COCONet White Paper for CGPS sites in Panama

R.A. Bennett, T.K. Rockwell, D. K. Adams, E. R. Kursinski, A. Douglas

Internal deformation and seismic hazards of Panama: A boundary zone between the Caribbean, South America, Cocos, and Nazca plates

New CGPS stations in Panama are required to test whether Panama is internally stable or rapidly deforming, with important implications for seismic hazard in Central America, and especially for the Panama Canal through which > 300 million tons of international commerce is transported annually. Additional continuous GPS (CGPS) stations are required to complement a new narrow aperture CGPS array established by the Panama Canal Authority (ACP) in 2009 in central Panama (Figure 1). The ACP network establishes a needed core of stations across two major active fault zones, but due to its narrow aperture does not by itself address critical questions regarding fault slip rates, which are crucial for seismic hazards assessment and understanding of Central America and Caribbean tectonics.

In the past, some workers have assumed that Panama accommodates internal deformation, and have identified several potentially active faults as part of this deformation (Mann and Corrigan, 1995). The general "S" shape of the isthmus has also led some to conclude that Panama is being oroclinally bent northward, producing folding and thrusting into the Caribbean (Silver et al., 1990; Mann and Kolarsky, 1995). In contrast, the CASA geodetic campaign (Trenkamp et al., 2002) revealed high rates of subduction along the Middle America and Colombian trenches, and the general convergence of Central and South America, but due to the large uncertainties of the campaign data set, the small relative motions among sites in central Panama were not well resolved (Figure 2). Preliminary work on one of the potentially active faults, the Rio Gatun fault, led Schweig et al. (1999) to conclude that the fault was inactive, thereby supporting the CASA implications for internal stability, and therefore a low level of seismic hazard (Cowan et al., 1998; Peterson et al., 2003). More recently, work by ECI (2005; 2006; 2007), as part of a seismic hazard assessment for the Panama Canal Expansion project, found that Schweig et al. (1999) had missed the fault and that there has not only been repeated late Holocene activity on the Rio Gatun fault, but that the slip rate for both the Rio Gatun and the Limon faults is in the 3-8 mm/yr range. They also found unequivocal evidence of historical rupture (past 500 years) on both of these two faults, which probably correspond to the historical earthquakes of 1873 and 1621, respectively. These new results led to a reassessment of the regional tectonic structure of Panama and development of a new model for what drives the activity of faults in central Panama (Rockwell et al., 2010ab). The new model predicts that much of the central Panama deformation is being driven by continued convergence in western Panama, but east of the Panama Fracture Zone. This convergence requires slip on faults in the Azuero Peninsula, which in turn feed the activity of faults in central Panama in the vicinity of the Panama Canal. This model needs to be tested, as understanding the activity of faults in central Panama is important in quantifying their role in the continuing collision of Central and South America, as well as assessing the potential seismic hazard to the Panama Canal, the primary artery for transmission of goods from Asia to the eastern US and Europe.

Understanding of the tectonic framework of Panama is key to interpretation of geodetic data from all of Central America, the Caribbean, and northern South America, as well as for the correct assessment of seismic hazard throughout the region. The collision of Central and South America led to the closure of the Miocene seaway, thereby ending circulation between the Atlantic and Pacific oceans. Directly or indirectly, this event is thought to be a major contributing factor in the cooling of the northern hemisphere resulting in the onset of cyclic glaciation. Quantifying the continued deformation will improve our understanding of local and regional seismic hazard, and provide critical new insights into the ongoing collision between Central and South America.

The broader impacts afforded by an expanded network of CGPS stations in Panama—as shown for example in Figure 1—are profound. The Panama Canal serves as the conduit through which trillions of dollars of trade is transported between Asia and eastern North America and Europe, and closure of the Canal due to an earthquake would have far-reaching effects on the global economy. Installation of new CGPS stations would benefit from the experience gained in the construction of the ACP network, which employed deep drilled braced monuments for maximum stability. The Panama Canal Authority (ACP – Autoridad de Canal de Panama) could help to coordinate future installations, and would also likely serve as a data download center.

GPS Meteorology in Panama: A Climatologically Unique Location.

In the Tropics, water vapor plays the critical role in the atmospheric energy budget both through its radiative effects and its influence on the occurrence and intensity of deep precipitating convection. Unlike tropical temperature fields, water vapor can be quite variable in time and space and is highly dependent on the occurrence of deep convection. Unfortunately, meteorological observations have traditionally been sparse in the Tropics making it difficult to assess the complex feedbacks between convection and water vapor. Within the last decade, the number of GPS PWV sites has increased dramatically as they have proven quite useful in providing all-weather, frequent and precise measurements of total column water vapor. However, they are still quite sparse in the deep tropics. The augmentation of GPS Meteorology in the Caribbean region through COCONET promises a significant improvement in the spatial and temporal density of column water vapor measures.

