THE HURRICANE-FLOOD-LANDSLIDE CONTINUUM

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In August 2004, representatives from NOAA, NASA, the USGS, and other government agencies convened in San Juan, Puerto Rico for a workshop to discuss a proposed research project called the Hurricane-Flood-Landslide Continuum (HFLC). The essence of the HFLC is to develop and integrate tools across disciplines to enable the issuance of regional guidance products for floods and landslides associated with major tropical rain systems, with sufficient lead time that local emergency managers can protect vulnerable populations and infrastructure. All three lead agencies are *independently* developing precipitation-flood-debris flow forecasting technologies, and all have a history of work on natural hazards both domestically and overseas. NOAA has the capability to provide tracking and prediction of storm rainfall, trajectory and landfall and is developing flood probability and magnitude capabilities. The USGS has the capability to evaluate the ambient stability of natural and man-made landforms, to assess landslide susceptibilities for those landforms, and to establish probabilities for initiation of landslides and debris flows. Additionally, the USGS has well-developed operational capacity for real-time monitoring and reporting of streamflow across distributed networks of automated gaging stations (http://water.usgs.gov/waterwatch/). NASA has the capability to provide sophisticated algorithms for satellite remote sensing of precipitation, land use, and in the future, soil moisture. The Workshop sought to initiate discussion among three agencies regarding their specific and highly complimentary capabilities. The fundamental goal of the Workshop was to establish a framework that will leverage the strengths of each agency. Once a prototype system is developed for example, in relatively data-rich Puerto Rico, it could be adapted for use in data-poor, low-infrastructure regions such as the Dominican Republic or Haiti.

Hurricanes, typhoons and cyclones strike Central American, Caribbean, Southeast Asian and Pacific Island nations even more frequently than the U.S. The global losses of life and property from the floods, landslides and debris flows caused by tropical

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storms are staggering. One of the keys to reducing these losses, both in the U.S. and internationally is to develop improved forecasts of what is about to happen from several hours to days before the event. Particularly in developing nations where science, technology and communication are limited, advance-warning systems can have great impact. Warnings of even a few hours or days can mitigate or reduce catastrophic losses of life. In some instances, the loss of life and property is the direct result of the storm because of the high winds and rains. However, 82% of tropical cyclone deaths are due to flooding, most of which occurred well inland of landfall (Fig. 1). For example, during late October 1998, Hurricane Mitch formed in the southwestern Caribbean and slowly intensified as it moved west-northwest. Mitch eventually reached Category 5 status, with maximum winds of 180 mph and the fourth-lowest central pressure ever measured in an Atlantic hurricane. This immense storm literally engulfed Central America where it remained almost stationary for several days, drawing moisture from both the Pacific Ocean and the Caribbean Sea. The countries of Guatemala, Honduras, El Salvador and Nicaragua, in particular, were deluged with rain, triggering intense floods and thousands of landslides. In one instance, at least 2000 people from a single village were buried alive by a massive lahar (debris flow) that traveled 13 miles down the slope of the Casitas volcano in northwestern Nicaragua. Hurricane Mitch became the second most deadly Atlantic Hurricane in 200 years, killing over 9000 people and causing many billions of dollars in loss. Although NOAA released warnings for dangerously heavy rainfall during Mitch, much of this information never reached local municipal officials in the Central American countries due to inadequate communication networks. In addition, the countries impacted the most have only modest national weather services. It is likely if each country had been better informed and prepared, loss of life might have been substantially reduced. Useful tools for predicting the occurrence of rainfall-triggered landslides in populated areas are rainfall intensity/duration thresholds. The characteristics of prior events can be used as a partial guide to future landslide activity. When combined with data on the physical properties of the hillslope, a foundation is provided for evaluating the susceptibility of similar areas to landsliding (Bucknam et al, 2001). USGS and NOAA scientists use a variety of sophisticated operational hydrologic models for prediction of flooding, which could be adapted for use in data-poor settings such as the island of Hispaniola.

This paper provides an overview of the Workshop's goals, presentations and recommendations with respect to the development of the HFLC.

The Response: An End-to-End Prediction System for Heavy Rainfall, Flooding, and Landslides

It was generally acknowledged that the United States has the elements of science and technology that can make a profound difference in the response to these potential disasters, both domestically and internationally.

The essence of the HFLC vision is to develop and integrate tools across disciplines that enable the U.S. to issue regional guidance products of floods and landslides associated with major tropical systems, disseminating them to local emergency managers in time to protect vulnerable populations and livelihood systems.

We hope to integrate a wide range of scientific disciplines and apply them along a continuum from the tropical disturbance at sea to the floods and landslides that will ultimately result in loss of property and life; i.e. issue guidance products for the effects of landfall up to 48 hours before the event. We envision an initial project of three year's duration that will develop and transfer a warning system for a prototype region in the Caribbean, specifically the islands of Puerto Rico and Hispaniola. The system will include satellite observations to track and nowcast dangerous levels of precipitation, atmospheric and hydrological models to predict near-future runoff and streamflow changes in affected regions, landslide models to warn when and where landslides and debris flows are imminent, and a coastal surge model to predict shoreline erosion. Figure 2 displays a conceptual diagram of what a guidance product might look like for a hurricane approaching the island of Puerto Rico. The figure is intended for use by a non-technical person and/or decision maker. Such an end-to-end system would require:

- Real time data acquisition by space borne, airborne, and surface instruments,
- Weather data analysis systems and forecast models, to provide timely and accurate precipitation estimates at regional and local scale
- Hydrological models that can continuously track soil moisture conditions and forecast extreme streamflow events
- Geological models that model and forecast landslide and debris flow hazards,
- Decision support systems that evaluate the range of threats to human populations, infrastructure, and economic systems stemming from these natural hazards, and
- An interactive hazard warning communication system, with fail-safe redundancy, that informs disaster managers at regional, national, and international levels in time to protect lives and property.

NASA, NOAA, and USGS have conducted research and development that have established new tools and systems that address these atmospheric and terrestrial elements of the Continuum. However, to date there has not been sufficient integration of these findings and technologies to meet the practical information needs of emergency response and disaster mitigation officials. The HFLC initiative seeks to close the gap between the scientific state of the art and the operational need for reliable and timely natural hazard information for the Caribbean islands of Puerto Rico and Hispaniola. (These islands themselves form a *continuum* in terms of available data, wealth and government infrastructure). A prototype study in this area, with its high probability of hurricanes will make it possible to demonstrate the relevance of such a system across a spectrum of technological and socioeconomic environments.

Assembling the end-to-end system will require interdisciplinary research and development to devise scientifically sound techniques for linking data assimilation systems and simulation models across the full HFL continuum. Some of the science and application questions that the HFLC Workshop examined were:

- Can quantitative precipitation estimation and forecasting be performed with sufficient detail, accuracy, and timeliness to drive hydrological models of soil moisture and peak stream flows that are the basis of hazard early warnings?
- Can the use of mesoscale forecast models improve the lead-time for hurricane warnings?
- What are the spatial and temporal scales of soil moisture and stream flow modeling that are needed to support simulation and forecasting of ground failures and floods stemming from tropical storms?
- Can debris flow and landslide models produce output that sufficiently characterizes these threats to permit decisive action by disaster managers at the local, regional, national and international levels?
- What are the scale and resolution requirements of debris flow and landslide models with respect to topography, geology, soils, ambient conditions, and land cover data?
- How can geographical information system (GIS) technology be used to integrate data and model output across the HFL continuum and be the core of a decision and information system? What are the key data base design issues to be addressed in devising a common geospatial-layered framework to assimilate all elements of the continuum?

Developed over a three-year period, the HFLC will have important, immediate applications to short-term prediction and warning of flooding and landslides in the prototype region, and the science and technology can be applied in the United States and worldwide. The information deliverables for the prototype region will be tailored to the societal and economic needs of the affected countries and will be carefully monitored and documented at the local level in order to provide feedback from forecasters and officials to the NASA-NOAA-USGS science team.

Precipitation Estimation

Ground-based radar is the tool of choice for estimates of precipitation, such as those from the NWS Doppler radar operated in Cayey, PR by the San Juan Forecast Office. Few underdeveloped countries have access to such radar data however. Furthermore, the horizontal extent of their coverage makes hurricane monitoring problematic. In most locations, satellite-based estimates may provide the best (and only) coverage. Fortunately, the launch of passive microwave instruments in 1987 (the Dept. of Defense's Special Sensor Microwave Imager, or SSM/I) and the Tropical Rainfall Measuring Mission (TRMM) in 1997 provide physically based, instantaneous rain estimates over both land and water. Deficiencies in temporal sampling can be overcome with geosynchronous (GEO) (IR) data. We envision using microwave-calibrated IR estimates at 15-30 minute intervals and horizontal resolutions as fine as 4 km. Such products are already available, and at no cost. A merged IR/microwave product of the NASA/TRMM program is created from five GEO IR's, three polar-orbiting satellite and TRMM (tropics) on a near real-time basis (4-6 h delay). This product is available at 3 h intervals and 0.25° resolution. The latest 3-hourly global rainfall and latest week of global rainfall accumulation can be found at http://trmm.gsfc.nasa.gov. This dataset is available at: ftp://aeolus.nascom.nasa.gov/pub/merged. An hourly product using only the calibrated IR data is also available.

