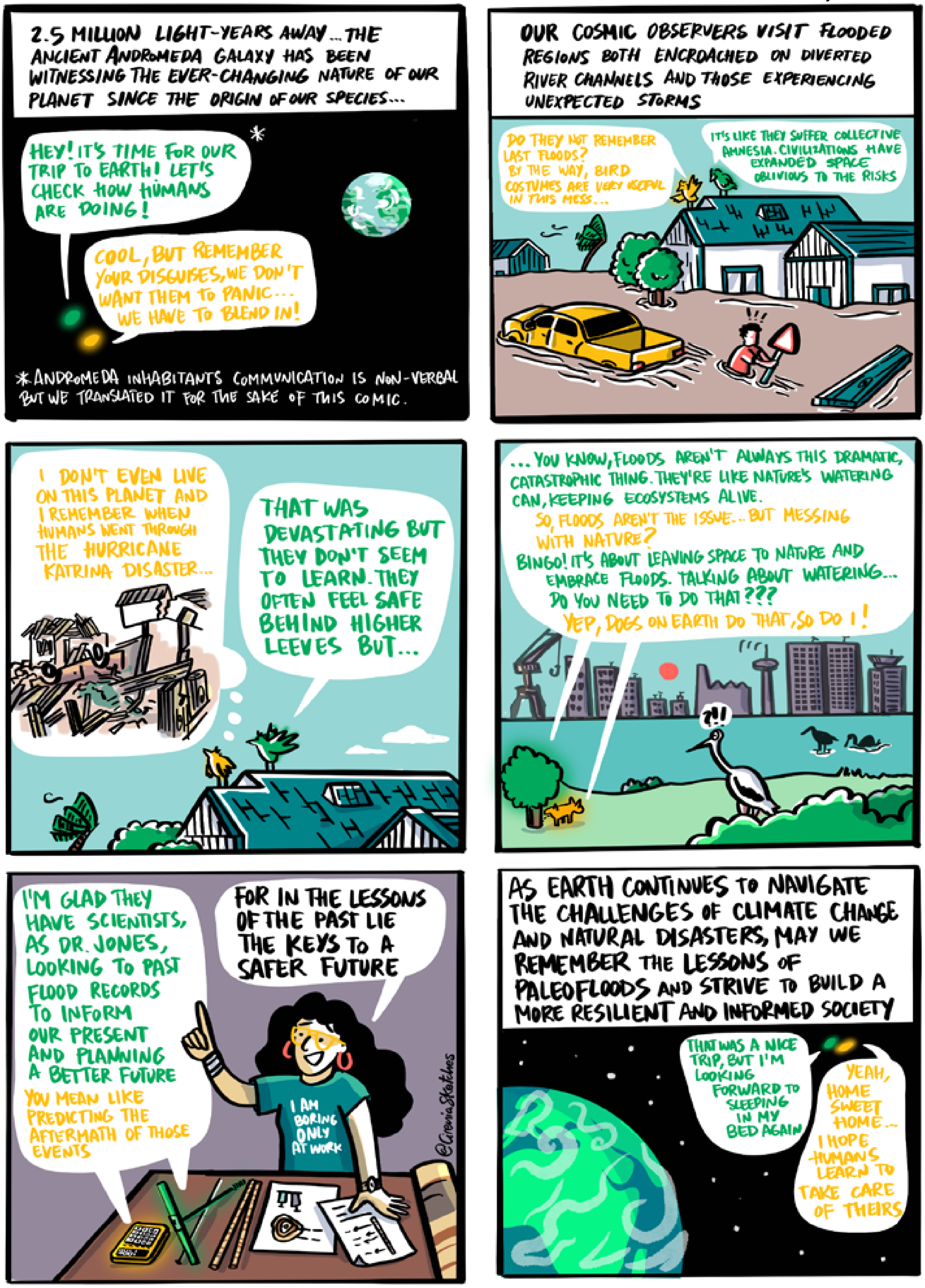
PALEOTHERAPY



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