Panama, in particular, is geographically unique and merits special attention in terms of the development of GPS meteorology. The Panama Bight and coastal plains of northwestern Colombia represent one of the rainiest locations on Earth (Horel and Cornejo-Garrido 1986; Poveda and Mesa 2000). The unique continental geometry of this narrow isthmus and its location between two very warm bodies of water, the Eastern Pacific Warm Pool (Xie et al. 2005; Raymond et. al. 2003; Raymond and Zeng 2005) and the tropical western Caribbean Sea, make it an ideal locale to study water vapor, both in terms of its meteorological/climatic variability and its complex relationship with deep precipitating convection (see Figure 3 for basic seasonal wind patterns and sea-surface temperatures). Given its latitude, Panama experiences two prominent features of the global general circulation, the Intertropical Convergence Zone (ITCZ) and the Trade-Wind regime that determine the wet and dry seasons, respectively, and intraannual precipitation variability. These large-scale circulation features are susceptible to variable climate forcing (e.g. changes in sea-surface temperature and, hence, water vapor fluxes) associated with various modes of oscillation in the climate system (e.g., El Niño/La Niña). Modifications in sea-surface temperatures in the Eastern Pacific associated with this interannual climate variability act together to modify larger-scale circulation patterns which, in turn, influence Trade Wind intensity, the Caribbean Low-Level Jet, and, hence, moisture convergence and precipitation over Central America and northwestern South America (Magaña et al. 1999; Raymond et al. 2003; Muñoz et al. 2008).

On a regional/local scale, the continental geometry and topography results in wind circulation patterns that lead to variability in the frequency and intensity of convective precipitation. For example, Mapes et al. (2003a,b) has shown that a wide variety of topography features (e.g. low-level gap along the Panama Canal) strongly modulate climatological values of precipitation (Mapes 2003a). These local topographic features influence mesoscale atmospheric dynamics and can help organize long-lived (~12 hours) mesoscale convective systems (~100km or greater) that account for substantial amounts of the total annual rainfall and may be the most important meteorological feature in the region. These mesoscale convective systems are dependent on and have important feedbacks with the distribution of water vapor over many spatial scales. At both the beginning and end of the tropical cyclone (TC) season, they can intensify to become TCs either in the Caribbean (if they move north) or in the Eastern Pacific if they move to the northwest.

Over longer term multi-year to decadal time scales, the region is affected by both the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO). Since 1998, the ITCZ appears to have shifted farther north in response to the South Pacific High being stronger than normal in the new cold phase PDO. If a strong South Pacific High and weaker North Atlantic High are the new norm (be it due to global warming or just the phase of PDO-AMO that the climate system is presently in), this implies an ITCZ shifted systematically farther north and stronger mid-summer drought potential along the west coast and weaker Atlantic trades and less orographic/speed convergence precipitation on the east coast. Precise and accurate observations that capture the critical temporal and spatial scales are needed to monitor and understand such modes of longer timescale variability and trends and predict their future behavior.

Such monitoring will enable us determine in the future whether the South Pacific High (Easter Island rise in sea level pressure (SLP) since 1997) is just the result of a natural variation of the PDO-AMO or if it is tied to a broader, systematic warming of climate. The Easter Island (South Pacific High) rise has been very strong and unlike that seen in the former cold PDO phase of the 1950s and 1960s. The Antarctic Oscillation is apparently also at a record and the unusual SLP may result from a colder Antarctic vortex and stronger westerlies which then lead to a stronger subtropical high formation which produces higher SLP at Easter Island. It could be that the change in PDO phase and the effect of the ozone hole are acting in concert to strengthen the post-1997 rise in pressure. The last 3 months have experienced a large SLP gradient between Easter and Costa Rica. Even in last winter's ENSO event, the gradient was well above normal suggesting that the El Niño was not active in the far Eastern Pacific, but rather only in the far Western Pacific where propagation of the Madden Julian Oscillation (MJO) halted near the dateline not advancing further to the east.

The cross equatorial flow index was devised to follow ITCZ movement and TC formation during burst band development when the high suddenly intensifies and pushes air across the Equator into Central America. It would be valuable to see how sensitive PW in Panama is to changes in this simple SLP gradient calculation and the resulting modifications in water vapor fluxes.

