Project Summary

Intellectual merit. The beauty and diversity of the Caribbean region result from geological and atmospheric processes that also pose serious threats to the large population within reach of seismic faults, hurricanes tracks, or sea-level change. The capacity to understand, prepare for, adapt to, and in some cases predict these natural hazards requires Earth observations on both large and small scales. This proposal aims at developing a large-scale geodetic infrastructure in the Caribbean that will form the backbone for a broad range of geoscience investigations and enable research on process-oriented science questions with direct relevance to geohazards.

The Continuously Operating Caribbean GPS Observational Network (COCONet) proposed here will consist of 50 new, and data from 50 existing, continuously operating GPS stations. COCONet will provide free, high-quality, low-latency, open-format data and data products for researchers, educators, students, and the private sector. These data will be used by local and foreign researchers to study solid earth processes such as plate kinematics and dynamics, and plate boundary interaction and deformation, including earthquake cycle processes. It will also serve atmospheric science objectives by providing more precise estimates of tropospheric water vapor and enabling better forecast of the dynamics of airborne moisture associated with the yearly Caribbean hurricane cycle.

COCONet will be installed and maintained by UNAVCO on behalf of the science and other user communities in the United States and abroad, thus leveraging UNAVCO's proven record of efficient and effective network management and its longstanding commitment to collaborative science.

Broader impacts. At the core of COCONet is the idea of coordinating and educating existing researchers, Caribbean governments and agencies, and GPS station operators toward the goal of creating a pan-Caribbean reference network that would be used for both scientific and socioeconomic purposes. The open data sharing approach, we hope, will lead to other organizations freely sharing data through community archives. These combined data can be used not only for science, but also by the public and private sectors for a variety of purposes, including local surveying, infrastructure monitoring, event response, and the creation of a comprehensive register of land-use, ownership and location for property within a country. Real-time data from COCONet will be made available to the International GNSS Service (IGS) to help densify a region of the globe with few existing real-time data streams. COCONet data may also be used to quickly estimate earthquake magnitude that, along with buoy and seismic data, will contribute to tsunami warning systems currently being developed in the Caribbean.

This project will contribute to the education of numerous graduate and undergraduate students in solid-earth, atmospheric, and geodesy fields by providing high-quality GPS data to the Caribbean research community. Support is included for a RESESS intern through UNAVCO, a SOARS student through UCAR, and a graduate student at Purdue.

COCONet (Continuously Operating Caribbean GPS Observational Network)
An Infrastructure Proposal for a Multi-hazard Tectonic and Weather Observatory

1. INTRODUCTION

The Caribbean is a region of lush vegetation, beaches, active volcanoes, and significant mountain ranges. As frequently is the case in areas of natural beauty, this environment was created through geological, oceanic, and atmospheric processes that are also natural hazards. Natural hazards pose particular risk in developing countries in the Caribbean that have seen a significant rise in population density, ongoing migration to coastal areas, and a growing inventory of substandard buildings. These demographic and social changes are taking place against a backdrop of increasing threat from evolving climate that produces a more vigorous hurricane environment and rising sea level. All of this means that renewed focus on the natural hazards of the Caribbean region has the potential to broadly and positively impact both science and risks to society.

The capacity to understand, prepare for, adapt to, and in some cases predict the variety of natural hazards impacting the Caribbean requires observations on both large and small scales. While university-based researchers are ideally situated to investigate individual research topics and can operate focused networks addressing specific problems, they do not typically have the resources to install and maintain regional observation systems and to service the broader community who will use the resulting data. Large integrated instrument networks play a crucial role in providing a regional context for area studies, but require a different approach to project and data management.

The Continuously Operating Caribbean GPS Observational Network (COCONet) is a planned fiducial network of GPS stations that will 1) provide constraints on the tectonics of the entire Caribbean region, 2) make atmospheric observations that can be used to test and extend climate models, 3) improve the analysis of local geodetic measurements by providing access to an integrated backbone of reference stations, and 4) increase our ability to predict the natural hazards that pose such a significant threat to the region. COCONet will be installed and maintained by UNAVCO on behalf of the science and other user communities in the United States and abroad, thus leveraging UNAVCO's proven record of efficient and effective network management and its longstanding commitment to collaborative science.

2. COCONet SCIENCE GOALS

In the following discussion we present the key solid-earth and atmosphere science questions that will be addressed by the COCONet infrastructure.

Solid Earth

Tectonic and volcanic activity along the boundaries of the Caribbean plate have formed a geography where the vast majority of the Caribbean population lives within reach of major active faults and volcanoes, and is therefore directly exposed to seismic and volcanic hazards. The January 12, 2010, earthquake in Haiti was a tragic reminder of this reality. The large oceanic extent of the Caribbean and the presence of many offshore active faults also make the region both a source and a receiver of tsunamis. Finally, the Central America and Lesser Antilles subduction zones are associated with explosive volcanoes that pose a direct threat to large population centers. The Caribbean domain and its population are clearly a prime target of a variety of geodynamic hazards. However, much of the region's tectonic context is still relatively unknown and the level of threat not yet quantified. For instance, only a few of the active plate boundary faults have well-determined geodetic slip rates. Some key plate boundary structures are not even considered in hazard assessments – including the Haiti fold-and-thrust belt, which may have been the source of the devastating January 12 earthquake.

The diverse tectonic context of the Caribbean region is an asset for process-oriented studies addressing a number of major science questions. This has long been recognized by the international tectonics and geophysics community. Although the U.S. has funded geodetic studies along several segments of the Caribbean plate boundary since the early 1990's (Figure 1), no concerted, multilateral effort has yet equipped the Caribbean region with a consistent geodetic infrastructure that would support both plate-wide research efforts and regional densifications. COCONet will form the backbone for a broad range of geoscience investigations in the Caribbean and enable research on process-oriented science questions, most with direct relevance to geohazards.

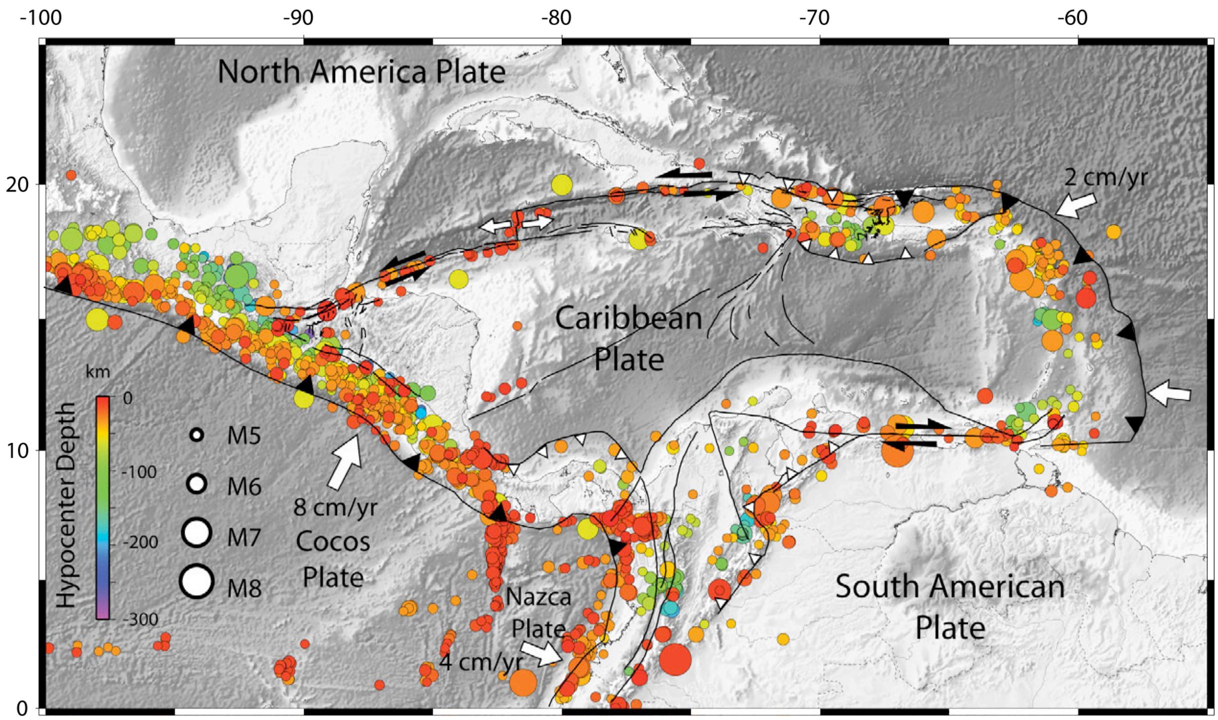

Figure 1. The Caribbean and Central America form a small lithospheric plate inserted between North and South America. While the North and South American plates show very little relative motion, the Caribbean plate is moving eastward relative to them along two major (distributed) east-west strike-slip fault zones along its northern and southern boundaries, at a velocity of ~20 mm/yr (Dixon et al., 1998; DeMets et al., 2001). To the east, the Caribbean plate is bounded by the Lesser Antilles subduction zone, where convergence occurs at ~20 mm/yr. To the west, in Central America, the Caribbean plate is bounded by subduction of the Cocos plate at a rate of ~70-90 mm/yr. White arrows and numbers in mm/yr indicate the relative plate motion rates and directions (from REVEL, Sella et al., 2002). The seismicity of the region defines the plate boundaries. It is shallow and confined to narrow regions along the northern and southern strike slip plate interfaces and more broadly distributed and deeper along the western and eastern subduction zones. Earthquake locations and magnitudes are from the NEIC data base (1974-present and NEIC data base of significant historical earthquakes).

Questions: What are the kinematics of the Caribbean domain? How rigid is the Caribbean plate? What Caribbean reference frame is appropriate for tectonic studies?

