THE HIMALAYA PROJECT

A project conceived by members of the ICES Foundation and its global partners to assist in the preservation, development and understanding of a critically important ecological and social-economic region which plays a major role in the future trajectory and well-being of our entire planet.

The north face of Mount Everest seen from the path to the base camp in Tibet Autonomous Region, China. Credit: Luca Galuzzi/Wikipedia.

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There is an opportunity to consolidate and bring together the multiple sciences and diverse studies that relate to this important region of the world, and thereby build a knowledge system to improve the region's resilience to damage and losses from natural and man-made disasters while improving the quality of life for inhabitants in the many villages, towns and cities downstream.

The Himalayan Mountains have enormous impact on surroundings near and far, with at least 16 nations directly impacted by its unique weather and climactic conditions, its glaciers and rivers, and its overarching biogeophysical expanse.

Although occupying just 11% of the world's land surface, together these15 nations make up 45% of the world's present population. But their cooperation and shared wisdom is unfortunately less than to be desired.

This document contains a project outline that has been conceived to improve communications and future collaboration between the countries involved, and to set them on a course for producing a ***unified knowledge system*** of the region. Our goal is to underpin the long-term creation of ecological civilizations with well harmonised bioregions and eco-cities in an era of changing climate and frequent natural hazards.

The Himalayan Project is a major element in the global vision and mission of Geneva-based, non-political, not-for-profit ***ICES Foundation (International Centre for Earth Simulation)***
www.icesfoundation.org and in cooperation with the following contributing partners, namely:

The Institute for Environmental Science (IES), University of Geneva, from which Professor Martin Beniston led the European Union, funded ACQWA Project – a 5 year project to integrate the multiple water systems and sub-systems of the European Alpine Region.:
http://www.unige.ch/environnement/index_en.html
http://www.unige.ch/climate/Publications/Beniston.html
http://www.unige.ch/climate/Projects/ACQWA.html

The Institute of Global Environment and Society (IGES), George Mason University, from which Professor Jagadish Shukla chairs a post-graduate program in Climate Dynamics, with special emphasis on the impact of a changing climate on the Asian Monsoons:
http://www.iges.org/home.html
http://www.iges.org/people/shukla.html
http://aoes.gmu.edu/climate_dynamics
http://icesfoundation.org/UsersFiles/FCKeditorFiles/file/Asian%20Monsoons%20in%20a%20Changing%20Climate.pdf

and

The Ecological Sequestration Trust (UK), from which Professor Peter Head leads an integrated approach to city-region resilience, holistic planning, and underlying business models:

http://ecosequestrust.org/category/about/
http://ecosequestrust.org/our-people/executive-team/
www.youtube.com/embed/VmHAWkeD0ok?rel=0

Other partners are expected to join this effort as soon as the funding mechanisms are secured.

AN OVERVIEW OF THE HIMALAYAS

The Himalayas are a young seismically active mountain range arching across the Tropic of Cancer in Asia with over 100 peaks exceeding 7000m that are still being pushed upwards by the tectonic collision of the northward moving Indo-Australian Plate with the Eurasian Plate. The mountains extend for 2,400 km in length and between 150km in width at the eastern end to 400 km width in the west.

High altitudes have induced the formation of over 35,000 glaciers within the Himalayas, forming the source of major river systems that flow both north and south into neighboring countries. The mountains also play a major role in the flow and direction of large-scale monsoon weather systems that regularly impact the region.

Geologically, the Himalayas and their immediate surroundings are often referred to as a 'Third Pole' of Planet Earth. The region suffers frequent large-scale disasters from earthquakes, avalanches, mudslides, rock falls, floods, and extreme weather events. In addition, the glaciers are in serious retreat due to global warming, and there is a shift in much of the biological makeup of the region due to such warming.

Socio-economically, the Himalayas hugely impact all food, agriculture, energy, transportation, industrial, and public health systems within the countries that depend on its rivers. There is a patchwork of micro and macro climactic conditions created by the mountain range. Because of long-term historical conflicts however, many of these countries do not pro-actively share or coordinate their knowledge of the many physical aspects of mountain life, even though Mother Nature herself functions across national borders in a very fluid and transparent manner.

The 16 nations that have most at stake are listed as follows in order of national population size:

	Population	Land Size
China	1,354.0M (12/2012)	9,569.90M km^2
India	1,210.6M (03/2011)	2,973.19M km^2
Pakistan	183.8M (07/2013)	856.69M km^2
Bangladesh	152.5M (07/2012)	130.17M km^2
Vietnam	88.8M (07/2012)	310.07M km^2
Thailand	65.9M (09/2010)	510.89M km^2
Myanmar	53.2M (07/2013)	653.51M km^2
Malaysia	29.8M (07/2013)	329.61M km^2
Nepal	26.5M (06/2011	140.80M km^2
Afghanistan	25.5M (01/2013)	652.23M km^2
Cambodia	15.1M (07/2013)	176.52M km^2
Tajikistan	8.0M (04/2013)	141.51M km^2
Laos	6.6M (07/2013)	230.80M km^2
Kyrgyzstan	5.6M (07/2012)	191.80M km^2
Mongolia	3.0M (07/2014)	1,564.12M km^2
Bhutan	.7M (07/2012)	47.04M km^2

Regional Population = 3,230M (45% of 7,100M world population according to UCSB world population clock).
Regional Land Size =18,291M km^2 (12.3% of 148,940M km^2 world land size)

THE TIBETAN PLATEAU

With an average elevation of over 4500m and covering an area of 2,500,000 square kilometers, this region is known as the 'roof of the world' and is the headwaters of most streams in the surrounding region, and is itself surrounded by numerous mountain ranges. Furthermore, the seasonal monsoon wind shift and weather associated with the heating and cooling of the Tibetan Plateau is the strongest such monsoon on Earth.

Such well known rivers as the Yangtze, Yellow, Indus, Brahmaputra, Salween and Mekong originate in the Himalayan and Tibetan Plateau region and supply a lifeline of water, food, transport and energy to neighbouring countries. However, these rivers cross national boundaries and are therefore in high dispute with respect to water usage rights, hydroelectric damming, fishing and pollution control.

Qin Dahe, the former head of the China Meteorological Administration and winner of the 2013 Volvo Environmental prize (http://www.environment-prize.com/) said:

"Temperatures are rising four times faster than elsewhere in China, and the Tibetan glaciers are retreating at a higher speed than in any other part of the world. In the short term, this will cause lakes to expand and bring floods and mudflows. In the long run, the glaciers are vital lifelines for Asian rivers, including the Indus and the Ganges. Once they vanish, water supplies in those regions will be in peril."

DESIGNING ECOLOGICAL CITIES and EXPANDING TRADITIONAL CITIES

In the past 30 years, China's urban population alone has jumped to more than 700 million from less than 200 million, causing violent clashes over expropriation of farmland for development, as well as water shortages, energy shortages, transportation difficulties, air pollution and other problems. The same trends can be observed in many parts of the 15-country region.

Developing smart, intelligent and eco-friendly cities is now the priority in the years ahead, and this will require a far-sighted understanding of local, regional and global climate change, especially with respect to seasonal monsoons, changing mountain snow pack, seasonal snow melt, river flows and lurking seismic hazards.

Protection of eco-services from important bio-regions is an equally important aspect of future development planning, since such bio-regions act to support the health of nearby villages and cities. Long-term water security, food security, public safety and quality of life are all at stake.

UNIFIED KNOWLEDGE SYSTEM

Although a vast amount of local knowledge is currently available, this knowledge is neither systematically compiled nor shared between the countries of the Himalayan Mountain Region. Nor is this knowledge updated with a clear understanding of local impacts from global climate change, global warming, and global sea-level rise. Our proposal is to help create this ***Unified Knowledge System*** by means of a consortium of international, independent, non-political organizations led by the ICES Foundation, and in cooperation with local and international bodies of high repute, such as:

ICIMOD: http://www.icimod.org/?q=abt
SASCOF: http://dhm.gov.np/uploads/getnotice/693527908sascof4_general%20information_nepal.pdf
LASG/IAP/CAS: http://www.lasg.ac.cn/

THE BASIS AND STRUCTURE OF THE UNIFIED KNOWLEDGE SYSTEM (UKS)

The basis of the UKS is a high-resolution digital elevation map (DEM) which provides a surface rendering on the complex geography that can be found throughout the entire Himalaya Region and to which the following multiple layers of additional data are attached: built environment, infrastructure, utility grids, power plants, transportation systems, land cover, farming and agricultural activities.

From this base map, a very large 3D file of information that describes all weather, hydrological and climate variables on a real-time basis will be accessible. This 'big data' file will be kept up-to-date by feeder data-streams coming in from local and regional authorities, and will include identifiable and quantifiable emissions information.

In addition to this surface information, the underlying sub-surface structure of the entire region will be defined and accessible from the base DEM, to the extent to which it is known. This file will contain all soil data, aquifers, geological faults and mineral deposits, as well as localized magnetic readings and historical seismic events.

Areas of local hazard will be of particular importance, and the best multi-physics, multi-science methods will be used to pinpoint the position of most likely occurrences. Hazards such as heavy rain, hail, flood, avalanche, glacial lake outbursts, landslide, mudslide, earthquake, fire, heat-wave, drought and many other hazards will be tracked and identified.

The essence of the UKS is an integrated holistic compilation of all the bio-geo-physical knowledge that is already known throughout the region, along with real-time feeds that keep the dynamic status of the territory available in an openly accessible manner.

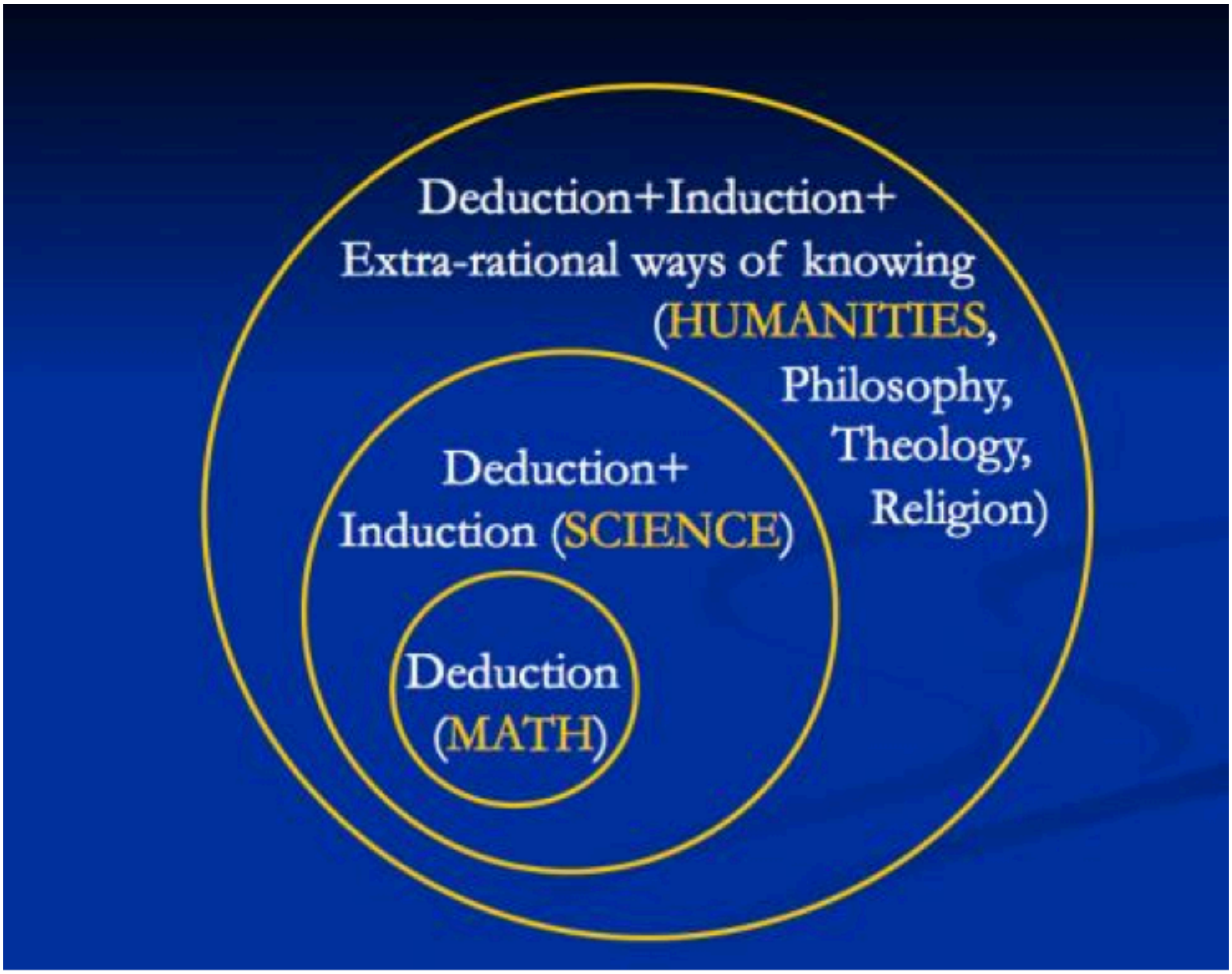
A vast amount of satellite-derived Earth Observation data will feed into the system, and will add value to specific user enquires. Such satellite data will emanate from both geo-stationary satellites as well as constellations of microsatellites operated by private companies.

Using such multi-level data captured and available within or linked to the UKS, a modelling, simulation and visualization service will be available that allows the user to drill down, access and visualize all elements of interest on a hyperlocal basis. This is essentially a '*real-time big data predictive visual analytics*' function that will provide 'look ahead' capabilities and project the forward state of the region, or any area of local interest.

Finally, the UKS will ingest and assimilate as much social-economic data as possible so as to project the forward evolution of geographical developments and thereby to understand any harmful impacts on the natural bio-geo-physical system, both short term and long-term. As a consequence, planners will be able to ask 'what if' questions that help clarify the consequences of adding hydro-electric dams to river systems, or changing land cover and agricultural methods, or extending city boundaries and infrastructure.

In particular, the UKS will assist nations to communicate and coordinate their skills on matters of common interest, and to assist each other in such important transboundary factors as:
Mountain and plateau tectonics: surface deformations, soil types, permafrost, tundra
Forests: deforestation, protection, biodiversity
Land use: agriculture, industry, energy, transportation, pollution, erosion
Monsoon timing and intensity: for both summer & winter events, effect of climate change
Precipitation: rain, snow, hail, frost, seasonal patterns
Glaciers: glacial retreat, glacial lake formation & stability
Catchment basins & rivers: floods, torrents, confluence, sedimentation & bedload dynamics
Hazards: earthquakes, rock fall, landslides, mudslides, run outs, floods, debris flow, avalanches, snow glide
Hazard mitigation geotechnical structures: retention basins, check dams, dykes, levees & protective nets
Risk mitigation: failure analysis, early warning systems, monitoring, maintenance & lifespan prolongation

VISUALIZING THE VAST SCOPE OF KNOWLEDGE TO BE INTEGRATED INTO UKS



Presentation by ICES to the China RESIST Project headed by Professor Han Dawei, University of Bristol (UK)
RESIST = Resilient Economy and Society by Integrated SysTems modelling
http://www.icesfoundation.org/UsersFiles/FCKeditorFiles/file/Uni%20Bristol%20re%20China.pdf

Collapse of Himalayan crust on to Indo-China:
http://visioterra.org/VtWeb/?LAYERSTACKID=84974e0bdf7348859eeec24343e7e120&sidePanel=false

Mysterious stone towers discovered in the Himalaya Mountains
https://www.youtube.com/watch?v=G8hH5y-dEsc

Hindu Kush Himalayan Monitoring and Assessment Programme (HIMAP)
http://hi-map.org

THE IMPORTANCE OF EARTHQUAKE LOSS ESTIMATES TO THE HIMALAYA REGION

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The Himalaya - collision zone between India and Asia - generates some of the deadliest earthquakes on this planet. In addition, this collision radiates compressive energy into the Chinese provinces to the north, east and northeast of the Himalayas that leads to great and devastating earthquakes. With more than 3 million deaths due to earthquakes, China leads the world in earthquake fatalities at this time (Utsu, 2002; ICES archives 2015). The total number of earthquake fatalities in the Himalayan belt from China to Iran exceeds 6 million. According to the loss predictions of Wyss (2005), India with its large population may eventually surpass China as the country with the largest number of accumulated earthquake fatalities. Therefore, we pay more attention to earthquake risk reduction along the southern front of the Himalaya.