Both model- and satellite-estimated rainfall can be incorporated into the proposed system, with model output applied before the event, and satellite estimates during and after the event. An example for the devastating floods and landslides in Haiti/Dominican Republic during May 2004 is shown in Figs. 5-7, representing respectively, the 72 h MM5 forecast of accumulated precipitation, the Multi-satellite Precipitation Analysis (MPA, Huffman et al, 2003) and an aerial photograph of the resultant flood and debris flow deposits. Satellite estimates also offer the potential for forecasting or nowcasting precipitation based on recent (3h) estimates. Figure 8 shows an example of the MPA rainfall estimated for Hurricane Isabel during a 12-day period in August 2004. Fortunately, and as noted in the estimates, the storm weakened as it approached landfall in the Carolinas.

Several kinds of remote and in situ data have the potential to provide observation-based precipitation data over large regions. In rough order of typical accuracy, they are rain gauges, weather radar, passive microwave satellite, passive infrared satellite, and satellite sounder. However, the order of availability of such data is almost exactly the reverse of the list. Gauges, in particular, are almost never available at the density required to provide accurate fine-scale estimates. At the same time, gauges are critical for providing ground truth and evaluating the other estimates. Algorithms that combine or merge the various satellite inputs are currently under development, but the concept is too new for a consensus in the community about a single best approach. The state of the field requires that the HFLC system be able to accept multiple observation-based estimates at different time/space resolutions, and to accept upgraded estimation schemes as the state of the art advances. All of the observation-based estimates exhibit large uncertainties at the finest scales, both because of the intrinsic small-scale variability that real rainfall exhibits and because of algorithmic, navigation, and time-offset errors in the estimates. The errors typically increase in land areas with complex terrain, which unfortunately is the kind of terrain in which flash floods and landslides are most likely. *As a result, it is a major goal of the HFLC to determine the best combination of scales and estimates for driving the flood and landslide models.*

We anticipate that the HFLC will employ different data sources as we move from routine broad-scale monitoring for new events down to focused nowcasts in individual basins:

Routine	– monitor background precipitation [model] Is a storm threatening?
36-48 hr	– is the storm a heavy, moderate or light rain producer? [model, satellite] - is the rain distribution symmetric about the center? [model, satellite]
12-24 hr	– is the storm following the model? [model, satellite]
< 12 hr	– nowcast at basin scale [radar, satellite]

Fig. 9 displays a conceptual diagram of this vision for the HFLC.

Forecast models

Forecasting of tropical cyclone track has improved greatly over the past 40 years (**Owens and Landsea, 2003),** rapidly approaching what is believed to be the predictability limit of 100 nautical miles for a one-day forecast. (This is a 1 m/s error over 24 hours.) Intensity forecasts (essentially the tail of the distribution of wind speed), as well as quantitative precipitation forecasting still show room for considerable improvement. However, recent advances have been made in both mesoscale models (Fig.3) and global models (Fig. 4).

The first step in producing an accurate high-resolution precipitation forecast that fully resolves the terrain of the Caribbean islands, is to provide quality initial fields that represent the atmospheric state as accurately as possible to the weather prediction model. The Local Analysis and Prediction System (LAPS: Albers, et al., 1996) developed at the NOAA Forecast Systems Laboratory integrates data from virtually every meteorological observation system into a very high-resolution gridded framework centered on the region of interest. LAPS is a fully integrated "go-anywhere" system that has been ported to a number of locations and hardware hosts. LAPS runs in a configuration that allows assimilation of all local observations combined with a previous forecast to ensure that there is spatial and temporal detail and consistency between current and previous observations. A cloud and precipitation analysis that utilizes radar currently exists in LAPS. This will be upgraded to include satellite estimate techniques that use the infrared (IR) and microwave channels. The forecast components of LAPS (MM5 [NCAR], RAMS [CSU] ,ETA [NWS] and WRF (NCAR and NWS) all offer excellent forecasts at high resolution. The forecast skill is enhanced by initializing the model with the diagnosed clouds and precipitation. This has demonstrated improved quantitative precipitation verification in the tropics (Taiwan) relative to standard operational models in the first six hours of the forecast (Jian et al, 2003). Precipitation is output at high temporal resolution and can thus match the input requirements of the hydrological and landslide models, which require frequent data updates, such as radar data at 6 minute intervals. Another promising research area is a mesoscale model ensemble. For this we can leverage existing work in the area of transportation weather to explore the utility of ensemble prediction in the system.

Hydrologic models

The estimation of areal distribution of precipitation is a long-standing problem of hydrology. Textbook methods, like Thiessen polygons and interpolation of isohyets from point observations, rely on proximity of stations as the basis of estimation. However, the spatial autocorrelation of rainfall is low, while gauges are sparsely distributed. Gauge observations are thought to accurately represent rainfall over an area less than 1 sq km, but even a relatively dense hydrometeorological network, like that in the United States, has only one gauge per 700 sq km. However, the network of 130 USGS rainfall stations on the 8,711 km^2 island Puerto Rico has an average density of one station per 67 km^2 (http://pr.water.usgs.gov/), which will permit more effective model calibration and testing. Sophisticated methods of GIS and geostatistics, like inverse distance weighting and kriging, lack a physical basis for estimating rainfall at locations between stations. The typical distance over which interpolation is performed far exceeds the "zones of influence" of the stations involved. For this reason, incorporation of radar (when available), physically based satellite observations and numerical modeling in the estimation of spatial patterns of precipitation is an active area of research and development.

Remote sensing is increasingly seen as a complement to spatial interpolation of precipitation station data. The Mekong River Commission began using satellite rainfall estimates (RFE) produced by NOAA with the algorithm of Xie and Arkin (1997) in 2001. This method blends station data, microwave imagery from polar orbiting satellites, and thermal infrared imagery from geostationary satellites to produce estimates of 24-hour accumulations on a 0.1 degree grid. The successful operations of the TRMM and other low-earth orbit (LEO) satellites have produced the unprecedented opportunity to study rainfall over tropical areas. The LEO observations, however, are sparse and have sampling deficiencies with respect to the diurnal cycle of precipitation. The half-hourly geosynchronous satellite observations provide sufficient sampling for precipitation on a global base but suffer from the lack of a direct physical link between infrared (IR) observations and precipitation mechanisms. In order to improve the existing IR-based techniques for rainfall estimation, the MPA uses the microwave-estimated rainfall observations to calibrate IR-based cloudiness information.

Hydrologic models will take the model- or satellite-estimated precipitation to create maps of flooding. An example is shown in Fig. 10, a mini-HFLC already underway in Southeast Asia. The Mekong River Project uses multiple inputs to a Geographic Information System (GIS) to produce estimates of river flooding.

Landslide models

The goal of the landslide component of this project is to develop and implement a system for forecasting the occurrence of landslides on a regional scale with a resolution that is consistent with the hurricane and flood forecast components and the available topographic and geologic data. The landslide forecasting system is based on a spatial model for landslide susceptibility to identify where landslides are likely to occur, and on a temporal model: a rainfall intensity-duration threshold that defines the minimum amount of rainfall required to trigger landslides in different geographic areas. Recently developed empirical susceptibility models and rainfall thresholds for Puerto Rico and Central America may be suitable for forecasting the temporal and spatial occurrence of landslides on the regional scale appropriate for the HFLC proposed system (Larsen and Simon, 1993).

Landslide and debris flow models are by necessity probabilistic, as the scale of the phenomenon is small compared to the resolution of the input rainfall estimates (Wieczorek et al, 2000; 2002). Nonetheless, simple solutions, such as the intensity versus duration diagram offer discrimination of landslide versus non-landslide rainfall conditions for Puerto Rico (Fig. 11). We plan to test slope and elevation to the model computed from Digital Elevation Model (DEMS) data (Fig. 12), improving the spatial scale of the estimates. The use of NASA Shuttle Radar Topography Mission (SRTM) or other altimetry data is also envisioned.

Issuing a warning of potential landslides requires evaluating incoming rainfall measurements and forecasts with rainfall threshold and landslide susceptibility models to identify areas where thresholds are likely to be reached or exceeded. As often as updated rainfall amounts and forecasts are available, the system will automatically compute the latest cumulative rainfall amounts, intensity and duration needed to compare each grid cell to the thresholds and compare the threshold condition to the (predetermined) susceptibility. The system will output graphic displays of high, medium, or low landslide probability for a specified number of hours into the future. In the case of high probability, the system could also trigger an alarm to alert authorities to the impending landslide hazard. Heavy rainfall has recently triggered numerous damaging debris flows in many different regions, e.g. central Virginia (Wieczorek et al., 2000), Guatemala (Bucknam et al., 2001), and Venezuela (Wieczorek et al., 2002).

Using the rainfall intensity-duration thresholds for triggering landslides established for Puerto Rico, the opportunity exists to test the ability to use real time rainfall estimates from radar and satellite data to categorize the likelihood of debris flows and to issue appropriate and timely warnings. With the capability of ground monitoring of rainfall and the documentation of debris flows within Puerto Rico, the new developing warning technologies can be evaluated and improved. Once the methodology is refined over a period of several years in Puerto Rico, the techniques can be applied to other nearby locations, e.g. Haiti, Dominican Republic, which have similar climatologic and geologic setting. If this system proves efficient, then debris-flow prediction and warning might become a possibly useful methodology in mountainous area of the United States.