The level of rigidity of the Caribbean plate remains poorly defined, in spite of its importance for the definition of an unbiased reference frame for plate boundary studies (e.g., DeMets et al., 2007). The addition of new continuous GPS (cGPS) sites in the Caribbean, away from plate boundaries, will allow for an improved estimation of intraplate deformation and for the definition

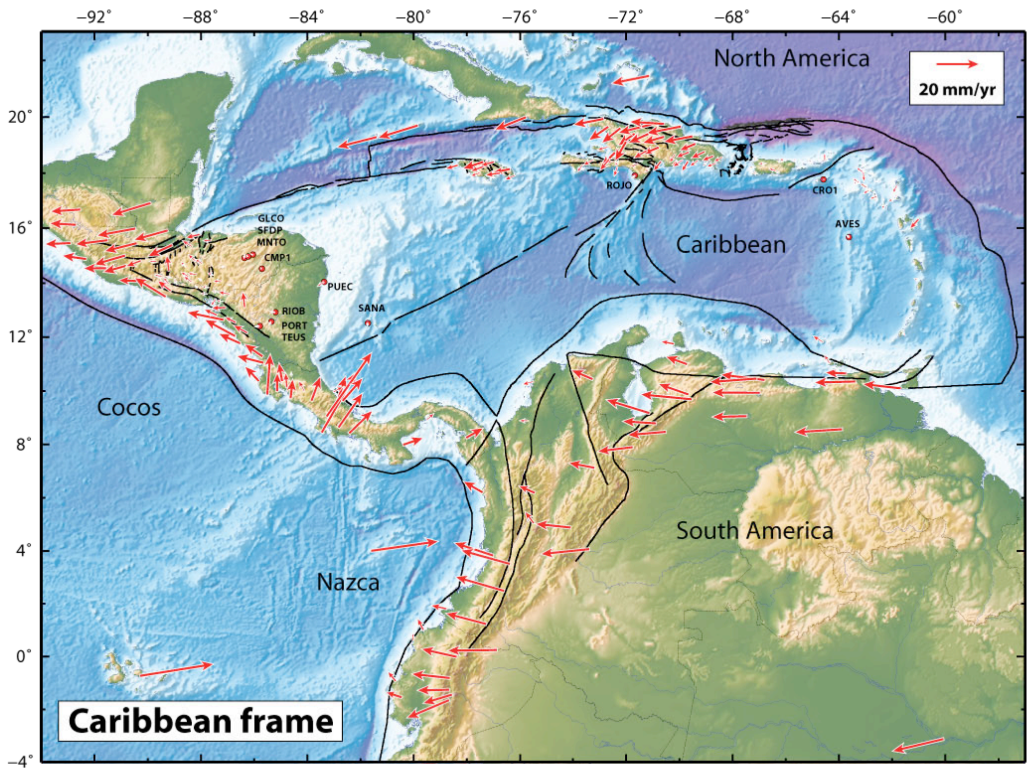

Figure 2. A combined GPS velocity field for the Caribbean region, incorporating data from 15 independent velocity field estimates (from Calais and Mann, 2009). Solid black lines indicate major active faults. While many interesting details of plate and microplate interaction are evident, this velocity field includes data from both permanent and campaign sites, with large variability in the quality of the velocity estimates. COCONet will densify the site distribution with 50 high-quality continuous GPS stations, adding important constraints in the Lesser Antilles block and in non-deforming regions of the North American plate, and will bring in data from up to 50 existing stations to allow the production of a comprehensive and unified regional velocity field. These 100 stations will be the backbone network defining a Caribbean frame to which smaller local networks can be referenced.

of a consistent Caribbean reference frame. This will advance models of relative plate motions between the North American, South American, Nazca, and Cocos plates, which provide the boundary conditions to plate boundary deformation processes in the Caribbean and Central America. This improved kinematic framework will, in turn, allow for more accurate estimates of integrated fault slip budgets and partitioning, and plate boundary zone deformation.

Current slip rate estimates for most active faults along the boundaries of the Caribbean plate remain poorly determined. As more GPS measurements are carried out, it becomes apparent that the plate boundary is fragmented into a complex kinematic puzzle. There is a need for a Caribbean-wide, kinematically consistent plate model that will provide constraints on the angular rotations for major microplates and slip rates on block-bounding faults (Figure 2). This information is critical for earthquake hazard assessment. The best way to get a self-consistent kinematic model – i.e., where all slip rates add up to the full plate motion rate – is to approach the problem at the scale of the entire Caribbean plate. The backbone GPS infrastructure proposed here will enhance our ability to precisely determine this plate-wide velocity field.

A consistent, plate-wide, kinematic model is also crucial for understanding the geodynamics of the Caribbean plate. Negredo et al. (2004) used geodetic data and a geodynamic model to propose that the Caribbean plate is driven by shear traction exerted at its base by eastward mantle flow. This is consistent with the limited number of studies of seismic anisotropy for this region (e.g., Russo et al., 1996) and with the model proposed by Russo and Silver (1994) that mantle flow beneath the Nazca slab is parallel to the trench and diverted around South America beneath the Caribbean plate. This model, however, was based on a very sparse geodetic data set and ignored the kinematic complexities along the Caribbean plate boundaries. The issue of forces driving the Caribbean plate must be revisited in the light of a consistent, plate-wide, kinematic model.

Questions: How is stress released at convergent plate boundaries? What controls interplate coupling? How does interseismic plate coupling change along strike?
A central issue in tectonics and seismology is the mode of stress release at convergent plate boundaries, where 90% of the Earth's seismic energy is released. The portion of plate interface that exhibits frictional stick-slip behavior and releases seismic energy is restricted in depth, and understanding the factors that control its down-dip extension is central to quantifying the associated hazard. More generally, the distribution of coupling at subduction zones in time and space is a key determinant of the level of hazard at convergent margins, and GPS data from subduction zones along the Caribbean plate boundary can provide a direct measurement of lateral variations in coupling (Manaker et al., 2008; LaFemina et al., 2009). The factors controlling this distribution of coupling – which may involve the mechanical strength of the plate interface as well as the subduction of collisional asperities – remain poorly understood overall. However, the nature and persistence of asperities and the behavior of the intervening weaker regions from one great earthquake to another and during the interseismic period are issues that can be addressed via the determination of interseismic strain accumulation using geodesy and comparison with coseismic slip patterns and seismicity.

Continuous GPS data from most subduction zones have led to the discovery of a new mode of plate boundary stress release in the form of transient slow slip events (Heki et al., 1997; Hirose et al., 1999; Ozawa et al., 2001; Burgmann et al., 2001; Lowry et al., 2001; Dragert et al., 2001). Documenting such episodic creep events, relating them to non-volcanic tremor or microseismicity, understanding why they occur and why they do not lead to instabilities that result in earthquakes, and determining how they affect estimates of interseismic velocity fields, is a critical research area requiring much additional study through improved temporal and spatial measuring of plate boundary deformation.

The Caribbean region allows for an unprecedented investigation of subduction earthquake cycle processes with geodetic data. Convergence rate and obliquity, as well as the nature of the subducting lithosphere, are highly variable along the Antilles arc from Barbados to Puerto Rico and along the Cocos – Central American margin into Colombia. Improved temporal and spatial sampling of the surface velocity field through the installation of COCONet will further our ability to investigate first order problems in earthquake cycle research, including slow slip events, the magnitude and spatial variability in plate coupling, the variability in strain partitioning, and how these processes relate to earthquake hazard.

Questions: What controls strain partitioning at convergent margins? How is stress transferred across plate boundaries?
Oblique subduction often induces a partitioning of strain in the overriding plate, resulting in distinct zones of trench normal and trench parallel deformation and the separation of crustal blocks from the overriding plate (e.g., Fitch, 1972; Jarrard, 1986; Beck, 1991; McCaffrey, 1992; Chemenda et al., 2000). Strain partitioning is a possible mechanism to explain the lateral transport of crustal slivers in plate boundary zones and their accretion to the margin of continents. Examples of strain partitioning are widespread, including subduction of the Indian plate beneath Sumatra (McCaffrey, 1991; Prawirodirdjo et al., 1997), the Pacific plate beneath

the Aleutians (Avé Lallemand and Oldow, 2000), the Cocos plate beneath Central America (DeMets, 2001; La Femina et al., 2002, 2009; Turner et al., 2007), and the North American plate beneath Hispaniola (Calais et al., 2002; Lopez et al., 2007). In many cases, such zones are characterized by a major strike-slip fault on the overriding plate, usually near the volcanic arc, that accommodates most of the trench parallel strain.

Because of their relatively shallow setting and close proximity to major populations centers (which tend to concentrate on continental margins), these strike slip faults have been the source of devastating earthquakes. For example, the 1972 M_w6.2 Managua earthquake in Nicaragua, which caused more than 11,000 fatalities, took place on a strike-slip fault normal to the Central America subduction zone. In the northeastern Caribbean, two major earthquakes occurred in 1842 and 1904 in northern Hispaniola, also on a strike-slip fault in the overriding plate. They destroyed the second major city of Haiti (Cap Haitien) and severely damaged the second major city of the Dominican Republic (Santiago), causing nearly 10,000 fatalities. Interestingly, these earthquakes were followed 50 years later by a series of M7.5 to M8 events on the subduction interface in northeastern Hispaniola (Dolan and Wald, 1998), which may suggest interaction between strike-slip faults in the overriding plate and the subduction interface through co- and post-seismic stress transfer.

It is generally thought that strain partitioning is controlled by stress transfer to the overriding plate, which in turn depends on plate motion obliquity (McCaffrey, 1992) and other factors such as friction at the plate interface (Chemenda et al., 2000), forearc strength (McCaffrey, 1992), or the pull force exerted by the subducting slab (Liu et al., 1995). For example, oblique subduction of the North American plate induces strain partitioning in Hispaniola, but not in adjacent Puerto Rico (Jansma and Mattioli, 2005), in spite of a similar plate motion obliquity. Manaker et al. (2008) argue that the spatial correlation between interplate coupling, strain partitioning and the subduction of buoyant oceanic asperities suggests that the latter enhance the transfer of interplate shear stresses to the overriding plate, facilitating strike-slip faulting in the overriding plate. Strain partitioning is also a prominent feature of Central American tectonics, where GPS data shows significant trench-parallel motion for most of the region (Turner et al., 2007). In central Costa Rica, however, partitioning occurs in a context where plate convergence is normal to the trench and coupling is low (La Femina et al., 2009). A mechanical model (La Femina et al., 2009) indicates that the thickened Cocos Ridge crust may resist subduction and act as an indenter, driving shortening and trench-parallel fore-arc motion.

The Caribbean region, including Central America and Colombia, is an exceptional locale to study strain partitioning and stress transfer across plate boundaries, in a variety of tectonic contexts. The backbone COCONet GPS network will provide essential infrastructure for the investigation of how stress is transferred across plate interfaces, what determines strain partitioning, and the mechanisms that control plate boundary zone segmentation.