The ICES Foundation, using its QLARM loss estimate system (Trendafiloski et al., 2011) and expert staff, will train and coach Himalaya countries on the use of the QLARM system for mortality and injury loss estimates associated with large earthquakes - in both *near real-time mode*, and in *scenario planning mode*.

Near Real-Time Mode: After most disastrous earthquakes, the extent of losses does not become fully known during the first few days because information from devastated areas does not flow freely, especially in difficult to access mountain areas. Even then, eyewitness reports are often confusing. Therefore, rapid and reliable estimates of likely losses, based on model calculations and teleseismic information, are essential for adequate and timely rescue and recovery operations. The ICES Foundation QLARM loss estimate facility is designed to address this situation. Loss estimates by QLARM are available within 30 minutes of significant earthquakes worldwide (Wyss, 2014) and include mean damage state, number of injured and number of fatalities for each settlement, and the sum of the human losses.

Before such losses can be estimated however, accurate information on the parameters of the earthquake in question must become available. For countries without dense high-quality seismograph networks, the source parameters have to be derived from global data. The earthquake parameters required for estimating event consequences are the hypocenters and the magnitude details.

Because of the distances between seismographs in the worldwide network, the travel time for seismic waves to reach a sufficient number of stations to allow a stable estimate of source parameters is about 10–15 minutes. Approximate source parameters become available by email after this delay. Only then, can the QLARM system commence preparations for loss estimates.

Given the location and magnitude of an earthquake, the QLARM system calculates intensity of shaking at the appropriate distance for every settlement in the database. Then the probability of all five damage grades is calculated for each of the building classes according to the respective fragility curves. In a third step, the number of fatalities and injured in three severity classes is calculated using a casualty matrix. It is necessary to include information on the current quality of building stock, soil properties, and present populations for these calculations to be accurate.

The moment tensor solutions distributed by the USGS, or others, can be of considerable help in refining QLARM loss estimates, especially if they also include estimates of rupture direction and fault finiteness. Improving the speed and quantity of moment tensor messages, together with the inclusion of identification of the fault plane and adding fault finiteness estimates, may well be one of the most useful additions for refining QLARM loss estimates in countries without dense local seismograph networks – such as in the countries addressed by this proposal.

It would be very desirable if more local and regional seismograph networks were able to electronically distribute high-quality calculations of earthquake epicenters in real time, especially depths, because this would cut about 10 minutes from analysis delays. The weakest parameter in teleseismic earthquake hypocenter data is the depth of the energy release. This parameter is of crucial importance because the damage caused at the Earth's surface decreases rapidly with increasing depth of the earthquake.
The magnitude of hypocentral errors (approximately 15 km for USGS teleseismic locations), could be reduced by a factor of 3 to 4, with good local data availability. This in turn could influence the estimate of the number of fatalities in some cases by a factor of 10. Although we are currently able to correctly separate disastrous earthquakes from non-consequential ones in over 90% of the cases, input from well-run regional and local seismograph networks could strongly improve the accuracy of QLARM loss estimates in near real-time mode.

Application of satellite images to loss quantification: Direct inspection of satellite photographs of the damage to the built environment immediately after an earthquake can significantly contribute to real-time loss estimates. The effective use of satellite imagery (e.g. Huyck et al., 2014; Taubenboek et al., 2014) requires that a satellite pass over the affected area, that the earthquake has occurred during daytime, and that clouds are not obstructing the view from space. Additional methods to quantitatively estimate the degree of damage to buildings and to derive from this the approximate number of injured should be developed.

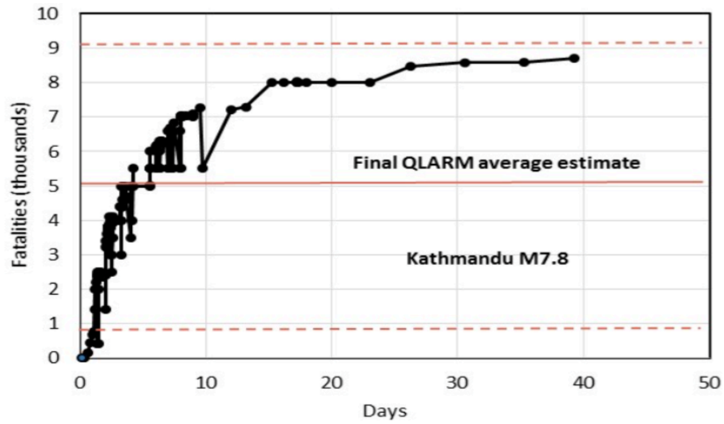
On the basis of satellite images, 3D models of cities can be developed, with the height of every building calculated from its shadow. On the basis of height, an approximate assignment of buildings to one or two groups of a given fragility class is possible. The fragility (inability to withstand shaking) is given as a probability that a building may sustain a certain degree of damage (e.g. collapse) as a function of intensity of ground shaking. From images of the Tandem InSAR mission the height of buildings can measured to 3m accuracy, which is to within one floor height of a building.

Creation of a local encyclopedia of soil conditions: Knowing the local soil conditions is important for estimating losses because these conditions can lead to amplifications of the ground accelerations by factors of 2 or more (e.g. Parvez and Rosset, 2014). However, reports on local conditions, including microzonation studies, are scattered in the literature (sometimes restricted to grey literature), and not generally known. Therefore, a collection of relevant information is needed. Alternatively, it may be possible to reach satisfactory approximations of the local enhancement of strong ground motion using surface topography [*Wald et al*., 2004].

The data sets in QLARM contain name, coordinates, estimated population, and a model for the vulnerability of buildings for about 2 million settlements worldwide. These data are used for peaceful purposes only.

China is leading the world at this time in earthquake fatalities and injured, but India may take this dubious position because of the great earthquakes looming in the Himalaya. There are three reasons for which these two countries suffer serious human losses due to earthquakes: Great earthquakes, a large population and weak buildings in some regions. In both countries, many of the disastrous earthquakes occur in mountainous areas where communication and access are especially difficult. Underestimating the number of casualties for several days after a large earthquake is common in China as well as in the Himalayan countries. For example, in the Wenchuan magnitude 8 earthquake of 12 May 2008, approximately 85,000 people were killed, but the responsible Chinese agency believed for several days that the fatalities only numbered about 5% of this. In Nepal a similar underestimation of casualties lasted for days after the M7.8 earthquake near Kathmandu on 25 April 2015 (Figure 1). By further testing QLARM loss estimates for China and Himalayan countries and by improving the datasets for this entire area, we can get a better quantitative understanding of earthquake losses in future.

Figure 1: Fatality reports by media and official agencies as a function of time after the M7.8 Kathmandu earthquake of 25 April 2015. The red horizontal line shows the final average loss estimate using QLARM with an approximation of reported intensities. The dashed horizontal lines show the 99% confidence limits.



Using the QLARM loss estimate system in scenario planning mode. Estimating losses before they have occurred will allow authorities to plan for, prepare and mitigate the future consequences as much as possible regarding what will happen eventually along these plate boundaries. After the events occur, it also affords an opportunity to compare the calculations with reality.

It is certainly disconcerting to calculate the numbers of fatalities and injured in future earthquakes because grim pictures result, and because such estimates are subject to many assumptions. Nevertheless, uncertain as these estimates may be, one must attempt to make them, as best one can. The motivation for such studies is to provide a quantitative basis for setting priorities in mitigation efforts and to prepare for the realistic scale of a likely disaster. Although the exact time of future earthquakes is unknown, there is no doubt that magnitude eight classes earthquakes will happen along the front of the Himalaya. The forces of plate tectonics that cause India to collide with Asia, thrusting up the most magnificent mountain chain on the planet, continue to generate great earthquakes in this collision zone (e.g. Bilham, 2006; 2014).

Quantitative estimates of potential losses caused by future great earthquakes along the Himalaya (Wyss, 2005) suggest that as many as 150,000 people may die, 300,000 may be injured and typically 3,000 settlements will be affected in single events. Scenario mode results used here vary and are based on ruptures of 150 km segments of the plate boundary at seven positions, where sufficient elastic energy is believed to be stored for magnitude eight earthquakes. The method of calculating these results was calibrated using the 17 disastrous Indian earthquakes that have occurred since 1980. About 50 settlements in the region are considered most at risk because in each settlement more than 2000 fatalities are calculated to occur.

Of the seven scenarios proposed in March by Wyss (2005), two have come true. In October 2005 the Kashmir M7.6 earthquake caused about 85,000 deaths, as Wyss had predicted (Wyss, 2006). In April 2015 the M7.6 Ghorka earthquake killed about half as many as Wyss (2005) had estimated in his Nepal scenario (Wyss, 2016).

The QLARM data sets and loss calculation system have proven very well calibrated for China. This is demonstrated by the retrospective calculation of the probable losses in the Haicheng, M7.3, 1975 earthquake, had no evacuation taken place. Wyss and Wu (2014) estimate that about 8,000 fatalities and 27,000 injuries were avoided. Quantitative estimates of losses by QLARM in future earthquakes in China and the Himalayas can therefore be of real use in reducing human suffering in the study area.

Together with Chinese, Indian and Nepalese expert seismologists The ICES Foundation will design scenario mode loss estimates for extended faulting in large earthquakes along faults that these experts deem likely to rupture.

Finally, and in addition, the data set in the QLARM system regarding settlements can be used to estimate losses due to calamities and disasters wrought by flooding, land slides and fires that are becoming more frequent in the Himalaya due to land-use change and global climate change.

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SEISMIC RISK IN THE HIMALAYA AND ITS MITIGATION

ICES Foundation

China currently leads the world in earthquake fatalities (Utsu, 2002; ICES archives 2015), but India will take over this dubious leadership when enormous casualties result from great Himalayan earthquakes in the not too distant future. Figure 1 shows the approximate rupture regions of historic earthquakes along the collision zone of India with Asia. Clearly, repeats of these and similar earthquakes will happen along this plate boundary.

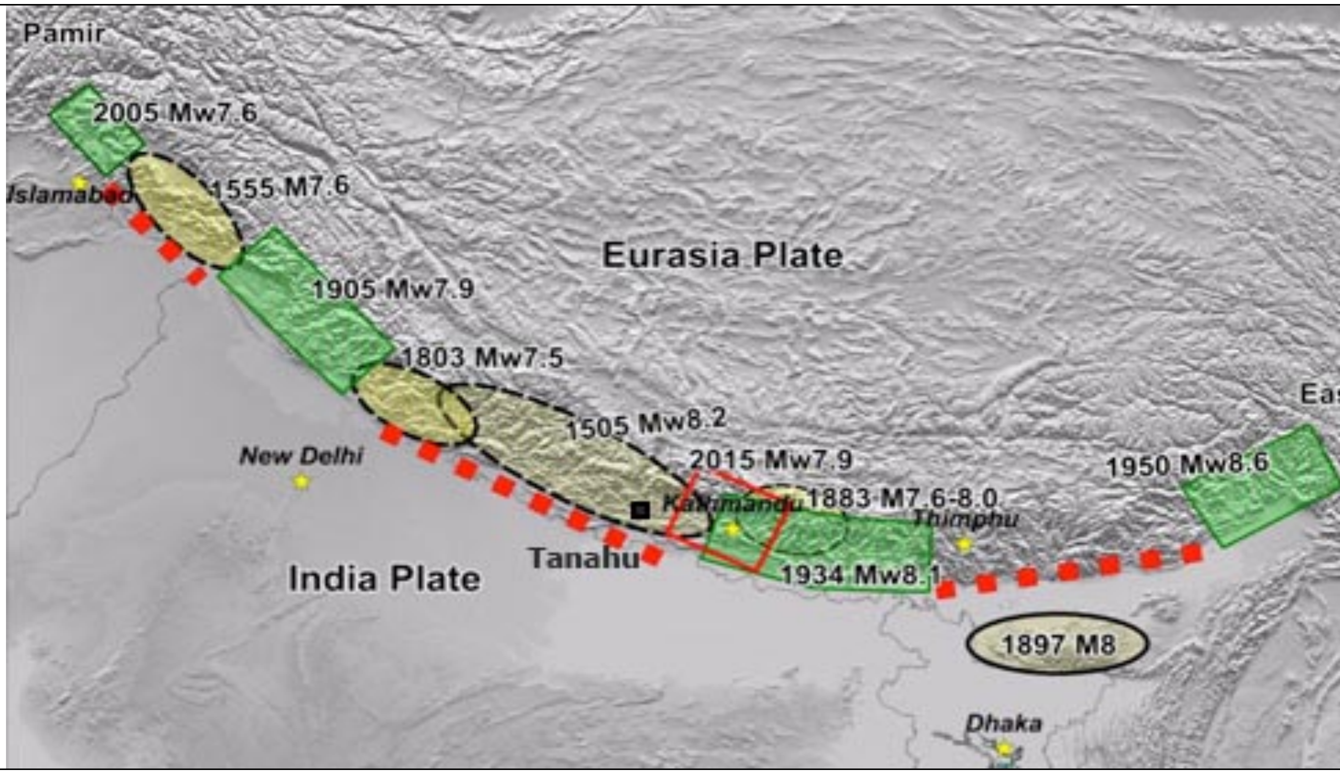

Figure 1: Map of schematic rupture areas of historic great earthquakes along the India-Asia collision zone. The most likely next segments to rupture in great earthquakes are marked by red dashes. The two earthquakes for which QLARM estimates had correctly predicted the losses are the M7.6 Kashmir 2005 and the M7.9 Kathmandu (Gorkha) 2015 earthquakes.

The Himalayan plate boundary is loaded by compression due to India advancing toward Asia, which will certainly produce great earthquakes with many meters of slip in the future (Figure 2). Because of the large population in this area, the human losses in future Himalayan earthquakes will surpass everything we have seen so far. The first earthquake in which the number of fatalities will be close to 1 million is likely in the Himalaya.

QLARM (Quake Loss Assessment for Response and Mitigation) is a tool operated by experts at the ICES Foundation, with which one can estimate numbers of fatalities and injured in scenario earthquakes. In such a scenario, one assumes a likely future rupture line and magnitude and calculates the strong ground motion resulting. The impact on the population in the region is then expressed in estimated numbers of fatalities and injured.

Loss scenarios claim only to predict the order of magnitude of fatalities. Nevertheless, the estimates of fatalities published in March of 2005 for the subsequent Kashmir earthquake (M7.6, October 2005) and the Gorkha earthquake (M7.8, April 2015) (Wyss, 2005) were correct to within approximately a factor of 2.5 (Wyss, 2006; Wyss, 2016, respectively) (Table 1).