Given these large-scale climate features and local-scale circulations affecting the Panama region, the resulting precipitation patterns lead to complex variability in the water vapor signals in both time and space. Currently, observation systems in place are not adequate (e.g., twice daily radiosondes in Corozal, Panama) to capture either the spatial or the temporal variability in water vapor at the time and space scales discussed above. Several GPS meteorological sites would improve greatly the ability to: 1) assess large-scale seasonal water vapor variability associated with the two dominate regimes, the Trade Wind regime and the Intertropical Convergence Zone (i.e., a climate variability scale) and 2) observe locally wind/water vapor convergence patterns associated with sea-breeze circulations over the isthmus (i.e., a water vapor/convection physics interaction scale). Recent work (Kursinski et al., 2008; Adams et al., 2011) has shown the value of GPS PWV in identifying propagating convective events and water vapor convergence locally (order of 10km). Installation of several collocated durable meteorological packages (~$2,000 per station) along the isthmus would present an ideal situation for gauging the strength of water vapor convergence along the sea-breeze penetrating the isthmus while concomittantly providing the necessary distribution to gauge to the larger scale signals associated with regional and climate scale variability.

REFERENCES

Adams, D. K., R. Fernandes, E. R. Kursinski, J. Maia, L. Sapucci, L. Machado, I. Vitorello, K. Holub, S.Gutman, Naziano Filizola, R.A. Bennett, 2011: A dense GNSS meteorological network for observing deep convection in the Amazon. *Atmos. Sci. Lett.*, (in press).

Cowan, H., Machette, M.N., Haller, K., and Dart, R., 1998, Map of Quaternary faults and folds of Panama and its offshore regions. ILP Task Group ll-2, scale 1:250,000.

Earth Consultants International, Inc. (ECI), 2005, Paleoseismic Investigation of the Gatún and Limón Faults in Central Panamá; ECI Project No. 2505; unpublished consulting report to the Autoridad del Canal de Panamá, Project No. 2505, September 30, 2005, 61p. + figures and appendices.

Earth Consultants International (ECI), 2006, Geomorphic Evaluation of the Miraflores, Pedro Miguel, Azota, and Caballo Faults, Central Panama; unpublished consulting report for the Autoridad del Canal de Panamá, Project No. 2614.01, November 2006, 36p. + figures and appendices.

Earth Consultants International (ECI), 2007, Paleoseismic Trenching of the Pedro Miguel Fault in Cocolí, Located Immediately Southwest of the Panama Canal, Panama; unpublished consulting report for the Autoridad del Canal de Panamá, Project No. 2614.02, February 2007, 31p. + figures and appendices.

Earth Consultants International (ECI), 2008, Quantitative characterization of the Pedro Miguel fault, determination of recency of activity on the Miraflores fault, and detailed mapping of the active faults through the proposed Borinquén Dam location; unpublished consulting report for the Autoridad del Canal de Panamá, Project No. 2708.05, January 31, 2008, 91p. + figures and appendices.

Horel, J. D., and A. G. Cornejo-Garrido, 1986: Convection along the coast of northern Peru during 1983: Spatial and temporal variation of clouds and rainfall. *Mon. Wea. Rev*., **114**, 2091–2105.

Kursinski E. R., R. A. Bennett RA, D. Gochis, S. I. Gutman, K. L. Holub, R. C. Masteler. M. Sosa, I. M. Sosa, T. van Hove, 2008: Water vapor and surface observations in northwestern Mexico during the 2004 NAME enhanced observing period. *Geophysical Research Letters* **35**: L03815, doi:10.1029/2007GL031404.

Magaña, Victor, Jorge A. Amador, Socorro Medina, 1999: The Midsummer Drought over Mexico and Central America. *J. Climate*, **12**, 1577–1588.

Mann, P. and Corrigan, J., 1990, Model for late Neogene deformation in Panama. *Geology*, **18**, 558-562.

Mann, P. and Kolarsky, R.A., 1995, East Panama deformed belt: structure, age, and neotectonic development. In Mann, P. (ed.) Geologic and Tectonic Development of the Caribbean Plate Boundary in South Central America, Geological Society of America Special Paper, 295, 111-130.

Mapes, B. E., T. T. Warner, M. Xu, and A. J. Negri, 2003: Diurnal patterns of rainfall in northwestern South American. Part I: Observations and context. *Mon. Wea. Rev.*, **131**, 799–812.