Question: How can we better understand and assess hazards in the Caribbean and Central American regions?

Earthquakes are a prime source of hazard in the Caribbean and Central America, where most of the population lives within active plate boundary zones. Examples of devastating events abound, from the M7.5 1976 Guatemala earthquake that took an estimated 23,000 lives to the M7.0 2010 Haiti earthquake, with an estimated death toll of 230,000. The high exposure, high vulnerability, and low preparedness level of many circum-Caribbean countries are clearly aggravating factors, but the hazard level is in most cases poorly defined, which hampers mitigation efforts. For instance, prior to the January 10 Haiti earthquake, the commonly accepted probabilistic seismic hazard map for the Caribbean region had Port-au-Prince at 0.13 g for 10% probability of exceedance in 50 years and an equivalent maximum intensity of 6 to 7 (http://www.oas.org/CDMP/document/seismap/). A revised version prompted by the January event (Frankel et al., 2010), which makes use of geodetic fault slip rates (Manaker et al., 2008), now puts Port-au-Prince at 0.6 g for 10% probability of exceedance in 50 years and an equivalent maximum intensity of 8 to 10. COCONet GPS stations will enable studies aimed at improving hazard assessment and at investigating the fundamental aspects of earthquake hazard such as interplate coupling, the roles of stress transfer and ETS events.

Several segments of the Caribbean plate boundary have had historical subduction zone earthquakes that generated tsunamis. For example, tsunamis triggered by the 1946 M8.0 Dominican Republic earthquake and the 1992 M7.2 Nicaragua earthquake caused casualties in the thousands. This latter event is the slowest earthquake on record. How does the Nicaragua margin, which appears to have low overall and/or shallow interseismic coupling (LaFemina et al, 2009; Correa-Mora et al, 2009), generate tsunamigenic earthquakes? Eruptions (Lindsay, 2005), edifice collapse (Boudon, 2007), and pyroclastic and debris flows from island-arc volcanoes in the Lesser Antilles also pose a significant tsunami hazard for the circum-Caribbean region (Mattioli et al., 2007). A basin-scale high-rate cGPS network may prove useful in a tsunami early warning system for both volcanogenic and seismogenic sources (Blewitt et al., 2009).

Finally, the Central America and Lesser Antilles subduction zones are associated with explosive volcanoes that pose a direct threat to major population centers. In the period 1999~2010, eight of Central America's volcanoes (Pacaya, Guatemala; Cerro Negro, San Cristobal, Telica and Concepcion, Nicaragua; Arenal, Poas and Turrialba, Costa Rica) and one of the Lesser Antilles ones (Soufriere Hills, Montserrat) have violently erupted, causing displacement of local populations and damage to infrastructure. A well-placed geodetic backbone network could provide stable sites for geodetic monitoring of the Caribbean and Central American's active volcanoes (see for example Elsworth et al., 2008; Mattioli et al., 2010 for applications for Montserrat). Reliable assessment of changes in volcanic behavior requires "stable" forearc sites and high temporal sampling available with cGPS sites (Turner et al., 2010).

Atmosphere

From a coupled atmosphere-ocean perspective, the most dominant feature of the Caribbean is that it is part of the second largest pool of very warm (> 28.5 C) water in the world (Wang and Enfield, 2001). These high sea-surface temperatures (SSTs) interact with the general circulation of the atmosphere through large-scale phenomena such as the El-Nino Southern Oscillation (ENSO) (Wang et al, 2006), the Madden-Julian Oscillation (MJO) (Maloney and Hartmann, 2000), the Atlantic Multi-decadal Oscillation (AMO) (Enfield et al, 2001; Wang et al., 2006), and other large-scale features of the global atmospheric circulation. The warm pool also influences circulation patterns outside of the region, primarily as a moisture source for the Gulf of Mexico and Central and North America, through Low Level Jets (LLJ) that concentrate the flow of moisture across the central American Isthmus, into the Sierra Madre Occidental, and up through the Great Plains of North America.

Current global and regional climate models have difficulty in simulating the complex hydrological cycle within the Caribbean (Chen et al 1999; Misra et al., 2009), where precipitation is five times larger over land than over oceans (Granger 1985). In addition, the diurnal cycle of rainfall over mountains in the Caribbean is particularly difficult for climate models and short-term numerical weather prediction models (Poveda et al., 2005) to recreate. Precipitable water vapor (PW) estimates from a broad network of land-based GPS/meteorological stations will dramatically improve our understanding of the hydrological cycle on a variety of length scales.

The most obvious weather hazard that affects the Caribbean region is hurricanes. These storms inflict serious personal and financial losses over the entire Caribbean region on a nearly annual basis. The National Hurricane Center estimates that Hurricane Katrina (2005) caused $40.6

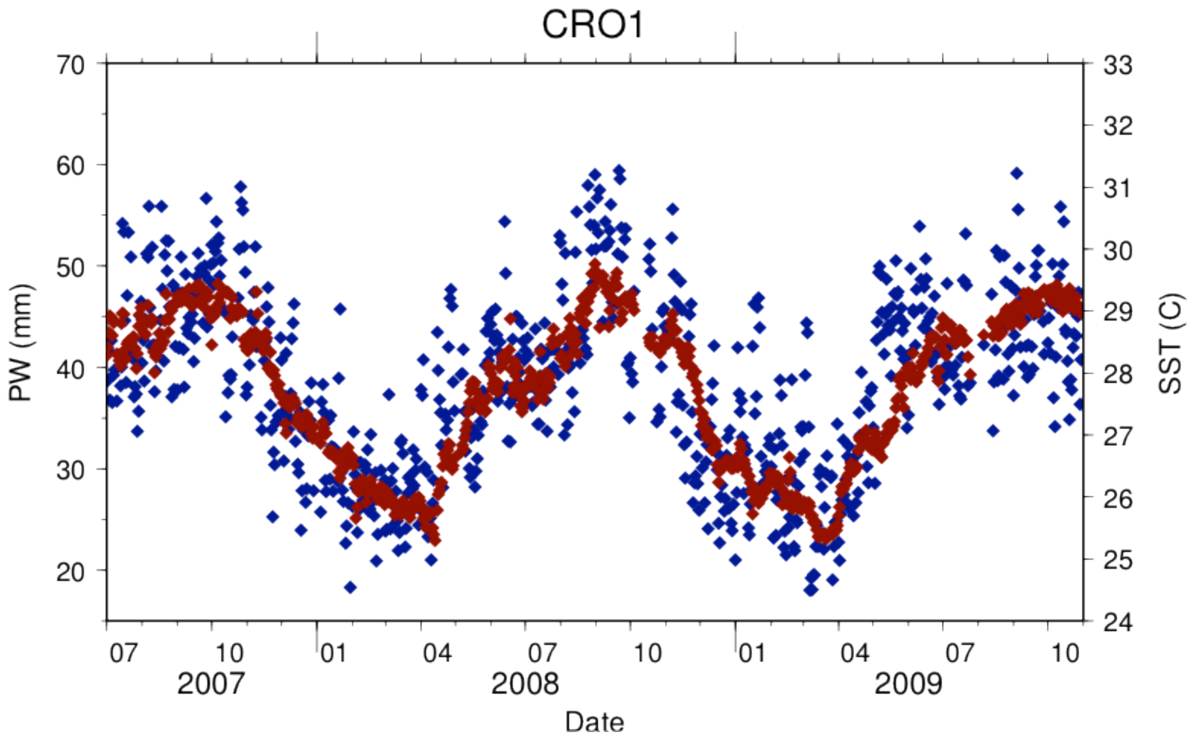

Figure 3. Time series of GPS derived PW (blue) and SST (red) from St. Croix. The strong coupling of SST and PW is evident, with variability in PW caused by advection of moisture across the station.

billion in insured and $81 billion in total losses. It also caused at least 2500 deaths, with most of the casualties occurring around New Orleans and along the U.S. Gulf Coast. Hurricane Ike (2008) caused 103 deaths – mostly in the nations of Cuba, Haiti, Turks and Caicos, and the Dominican Republic –as it slowly made its way through the Caribbean. Flooding associated with Hurricane Mitch (1998) induced landslides that killed at least 9000 people in Central America. While hurricane track forecasts have steadily increased in accuracy, forecasts of hurricane genesis and intensity changes are challenging. A recent review article (Knutson et al., 2010) indicates that projections of 21st century warming will increase storm intensities by up to 11% globally and increase the frequency of the most intense hurricanes.

Beginning in 2007, UCAR with NSF funding (ATM-0633587) established a network of GPS stations in the Caribbean to improve hurricane forecasts. The data from this network are analyzed in near-real-time at UCAR to produce precipitable water vapor (PW) estimates at 30-minute time steps. The results obtained so far from this network illustrate the potential of COCONet for atmospheric and oceanic studies. In particular, the data products that will be generated can provide useful information to test the following key questions:

Question: What are the physical mechanisms for the coupling between sea surface temperatures and atmospheric water vapor, and is this coupling confined to the atmospheric boundary layer or does it extend into the free troposphere?

Continuous and accurate estimates of PW can be used to evaluate the sensitivity of PW to changes in SST. In a study of multiple global PW data products, Trenberth et al. (2005) investigated the coupling between SST, PW and rainfall, not only establishing the importance of PW to the global hydrological cycle, but also emphasizing that because water vapor is the most abundant green house gas in the atmosphere, it is an important observation for climate. Trends in PW were observed to be increasing more consistently over oceans than land, but changes in PW related to ENSO variations were either of the same order, or slightly larger than the secular trends. Figure 3 shows a time series of GPS PW and Reynolds SST around the island of St. Croix (Reynolds et al, 2007). A regression of the two time series shows that approximately 70% of the PW variability can be explained by the local ocean surface, with the remaining variability attributable to advection of moisture through the atmosphere. COCONet will provide total column water vapor in both clear and cloudy conditions that can be used to measure air-sea coupling strength in a number of different ways. The distribution of stations across the Caribbean basin should provide an indirect way to measure water vapor fluxes along the boundaries of the region as easterly winds transport air parcels across the Lesser Antilles Islands, over the Caribbean Sea, and into either Central and South America or up through the Gulf of Mexico and eventually into the Great Plains of the United States. The latitudinal distribution of stations will test the strength of air-sea coupling through the Inter-Tropical Convergence Zone (ITCZ) and measure seasonal changes in this coupling as ocean SSTs evolve throughout the year. These data will be useful when evaluating atmosphere-ocean interactions in climate models, reanalysis products, and satellite observations (Mears et al., 2007; Mirsa, et al., 2009).