	Location.	Lat. (deg.)	Lon. (deg.)	Depth (km)	M	Expected Deaths (thousand)	Number Injured (thousand)	No Settle $I \geq 7$	No Settle $I \geq 5$
1	Assam	27.8	92.3	25	8.1	24 - 49	52 - 99	160	1900
2	Bhutan	27.3	89.5	25	8.1	76 - 151	163 - 274	270	2500
3	*Katmandu*	28.1	84.2	25	8.1	*21 -42*	*45 - 86*	*330*	*2600*
4	W. Nepal	28.7	81.8	25	8.1	11 - 22	24 - 53	370	2800
5	Garhwal	29.7	79.6	25	8.1	58 - 115	125 - 230	380	3000
6	Dehra Dun	30.7	77.7	25	8.1	96 - 199	210 -433	450	3300
7	**Kashmir**	33.0	75.0	25	8.1	67 - 137	146 - 293	550	4000

Table 1: Original estimates of 7 scenarios for earthquakes in the Himalaya (Wyss, 2005). The two scenarios that have since come true are high lighted in pink and yellow. The numbers of fatalities in Kashmir were approximately 85,000 and about 10,000 in Kathmandu.

If authorities and individuals had taken these 2005 warnings seriously, earthquake protection units (EPU) might have been constructed, saving numerous lives. An EPU, also called 'earthquake closet', is a strong construction in an area of approximately 2^2 meters within a dwelling, into which occupants of the vulnerable building can flee, once the initially small shaking starts (Wyss, 2012). Such a structure is similar to a tornado shelter, as available in lumber yards in the US. It is far cheaper than retrofitting the entire home and can even be assembled by the owner, if money is an issue. The probability to die in an earthquake in such a closet is 1,000 times less than to die in the house collapsing around the unit.
What earthquake risks is the population of sections of the Himalayan plate boundary facing? QALRM has been calibrated by estimating fatalities correctly in case of the Kashmir and the Nepal earthquakes (Wyss, 2006; Wyss, 2016). Therefore, it is reasonable to calculate updated scenarios for losses due to future earthquakes in the Himalayas, using QLARM.

A rupture along a plate boundary can be continued within years to decades by an adjacent rupture. It is not unlikely that the Gorkha, 2015 M7.8 earthquake may be followed by an M8 event west of it. The damage that is expected to result in such a case is shown in Figure 3. As this map demonstrates, the settlements are numerous. According to the QLARM estimate, the number of settlements that may be shaken with intensity VI or larger is 2,375 (damage and casualties may occur in poorly built settlements at this intensity); the number of people affected at Intensity VI+ shaking = 23 million; the number of injured = 500,000, and the number of fatalities = 160,000, all approximately.
An even larger disaster may be in store along the Himalayan plate boundary. Suppose, in a repeat of the 1505 earthquake, the entire segment covered by that rupture and marked by red dashes in Figure 1, should

break. In that case, an earthquake with M8.7 would result and the number of injured would exceed 1 million, with at least ½ a million fatalities (Figure 4).

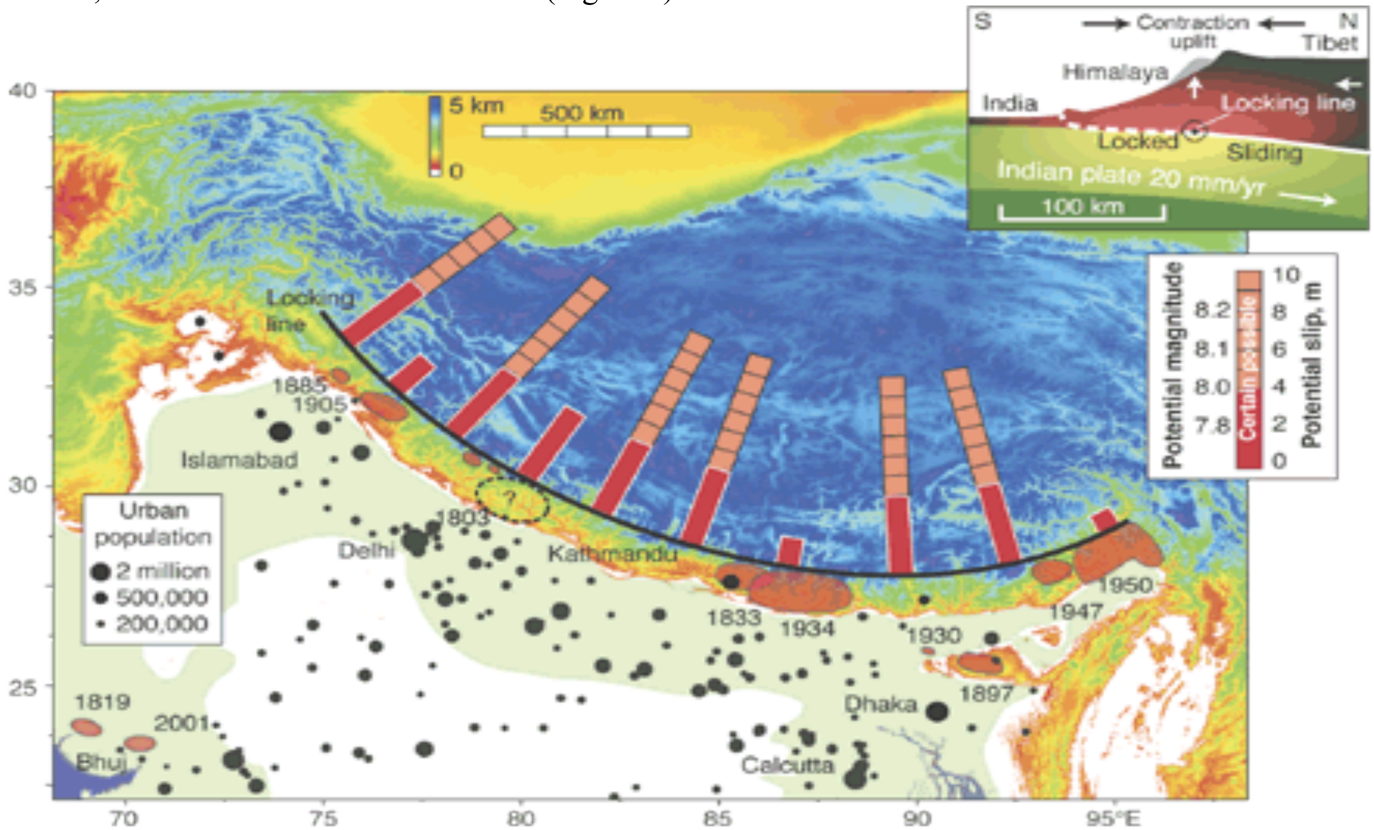

Figure 2: Map of the amount of slip stored along the Himalayan plate boundary assembled more than a decade ago (Bilham et al. 2001). Now the slip stored and the looming risk is even larger. The rate of accumulating slip is about 4 cm per year.

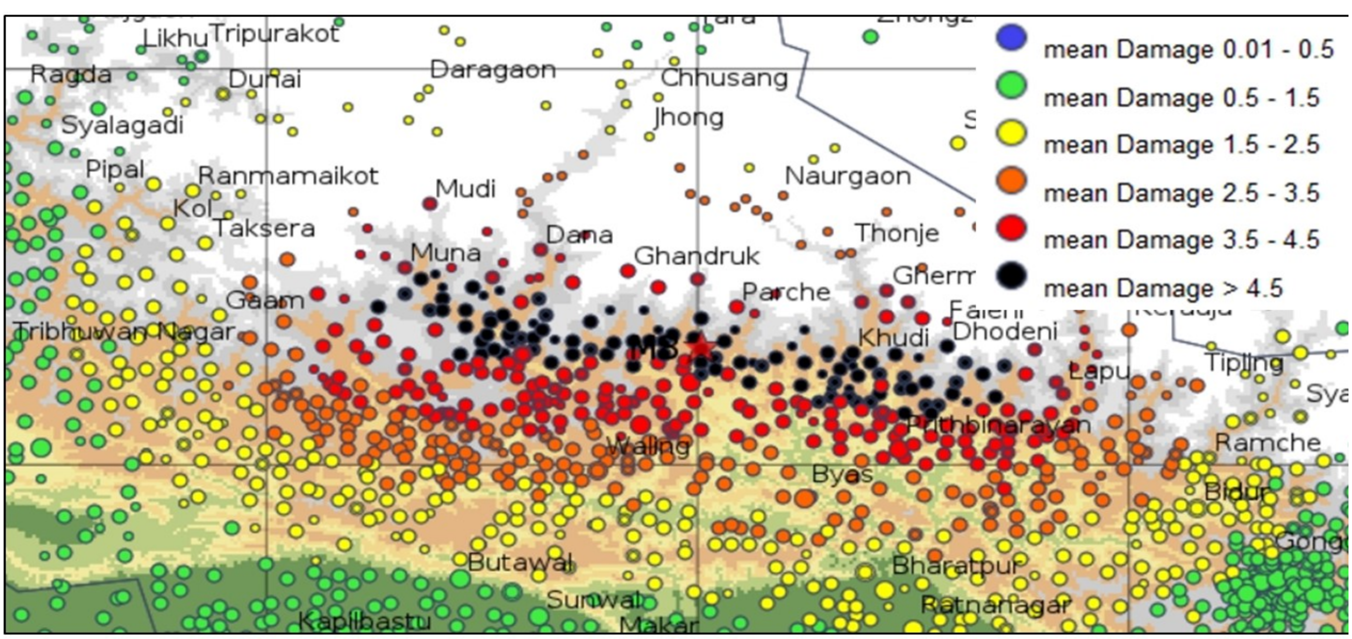

Figure 3: Map of mean damage in regional settlements if the rupture of the 2015 Nepal earthquake continued to the west in a hypothetical M8 earthquake along the same plate boundary. The scale of mean

damage goes from minor damage (green) to mostly collapse (black).

Earthquakes of magnitude 8+ cannot be avoided in the Himalaya. However, the resulting disaster could be reduced by taking mitigating measures beforehand. In the case of such a mega-disaster, any mitigating effort would result in an enormous reduction of the toll on lives and injured. The ICES Foundation is proposing to help reduce the enormous losses of lives expected in the Himalaya by quantitatively demonstrating how serious the earthquake risk is in this area and by guiding the people in constructing earthquake closets to protect themselves.

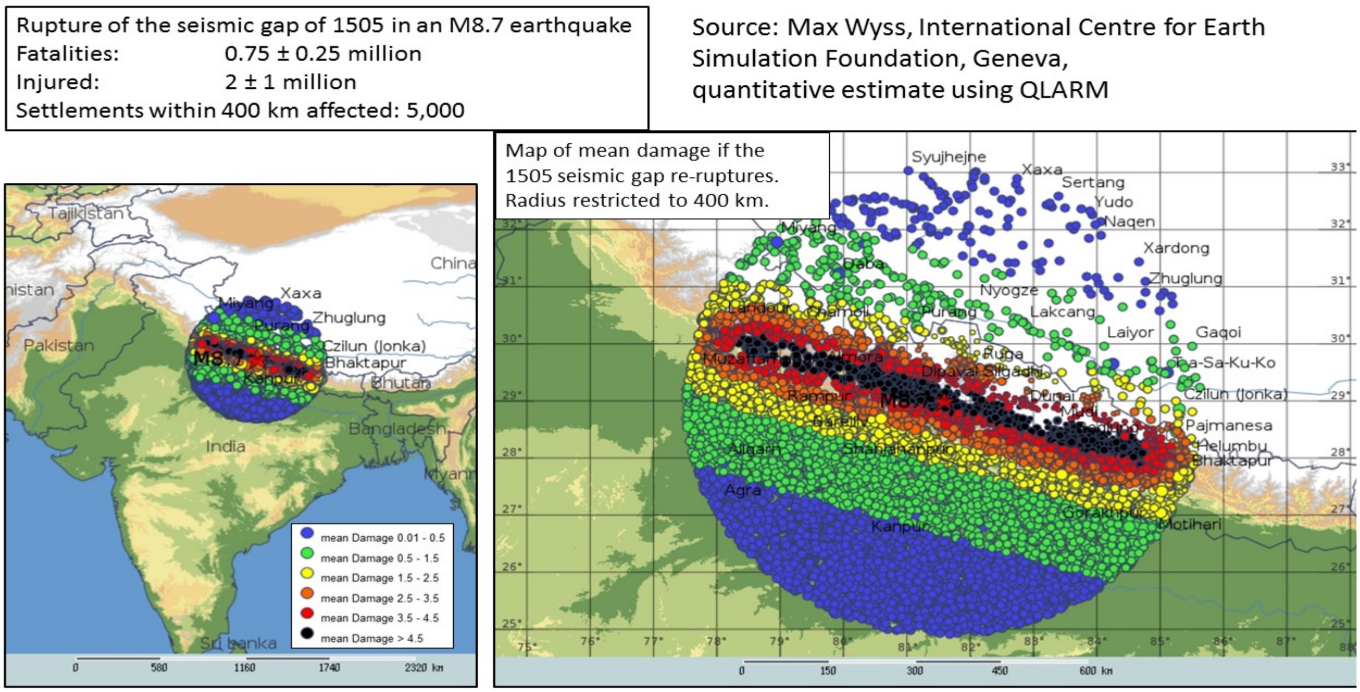

Figure 4: Map of the mean damage expected in case the 1505 earthquake repeats in an M8.7 event. The calculation is limited to a radius of 400 km.

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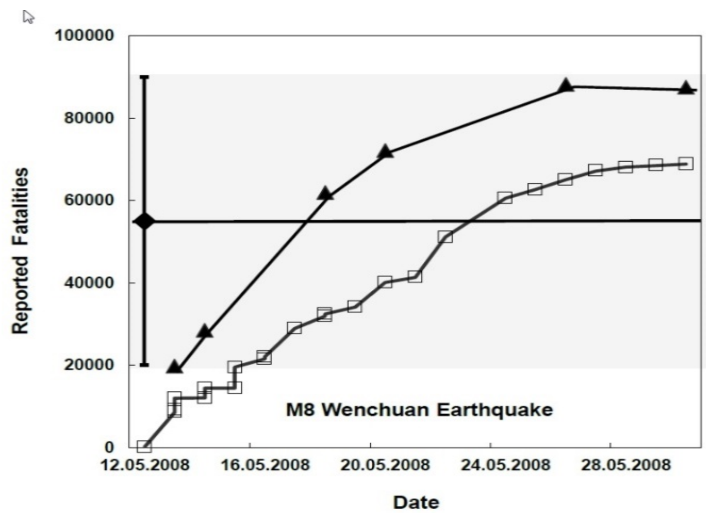
ICES Foundation

China is the country leading the world in earthquake fatalities and injured. The reason for this is a combination of three factors: Great earthquakes, a large population, and weak buildings in certain regions. The number of fatalities due to earthquakes since the year 186 BC equals about 3.1 million. This estimate is based on the list of deadly earthquakes by Utsu (2002), augmented for more recent events and accounting for 160 earthquakes in total. We show here that the computer tool QLARM and its dataset for China calculates losses in earthquakes correctly. It could be used to estimate casualties in likely future earthquakes quantitatively.

QLARM real time capability

Many of the disastrous earthquakes in China occur in mountainous regions where communication and access are especially difficult. For example in the Wenchuan magnitude 8 earthquake on 12 May 2008, approximately 85,000 people were killed, but the responsible Chinese agency believed for several days that the fatalities numbered about 5% of this. Figure 1 shows that the QLARM calculation assessed the Wenchuan earthquake disaster correctly many days before officials realized the extent of the calamity.