The role of GIS and delivery systems

Geographical Information System (GIS) technologies will be used to support research activities and product creation in the HFLC. These activities include:

- database development
- precipitation, flooding, and landslide processes modeling
- online decision support system development
- cartographic products (Web graphics and hard-copy maps)
- data products

GIS is a mature system of computer software designed for the acquisition, storage, manipulation, analysis, and display of geographically referenced (geospatial) data. The linkage of GIS with other technologies such as Web, GPS, and Internet data delivery services, should be powerful in its impact and will be essential to the success of the HFLC project.

The central and perhaps most important element of the GIS component is a data base of geospatial meteorological, geological, and geographical data sets without which process modeling, analysis, and the display of results would be difficult, if not impossible. Examples of essential geospatial data are:

- Distribution of near-real time precipitation rates and wind field
- Digital elevation model and consequent drainage network from which slope and aspect for the terrain and water flow paths are determined and orographic effects modeled
- Distribution of vegetation and soils coverage, from which moisture infiltration and landslide and debris flow susceptibility are modeled
- Distribution of urbanized areas, transportation networks, and critical facilities at risk from flooding, landslides, and debris flows

Precipitation, hydrologic, and landslide susceptibility modeling involve intense computations that translate physical and geological processes into outputs that must be visualized to be fully understood. The power of the GIS is to organize the geospatial data for developing suitable models and for displaying the results of the modeling. As the models are refined and as a decision support system for forecasts by meteorologists and hydrologists becomes operational, the GIS will continue to be an important support, if not operational, component.

Other issues

Three areas have been identified as primary targets for HFLC products: Puerto Rico, the Dominican Republic, and Haiti. In order to ensure that the products are targeted to the correct users in each area, it is necessary to assess the institutional structure and formal/informal networks through which disaster or hazard communications pass and decisions are made. Comfort et al (2001) note the difficulty in coordinating disaster response when several levels of government and non-governmental agencies share responsibility, and stress the importance of increasing local or regional capacity for communication and coordination. An essential step in developing response capacity is analyzing existing networks and communication channels. To accomplish this, government officials in each of the three study areas must be informed about the HFLC. Then researchers will interview representatives from disaster or hazard management entities to determine how these representatives respond to hazard or disaster information or warnings. Analyzing interview results will provide a schematic of the disaster/hazard management system, the formal and informal communication networks, and a listing of constraints and information gaps for response to specific types of hazards. This is similar to an approach described by Chan (1997) in which individuals responsible for flood hazard management were surveyed to evaluate the efficacy of certain institutional arrangements in reducing the impacts of floods.

The means of delivery of warning systems will vary by geographic area, because acceptance of technology and innovation is affected by economic, cultural, and social variables (Hammock, no date).

The second part of the assessment involves starting from the household level and asking individuals to respond to questions about where they would turn for information or assistance if confronted with a hazard or disaster, and what kinds of assistance or response would they expect. The researchers will then scale up to higher levels of community hierarchy by asking each identified level of assistance or response about their ability to provide the requested assistance, what constraints they face, what limits to their authority exist, and when they would turn to the next level for assistance. The resulting assessment will provide detailed information about needs and expectations for disaster assistance or information at all levels and for specific types of disasters or hazards.

Figure 13 presents a NASA Integrated System Solutions diagram that serves as the architectural base of the HFL strategy. This "missions, to models, to decision support systems" is the basis of the engineering approach to be taken to move earth science observations and models to decision makers involved in providing watches and warnings related to flood/landslide hazards caused by precipitation. In the context of the HFLC however, policy decisions and management decisions are often not the final impacts of the research. There is an implementation phase that follows the decision phase leading to "values and benefits to citizens and societies" (i.e it's not the decisions that provide value, but the actions following those decisions). Ultimately, the output from these DSS's should be effective and easily interpreted by non-technical people and local decision makers. A graphic example for inundation mapping superimposed on a street-scale map is shown in Fig. 14.

How many people are affected? What is their level of social vulnerability?

To determine the number of affected people and their levels of vulnerability would involve several steps. First, data about existing or potential HFL hazards would be used to identify specific geographic areas where people are at risk. Census data will be used and mapped where available, using GIS tools. This will provide a preliminary assessment of the intersection of hazards and human populations.

A second step involves assessing social vulnerability in geographic locations where the risk for disaster is estimated to be high. Some factors thought to increase social vulnerability include limited access to political power and representation, lack of access to resources (including information, knowledge, and technology); lack of social capital (including social networks and connections); and the presence of frail or infirm individuals. Other factors that affect social vulnerability include beliefs and customs, building stock and age, and type and density of infrastructure and lifelines (see Cutter, Boruff, and Shirley 2003). For the proposed assessment these factors will be operationalized and measured to develop and index of social vulnerability that can be mapped as a layer on a GIS based map. Methods for measuring the variables will include examination of existing data (such as census, infrastructure, or insurance data) and development of primary data. In the United States social vulnerability assessments have been conducted using available census data but it is not known whether comparable data are available in Haiti or the Dominican Republic.

Summary

Hurricanes, typhoons and cyclones strike Central American, Caribbean, Southeast Asian and Pacific Island nations even more frequently than the U.S. The global losses of life and property from the floods, landslides and debris flows caused by tropical storms are staggering. In January 2005, severe flooding and killer landslides struck the coastal ranges of Southern California. One of the keys to reducing these losses, both in the U.S. and internationally is to have better forecasts of what is about to happen from several hours to days before the event. Particularly in developing nations where science, technology and communication are limited, advance-warning systems can have great impact. Warnings of even a few hours or days can mitigate or reduce catastrophic losses of life. In some instances, the loss of life and property is the direct result of the storm because of the high winds and rains. However, 82% of tropical cyclone deaths are due to flooding, most of which occurred well inland of landfall.

The essence of the HFLC vision is to develop and integrate tools across disciplines that enable the U.S. to issue regional guidance products of floods and landslides associated with major tropical systems, disseminating them to local emergency managers in time to protect vulnerable populations and livelihood systems.

We intend to interface a wide range of scientific disciplines in a continuum from the tropical disturbance at sea to the floods and landslides that will ultimately result in loss of property and life; i.e., issue guidance products for the effects of landfall up to 48 hours before the event. We envision an initial project of three year's duration that will develop and transfer a warning system for a prototype region in the Central Caribbean, specifically the islands of Puerto Rico and Hispaniola. There have been improvements over the past decade in data coverage over these islands, especially Puerto Rico. These include NEXRAD and an extensive raingauge network, as well as TRMM satellite coverage. We also have increased knowledge of island geomorphology (soils, bedrock, vegetation, slope). Models have been developed that couple rain intensity and duration with landslide occurrence in this region. The system will include satellite observations to track and nowcast dangerous levels of precipitation, atmospheric and hydrological models to predict near-future runoff and streamflow changes in affected regions, landslide models to warn when and where landslides and debris flows are imminent, and a coastal surge model to predict shoreline erosion. The current revolution in dissemination systems and communications will permit us to develop and deliver in a timely fashion tailored graphical products to local weather offices and emergency management officials in the affected islands.

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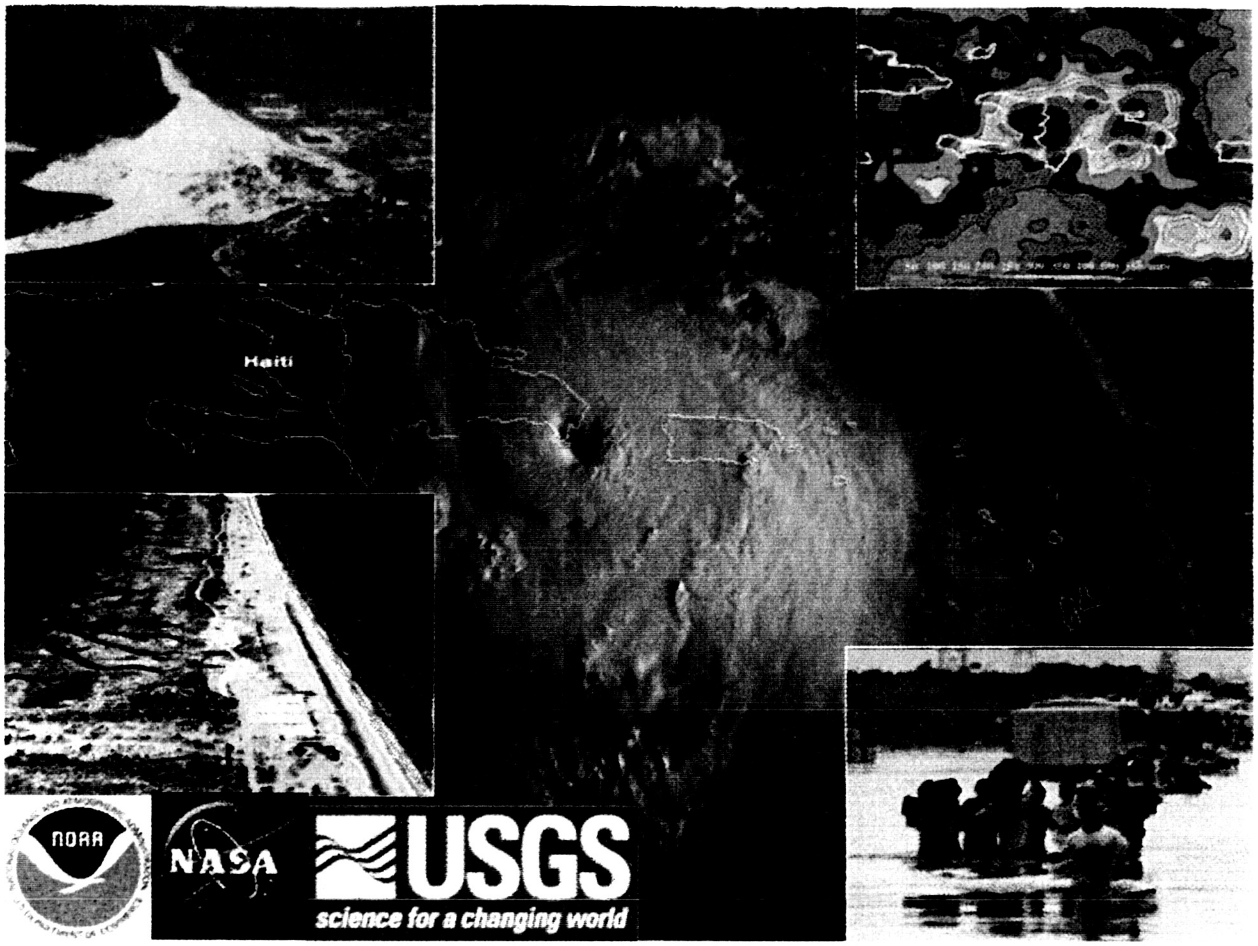