Question: What is the impact of continuous estimates of PW on hurricane intensity forecasts?

A number of environmental conditions are thought to strongly influence hurricanes, including vertical wind shear, aerosols, and most importantly warm sea surface temperatures. Hurricanes could not form without warm ocean surfaces. As one might suspect, the strongest link between the ocean and the atmosphere comes through the evaporation of moisture. A study of hurricane

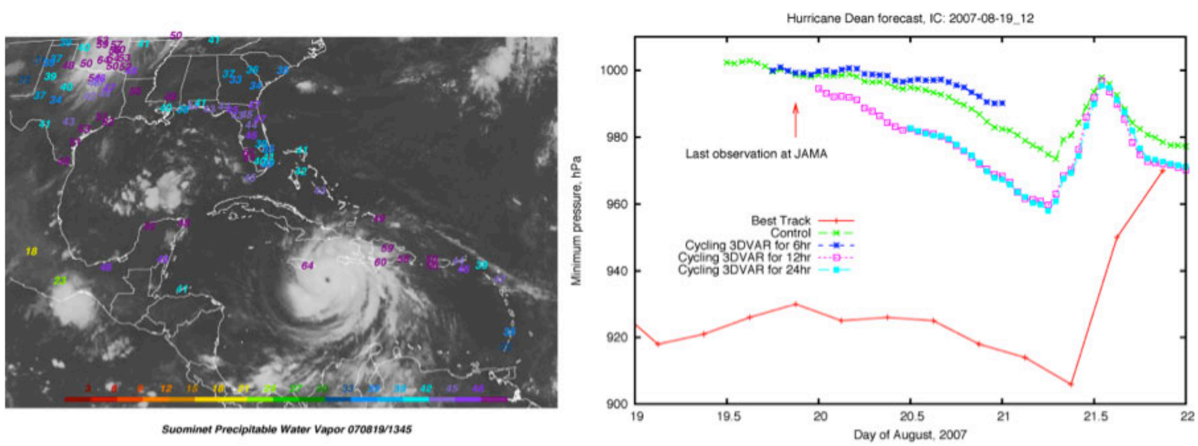

Figure 4. PW estimates, color coded by amount, overlaid upon a GOES IR4 image (left) are shown during Hurricane Dean in 2007. The impact of these observations on the forecast of minimum surface pressrure of Dean are shown on the right. The best estimate of minimum surface pressure from the National Huricane Center is shown in red. The forecast of minimum surface pressure is shown as green (no GPS data used), blue (6 hours of data assimilated), pink (12 hours), and turquoise (24 hours). The use of continuous PW estimates reduces the forecasted minimum surface pressure by almost 20 hPa.

Bonnie (Braun, 2006) concluded that the ocean source of water vapor within the hurricane eye-wall accounted for only 4% of the total water vapor budget, with the remaining moisture coming from radial transport of moisture within the lowest 500 m of the boundary layer. The radial extent of this transport can be up to 2,000 km, implying that hurricane evolution and maintenance is a function of atmospheric conditions over a relatively large spatial scale. In conjunction with finer grid spacing in models, improved moisture analysis fields hold the potential for significant improvement in intensity forecasts as well as answering scientific questions associated with the hydrological cycle and interactions of water with atmospheric phenomena such as hurricanes.

The large aperture and continuous operation of COCONet will provide a water vapor product that will capture tropical storm systems in various phases of development (genesis, intensification, maturation, and weakening). These data will measure latent energy available to the atmosphere over various spatial scales and at high temporal resolution. Comparison with model analyses and forecast fields will provide diagnostic information for investigations researching hurricane genesis and intensification and will provide a baseline for improving forecasts that either underestimate or overestimate changes in storm strength. As an example, a statistical comparison of GPS PW to the Global Forecast System (GFS) analysis fields shows a significantly larger difference between the two over the Gulf of Mexico and Caribbean (larger than 3 mm rms with a bias of 1.6 mm) versus the broader continental United States (2 mm rms with almost no bias).

The UCAR GPS network in the Caribbean has been shown to positively improve hurricane intensity forecasts. Figure 4 shows GPS PW estimates overlaying a GOES-IR satellite image. These data were assimilated into the Weather Research and Forecasting (WRF) model at 12-km resolution and found to improve the minimum surface pressure of Hurricane Dean (2007) by approximately 20 hPa. Increased model resolution, as well as improved cloud microphysical and boundary layer schemes (Li and Pu, 2008), are also known to impact intensity forecasts, but the results from hurricane Dean are encouraging. It is likely that improvements in moisture observations will complement model improvements.

Similar research using satellite-derived PW fields have also shown the positive impact of PW in hurricane intensity forecasts (Chen et al., 2004; Chen et al., 2008). These studies highlight the relatively large uncertainties in satellite-derived PW estimates (5.5 and 3.3 mm rms for MODIS infrared and near infrared data products) and their degradation or complete failure in the presence of clouds or rain. GPS PW is insensitive to this liquid water, making it a complementary observation within hurricane systems. PW estimates will also allow for calibration of the microwave satellite systems that provide the bulk of the information on atmospheric water vapor over oceans. A network such as COCONet would create a basin-wide reference system to calibrate and validate satellite observations, reducing their errors and indirectly increasing the value of these satellite products for initializing weather prediction models.

Once COCONet is established and operational, it will produce data from multiple tropical storms each year, forming a collection of data both distant from and near to storm environments. Stations that are relatively far from the storms will be used to measure the strength of sinking air caused by outflow that suppresses humidity in the free troposphere. Stations that are within one or two hundred kilometers of the storm center will sample an atmosphere that is influenced by inflow and rain bands that not only cause significant precipitation, but also interact with the storm circulation through latent heat release in a convective environment. A few stations each year will also directly sample the deep convection along the eyewall as well as the eye itself.

Question: Can severe precipitation forecasts that are not related to hurricanes be improved in the region?
Most of the severe weather that impacts the Caribbean is related to moist convective processes that evolve over time scales from hours to days. GCMs and other atmospheric models do not resolve these processes with enough fidelity to accurately model the convective systems that lead to precipitation. Many of these models use PW as a parameter in controlling cloud microphysical schemes (Neelin et al., 2009; Jury, 2009). COCONet will provide a continuous time series of integrated water vapor and surface observations (horizontal wind, rain, relative humidity, pressure, and temperature), with a resolution of at least 30 minutes, to effectively

observe these small-scale features. These data, and the distribution of COCONet stations throughout the Caribbean will aid in quantifying the variability in water vapor in the region. These data should be useful in understanding precipitation processes caused by land-sea circulations, rain shadows across islands, and the orographic rainfall associated with the larger islands of Hispaniola, Puerto Rico, and Jamaica.

Other contributions of COCONet

In addition to GPS-based data and products, COCONet will provide continuous observations of surface temperature and pressure, relative humidity, horizontal winds, and precipitation. These data will augment existing surface observations that are generally sparse and incomplete (Peterson, et al., 2002; Jury, 2009). Measurements such as these are necessary to observe the expected changes in precipitation and extreme weather events that are anticipated over the next century. Additionally, access to a continuous stream of surface observations with close proximity to tropical storms will be of great use to scientific process studies and operational forecasts made by the National Hurricane Center and local forecast offices.

COCONet will also contribute to studying sea-level rise (SLR), another significant threat to the Caribbean that is expected over the next century. A report from the Caribbean Environmental Program (CEP) was summarized by Lewsey et al., (2004) and illustrated the threat of SLR by noting that each centimeter of SLR will correspond to a shoreline retreat of several meters. This change will drive increased flooding during storms, the loss of productivity of lagoons and estuaries due to salination, and the destabilization of soil through the loss of mangrove forests.

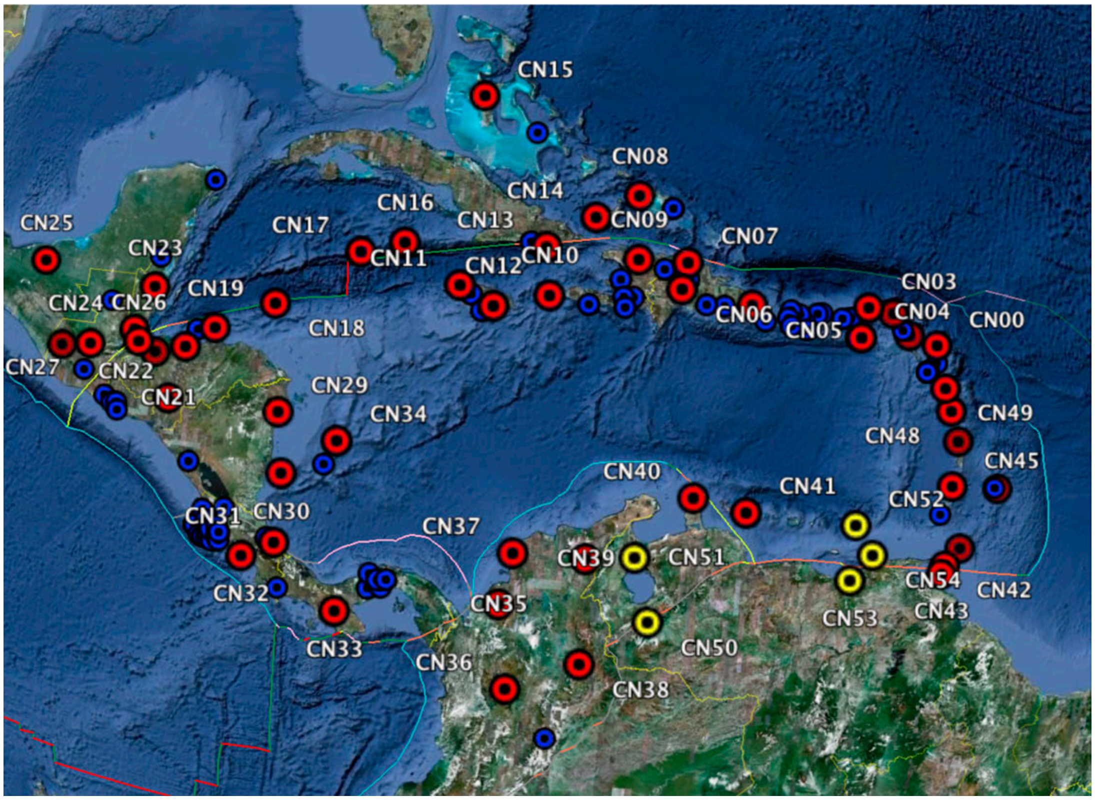

Figure 5. Existing and proposed GPS network design for COCONet. The fifty proposed Caribbean GPS stations are shown in red. Existing GPS station with a high probablity of getting free and open data access are shown in Blue. Stations in Yellow are deemed critical for tectonic studies but are not included in this proposal due to difficulties associated with working in Venezuela.