Figure 1: Fatalities (open squares) and the sum of fatalities plus missing (solid triangles) as a function of the date after the Wenchuan M8 earthquake 2009, as reported by the Chinese News Agency, compared to the estimate by the QLARM team 100 minutes after the disaster (diamond), with its uncertainty (vertical bar). This early estimate was performed with input from a Chinese colleague who believed the magnitude was 8 not 7.5 as first reported in the west.



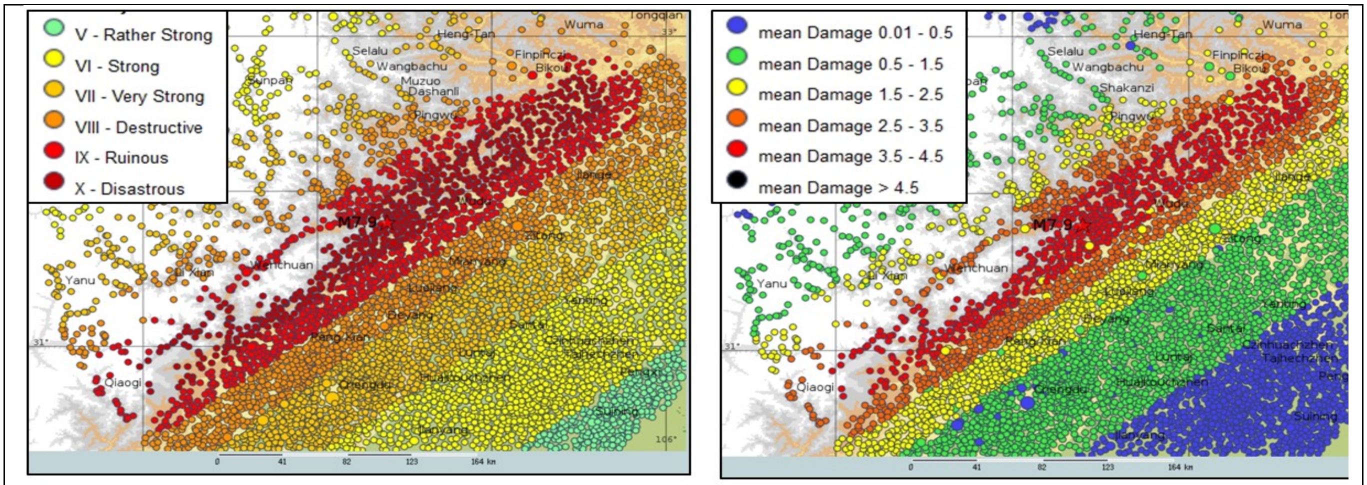


Figure 2: Maps of Intensity (left) and Mean Damage (right) calculated by QLARM for the M8 Wenchuan earthquake. Each dot represents a settlement in the dataset of QLARM.

The maps in Figure 2 show that the coverage of settlements in the QLARM database is dense. For China, the database contains 177,827 settlements, based on the 2010 census. The correct calculation of the total number of fatalities by QLARM during the first minutes, without input from the affected area, qualifies the value of using QLARM for estimating losses for earthquakes in China. This has been confirmed again more recently since 2008 in the case of the 20 earthquakes around the globe for which QLARM received an SMS requesting a calculation (Table 1).

Year	Month	Day	Lon	Lat	dep	M	Fat(min)	Fat(max)	Fat(obs)	Inj(obs)	Alert	Delay (min)
2008	1	9	85.15	32.34	10	6.3	0	10	0		yellow	29
2008	5	12	103.27	31.08	10	8.0	40'000	100'000	87,652	374,171	red	100
2009	8	28	95.68	37.72	10	6.2	0	10	0		yellow	32
2010	4	13	96.67	33.26	45	6.9	200	4'000	2'968	10'701	red	23
2011	11	1	43.63	82.38	10	6.0	0	200	0		orange	47
2012	3	8	81.46	39.39	10	5.8	0	0	0		green	31
2012	6	29	84.79	43.45	20	6.4	0	50	0	52	yellow	25
2012	8	12	82.54	35.67	10	6.3	0	10	0		yellow	46
2013	4	20	102.96	30.28	12	6.6	200	2'300	217	12'211	red	44
2013	7	21	104.18	34.52	10	5.9	0	300	95	1'243	orange	34
2014	2	12	82.59	36.04	10	6.8	0	50	0		yellow	31
2014	10	7	100.52	23.41	10	6.0	0	400	1	300	orange	62
2014	11	22	101.62	30.30	10	5.8	0	200	5	54	orange	19
2014	12	6	100.48	23.36	8	5.5	0	10	1	22	yellow	59
2015	2	22	85.69	44.18	10	5.8	0	5	0		yellow	23
2015	4	25	87.26	28.37	10	5.7	0	20	0		yellow	464
2015	7	3	78.21	37.44	10	6.1	0	200	3	71	orange	316
2016	1	13	84.24	42.21	10	5.6	0	0	0		green	60
2016	1	20	101.58	37.72	10	5.9	0	50	0		yellow	24
2016	5	11	94.99	32.04	10	5.5	0	10	0		yellow	35

Table 1: List of real time alerts by QLARM since 2008. The minimum and maximum estimates of fatalities are compared with the observed numbers (USGS or the Relief Web). The delay with which the alerts were received by subscribers is given in the last column..

During the period covered by Table 1, two significant earthquakes occurred for which QLARM did not get an SMS requesting calculation. For these two earthquakes in the list a communication problem increased the delay an order of magnitude above the normal. The median delay time, counting all events however, was 35 minutes.
All of the real time calculations contained the actual observed number of fatalities within their estimate range, meaning that the loss estimates were all correct. The reason for QLARM estimates of fatalities being on the high side is that in real time the hypocenters are afflicted by certain errors. Moving the hypocenters closer to settlements within the errors, can give higher fatality counts, for example. Because this may exist in reality the QLARM operator accounts for this possibility.

QLARM estimate of lives saved in the Haicheng M7.3 earthquake.
Given the proven correct estimates of fatalities by QLARM as detailed in the previous section, we have calculated how many lives were saved by the evacuation before the Haicheng, M7.2, 1975 earthquake (Wyss and Wu, 2014). This is the only estimate of fatalities saved by an evacuation before an earthquake that we know of.

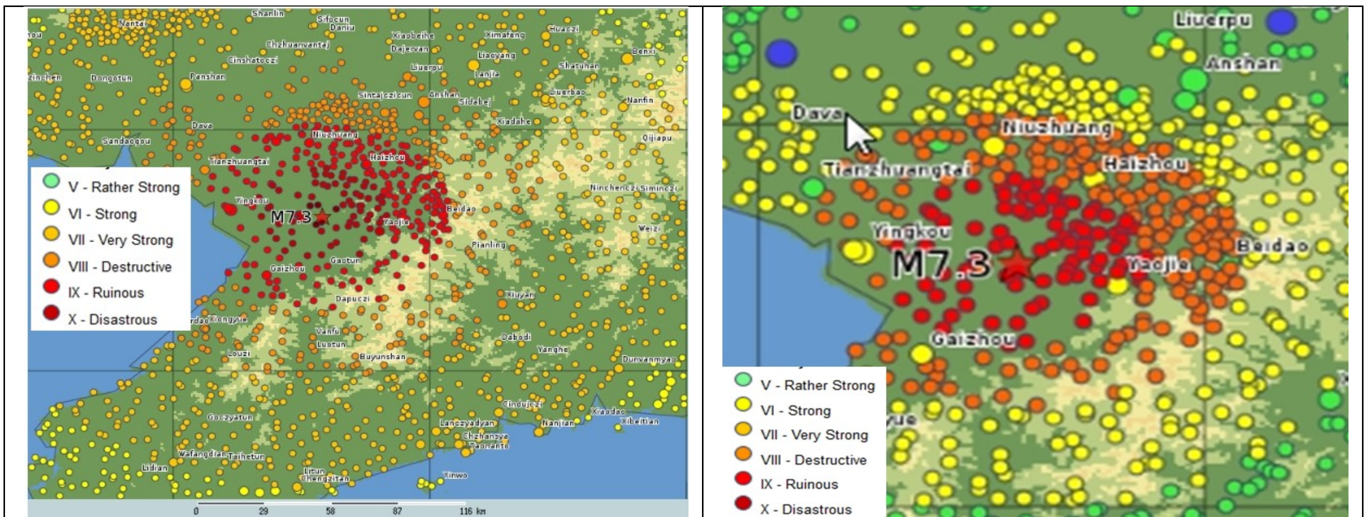


Figure 3: Maps of estimated Intensities in a large area (left) and Mean Damage in the epicentral area for the Haicheng 1975 earthquake, modeled as a point source using QLARM.

In this case, we calculated how many people would have died if the normal number of people had been at home. First, we estimated the Intensities, using various attenuation relationships. The best fitting match of Intensities is shown in Figure 3 left. Next we estimated the total number of fatalities expected if 20% fewer people lived in the area at the time of the earthquake than in the census of 2010. Table 2 shows the comparison of our results with actual observed number of fatalities according to two sources (Quan, 1988 and Wang et al., 2006).

Population	Fat(calc)	Fat(obs)	Fat calc-obs	Inj(max)	Inj(obs)	Inj Ave-Obs	Source observed
2010	11,800			60,000			
1975	9,400	1,328	8,100	48,000	16,980	31,000	(Quan, 1988)
1975	9,400	2,041	7,400	48,000	24,538	23,500	(Wang *et al.*, 2006)

Table 2: Comparisons of the average calculated (calc) numbers of fatalities (Fat) and of the maximum number of injured (Inj) that would have resulted without evacuation, with the respective observations (obs) as cited by the two sources given in the last column. The top row shows the results using the population numbers of 2010. For the second and third rows it is assumed that the rural population in the epicentral area numbered 20% less in 1975 than in 2010.
We concluded that about 8,000 fatalities and 27,000 injured, had been saved respectively. Although the error margin of ± 60%, is large, the order of magnitude is correct.

Using the QLARM loss estimate system for China in scenario planning mode.
Estimating losses before they have occurred will allow authorities to plan for, prepare and mitigate the future consequences as much as possible, knowing approximately what will happen eventually along these plate boundaries. After the events occur, it also affords an opportunity to compare the calculations with reality.

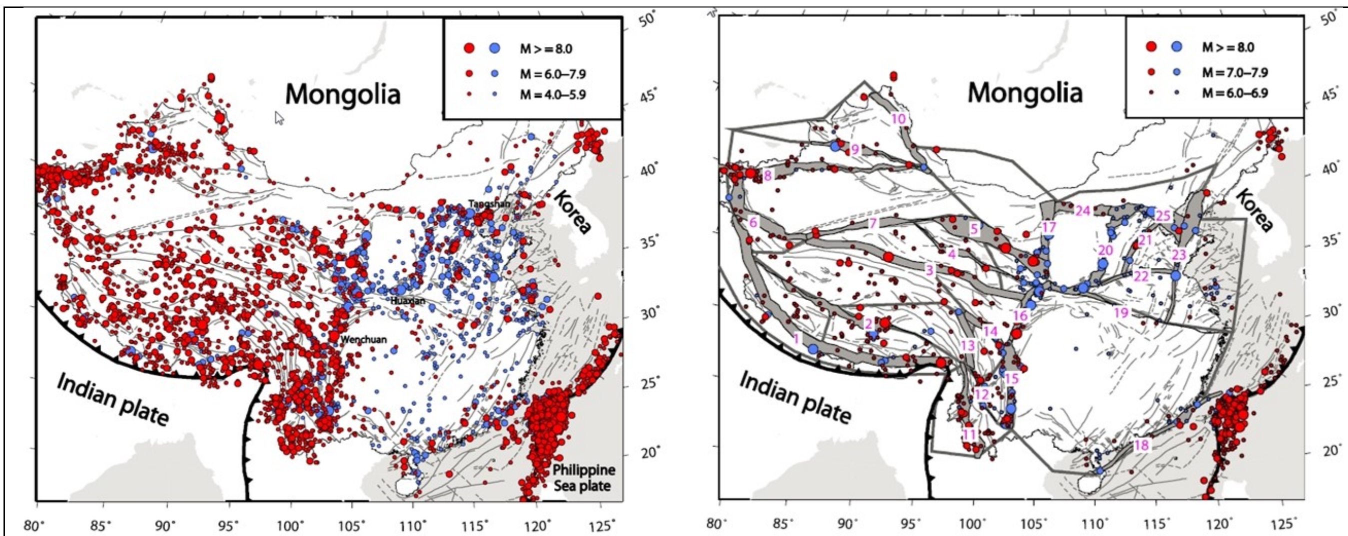


Figure 4: Maps of the epicenters in China (left) and of the major as well as minor active faults (right) (from Wang et al., 2001).

The seismicity of China is complex, with the western part most active, although the northern part has experienced many historic earthquakes as well (blue in Figure 4, left). From this complicated picture, Wang et al. (2011) have extracted the major fault zones and positioned the major earthquakes (Figure 4, right).

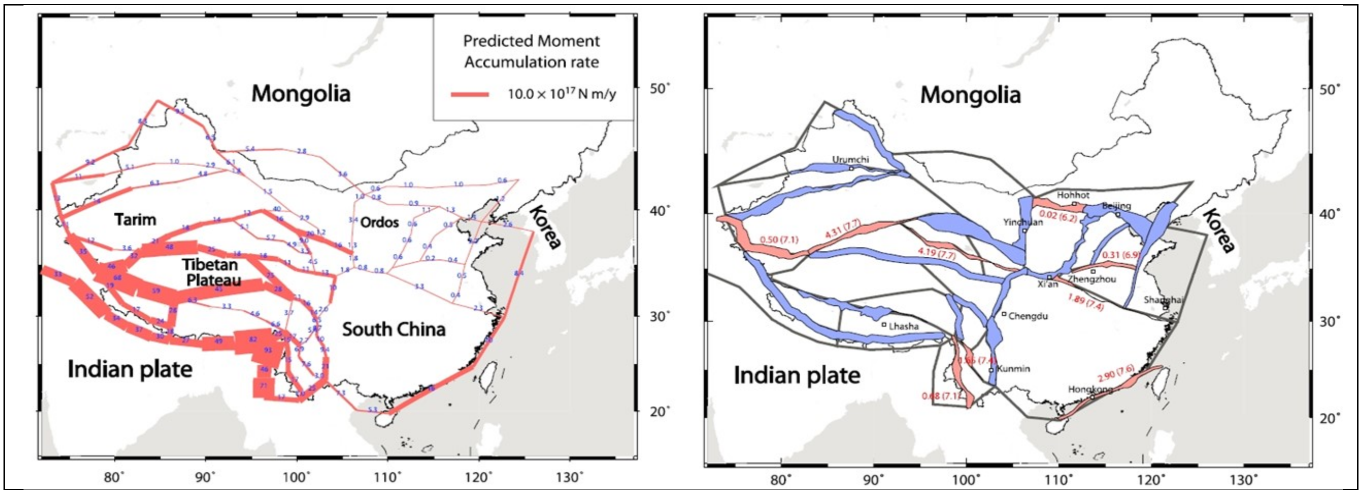


Figure 5: Map of predicted moment accumulation rate according to the model by Wang et al. 2001 (left). Map on the right shows faults with moment deficits, colored pink, along which Wang et al. (2011) expect earthquakes with Magnitudes as indicated.