Mapes, B. E., T. T. Warner, and M. Xu, 2003b: Diurnal patterns of rainfall in northwestern South America. Part III: Diurnal gravity waves and nocturnal convection offshore. *Mon. Wea. Rev*., **131**, 830–844.

Peterson, M., Schweig, E., Mueller, C., Harmsen, S. and Frankel, A., 2005, Preliminary update of the probabilistic seismic hazard analysis for sites along the Panama Canal Zone: 25 p.

Poveda, G., and O. J. Mesa, 2000: On the existence of Llorø (the rainiest locality on Earth): Enhanced ocean–land–atmosphere interaction by a low-level jet. *Geophys. Res. Lett.*, **27**, 1675–1678.

Raymond D., and Coauthors, 2004: EPIC2001 and the coupled ocean–atmosphere system of the tropical east Pacific. *Bull. Amer. Meteor. Soc.*, **85**, 1341–1354.

Raymond. D. and X. Zeng, 2005: Modelling tropical atmospheric convection in the context of the weak temperature gradient approximation. *Quart. J. Roy. Meteor. Soc.*, **131**, 1301–1320.

Rockwell, T.K., R.A. Bennett, E. Gath, P. Franceschi, Unhinging an indenter: A new tectonic model for the internal deformation of Panamá, *Tectonics*, **29**, doi:10.1029/2009TC002571, 2010a.

Rockwell, T.K., E. Gath, T. González, C. Madden, D. Verdugo, L.A. Owen, M. Fuchs, A. Cadena, P. Williams, E. Weldon, P. Franceschi, Neotectonics and Paleoseismology of the Limón and Pedro Miguel Faults in Panamá: Earthquake Hazard to the Panamá Canal, BSSA, 100, 3097-3129; DOI: 10.1785/0120090342, 2010.

Schweig E., Cowan, H., Gomberg, J., Pratt, T., and TenBrink, A., 1999, Design earthquakes for the evaluation of seismic hazard at Gatun Dam and vicinity. Report to the Panama Canal Commission for Interagency Agreement number CNP-93786-NN-29 between the Panama Canal and the U.S. Geological Survey, dated August 9, 1999, 60p.

Silver, E.A., Reed, D.L., Tagudin, J.E., and Heil, D.J., 1990, Implications of the north and south Panama thrust belts for the origin of the Panama Orocline. *Tectonics*, **9** (2), 261-281.

Trenkamp, R., Kellogg, J.N., Freymueller, J.T., and Mora, H.P., 2002, Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. *J. South American Earth Sciences*, **15**, 157-171.

Xie, Shang-Ping, Haiming Xu, William S. Kessler, Masami Nonaka, 2005: Air–Sea Interaction over the Eastern Pacific Warm Pool: Gap Winds, Thermocline Dome, and Atmospheric Convection. *J. Climate*, **18**, 5–20. doi: 10.1175/JCLI-3249.1

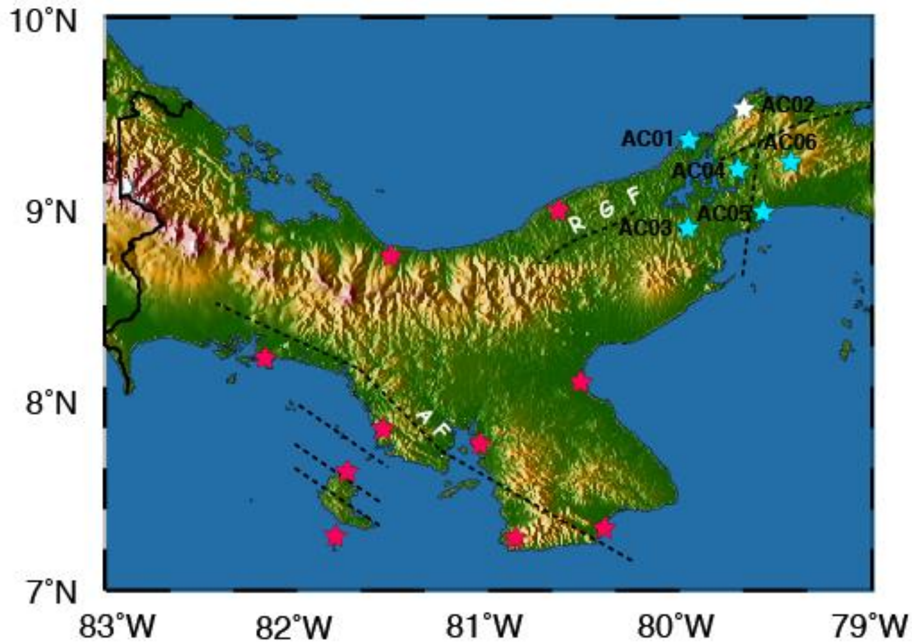

Figure 1. Map of existing (blue stars) and needed CGPS stations in Panama (red stars). Existing stations form the new ACP network located near the Panama Canal. The white station is a planned addition to the ACP network for 2011. The new stations are required to constrain slip rates along the western Gatun fault and related faults in western Panama, as well as the Azuero fault zone in southwestern Panama.