A well-designed COCONet, with stations located near existing tide gauges in the region, will help place SLR into a global frame, helping to separate changes in land heights from sea level variations.
Because of its global reach and precision, GPS is the technique of choice for sustainable geodetic operations worldwide. By providing free public access to high-quality (and in a few cases high-rate) GPS data, COCONet will benefit surveyors, planners, GIS specialists, and national mapping agencies in the Caribbean. Streaming data from COCONet stations will enable researchers and local agencies to more effectively monitor ground deformation due to hazards such as local landslides in independent observation efforts. COCONet products such as precise site positions and velocities in a well-defined geodetic framework will allow practitioners to tie their own surveys to a well-defined global geodetic reference frame. The improved monitoring of plate motion and plate boundary deformation enabled by COCONet will facilitate the definition and use of dynamic reference systems by Caribbean countries, should those become of interest.

COCONet data will also help improve the tsunami monitoring and detection capabilities of the Caribbean Tsunami Warning System (Blewitt et al., 2009; Sobolev, 2007). During the 5th Session (March, 2010) of the UNESCO Intergovernmental Oceanographic Commission's (IOC) Intergovernmental Coordination Group for the Tsunami and other Coastal Hazards Warning System for the Caribbean Sea and Adjacent Regions (ICG/CARIBE EWS), the potential applications of GPS data for tsunami warning were recognized. The ICG/CARIBE EWS urged its 28 member states and territories, including the USUA, to upgrade and/or install GPS stations for high-rate data and consider their collocation with existing and planned seismic and sea level stations. It also instructed its working groups to evaluate the needs and state of art in GPS for tsunami monitoring applications. COCONet will implement many of these recommendations and therefore would be a most welcome contribution of the USA to the ICG CARIBE EWS (pers. comm, C. von Hillebrandt-Andrade NOAA NWS Caribbean Tsunami Warning Program).

In February 2010, the NOAA National Weather Service established the Caribbean Tsunami Warning Program (CTWP) in Mayaguez, Puerto Rico as the first step of the phased deployment of a Caribbean Tsunami Warning Center. COCONet complements the objectives of this newly established NOAA initiative to strengthen and explore new technologies for improved tsunami warning guidance. The CTWP has offered to help in the organization of COCONet's planned scientific and technical workshops, since it maintains a database of and is in contact with the operators of seismic, sea level and GPS station operators in the region.

Landslides are regarded as one of the major geological hazards in nearly all Caribbean countries. GPS networks have been increasingly used to monitor the movement of major landslides. COCONet will provide a continuous reference network for organizations conducting focused GPS-based landslide science investigations and monitoring.

3. COCONet DEPLOYMENT AND DATA PRODUCTS PLAN

We propose to install a pan-Caribbean network of 50 collocated, permanent, and continuously-operating Global Positioning System receivers and meteorological stations to facilitate an improved understanding of the kinematics and dynamics of the boundary between the Caribbean and surrounding tectonic plates and to improve Caribbean water vapor and hurricane intensity forecasts – all leading to a more complete understanding of the major regional hazards. This network (COCONet, Figure 5.) will leverage aspects of the recently completed EarthScope project, including community building and enfranchisement; standardized network planning, design and instrument procurement; reconnaissance, permitting, equipment installation and documentation procedures; data transmission, processing, and archiving; and free and open access to all data and derived data products. The network will also leverage the expertise of U.S. as well as Caribbean and Central American researchers to guide station siting and station operations and maintenance.

COCONet will provide a single unified GPS network spanning the Caribbean region, with standardized monumentation, equipment, dataflow and data processing. COCONet does not replace existing national and local GPS networks, but extends them spatially and provides for their improved integration into regional and global reference frames. This is of particular importance for the study of fault systems that cross national boundaries, as well as for characterizing broader interaction between the region's major tectonic plates and associated microplates. Tsunami early warning and emerging meteorological applications using GPS also require large-aperture integrated networks because the length scale of the processes involved can be several hundred kilometers or greater.

Table 2. Project Time Line and Project Staffing for Reconnaissance, Permitting, and Installation Phase

Reconnaissance/Siting	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Number of Stations Sited	50	0	0	0	0
UNAVCO Engineer Travel Days (1 person x 5 days per station)	250	0	0	0	0
In-country Engineer Days	250	0	0	0	0
PI Days	70	0	0	0	0
PI International Flights	10	0	0	0	0
UNAVCO Engineer International Flights	50	0	0	0	0
Engineer Regional Flights	5	0	0	0	0
Vehicle Rentals/Taxi Days	250	0	0	0	0
Permitting	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Number of Stations Permitted	10	25	15	0	0
Installations	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Stations Installed	10	25	15	0	0
UNAVCO Prep Engineer Days (1 person x 10 days per station)	100	250	150	0	0
UNAVCO In-Field Engineer Days (2 UNAVCO persons x 5 days per station)	100	250	150	0	0
UNAVCO Engineer International Flights	20	50	30	0	0
Engineer Regional Flights	4	10	6	0	0
Vehicle Rentals/Taxi Days	50	125	75	0	0
Reconnaissance, Permitting, and Installation Staffing	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Total Eng-Days Required	450	500	300	0	0
Engineer FTEs Required	2	2.22	1.33	0	0
Project Management FTEs Required	0.50	0.5	0.35	0	0
Permitting FTEs Required	0.75	0.50	0.10	0	0

One of the strengths of the COCONet concept is that it will solicit ongoing data contributions from up to 50 stations in existing GPS networks (Figure 5, in blue), with those data archived and processed alongside data from COCONet installations. This effectively densifies the installed station base, as well as allows COCONet to concentrate resources on tectonically complex regions (such as the plate boundaries in Guatemala and Columbia) without loss of coverage in well-instrumented areas (Puerto Rico, western Costa Rica, Panama). This combined network of

Table 3. Project Staffing for COCONet Operations and Maintenance.

Operations and Maintenance	Year 1	Year 2	Year 3	Year 4	Year 5
Stations Installed	10	35	50	50	50
Anticipated O&M Visits	0	7	23	33	33
UNAVCO Trouble-shoot and Prep Engineer Days (1 UNAVCO engineer x 4 days/station)	0	140	200	200	200
UNAVCO In-Field Engineer Travel Days (1 UNAVCO engineer x 4 days/visit)	0	28	92	132	132
Local Representative In-Field Travel Days	0	14	46	66	66
UNAVCO Engineer International Flights	0	5	17	25	25
Engineer Regional Flights	0	2	6	8	8
Vehicle Rentals/Taxi Days	0	28	92	132	132
Operations and Maintenance Staffing	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Total Eng-Days Required	0	168	292	332	332
Engineer FTEs Required	0.00	0.75	1.30	1.48	1.48
Project Management FTEs Required	no additional	no additional	no additional	0.25	0.25

new and existing stations will provide much broader station coverage than exists today and will serve as a solid foundation for addressing the science objectives described above.

Station Instrumentation

The project budget covers the procurement, installation, operations, and maintenance of 50 dual-frequency GNSS-capable GPS receivers and choke ring antennas. Each station will be modeled on a PBO Short Drilled Braced Monument (SDBM) design (Figure 6) with a stainless steel monument and antenna adaptor. The GPS receiver will be low-power, high-memory, internet-enabled system capable of tracking all GPS observables, including L2C and L5. The receivers will have a web-based interface for troubleshooting and the ability to do instrument diagnostics in the field without a computer. Since this proposal leverages the PBO Management System for data retrieval, receiver download protocols have to work with existing data download software at UNAVCO. The choke ring antenna will have a broadband element capable of tracking modern GNSS signals and be able to accept a SCIGN style monument adaptor and tall radome. The antenna will come with phase center offsets and variations (PCV) corrections calibrated using an Automated Absolute Field Calibration (for example: http://www.geopp.de) from the manufacturer. Meteorological systems will include a multi-

Figure 6. A short-drilled braced monument (SDBM) installation in the EarthScope network. A similar monument and station configuration is proposed for COCONet.

weather sensor capable of measuring wind speed and direction, liquid precipitation, barometric pressure, temperature and relative humidity. The met sensors will be compatible with the standard NMEA GPS met/tilt interface since they will use the GPS receiver as a data logger.

Station Installation

Siting, Reconnaissance, Permitting

Initial site locations were chosen based on gaps in geodetic coverage in the Caribbean (see Figure 5 and Table 1 located at the end of the proposal). Site locations will be refined and potential site contacts will be identified in the community kickoff meeting. The initial site visit will allow existing NSF-supported Caribbean researchers or a project PI and a UNAVCO engineer to discuss the project with local researchers, put the program into a local science context, discuss the benefits of open data sharing, and do preliminary site(s) selection. In most cases a follow-on reconnaissance visit will be needed to document main and alternative locations and initiate permit discussions with local landholders. The completion and documentation of permits will be handled by a UNAVCO Land Use Permit Coordinator. The project will budget for approximately $3000 in one-time permit fees.

Sites will be chosen based on science target, sky visibility, availability of competent bedrock, proximity to power and data communications infrastructure, and overall site security. We will strive to locate stations at secure, existing facilities with local site contacts who can assist with operations and maintenance as needed. We will also attempt to site stations in locations suitable for both GPS and sea-level observations using tide gauges. We plan to have all station siting completed within one year after the planned Project Kick-off Community Meeting.