The important information to know is which faults are most likely to rupture in the near future. As reliable prediction of earthquakes is currently not possible, an estimate of strain accumulation is key. Wang et al. (2001) proposed a model by which the strain accumulation in units of seismic Moment is derived (Figure 5, left). This Figure makes it quantitatively visible that the greatest strain accumulation occurs in the SW, with the center eastern part (CE) riddled with faults along which the strain accumulation rates are very low. That means large earthquakes are expected in the SW, but there can be surprises in the CE. These facts are generally known and they make it difficult to anticipate earthquakes in China. Nevertheless, Wang et al. (2011) mark sections pink where large earthquakes are to be expected, according to their model.

The question QLARM calculations may answer is this: What order of magnitude of casualties should one expect if one of the fault sections marked pink by Wang et al. (2011) should rupture in an earthquake with the M indicated by Wang et al. (2011)?
Figure 6 shows the maps of intensities and mean damage to be expected, due to an earthquake of M7.4 (that is 150 km rupture length) that emanates from Xi'an toward the SE, along the pink line in Figure 5. In such a case tens of thousands would probably die and up to 100,000 injured would have to be cared for. These numbers are very high because the population living in the area of strong shaking (MMI ≥5.5) is more than 18 million, distributed in about 3,000 settlements.

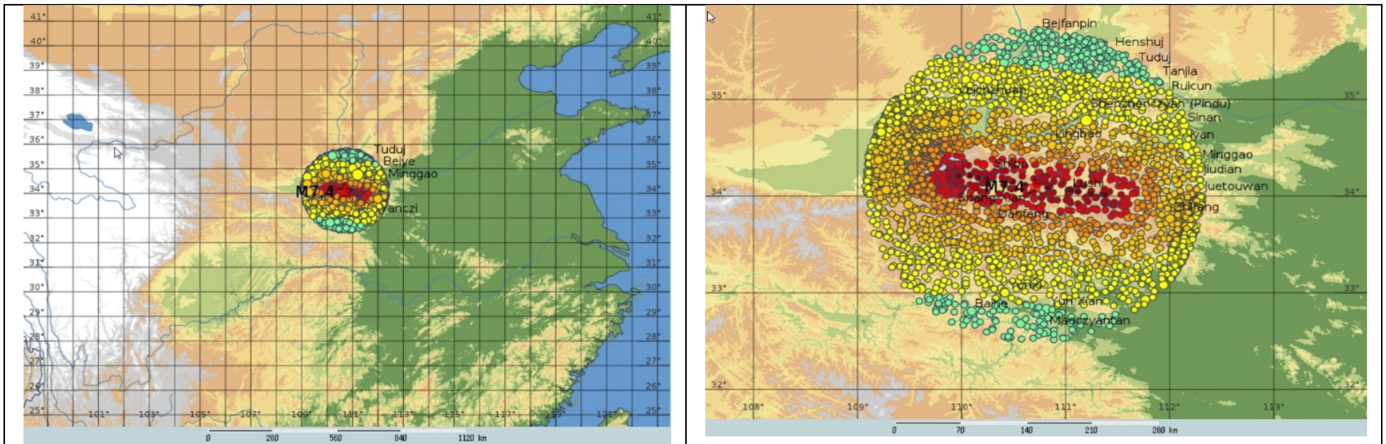


Figure 6: Map of approximate intensities (left) and mean damage (right) in case of a hypothetical earthquake of M7.4 (150 km rupture length, east of Xi'an. The calculation is limited to a radius of 400 km. This is only a rough test without detailed consideration of the fault line and magnitude. No endorsement is implied of such an earthquake to occur.

We stress that the model shown in Figure 6 is hypothetical and only approximately follows the suggestion by Wang et al. (2011) that east of Xi'an the seismic moment necessary for an earthquake of M7.4 may have accumulated by now. We purposely do not give specific numbers for the estimates of fatalities and injured and do not show close up maps. No action is recommended on the basis of the loss estimate in Figure 6. This is simply a quantitative estimate of a fact that is generally known, namely: If a large earthquake happens in a populated part of China, the losses will be serious.
More reliable scenarios could be calculated for any active fault in China using QLARM, and with the collaboration of Chinese experts.

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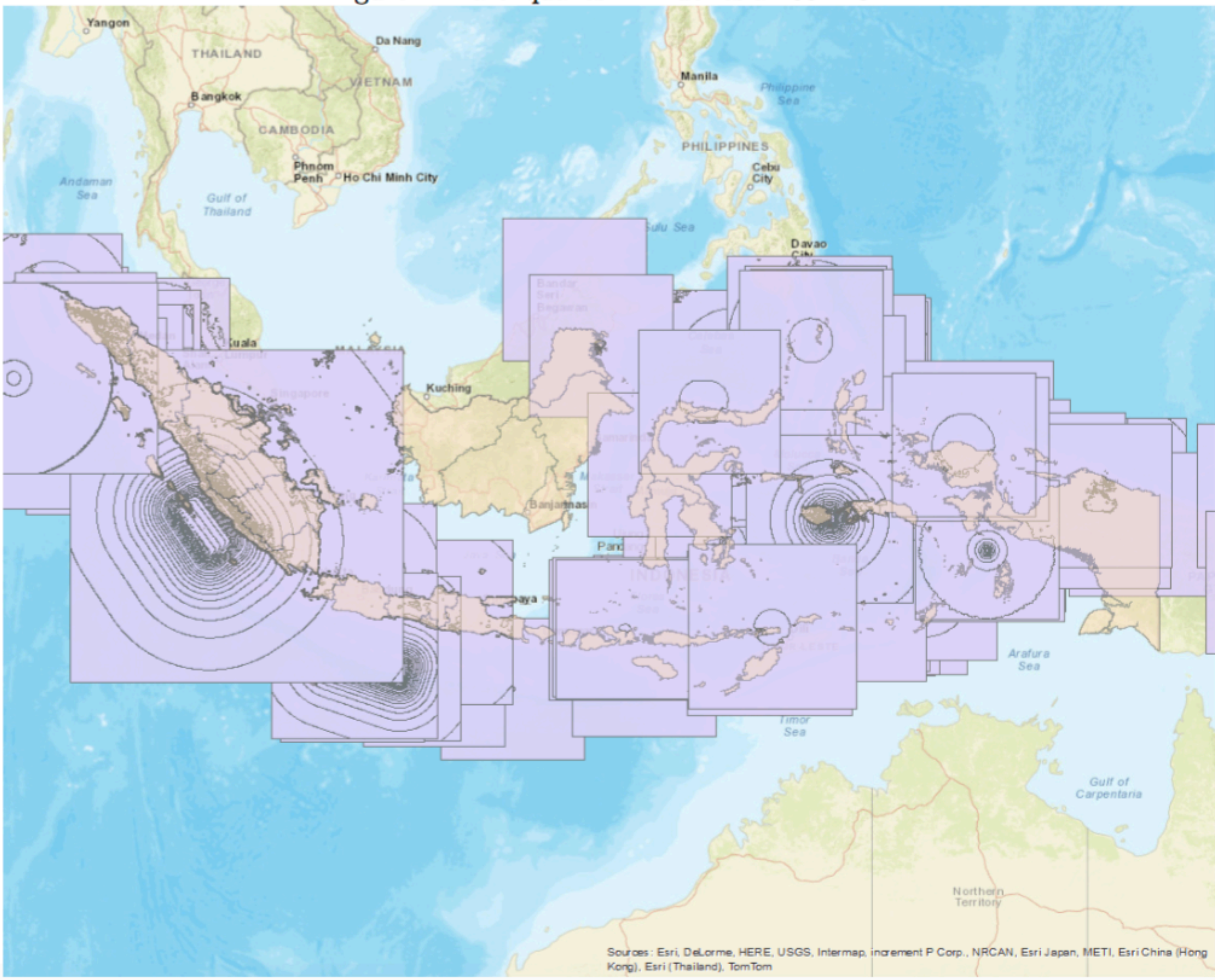
Wang, H., M. Liu, J. Cao, X. Shen, and G. Zhang (2011). Slip rates and seismic moment deficits on major active faults in mainland China, *J. Geophys. Res.* **116**, doi:doi:10.1029/2010JB007821.

Wang, K., Q.-F. Chen, S. Sun, and A. Wang (2006). Predicting the 1975 Haicheng Earthquake, *Bull. Seismol. Soc. Am.* **96**, 757-795, doi:10.1785/0120050191.

Wyss, M., and Z. L. Wu (2014). How Many Lives Were Saved by the Evacuation Before the M7.3 Haicheng Earthquake of 1975?, *Seismol. Res. Lett.* **85**, 126-129, doi:10.1785/02201 30089.

Figure 2: Earthquakes in Indonesia 2004-2014



Source: USGS

Press Release 2 September 2015

LASG/IAP and ICES sign collaboration agreement for the Himalayan Region and establishment of Asian Centre for Earth System Simulation

Mountains are among the regions that are most sensitive to climate change and to the impacts of human activities. The Himalayan Region, characterized by the massive mountain ranges of the Himalaya, has therefore attracted wide research interest. The State Key Laboratory of Numerical Modelling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS) signed a cooperation agreement with the International Centre for Earth Simulation (ICES) Foundation on 19 August, 2015 to boost research on the dynamics of the Himalayan Region. Following the agreement, an Asian Centre for Earth System Simulation (ACESS) will be established.

ICES Foundation is a Geneva-based, not-for-profit organization and the Himalaya Project is a major element in its global vision and mission. LASG/IAP has been devoted to Tibetan Plateau research since 1980s, including its impact on monsoons and climate. Both parties have agreed to collaborate and to share expertise and knowledge with ACESS such that they build value and working experience in matters relating to the Himalayan Region and its impact on weather, climate, geological, biological and socioeconomic factors throughout Asia and the rest of the world - with focus on data visualization, climate modeling, water & energy resources, and disaster risk reduction. At present the ACESS International Project Office (IPO) is located in LASG/IAP.

LASG/IAP/CAS will be primarily responsible for carrying out research and development projects in China and for leveraging its local knowledge, contacts and expertise. The responsibilities of ICES include advising ACESS in the use of advanced digital visualization techniques and implementing quality control systems of an international standard while assisting ACESS to collaborate with other members of the ICES community.

Director-General of IAP/CAS Prof. ZHU Jiang, wished the cooperation could take full advantage of both parties' strength and develop new climate system insights for the Himalaya Project. One of four advisors of the IPO and also a CAS academician, Prof. WU Guoxiong commented that, "The signing of the project and inauguration of ACESS is a continuation of the successful collaboration between LASG/IAP and ICES as well as other international agencies in the previous stages of Tibetan Plateau research. Formation of ACESS signals a new phase of cooperation in the field".

Dr. Robert Bishop, President & Founder of ICES indicated the importance of Himalaya and Tibetan Plateau dynamics to the entire world system and that this partnership would shed new light on the extent of their global impact.

Background:

LASG/IAP was founded in 1985 and its priority research areas include: (I) Earth System model development and application, (II) weather and climate dynamics, (III) the predictability of weather and climate, and (IV) geophysical fluid dynamics. http://www.lasg.ac.cn/

ICES is a non-profit organisation whose mission is to collate and integrate global pools of knowledge from across scientific and socio-economic disciplines and develop holistic modelling and simulation to predict the future directions and scenarios of various Earth Systems, especially those affecting climate change, extreme weather, geoengineering, resource depletion, fresh water availability, food security, public health and safety, and hazard reduction and mitigation. http://www.icesfoundation.org

"The Himalaya Project" has been conceived by ICES to improve communication and collaboration among governments, academic and commercial organizations in the 16 nations that are either bordering, exercising jurisdiction or directly impacted by events occurring in the Himalayan Region, so as to produce a unified knowledge system of the region. Such a unified knowledge system (UKS) will collate and process various data to help assess the regional and global impact of human behaviour within the area as well as to help mitigate the occurrence of natural disasters. At the same time, the UKS will help in the design and maintenance of a thriving ecological civilization throughout the region.

LASG/IAP-ICES Partnership presentation given at the ICES Biennial Workshop in Geneva by Professor Wu Guoxiong on 5th November 2015

Other Key presentation material available from the various Key State Laboratories of the Chinese Academy of Sciences:

Introduction to LASG/IAP/CAS: ***L***aboratory for ***A***tmospheric ***S***ciences & ***G***eophysical fluid dynamics

Himalayas Climate Modeling: development of a high-resolution Earth System Model and Asian climate change risk assessment

Variation in the Coupled Land-Atmosphere System over the Tibetan Plateau and its global climate impact

Land Surface Hydrology Modeling

High Resolution Ocean Model and Coupled Model at LASG/IAP/CAS

Current super El Nino event and impacts on China climate in spring and summer
http://www.bulletin.cas.cn/ch/reader/view_full_html.aspx?file_no=20160211&fl%20ag=1

Monsoons in a changing climate
http://indico.ictp.it/event/8054/other-view?view=ictptimetable

APPENDIX A (films, videos & written materials)

The unique geology of the Himalayan Region:

Mount Everest: how it was made
https://www.youtube.com/watch?v=rZNm9_LiyXk
K2: the world's most dangerous mountain climbing
https://www.youtube.com/watch?v=TZaGDoa9vtQ
Constraining the timing of the India-Asia continental collision by the sedimentary record
http://download.springer.com/static/pdf/968/art%253A10.1007%252Fs11430-016-9003-6.pdf?originUrl=http%3A%2F%2Flink.springer.com%2Farticle%2F10.1007%2Fs11430-016-9003-6&token2=exp=1496735940~acl=%2Fstatic%2Fpdf%2F968%2Fart%25253A10.1007%25252Fs11430-016-9003-6.pdf%3ForiginUrl%3Dhttp%253A%252F%252Flink.springer.com%252Farticle%252F10.1007%252Fs11430-016-9003-6*~hmac=835ec5eed86ccddd36368605baf705a37f2ae0d3d61e1774ea672c01f93b1f33
New insights into continental deformation in northwestern Tibet
https://eos.org/research-spotlights/new-insights-into-continental-deformation-in-northwestern-tibet?utm_source=eos&utm_medium=email&utm_campaign=EosBuzz051118
Fossils provide new clues to Tibetan Plateau's evolution
https://eos.org/articles/fossils-provide-new-clues-to-tibetan-plateaus-evolution?utm_source=eos&utm_medium=email&utm_campaign=EosBuzz121517
Himalayan migration northward found to be the result of tectonic lift
http://phys.org/news/2016-08-himalayan-migration-northward-result-tectonic.html
Dynamic topography produced by lower crustal flow against rheological strength heterogeneities bordering the Tibetan Plateau
http://math.mit.edu/~bush/wordpress/wp-content/uploads/2012/10/Dynamic_topography1.pdf
Ancient buried canyon discovered in South Tibet
http://www.caltech.edu/content/caltech-geologists-discover-ancient-buried-canyon-south-tibet
Satellites peer into rock 50 miles beneath Tibetan Plateau
https://news.osu.edu/news/2015/07/21/satellites-peer-into-rock-50-miles-beneath-tibetan-plateau/
Sediment transport processes across the Tibetan Plateau inferred from robust grain-sized lake sediments
https://www.clim-past.net/10/91/2014/cp-10-91-2014.pdf
New research shows Chinese continental shelf of exotic origin collided with continental China 100M years ago
http://thewatchers.adorraeli.com/2015/09/23/new-research-shows-chinese-continental-shelf-of-exotic-origin-collided-with-continental-china-100-million-years-ago/
Himalaya Tectonic Dam with a discharge
http://www.gfz-potsdam.de/en/media-communication/press-releases/details/article/tektonischer-himalaya-staudamm-mit-abfluss/?cHash=d30794c4615bf0089dffd30e1e406d
High-resolution interactive modeling of the mountain-glacier interface: an application over Karakoram
https://www.the-cryosphere.net/7/779/2013/tc-7-779-2013.pdf
Geology and geography of Tibet and Western China
http://www.shangri-la-river-expeditions.com/wchinageo/wchinageo.html
Deciphering the Bay of Bengal's tectonic origins
https://eos.org/research-spotlights/deciphering-the-bay-of-bengals-tectonic-origins?utm_source=eos&utm_medium=email&utm_campaign=EosBuzz82616
A preliminary study of rare-metal mineralization in the Himalayan leucogranite belts, South Tibet
http://engine.scichina.com/publisher/scp/journal/SCES/60/9/10.1007/s11430-017-9075-8?slug=full%20text
Analytical and numerical simulations of uplift processes at the Tibet-Sichuan boundary
https://link.springer.com/content/pdf/10.1007%2Fs11589-017-0185-4.pdf