Cover figure. Illustration of the Hurricane-Flood-Landslide Continuum concept, an intergovernmental agency project described in the article by Negri et al

Fresh Water Flooding is Leading Cause of Tropical Cyclone Deaths

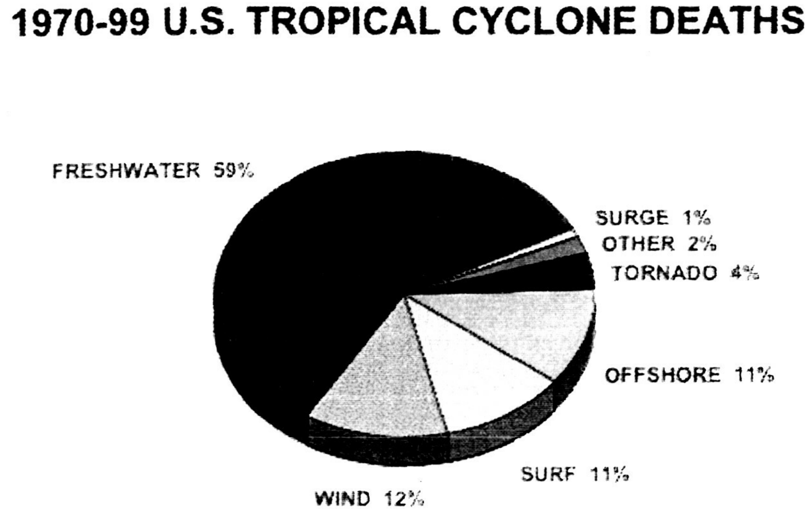


Figure 1. Distribution of tropical cyclone deaths, courtesy of NOAA/NWS Tropical Prediction Center

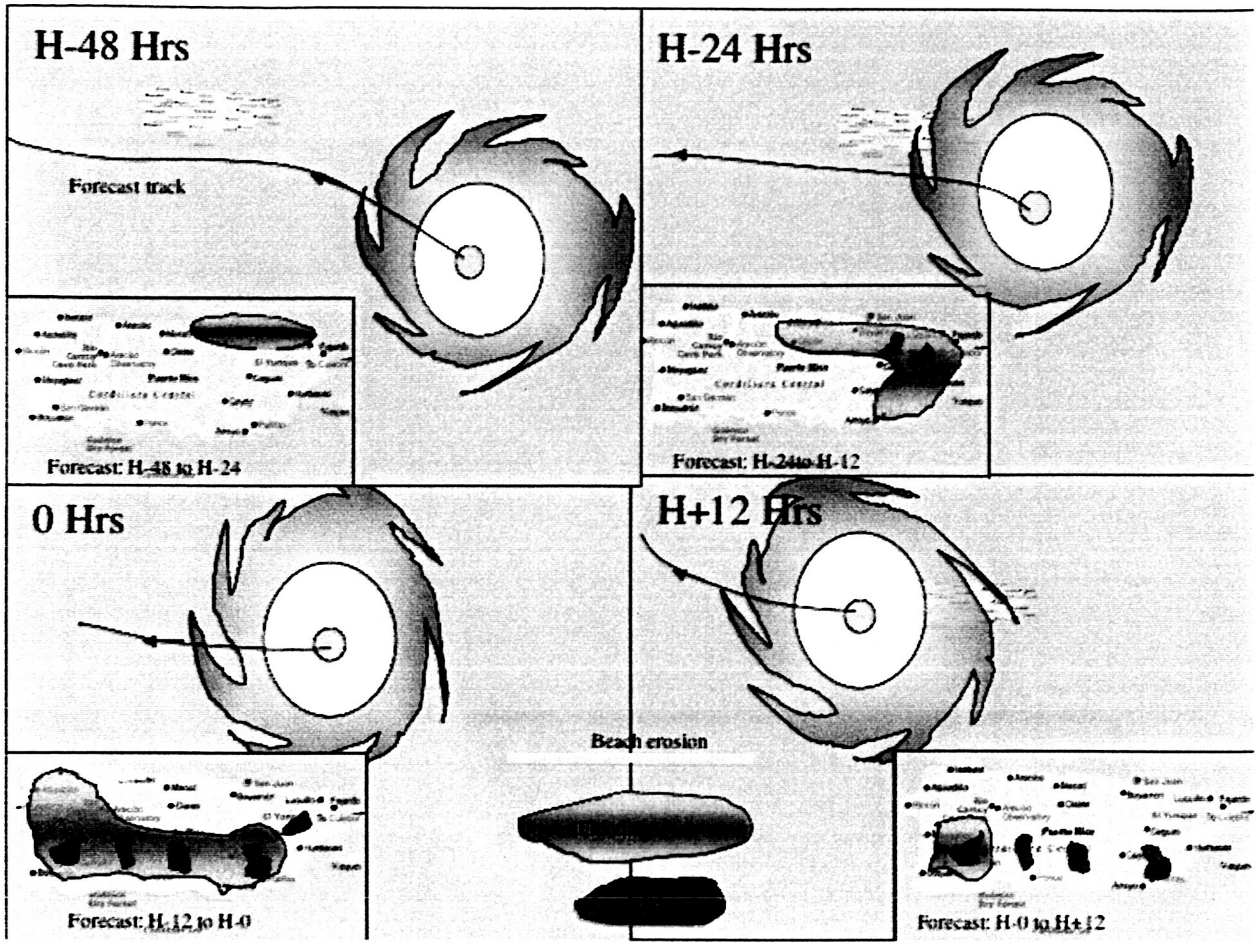


Figure 2. A conceptual diagram of potential guidance product for flooding, landslides, and beach erosion, 48-hour forecast through 12 hours after the event

MM5 Forecasts for Hurricane Charley

09Z Initialization ✦ 15Z initialization ★ Actual Path ◎

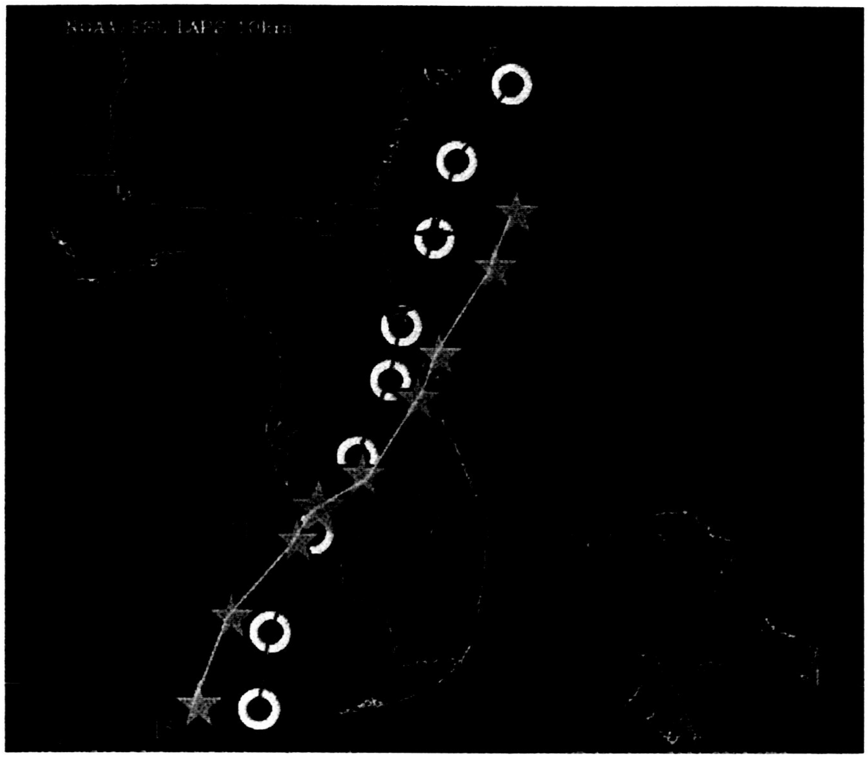


Figure 3. Hurricane Charley 24-hour forecast track for limited window (domain as shown). Ring shows official track labeled at 6-hr intervals. Five-pointed star shows MM5 forecast (initialized at 15 GMT with Eta boundary conditions and LAPS analysis); positions also labeled at 6-hr intervals. At 15 GMT Charley's eye was in the domain. Forecast track compares well with the official track until 21GMT at which point the forecast slowed the propagation speed. Four-pointed star shows forecast position from MM5 initialized at 0900GMT when Charley's eye was outside the domain. Track is much poorer. This modeling system shadows an identical operational system running at Cape Canaveral.