Station Installation, Power, and Communications

Stations will be installed in bedrock using UNAVCO's PBO-standard Short Drilled Braced techniques and stainless steel monument materials (see http://pboweb.unavco.org/dmsdocs/Root%20Folder/PBO%20Operations/Miscellaneous%20Documents/SDBM%20installation.pdf). Other monument types will be considered if needed to meet site-specific contingencies. Alternative monuments will be discussed with the COCONet Science and Station Siting Advisory Committee prior to installation. GPS instruments, gel-cell batteries and data communications systems will be housed in a corrosion-proof, secure, vented, and fully grounded non-metallic enclosure. We will attempt to minimize the amount of metal at the site, to reduce corrosion and potential operations and maintenance costs. All instruments will be battery-powered, with batteries charged with AC and/or solar power. Data communications will be a combination of local internet, cellular modem, and VSAT. We anticipate that 10 of the 50 stations installed will be able to support real-time streaming of high-rate data (1-sample/sec), with most of the remaining 40 stations able to stream standard 15-second data for GPS PW estimates. Standard 15-sec data files will be downloaded from all stations every 24 hours.

Project Installation Timeline and Budget Assumptions

The reconnaissance activities for the construction of fifty stations will be completed in the first year of the project. We propose a 3-year permitting and installation phase that includes 10 stations in Year 1, 25 stations in Year 2, and 15 stations in Year 3. Permitting costs are estimated at $3000 per station for fifty stations, which will be paid during the first two years of the project. Shipping costs are estimated at $3500 per station. Operations and maintenance activities will run concurrently with installation activities. Engineering travel and staff time for the reconnaissance, permitting, and installation phase is determined using the assumptions shown in Table 2. It is based on five days per station (one UNAVCO engineer) for reconnaissance and five days per station (two UNAVCO engineers) for station installations. Ten days per station (one UNAVCO engineer) are estimated for purchasing equipment, shipping, and other pre-installation preparation activities. Total engineer-days required is 450, 500, and 300 during the first three years, which corresponds to an engineering staff level of 2.0 FTE in Year 1, 2.22 FTE in Year 2 and 1.33 FTE in Year 3.

Project management is estimated at 0.50 FTE for the first two years and 0.35 FTE for the third year of the project. A permitting coordinator is budgeted at 0.75 FTE, 0.50 FTE, and 0.1 FTE, respectively, for the first three years of the project. We recognize that U.S. investigators who have been working in the Caribbean region for many years have extensive scientific and cultural knowledge of the area. Consequently, travel expenses are included in the first year of the project for 10 U.S. investigators to make in-country introductions and assist UNAVCO engineers with initial siting and permitting discussions.

Station Operations and Maintenance (O&M)

The purpose of COCONet is to generate, analyze, archive, and distribute freely available, high-quality, timely, and relevant geodetic data products to the geodesy and other communities. Operations and maintenance activities are budgeted only for the 50 new stations installed, not for the 50 existing stations. As the network buildout occurs, we will use construction staff to maintain stations where possible. However, given the large distances between stations and to ensure the highest level of uptime for the network, we budgeted for operations and maintenance activities separately. Operations and maintenance personnel will be responsible for monitoring the network, troubleshooting problem stations, equipment repair/replacement, corrosion mitigation, cleaning solar panels, brush clearing, fence repair, and updating landowners and local researchers on the COCONet project and science contributions. For stations requiring unscheduled maintenance, we will first try and resolve issues with local site contacts. If this fails to bring the station on line we will attempt to remotely analyze the failure, determine a suitable repair strategy, and deploy an engineer to fix the broken station. At the Project Kick-off Community Meeting COCONet PI's will begin discussions with existing data stakeholders on how future requests to NSF for O&M will include support for existing sites in the circum-Caribbean region, in particular those that were installed or are maintained with NSF and other U.S. federal funds. We anticipate that many of the NSF and other U.S. federally funded sites could easily be incorporated into the COCONet O&M plan for a marginal incremental cost.

O&M Budget Assumptions - Personnel and Travel

We anticipate no maintenance visits during the first year, 7 maintenance visits during the second year, and 23 maintenance visits during the third year (Table 3). Starting in Year 4, once the network has been completed, we anticipate 33 four-day maintenance visits per year to maintain the network. We also budget for five days of travel each year for local collaborators to assist with routine issues which corresponds to one station visit every 1.5 years.

Staffing levels for operations and maintenance are based on anticipated engineer days required each year. We assume 4 engineer-days/year/station (network monitoring, troubleshooting, shipping, equipment preparation, etc.) plus 4 in-field engineer days per maintenance visit. The total engineer-days required for operations and maintenance is 168, 292, 332, and 332 during Years 2~5 of the project. This corresponds to an operations and maintenance field engineering staff level of 0.75 FTE in Year 2, 1.3 FTE in Year 3, 1.48 FTE in Year 4, and 1.48 FTE in Year 5. As the project transitions to operations and maintenance, the project management component is reduced accordingly from 0.35 FTE in Year 3 to 0.25 FTE in Years 4~5.

One of the problems UNAVCO has had in the past in supporting global networks is the lack of funding to support the in-country host institution for fieldwork. We address this problem in this proposal by budgeting for costs associated with in-field travel for a local collaborator to assist the UNAVCO engineer during some maintenance site visits. This will promote a sense of teamwork and collaboration between the U.S. investigator, UNAVCO, and the local collaborator and will provide a transfer of knowledge for maintenance activities in future years.

O&M Budget Assumptions - Data Communications

Ongoing data communications costs are estimated using both cellular and VSAT technologies and phased in according to the buildout schedule. Cellular costs are estimated at $100/month/station and VSAT costs are estimated at $160/month/station. For 10 stations, we assume radios will be required to telemeter data from the station to either a cellular or VSAT relay.

O&M Budget Assumptions - Equipment and Replacement Costs
Half the equipment and materials will be purchased in first year of the project. The remaining equipment and materials will be purchased in the second year of the project. Replacement costs are estimated at 10% per year for the GPS receiver, GPS antenna, meteorological instrument, data communications, and power systems. No replacement costs are expected during the first year of the project or for the monument hardware. The replacement rates are budgeted at a higher rate than PBO due to a more corrosive environment in the Caribbean and unknown security at the sites.

COCONet Data Flow, Processing, and Archiving

The COCONet Project will leverage existing data flow, data processing, and data product distribution and display using tools, procedures and analysis methodologies established during the PBO project (Figure 7). COCONet stations will be downloaded daily using the PBO Data Flow System and all received data will be quality-checked using the UNAVCO Translate, Edit, and Quality-Check (teqc) tool. In addition, data will be streamed in real-time from most or all COCONet stations, with 10 stations planned for 1 Hz high-rate data flow, and the remainder at the 15-second standard data rate. The 1 sample/sec and 15-second data streams will be used to support atmospheric applications of COCONet, but they are also expected to be useful for geodetic applications related to volcanic eruptions, and rapidly monitoring post-seismic slip

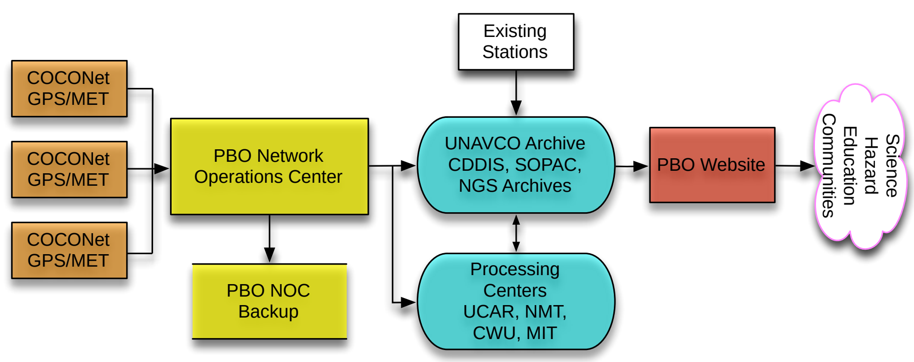

Figure 7. Data flow and data processing framework for COCONet and existing Caribbean GPS stations. The project will utilize the EarthScope Plate Boundary Observatory data processing strategy for station positon and velocity estimation, and UCAR will process the data for estimates of precipitable water.

events. Station metadata will be stored in the PBO Metadata Management and database systems.
UNAVCO plans to transmit, quality control, archive, and process standard daily 15-second data sets for 50 new COCONet stations and 50 existing stations in the Caribbean. The archiving and processing timeline is based on the availability of data and gradually ramps from Year 1 to Year 4 (Figure 8). Standard 15-sec data archiving and processing has been budgeted at $250 and $365 per station per year respectively. We will also archive, stream, and process high-rate (1 sample/sec) data at UNAVCO from 10 GPS stations starting in Year 3 at a cost of $800 per station/year.

For data products we anticipate being able to achieve 1.) >85% overall data return for standard 15-second files, 2.) 100% Level 1 and 2 data product generation from downloaded data, and 3.) 100% of the data acquired placed in long term archives.

Data from both new and existing stations will be transferred to the UNAVCO Archive and sent to PBO's GPS Analysis Centers (ACs) at New Mexico Tech and Central Washington University. The ACs use the GAMIT and GIPSY-OASIS GPS processing software to generate loosely-constrained station position estimates. The PBO GPS Analysis Center Coordinator at MIT will produce combined GPS station position and velocity estimates in SINEX or similar format, simplified position time series and velocity field estimates in ascii/XML formats, and related products. The PBO project has shown conclusively that this strategy of having multiple independent processing centers coordinated through another center is the best way to produce the high-quality geodetic products required to address the science goals of large infrastructure projects. All data, data products, and metadata will be archived by the UNAVCO Facility in Boulder, accessible via the UNAVCO website, and freely available to the research community without artificial delay.