Impact of earthquakes within the Himalaya Region:

Trouble with tremors
http://www.ekantipur.com/2015/01/15/opinion/trouble-with-tremors/400361.html
Entire Himalayan arc can produce large earthquakes
https://news.agu.org/press-release/entire-himalayan-arc-can-produce-large-earthquakes/
Did an earthquake shrink Mt. Everest? India is going to check
https://www.washingtonpost.com/news/worldviews/wp/2017/01/24/did-an-earthquake-shrink-mount-everest-india-is-going-to-check/?hpid=hp_hp-cards_hp-card-world%3Ahomepage%2Fcard&utm_term=.4ddc4823da49
Better understanding seismic hazards
https://asunow.asu.edu/20160822-discoveries-asu-researchers-earthquake-faulting-mountain-building
Human losses expected in Himalayan earthquakes
http://www.wapmerr.org/publication/Wyss_Himalaya_Scenarios2005.pdf
Ancient temples in the Himalaya reveal signs of past earthquakes
http://www.seismosoc.org/news/ssa-press-releases/srl/
IIT Roorkee's new warning system claims to alert before earthquake strikes
https://indianexpress.com/article/technology/science/iit-roorkees-new-warning-system-claims-to-alert-before-earthquake-strikes-5511409/
Bhutan earthquake opens doors to geophysical studies
https://eos.org/project-updates/bhutan-earthquake-opens-doors-to-geophysical-studies?utm_source=eos&utm_medium=email&utm_campaign=EosBuzz081718
New models explain unexpected magnitude of China's Wenchuan quake
https://eos.org/research-spotlights/new-models-explain-unexpected-magnitude-of-chinas-wenchuan-quake
Key factors influencing the mechanism of rapid and long runout landslides triggered by 2008 Wenchuan quake
http://www.geoenvironmental-disasters.com/content/pdf/s40677-014-0001-6.pdf
Location and moment tensor inversion of small earthquakes using 3D Green's functions in models with rugged topography: application to the Longmenshan fault zone
http://link.springer.com/article/10.1007/s11589-016-0156-1?utm_campaign=CON29747_1&utm_medium=newsletter&utm_source=email&wt_mc=email.newsletter.8.CON29747.ISI_1
Geographical analysis of community resilience to seismic hazard in Southwest China
http://link.springer.com/article/10.1007/s13753-016-0091-8?utm_campaign=CON30776_1&utm_medium=newsletter&utm_source=email&wt_mc=email.newsletter.8.CON30776.internal_1
Pathways to earthquake resilience in China
http://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9893.pdf
How early warning systems brought rapid relief to quake victims in China
http://www.sixthtone.com/news/1000692/how-early-warning-systems-brought-rapid-relief-to-quake-victims
Earthquake loss estimates applied in real time and to megacity risk assessment
http://www.wapmerr.org/publication/ISCRAM_Wyss.pdf
Why earthquakes in China are so damaging
https://www.theatlantic.com/china/archive/2013/07/why-earthquakes-in-china-are-so-damaging/278092/
The population in China's earthquake-prone areas has increased by 32 million along with increased urbanization
http://iopscience.iop.org/article/10.1088/1748-9326/11/7/074028/pdf
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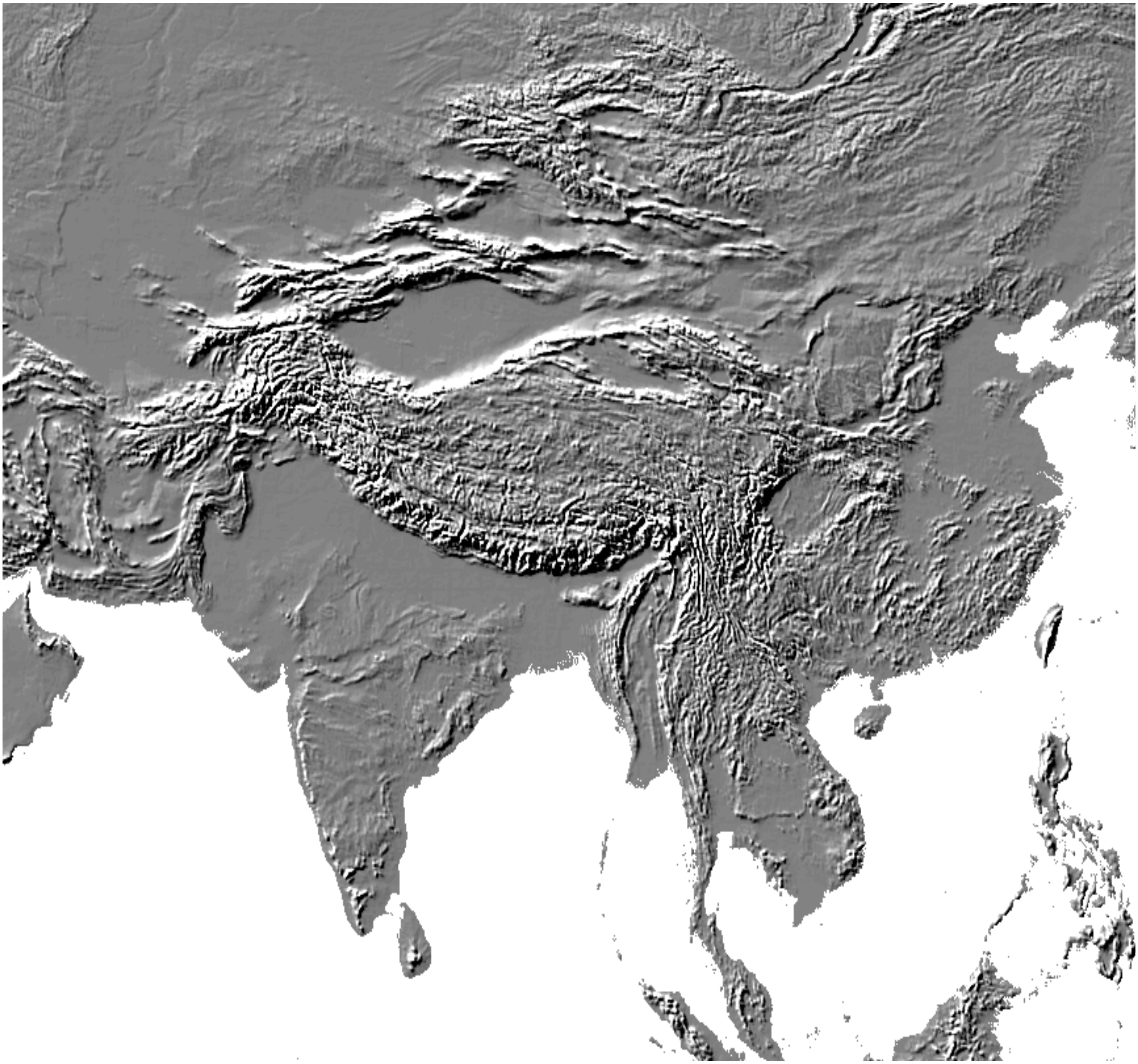
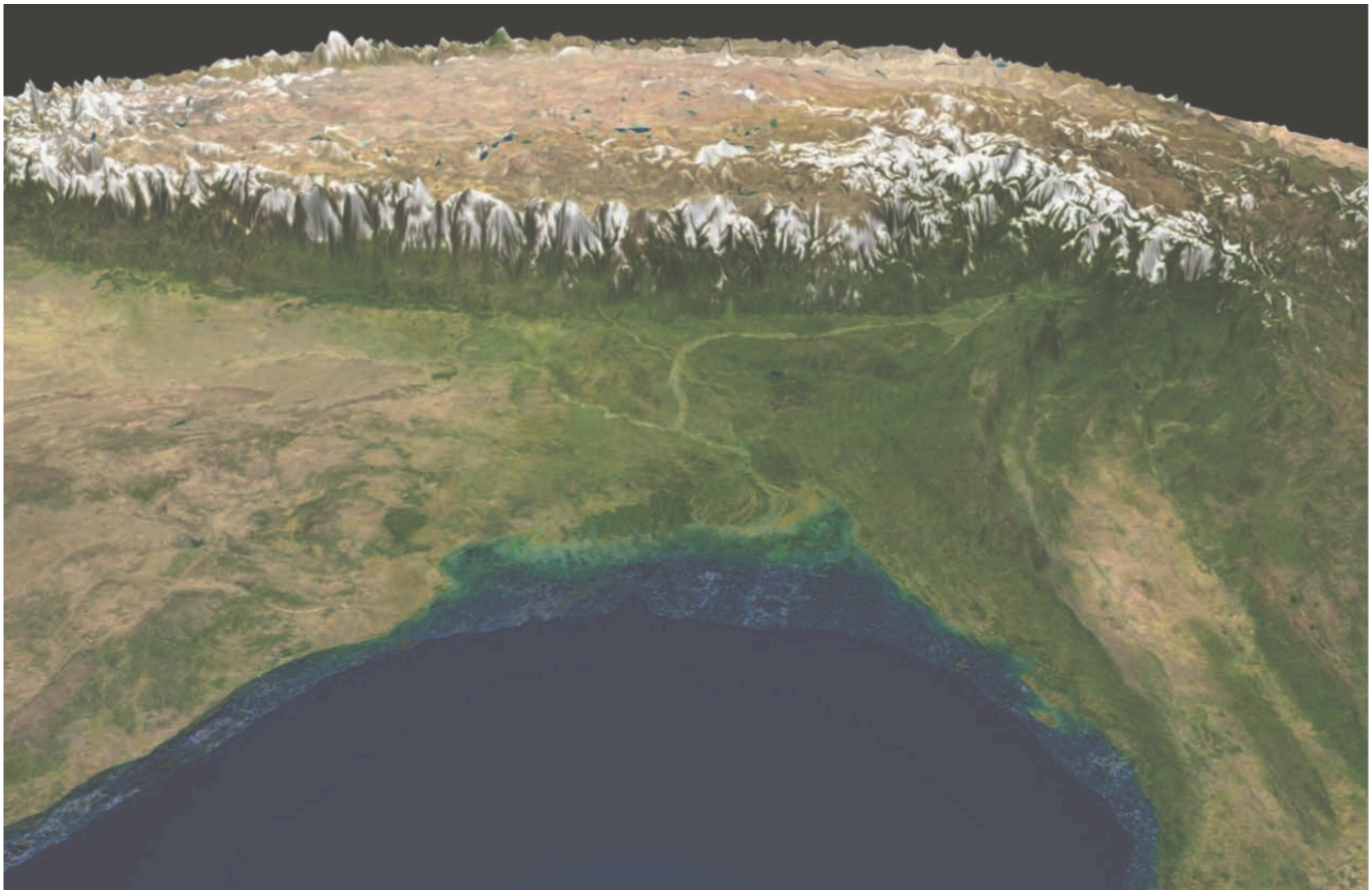
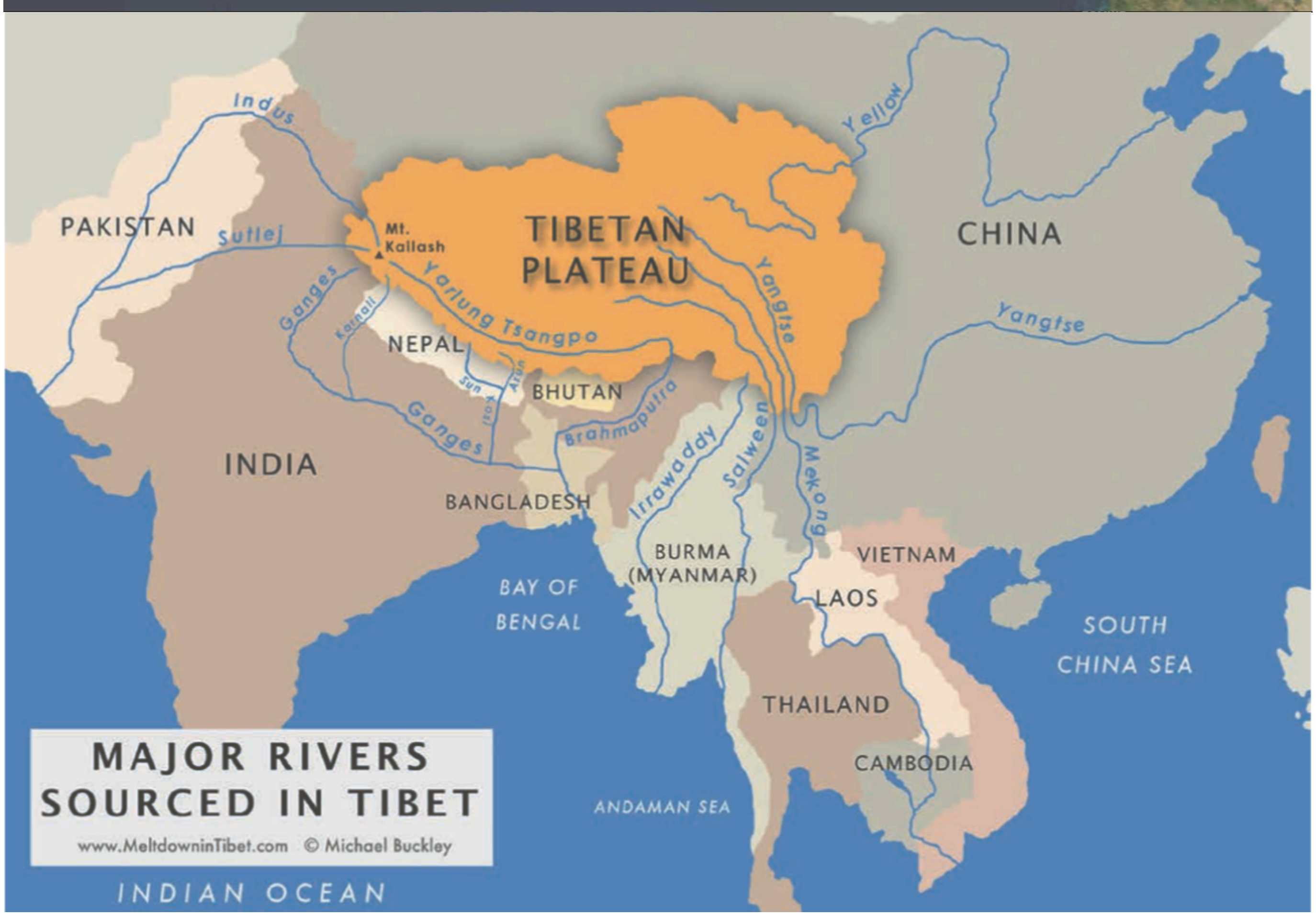
20-years of community-based DRR experience from a dryland village in Indonesia
https://jamba.org.za/index.php/jamba/article/view/502/877