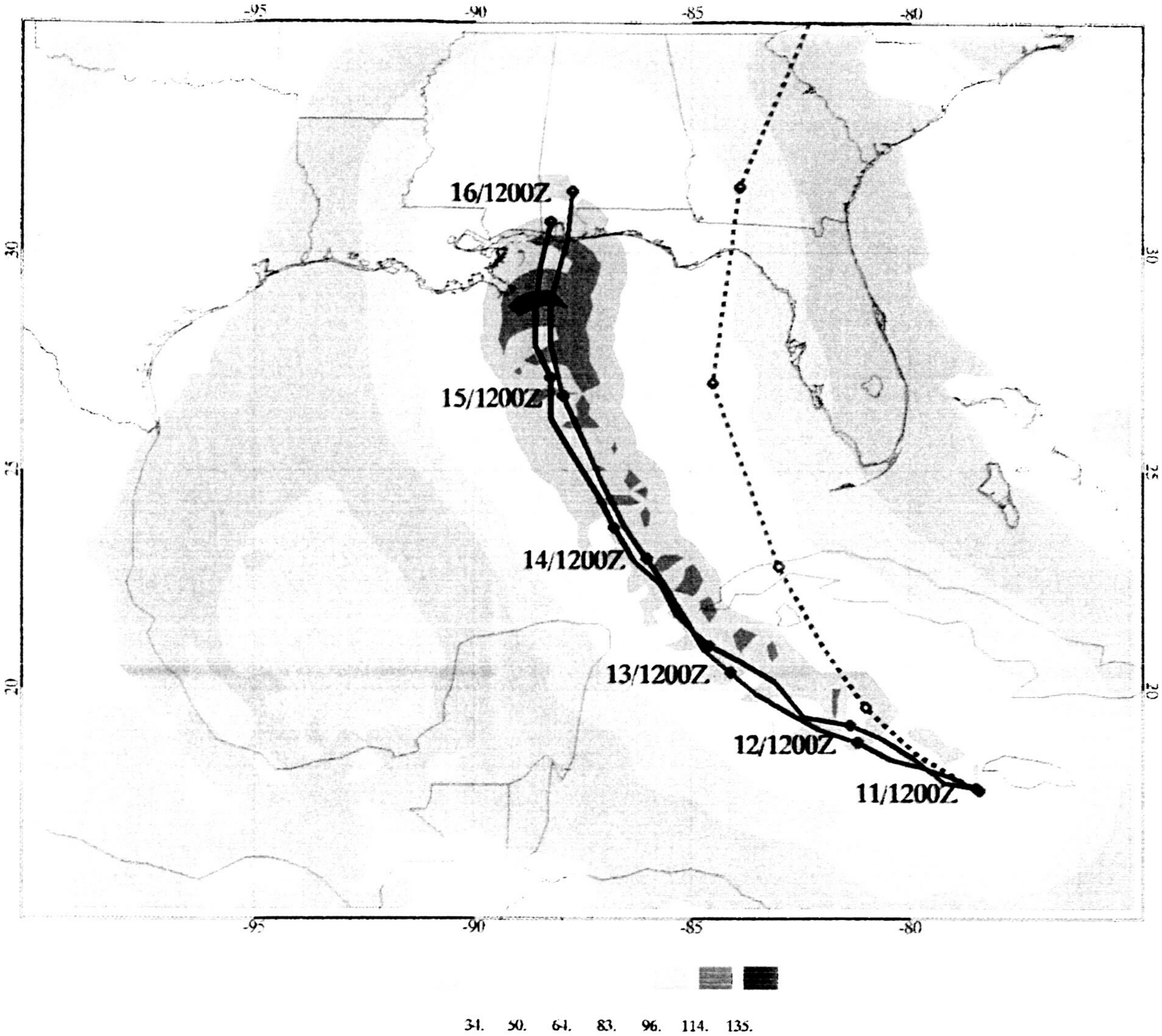


Figure 4. NASA fvGCm (global model) of track and precipitation from Hurricane Ivan (from Atlas et al, 2004)

Window MM5 Forecast for Dominican Republic/ Haiti
Flash Floods IT 00Z May 22, 2004

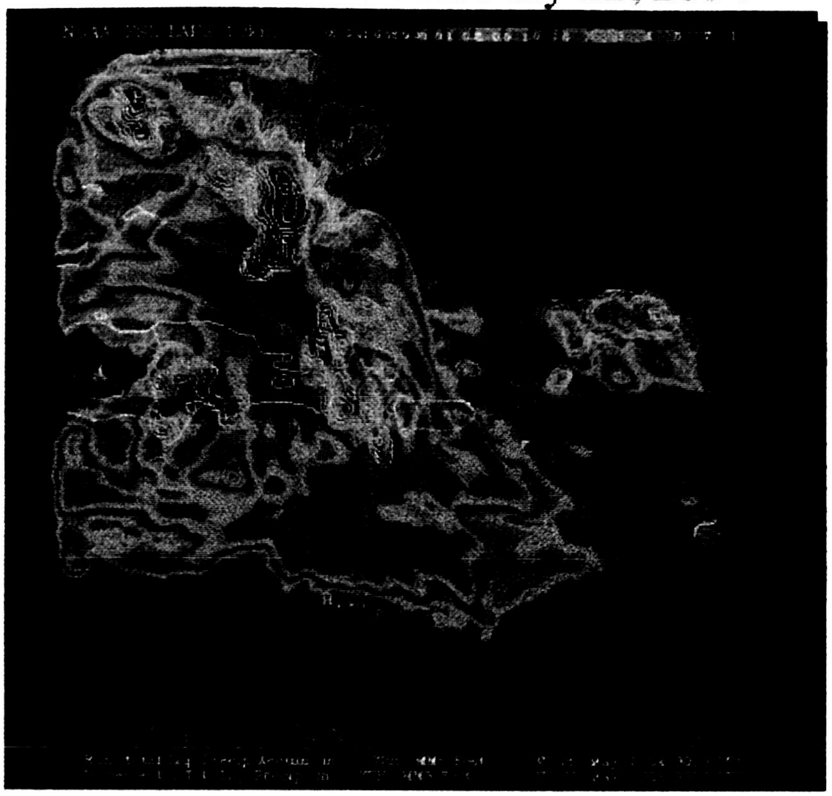


Figure 5. 72-hr precipitation forecast valid at 25 May 2004 00GMT from LAPS/MM5 roving 10-km grid window over Hispaniola and Puerto Rico. Boundary conditions were from NCEP GFS model. Red areas indicate precipitation 175mm to 400mm and above. See verification from TRMM satellite in Figure 6. Precipitation coverage patterns were good but forecasts showed a negative bias