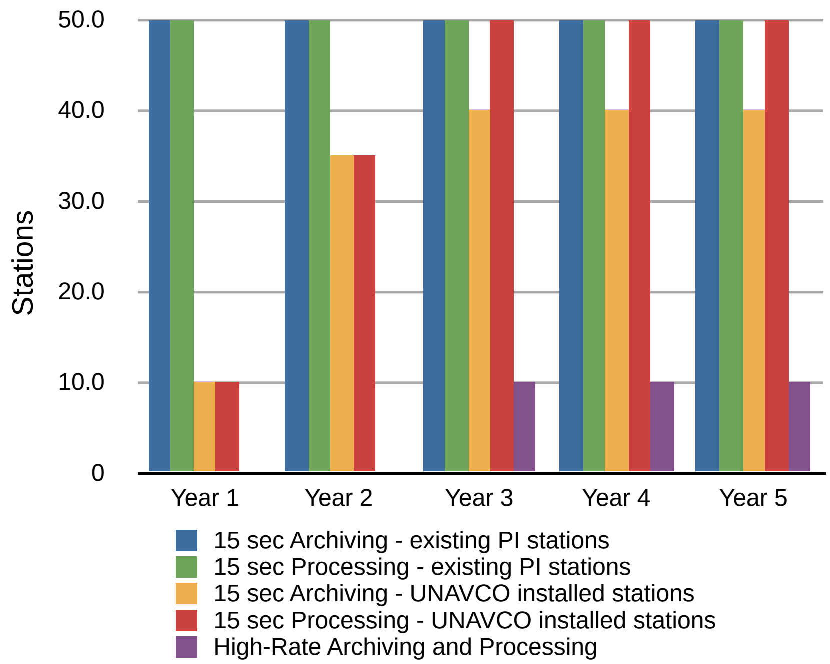

Figure 8. COCONet Data Archiving and Processing Schedule indicating archiving and processing of existing stations in years 1-5 and a ramping of processing and archiving activities for new UNAVCO installed stations throughout the project period. High rate data processing and archiving begins in year 3.

UCAR will supplement the PBO AC analysis with an additional near real-time atmospheric data product that will include PW estimates and zenith wet and hydrostatic delays with a time resolution of 30 minutes. These low-latency derived data products will be useful for assimilation into numerical weather models that are initiated from 2 to 24 times each day. These frequent initializations are needed to maximize the input data available to describe the most current atmospheric conditions. The UCAR analysis will be accomplished using the Bernese GNSS software and will incorporate several processing enhancements that have been shown to improve the quality of the derived products for atmospheric applications. First, the PW estimates

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will be based on a tightly-constrained set of coordinates computed from a combination of solutions obtained over the previous ten days of data. This method of tightly constraining coordinates has shown to produce the most accurate PW estimates by reducing the number of degrees of freedom in the solution space. Additional attributes of the UCAR analysis will be the utilization of direct tropospheric mapping functions derived from the Global Forecast System (GFS) model fields and the use of forecasted atmospheric temperature profiles to scale delay to water vapor, thereby minimizing diurnal error sources in PW retrievals that are created by climatologies based on twice-daily radiosonde profiles. UCAR will analyze the data in both near real-time and daily time frames. The near real-time analysis will be computed hourly to maximize the impact of the network for atmospheric research, while also balancing data availability from sites that do not have the capacity to provide continuous data streams.

UCAR will distribute these atmospheric data products to the broader atmospheric community using the Local Data Management (LDM) data distribution system that is considered the de-facto standard among university research groups. The derived PW estimates will also be available in a number of different data formats including netCDF, troposphere SINEX files, and standard ascii tables. The netCDF and ascii data products will be archived at the UNAVCO Facility and at UCAR.

4. COMMUNITY BUILDING AND ENFRANCHISEMENT

EarthScope was an infrastructure project that relied heavily on the science community to define scientific targets in critical areas of active research. EarthScope's facilities and associated grant program supporting integrated Earth science research and education are providing a framework for basic and applied geological research across the United States and North America. The Caribbean, however, is not North America. It has unique science targets and fundamental research objectives, siting and environmental constraints, a geography that spans many countries, and an active Caribbean, North American, and foreign research community. If COCONet is to fully succeed, existing investigators and the in-country research community should be included at all levels of project planning and execution. It will therefore be critical to: 1.) convene a community meeting of researchers in the first year of the project to fully engage PIs who are working in the Caribbean; 2.) encourage these PIs to make in-country introductions and assist with initial siting and permitting discussions; 3.) work with local researchers and organizations on the final siting, permitting, and construction of stations, and ongoing data flow; and 4.) engage and educate local researchers and universities who will be able to improve their expertise in GNSS operations and assist with network operations and maintenance.

Project Kick-off Community Meeting

In year one we propose a meeting of existing NSF-supported researchers, Caribbean researchers and key contacts, and selected foreign researchers. We will make a specific effort to engage foreign groups that are already collecting continuous GPS data in the Caribbean and Central America, including the Institut de Physique du Globe (French Lesser Antilles), the Seismic Research Center at the University of West Indies (Trinidad), INGEOMINAS (Colombia), and other institutions already active at collecting and analyzing GPS data in the Caribbean. The meeting will be organized by the University of Puerto Rico to refine the overarching science goals for the network and to define and prioritize additional science experiments (e.g. landslides, LiDAR, sea level experiments) that can capitalize on this investment in a pan-Caribbean infrastructure. The meeting will also serve to:

- Refine the station siting plan (Table 1, Figure 5) and gain consensus on the list of existing stations in the Caribbean whose monument quality and data accessibility make them candidates for inclusion in COCONet archiving and processing.
- Appoint a COCONet Science and Station Siting Advisory Committee that will assist the COCONet PIs throughout the life of the project.

- Identify critical stations operating in the Caribbean that could be upgraded to geodetic quality and encourage operators of closed networks (e.g. stations operated by Institut de Physique du Globe and the University of West Indies, or INGEOMINAS) to share their data in open-access archives (UNAVCO, CDDIS, NGS, and SOPAC).
- Refine and plan a Year 3 course to train local researchers and key contacts in the operations and maintenance of permanent GPS stations, methodologies for distributing standard and real-time data products in-country, and the processing of geodetic quality data. This technology transfer to the Caribbean investigator community is essential for creating and ensuring a climate of free and open access to COCONet geodetic data, ensuring that in-country investigators benefit from the success of the project, and reducing project costs by having local investigators involved in routine operations and maintenance tasks.

Working with Existing Investigators

One of the key reasons the EarthScope Plate Boundary Observatory (PBO) construction project succeeded on-time and on-budget was the early recognition that the existing investigator community held a tremendous amount of knowledge about local deployment and siting conditions and could provide contacts and insights into local politics. The science community was responsible for creating PBO's initial siting plan and community members were enlisted on committees to recommend alternative installation locations as needed. In areas like Alaska, community knowledge about the operational constraints of working in harsh, cold, and logistically difficult climates has been invaluable to keeping the PBO network at 95% operational overall.

For COCONet, heat, humidity, corrosion, and vandalism are all issues, and we plan to use the existing Caribbean research community to help plan and execute the project so a successful outcome is ensured. At the community meeting discussed above, we will identify U.S., in-country, and foreign investigators who can provide critical assistance in countries where stations are planned. For selected U.S. investigators, we propose to pair them with a UNAVCO engineer and pay their travel to assist in introductions, explain the infrastructure and science rational to key local investigators and agencies, discuss the reasons for and benefits of a free and open data policy, identify local scientists/engineers who can help UNAVCO personnel with construction and operations and maintenance, do preliminary station siting, and assist in permitting discussions if needed. For countries in which there are currently no active U.S. investigators, one of the PI's (Calais, Jackson, Braun) will take the lead in establishing contacts and doing the preliminary political groundwork.

Working with Local Investigators and Collaborators

UNAVCO has a 25-year history of working with local collaborators around the world to maximize station quality and data flow while minimizing operations and maintenance costs. Once the initial COCONet siting has been done, UNAVCO engineers will work with previously identified interested local researchers and organizations in the final siting, permitting, and construction of stations, while keeping the Advisory Panel informed as the project progresses. Our plan is to work alongside local investigators and educators in order to effectively transfer knowledge about GPS and MET station installation, data communications, and operations and maintenance. The working collaboration will also help identify key operational personnel who would participate in the Year 3 operations, maintenance and data flow training.

Project Operations Meeting

A key issue confronting investigators working in the Caribbean is how to identify local long-term contacts who are interested in the science and hazards of the Caribbean and how to keep them interested in a project like COCONet as it moves through planning, design, and implementation. Of even greater importance is how to keep local partners engaged during long-term operations and maintenance while identifying parts of the project that can give back to the local research and hazards community. To this end, we propose to convene an operations and maintenance, data flow/archiving, and data processing meeting at the University of Puerto Rico in the third year of the project. The meeting would be limited to a few instructors from the UNAVCO community and between 15-20 Caribbean collaborators who show the potential for extending research and science opportunities within their respective countries. The meeting would focus primarily on longer-term operations and maintenance training for GPS stations installed in the Caribbean but would include discussions of general GPS theory for crustal deformation, GPS data processing, higher-level data products generation, and real-time GPS data distribution for local societal benefit.

5. COCONet – PROJECT MANAGEMENT

This collaborative infrastructure project has four participants: UNAVCO, Purdue University, the University of Puerto Rico Mayaguez, and UCAR/COSMIC. UNAVCO will have primary responsibility of station siting, installation, maintenance, data flow and data processing management. Purdue will serve as the geodetic lead in the project. UCAR will be the atmospheric lead. The University of Puerto Rico Mayaguez will be the regional coordinator and organize the project kick-off meeting in Year One and a project operations meeting in Year Three.

Dr. Meghan Miller, president of UNAVCO will oversee all of UNAVCO participation in COCONet, including project oversight and community relations. Dr. Mike Jackson will manage the infrastructure installation and data flow effort for UNAVCO with salary support coming from existing community-based NSF awards. Funds are allocated within this proposal to cover UNAVCO project management and domestic/foreign travel, field engineer time, data flow and archiving, and and data products generation through subawards. All COCONet activities will be managed using Earned Value Management (EVM) and project-tracking methodologies similar to those used to bring the NSF funded EarthScope to completion on schedule and budget. Dr. Jackson will participate in all aspects of the project including planning meetings, site visits and training. A major focus of his effort, along with the other PI’s, will be leveraging the efforts of COCONet to get investigators in the Caribbean to share data openly. Dr. Jackson will be a member of the COCONet Science and Siting infrastructure committee.

Dr. Eric Calais will manage the scientific integrity of the project and ensure that the project meets the stated science goals. Dr. Calais will provide scientific and strategic guidance for station siting and installations, liaise with the international community involved in research using geodetic infrastructure in the Caribbean, and ensure the scientific integrity of the project. As part of this proposal Dr. Calais will oversee the activities of a graduate student who will work on the science challenges presented in this proposal. Dr. Calais will be a member of the COCONet Science and Siting infrastructure committee.