MAJOR RIVERS
SOURCED IN TIBET
www.MeltdowninTibet.com © Michael Buckley
TIBETAN PLATEAU
Mt. Kailash
PAKISTAN
INDIA
NEPAL
BHUTAN
BANGLADESH
BURMA (MYANMAR)
CHINA
VIETNAM
LAOS
THAILAND
CAMBODIA
BAY OF BENGAL
ANDAMAN SEA
SOUTH CHINA SEA
INDIAN OCEAN
Indus
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Karnali
Yarlung Tsangpo
Brahmaputra
Irrawaddy
Salween
Mekong
Yangtse
Yellow

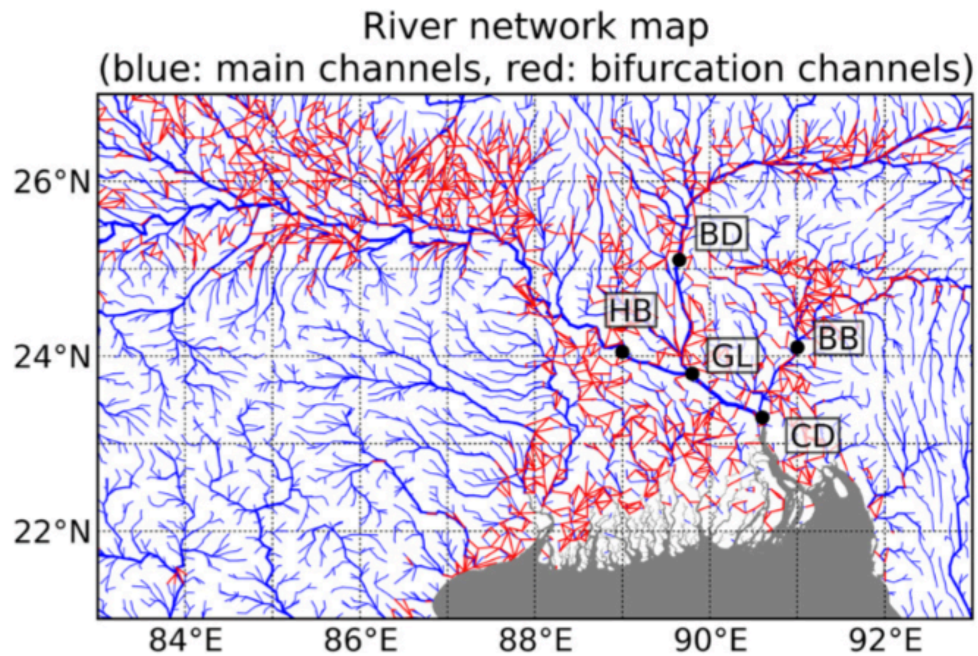

Figure 1. The river network map around Bangladesh with locations and names of the selected stations. The blue and red lines indicate main channels and bifurcation channels, respectively. Bifurcation channels are both diverging river channels and flow routes in floodplains during floods [20]. HB: Hardinge Bridge, BB: Bhairab Bazar, CD: Chandpur, BD: Bahadurabad, and GL: Goalondo. HB and BD are the stations gauging river discharge, and others are those gauging water levels.

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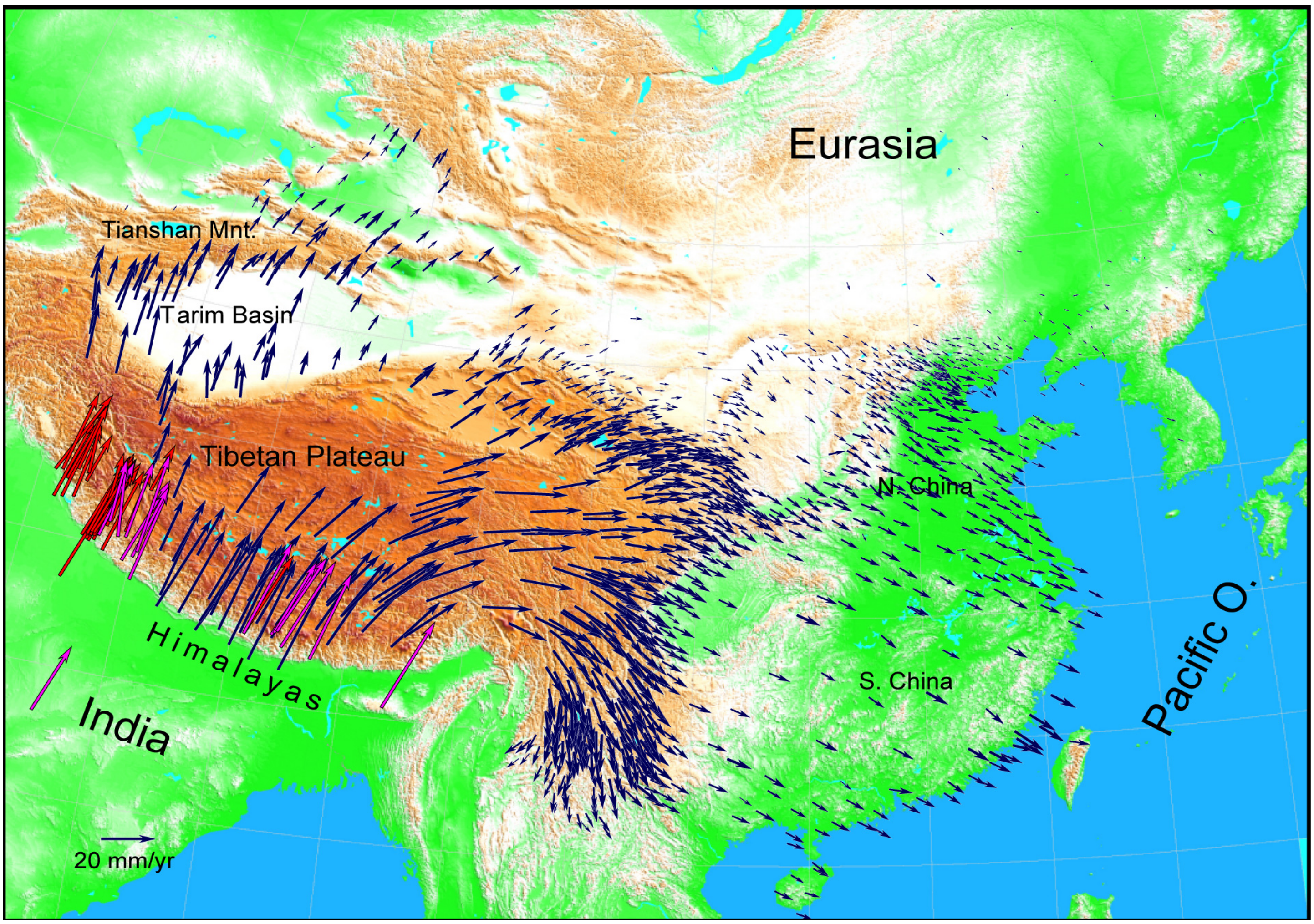
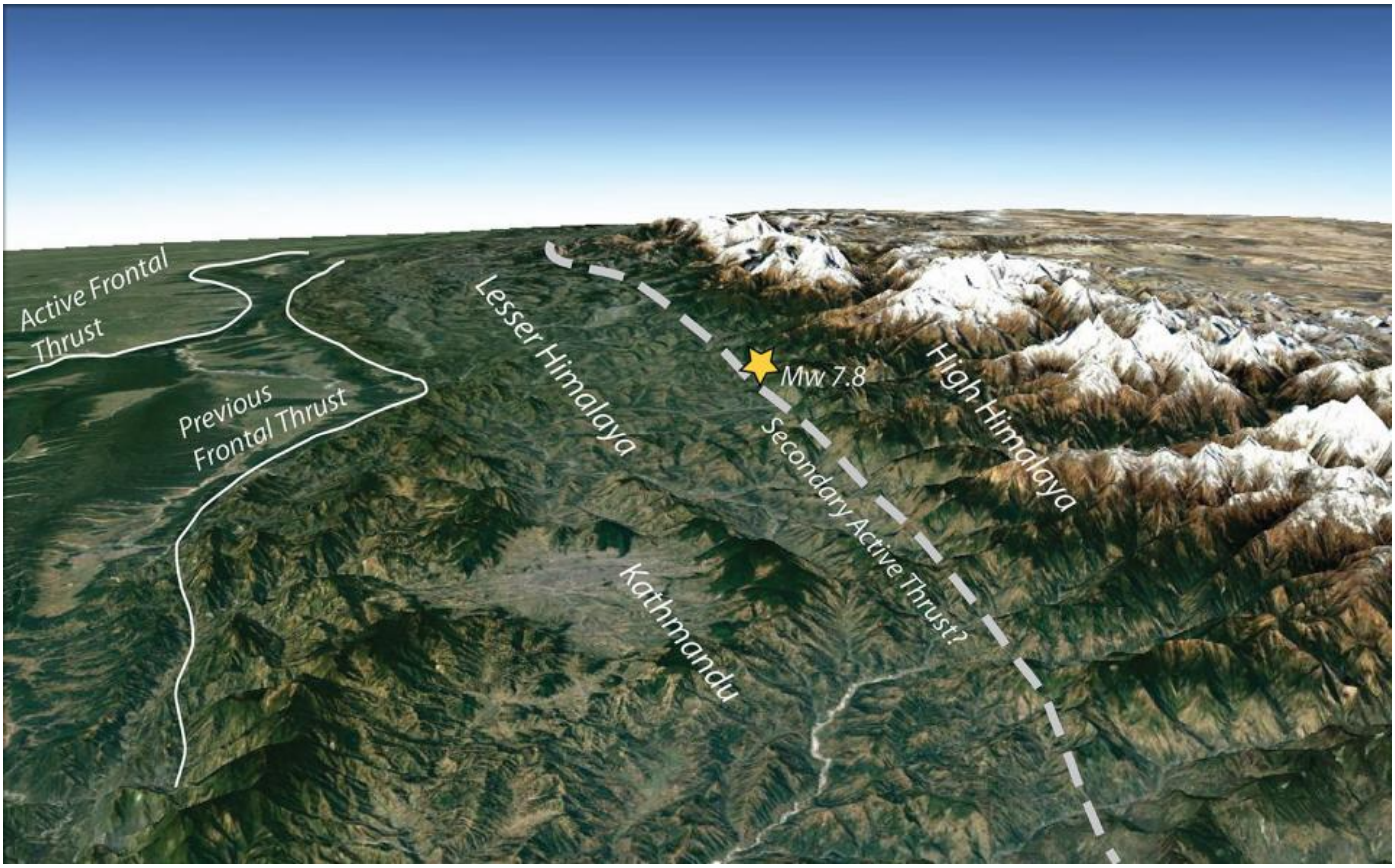
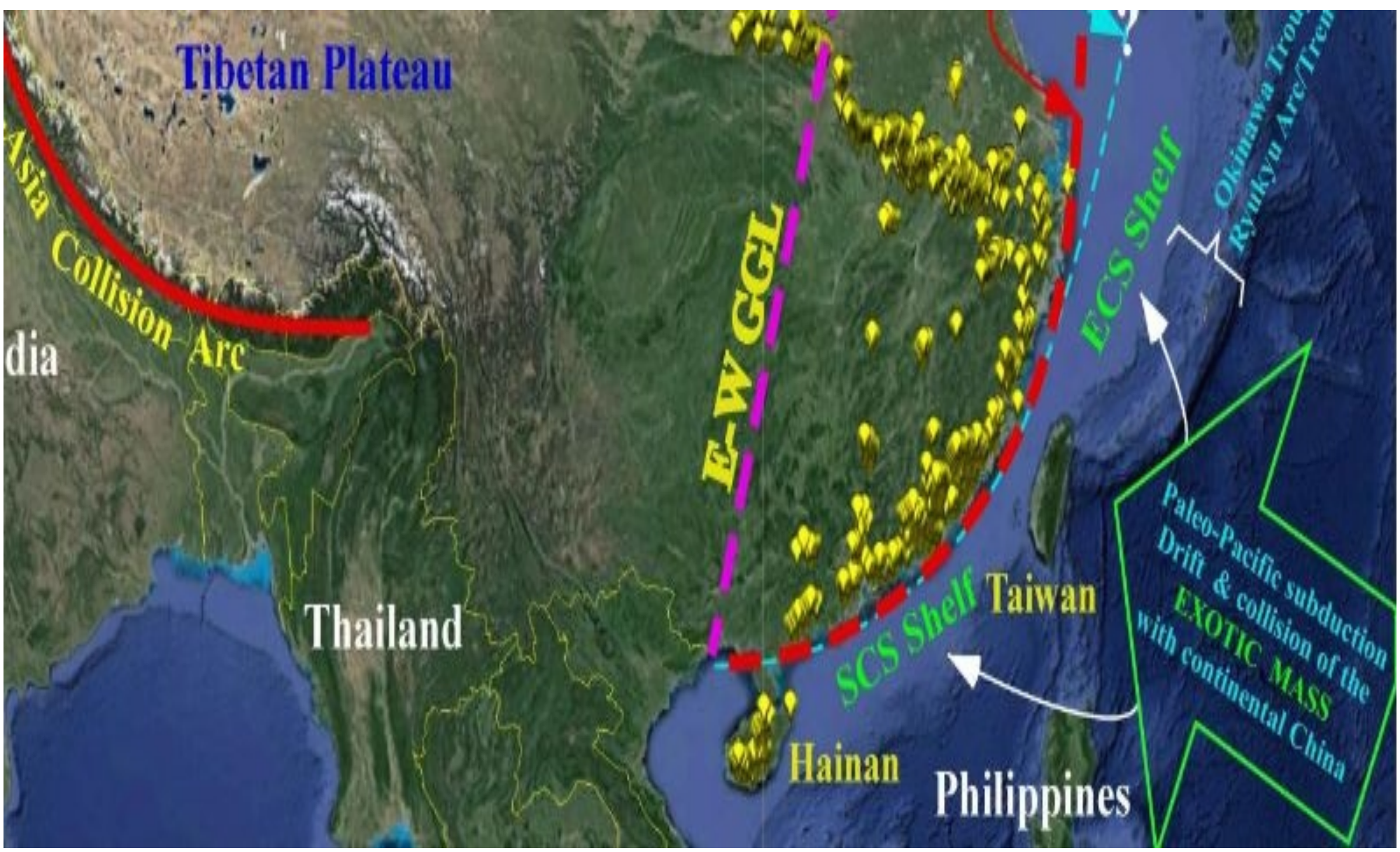
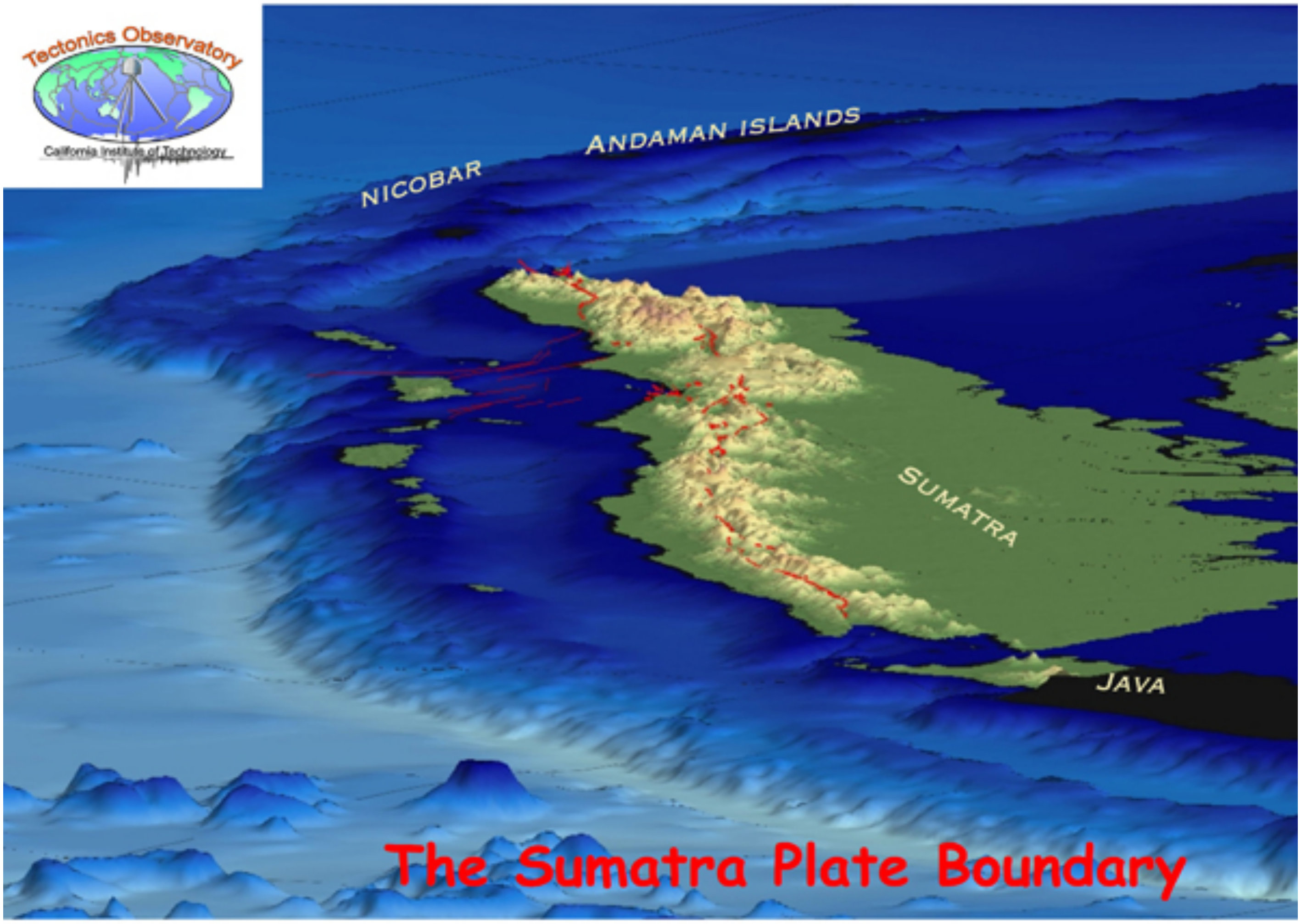
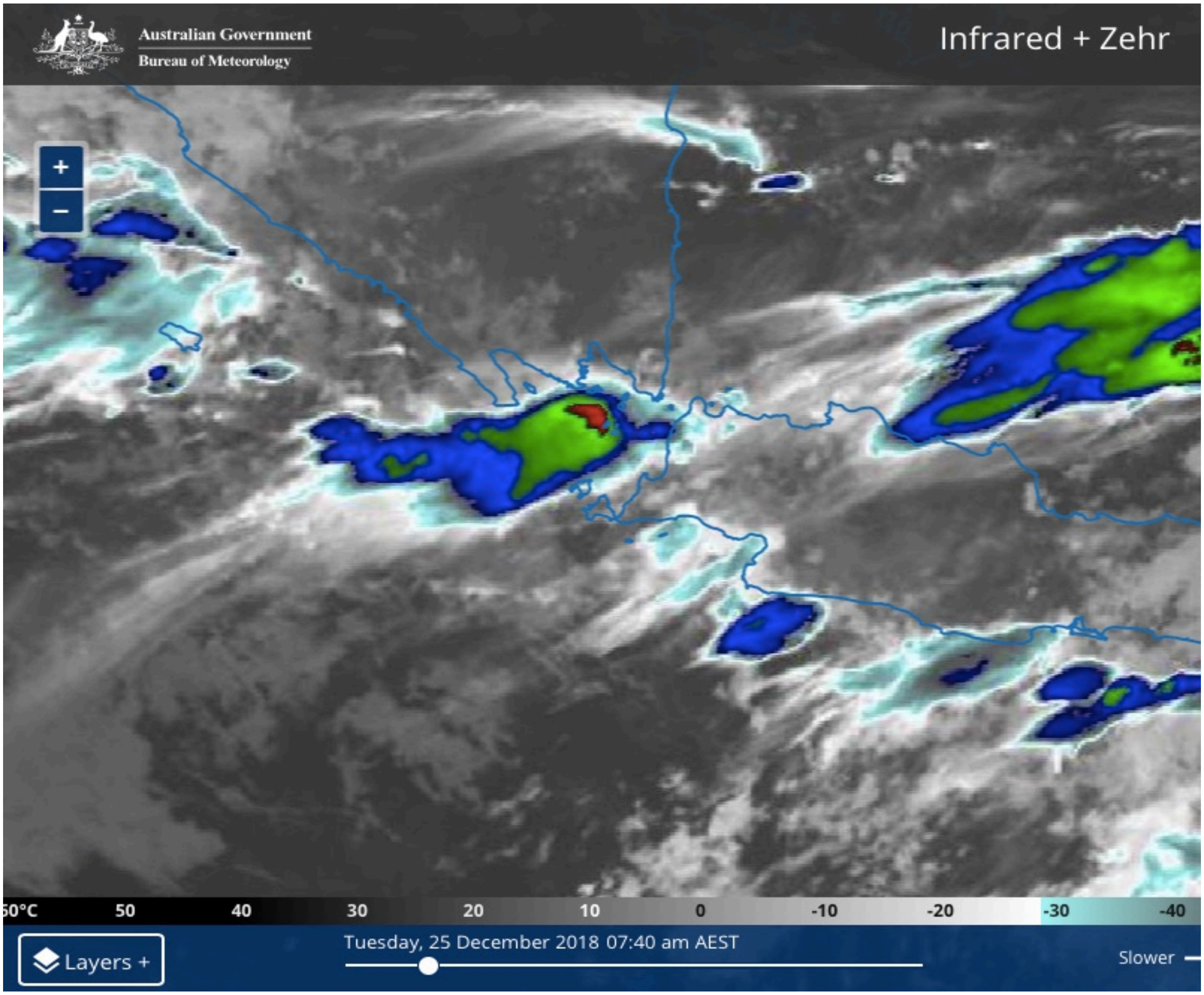