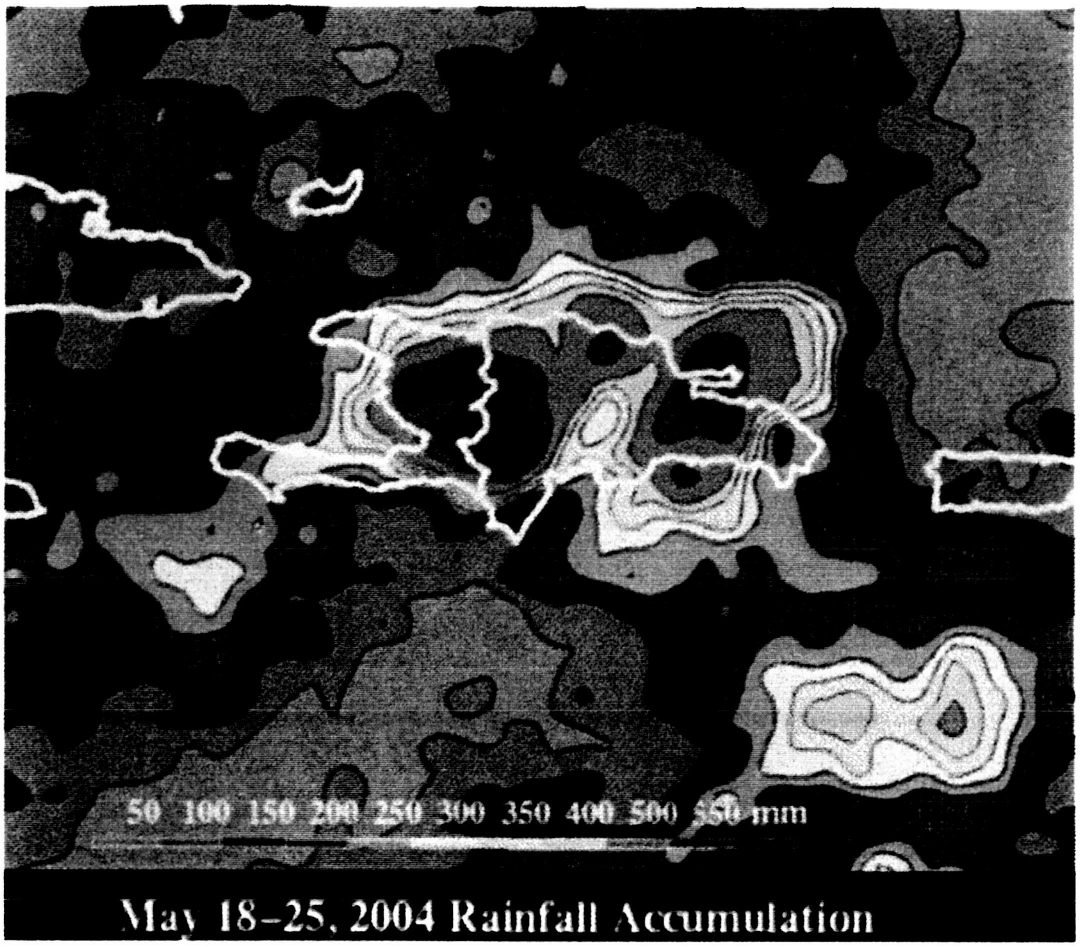
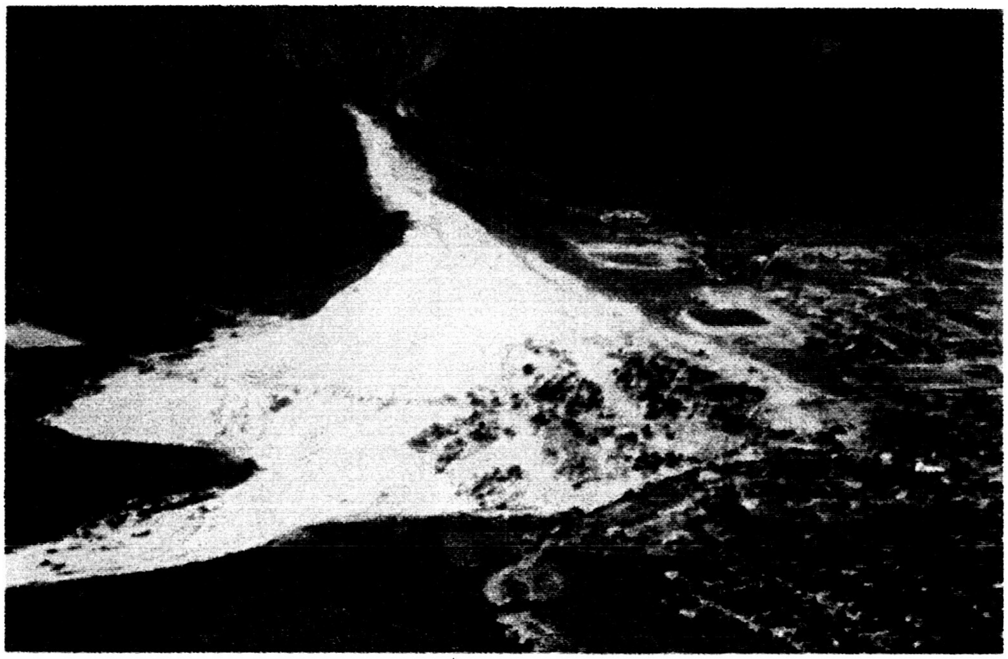


Figure 6. Estimated precipitation from the Multisatellite Precipitation Analysis for same period as cited in Figure 5.

Dominican Republic, May 23-24, 2004



Aerial view of sediment fan at Jimaní. (from Ed Harp, Mark Smith, USGS)

Figure 7. Aerial photograph of alluvial fan at Jimani, Dominican Republic, showing fresh flood and debris-flow deposits from May 2004 storm. (Photo from Ed Harp, Mark Smith, USGS).

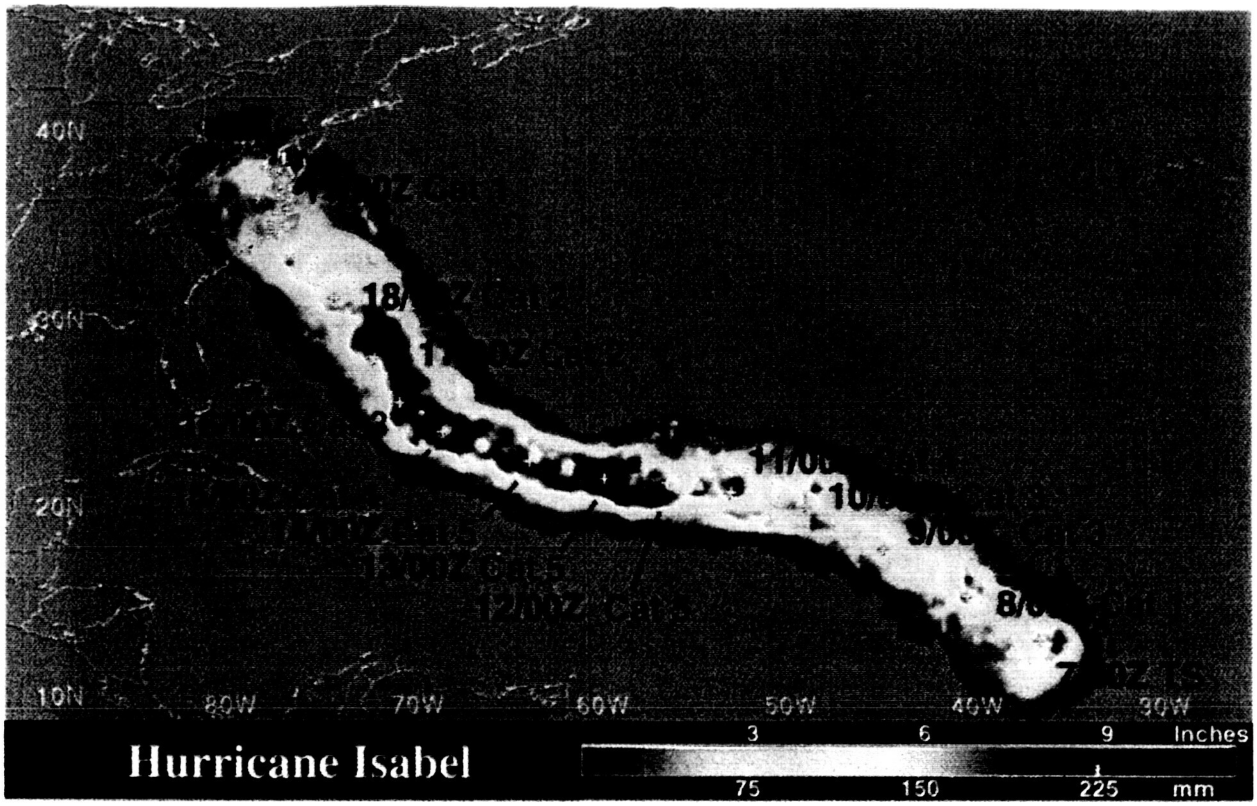


Figure 8. MPA estimates for Hurricane Isabel, superimposed with intensity, courtesy NASA/TRMM web site

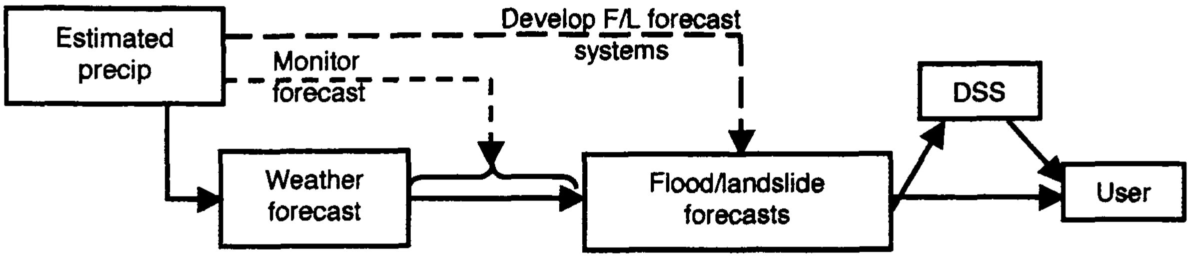


Figure 9. Box diagram of the vision for the HFLC system. Observationally based precipitation estimates will be used in the development phase to assist in crafting the flood and landslide forecasting system (long dashes) and in operations as input to the weather forecast models (solid) and as a monitoring tool to assess the fidelity of the forecasts to subsequent events (short dashes).