UCAR, through Dr. John Braun, will lead the atmospheric portion of the project. UCAR’s responsibility will be to ensure the suitability of the COCONet infrastructure for atmospheric research and to carry out the analysis of COCONet raw data to produce integrated water vapor derived data for atmospheric research. The UCAR budget contains support for Co-Investigator Dr. John Braun, a GPS data analyst, and administrative and system administration support for COSMIC. Dr. Braun will participate in all aspects of the project including planning meetings, site visits and training. Dr. Braun will be a member of the COCONet Science and Siting infrastructure committee.

Dr. Guoquan (Bob) Wang at the The University of Puerto Rico Mayaguez will be the regional coordinator and organize the project kick-off meeting in Year One and a project operations meeting in Year Three. UNAVCO will sponsor the meeting in Puerto Rico. Dr. Wang and his students will participate in field activities as necessary. Dr. Wang will be a member of the COCONet Science and Siting infrastructure committee.

6. COCONet – BROADER IMPACTS

The COCONet infrastructure will provide unparalleled access to low-latency, open data and data products from high quality GPS stations for researchers, educators, students, and the private sector. We will do this by establishing new geodetic infrastructure and coordinating the sharing of data from existing stations. Data from the real-time streaming stations will be made available to the International GNSS Service (IGS). These stations will densify a region of the globe that have few existing real-time data streams. Data from these stations can then be used to compute real-time satellite orbits and clock corrections, improving the quality of IGS data products for the entire geodetic science community. The data will be used by local and foreign researchers to study plate kinematics and dynamics, stress release and intraplate coupling, and the science and hazards associated with earthquakes. The data will be used to provide more precise estimates of tropospheric water vapor enabling agencies to better forecast the dynamics of airborne moisture associated with the yearly Caribbean hurricane cycle. COCONet station data can also be used to quickly estimate earthquake magnitude which, along with buoy and seismic data, could lead to better prediction of the occurrence of large tsunamis.

This project will contribute to the education of numerous graduate and undergraduate students in solid-earth, atmospheric, and geodesy fields by providing high-quality GPS data to the Caribbean research community. Support is included for a graduate student at Purdue. In addition, we budget support for a RESESS (Research Experience in Solid Earth Science for Students) intern through UNAVCO. One goal of RESESS (http://resess.unavco.org/resess.html) is to increase the number of individuals from underrepresented populations who complete Masters and PhD degrees in solid Earth geoscience. The RESESS intern would be involved in COCONet field and station installation work, including making use of COCONet data for a senior thesis. Our goal would be to engage and encourage an undergraduate student to pursue a graduate degree in geology and geophysics. One of the PI's (Jackson) was a RESESS mentor in the past and Calais sponsored a RESESS intern for work in the Afar of Ethiopia.

Similar to the RESESS program, the SOARS (Significant Opportunities in Atmospheric Research and Science - www.soars.ucar.edu) program has a mission to broaden the participation in atmospheric and related sciences. The UCAR/COSMIC program will provide future SOARS students the opportunity to work on COCONet related research topics. Specific topics may include comparisons of COCONet data products to satellite observations, comparisons to reanalysis fields, and case studies of specific hurricanes. SOARS students will also have the opportunity to participate in international science conferences supported within the COSMIC student opportunities project, formerly known as the AWARE Program (http://www.cosmic.ucar.edu/students.html).

The UNAVCO and UCAR Education and Outreach programs will use data and results from COCONet to create presentation materials for educators, teachable moment presentations, and short courses. UNAVCO Education and Outreach staff will be included both the initial planning meeting and the project operations meeting in Year Three. At the core of COCONet is the hope of coordinating and educating existing researchers, Caribbean governments, agencies, and GPS station owners in the goal of creating a pan-Caribbean reference network that can be used for both scientific and private purposes. The open data sharing approach, we hope, will lead to other organizations freely sharing data through community archives. Their data, combined with those of COCONet, can be used not only for scientific purposes, but also to help Caribbean governments, agencies, and the private sector to create a comprehensive register of land-use, and ownership and location for property within a country. In these ways, COCONet will build scientific, technical and educational capacity in the region and serve as a successful model for regional cooperation and community building.

Table 1. GPS station location proposed for COCONet listed by country and tectonic plate and science target.

PNUM	Country	Locale	Plate	Target
CN00	Barbuda	Codrington	Carribean	Covergence on subduction zone at western edge of Caribbean plate
CN01	St. Barthelemy	St. Barthelemy	Caribbean	Covergence on subduction zone at western edge of Caribbean plate
CN02	Anguilla	Sombrero Island	Caribbean	Relative motion between Hispaniola-PR and Caribbean plates
CN03	British Virgin Isl.	Anegada	Hispaniola-PR	Relative motion between Hispaniola-PR and Caribbean plates, on Muertos Trench
CN04	Puerto Rico	Vieques Island	Caribbean	Relative motion between Hispaniola-PR and Caribbean plates, on Muertos Trench
CN05	Domincan Rep.	Punta Cana	Hispaniola-PR	Define center of eastern Hispaniola-PR microplate
CN06	Domincan Rep.	Constanza	Hispaniola-PR	On convergence zone between Enriquillo-Plantain Garden and Septentrional faults
CN07	Domincan Rep.	Puerto Plata	Hispaniola-PR	Motion across Septentrional fault relative to existing stations to south
CN08	Turks and Caicos	Providenciales	N. America	Define Bahama Platform north of Hispaniola-PR microplate
CN09	Haiti	Cap Haitien	Gonave	Relative motion between Hispaniola-PR and N. America plates, on Septentrional FZ
CN10	U.S. Territory	Navassa Island	Gonave	Motion on Enriquillo fault offshore western Haiti
CN11	Jamaica	Montego Bay	Gonave	Relative motion between Gonave and Caribbean plates, on Walton FZ
CN12	Jamaica	Kingston	Carribean	Relative motion between Gonave and Caribbean plates, on Enriquillo-P.G. FZ
CN13	Cuba	Guantanamo Bay	Gonave	Relative motion between Gonave and N. America plates, on Oriente FZ
CN14	Bahamas	Great Inagua Isl.	N. America	Define Bahama Platform north of Gonave microplate
CN15	Bahamas	Andros Town	N. America	Define stable N. America plate
CN16	Cayman Islands	Cayman Brac	N. America	Relative motion between Gonave and N. America plates, on Oriente FZ
CN17	Cayman Islands	Grand Cayman	N. America	Relative motion between Gonave and N. America plates, on Oriente FZ
CN18	Honduras	Swan Islands	Caribbean	Motion on Swan Islands FZ far offshore
CN19	Honduras	Isla de Guanaja	Caribbean	Motion on Swan Islands FZ offshore
CN20	Honduras	La Lima	Caribbean	Relative motion across Motagua FZ
CN21	Honduras	Tegucigalpa	Caribbean	Motion of easternmost Caribbean plate north of Guayape FZ
CN22	Honduras	La Ceiba	Caribbean	Define Caribbean plate south of Swan Islands FZ
CN23	Belize	Belize City	N. America	Define Caribbean plate north of Swan Islands FZ
CN24	Belize	Punta Gorda	N. America	Relative motion across Polochic FZ
CN25	Mexico	Villahemosa	N. America	Define stable N. America plate
CN26	Guatemala	Puerto Barrios	N. America	Relative motion across Motagua FZ to south and Polochic FZ to north
CN27	Guatemala	Coban	N. America	Relative motion across Polochic FZ
CN28	Guatemala	Chimusinique	N. America	Relative motion across Polochic FZ
CN29	Nicaragua	Puerto Cabezas	Caribbean	Define center of easternmost Caribbean plate
CN30	Nicaragua	Corn Island	Caribbean	Define center of easternmost Caribbean plate
CN31	Costa Rica	Moin	Caribbean	Relative motion of Panama and Caribbean plates, just north of Siquirres-Matina FZ
CN32	Costa Rica	Puerto Quepos	Panama	Relative motion of Panama and Caribbean plates, south of Siquirres-Matina FZ
CN33	Panama	Sant. de Veraguas	Panama	Define center of Panama microplate
CN34	Columbia	Isla de Providencia	Caribbean	Define center of easternmost Caribbean plate
CN35	Columbia	Monteria	N. Andes	Relative convergence between N. Andes and Panama blocks
CN36	Columbia	Medellin	N. Andes	Define center of N. Andes block
CN37	Columbia	Cartagena	N. Andes	Convergence between N. Andes and Caribbean plates
CN38	Columbia	Bucaramanga	N. Andes	Relative motion across Guaycaramo FZ, relative to existing stations to south
CN39	Columbia	Valledupar	N. Andes	Motion of Maracaibo block, convergence between N. Andes and Caribbean plates
CN40	Aruba	Oranjestad	N. Andes	Convergence between N. Andes and Caribbean plates
CN41	Netherland Antilles	Bonaire	Caribbean	Relative motion between N. Andes and Caribbean plates
CN42	Trinidad & Tobago	Trinidad	Caribbean	Relative motion between S. America and Caribbean plates, on Central Range FZ
CN43	Trinidad & Tobago	Trinidad	S. America	Relative motion between S. America and Caribbean plates, on Central Range FZ
CN44	Trinidad & Tobago	Tobago	Caribbean	Relative motion between S. America and Caribbean plates, N of Central Range FZ
CN45	St. Vincent	St. Vincent	Caribbean	Covergence and coupling on subduction zone at western edge of Caribbean plate
CN46	Barbados	Barbados	Caribbean	Covergence and coupling on subduction zone at western edge of Caribbean plate
CN47	French W. Indies	Martinique	Caribbean	Covergence and coupling on subduction zone at western edge of Caribbean plate
CN48	Dominica	Dominica	Caribbean	Covergence and coupling on subduction zone at western edge of Caribbean plate
CN49	Guadeloupe	Pointe-a-Pitre	Caribbean	Covergence and coupling on subduction zone at western edge of Caribbean plate
CN50	Venezuela	Merida	S. America	Relative slip across Bocono FZ
CN51	Venezuela	Maracaibo	S. America	Motion of Maracaibo block
CN52	Venezuela	Isla la Blanquilla	Caribbean	Extension between N. Andes and Caribbean plates
CN53	Venezuela	Barcelona	S. America	Relative motion between S. America and Caribbean plates, on El Pilar FZ
CN54	Venezuela	Isla de Margarita	Caribbean	Relative motion between S. America and Caribbean plates, on El Pilar FZ

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