Active Frontal Thrust
Previous Frontal Thrust
Lesser Himalaya
Mw 7.8
High Himalaya
Secondary Active Thrust?
Kathmandu

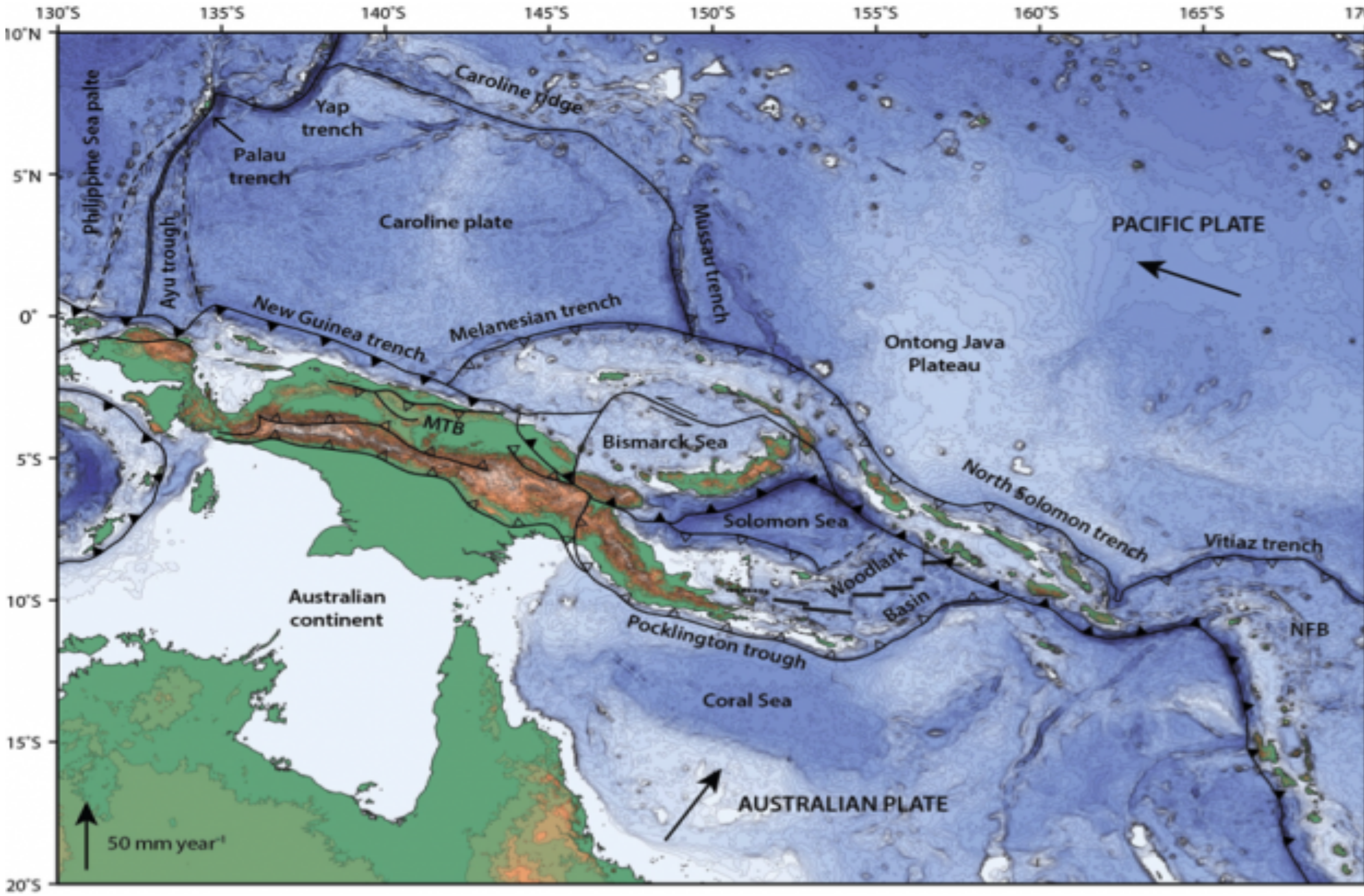

Tibetan Plateau
Asia Collision Arc
dia
E-W GGL
ECS Shelf
Okinawa Trou
Ryukyu Arc/Tren
Thailand
SCS Shelf
Taiwan
Hainan
Philippines
Paleo-Pacific subduction Drift & collision of the EXOTIC MASS with continental China


Tectonics Observatory
California Institute of Technology
ANDAMAN ISLANDS
NICOBAR
SUMATRA
JAVA
The Sumatra Plate Boundary


▲ VOLCANOES IN INDONESIA



Anak-Krakatau volcano (Sundra Straights) erupting and triggering tsunamis that killed 300+ people



130°S
135°S
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10°N
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0°
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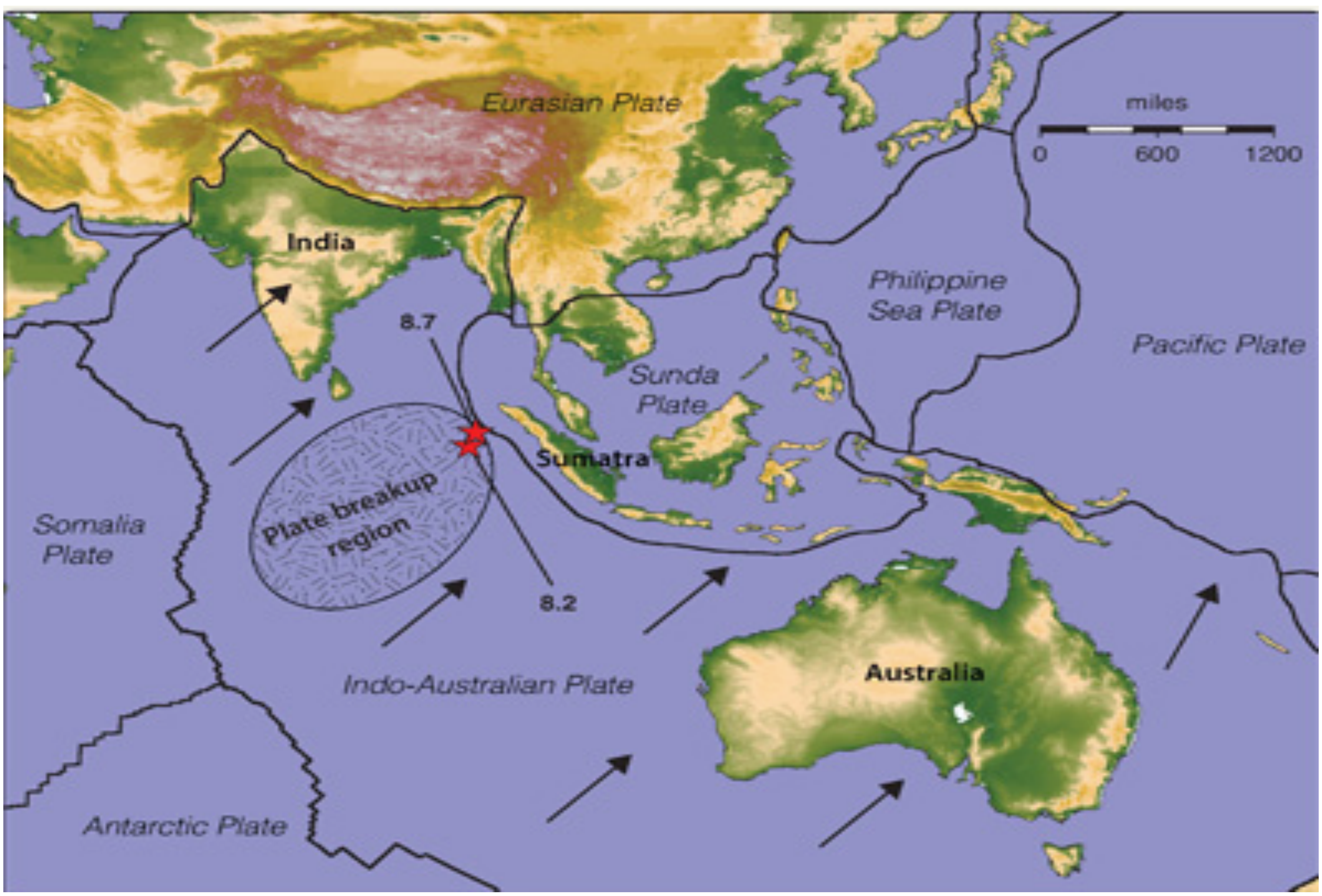
10°S
15°S
20°S
Philippine Sea palte
Ayu trough
Palau trench
Yap trench
Caroline ridge
Caroline plate
Mussau trench
PACIFIC PLATE
New Guinea trench
Melanesian trench
Ontong Java Plateau
MTB
Bismarck Sea
North Solomon trench
Solomon Sea
Vitiaz trench
Woodlark Basin
Australian continent
Pocklington trough
NFB
Coral Sea
AUSTRALIAN PLATE
50 mm year⁻¹



Eurasian Plate
miles
0
600
1200
India
Philippine Sea Plate
Pacific Plate
8.7
Sunda Plate
Sumatra
Plate breakup region
Somalia Plate
8.2
Indo-Australian Plate
Australia
Antarctic Plate