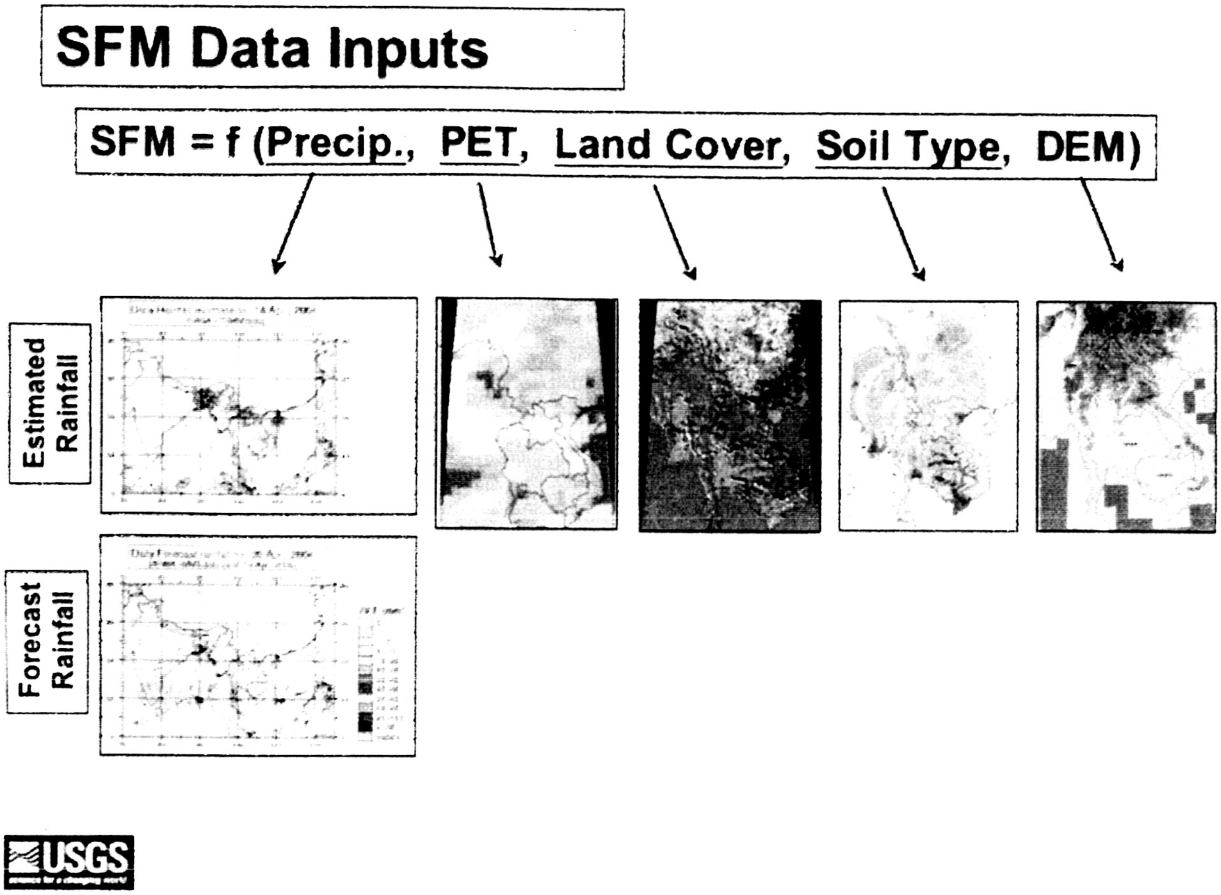


Figure 10. Example of flood modeling for the Mekong R project

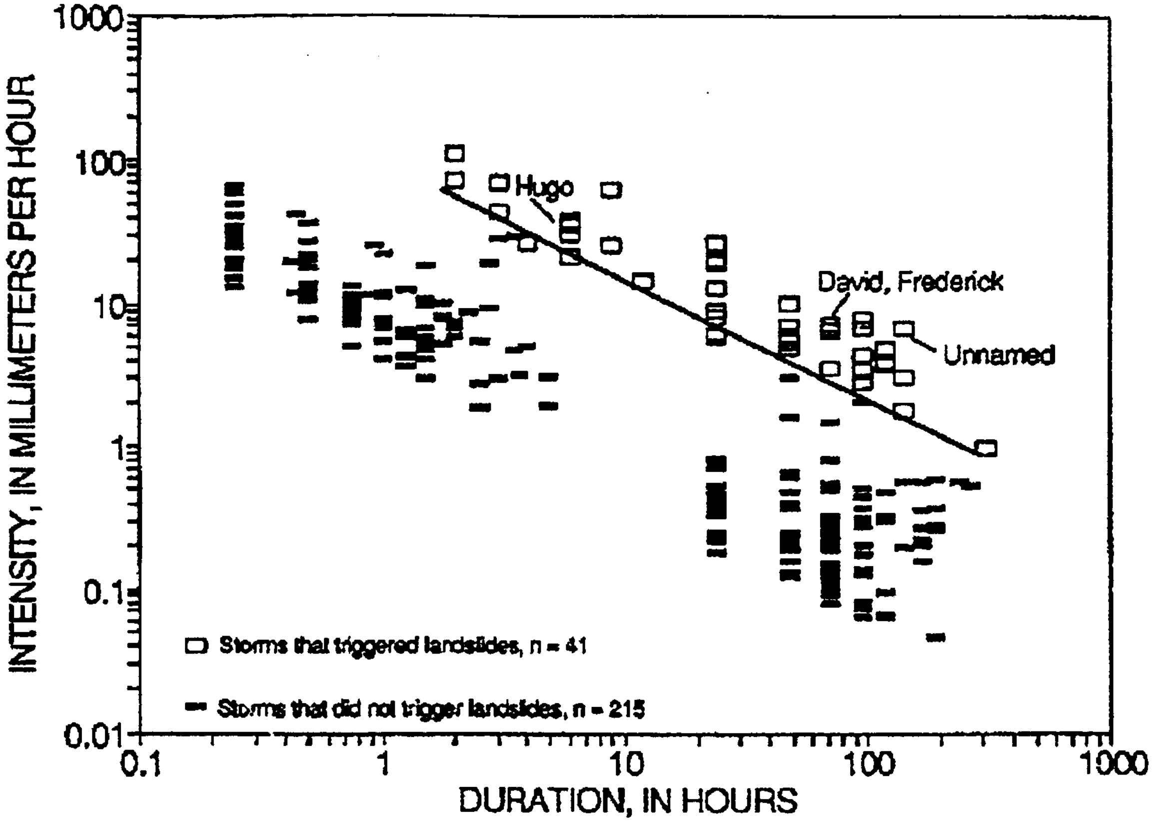


Figure 11. Relation between average rainfall intensity and duration for 256 storms in Puerto Rico dating from 1959 to1991. The 41storms plotted above the threshold boundary triggered abundant landslides (from Larsen and Simon, 1993)

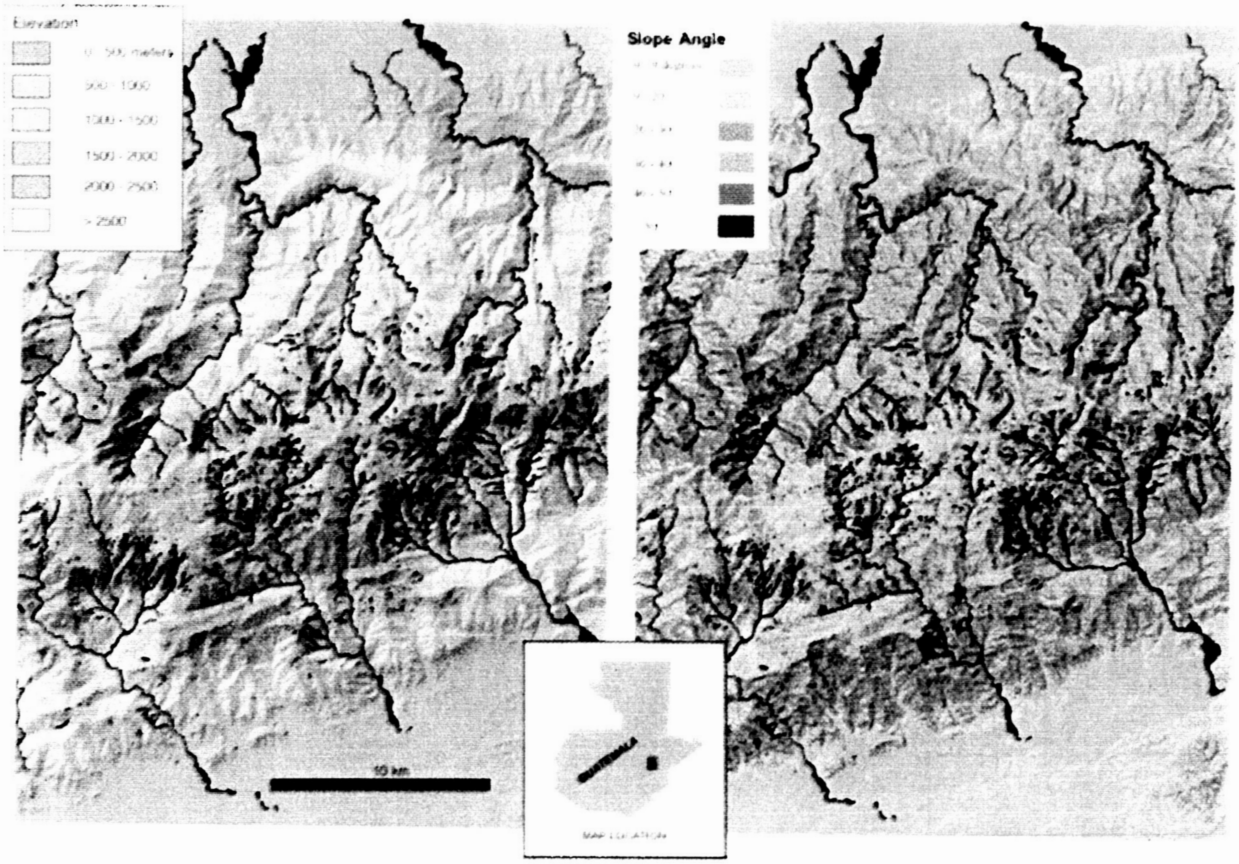


Figure 12. DEMS data of elevation and slope for potential use in a landslide model, from Coe et al, 2004

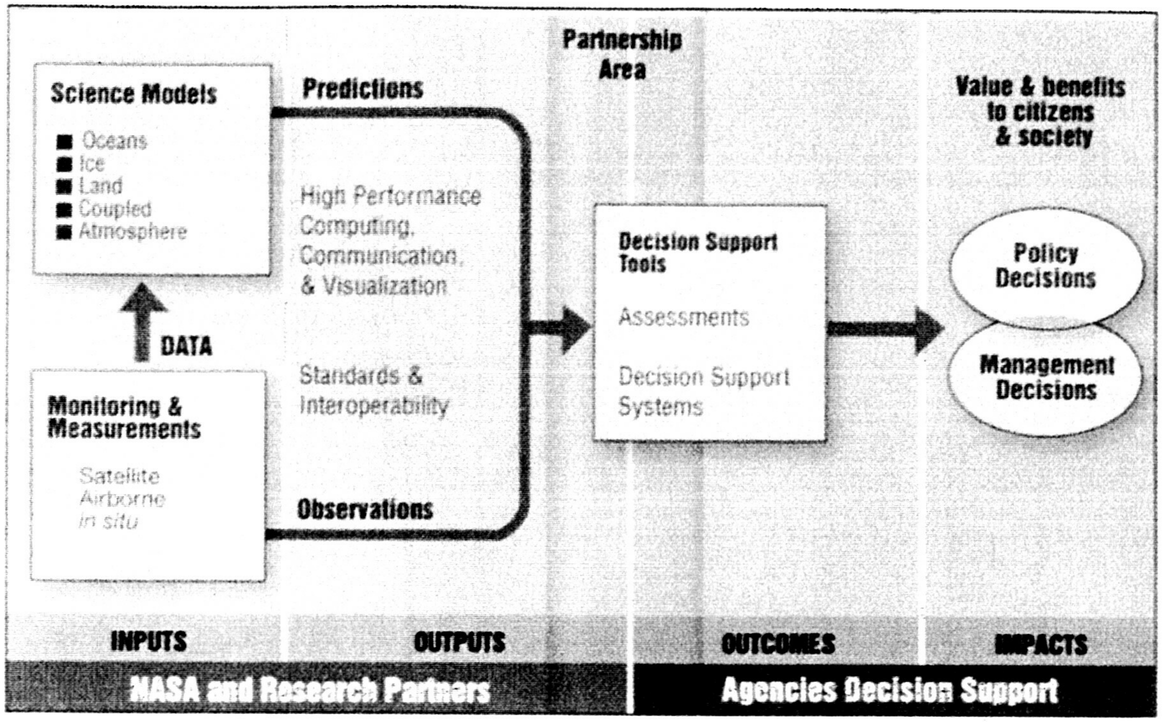


Figure 13. Example of a NASA Decision Support System (DSS)

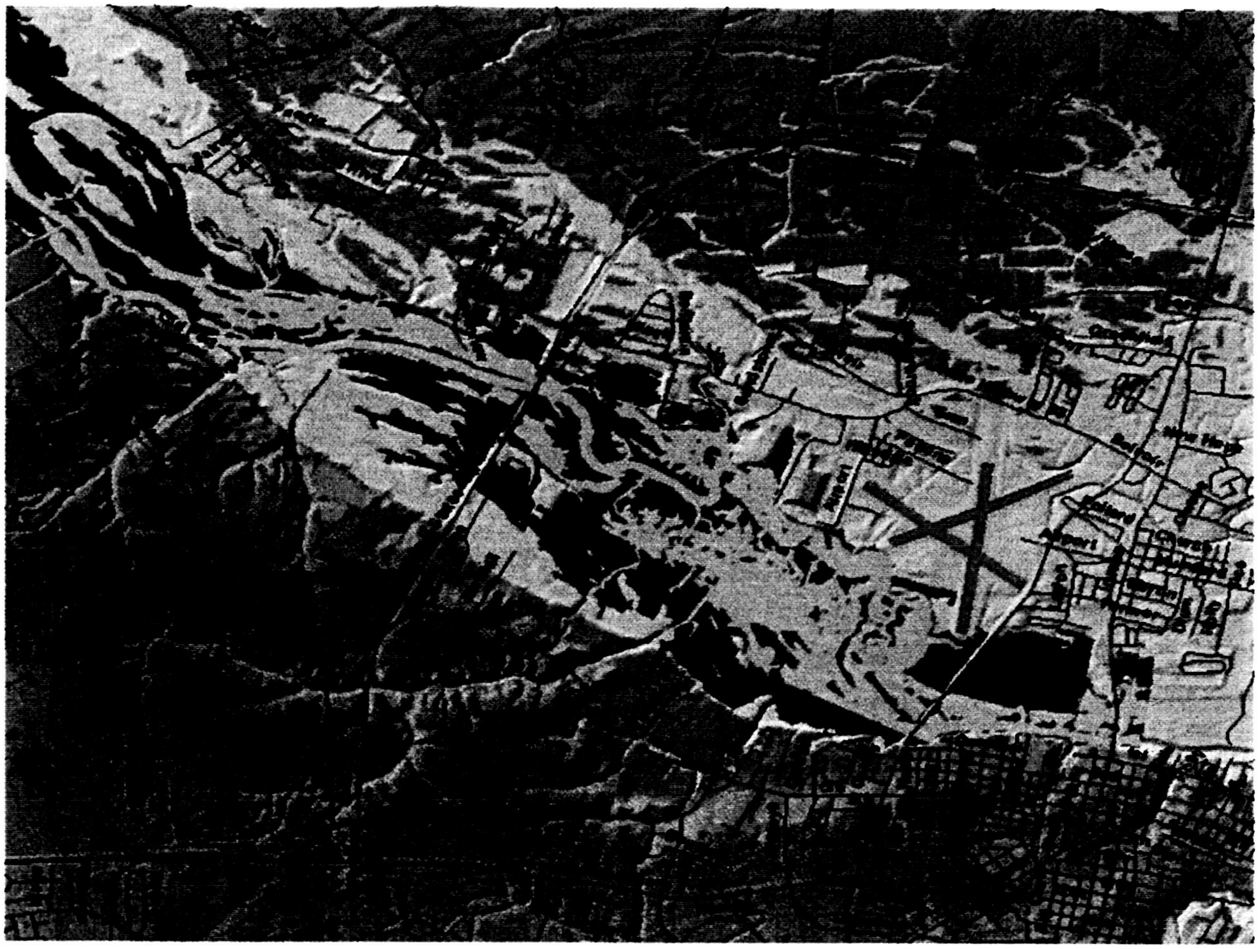


Figure 14. Graphic output from a flood model, courtesy of NOAA/NWS Southeast River Forecast Center and NOAA Coastal Services Center

POPULAR SUMMARY

This paper describes the results of workshop held in August 2004 in San Juan, Puerto Rico to formulate a proposed interagency project called the Hurricane-Flood-Landslide Continuum (HFLC). The project is a joint collaboration between NASA, NOAA and the U.S. Geological Survey.

Hurricanes, typhoons and cyclones strike Central American, Caribbean, Southeast Asian and Pacific Island nations even more frequently than the U.S. The global losses of life and property from the floods, landslides and debris flows caused by tropical storms are staggering. In January 2005, severe flooding and killer landslides struck the coastal ranges of Southern California. One of the keys to reducing these losses, both in the U.S. and internationally is to have better forecasts of what is about to happen from several hours to days before the event. Particularly in developing nations where science, technology and communication are limited, advance-warning systems can have great impact. Warnings of even a few hours or days can mitigate or reduce catastrophic losses of life. In some instances, the loss of life and property is the direct result of the storm because of the high winds and rains. However, 82% of tropical cyclone deaths are due to flooding, most of which occurred well inland of landfall.

The essence of the HFLC vision is to develop and integrate tools across disciplines that enable the U.S. to issue regional guidance products of floods and landslides associated with major tropical systems, disseminating them to local emergency managers in time to protect vulnerable populations and livelihood systems.

We intend to interface a wide range of scientific disciplines in a continuum from the tropical disturbance at sea to the floods and landslides that will ultimately result in loss of property and life; i.e., issue guidance products for the effects of landfall up to 48 hours before the event. We envision an initial project of three year's duration that will develop and transfer a warning system for a prototype region in the Central Caribbean, specifically the islands of Puerto Rico and Hispaniola. There have been improvements over the past decade in data coverage over these islands, especially Puerto Rico. These include NEXRAD and an extensive raingauge network, as well as satellite coverage from the Tropical Rain Measurement Mission (TRMM). We also have increased knowledge of island geomorphology (soils, bedrock, vegetation, slope). Models have been developed that couple rain intensity and duration with landslide occurrence in this region. The system will include satellite observations to track and nowcast dangerous levels of precipitation, atmospheric and hydrological models to predict near-future runoff and streamflow changes in affected regions, landslide models to warn when and where landslides and debris flows are imminent, and a coastal surge model to predict shoreline erosion.