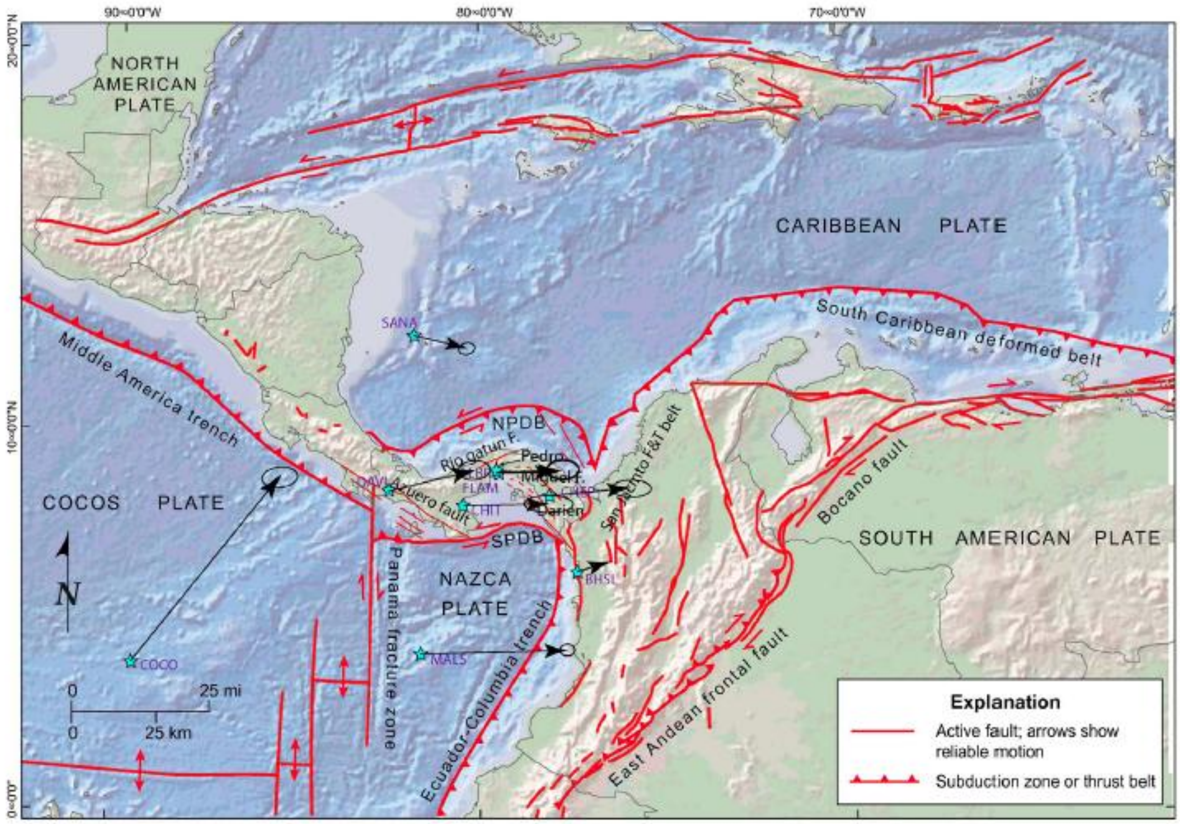

Figure 2. The modern tectonic setting of Central America. The campaign GPS network from Trenkamp et al. (2002) is indicated by the blue stars. The small but important internal deformation of Panama now recognized in paleoseismological and modern CGPS data sets was not recognized using this earlier data set due large velocity estimate uncertainties. Due to the small amplitude of the signal, extreme vegetation, and highly variable water vapor, neither InSAR nor campaign GPS is unlikely to reveal the details of the crustal deformation field in central Panama in sufficient detail for hazards assessments and tectonic studies. Despite the small slip rate on the fault < 10 mm/yr, the hazards potential is very high given the proximity of active faults to the Panama Canal.

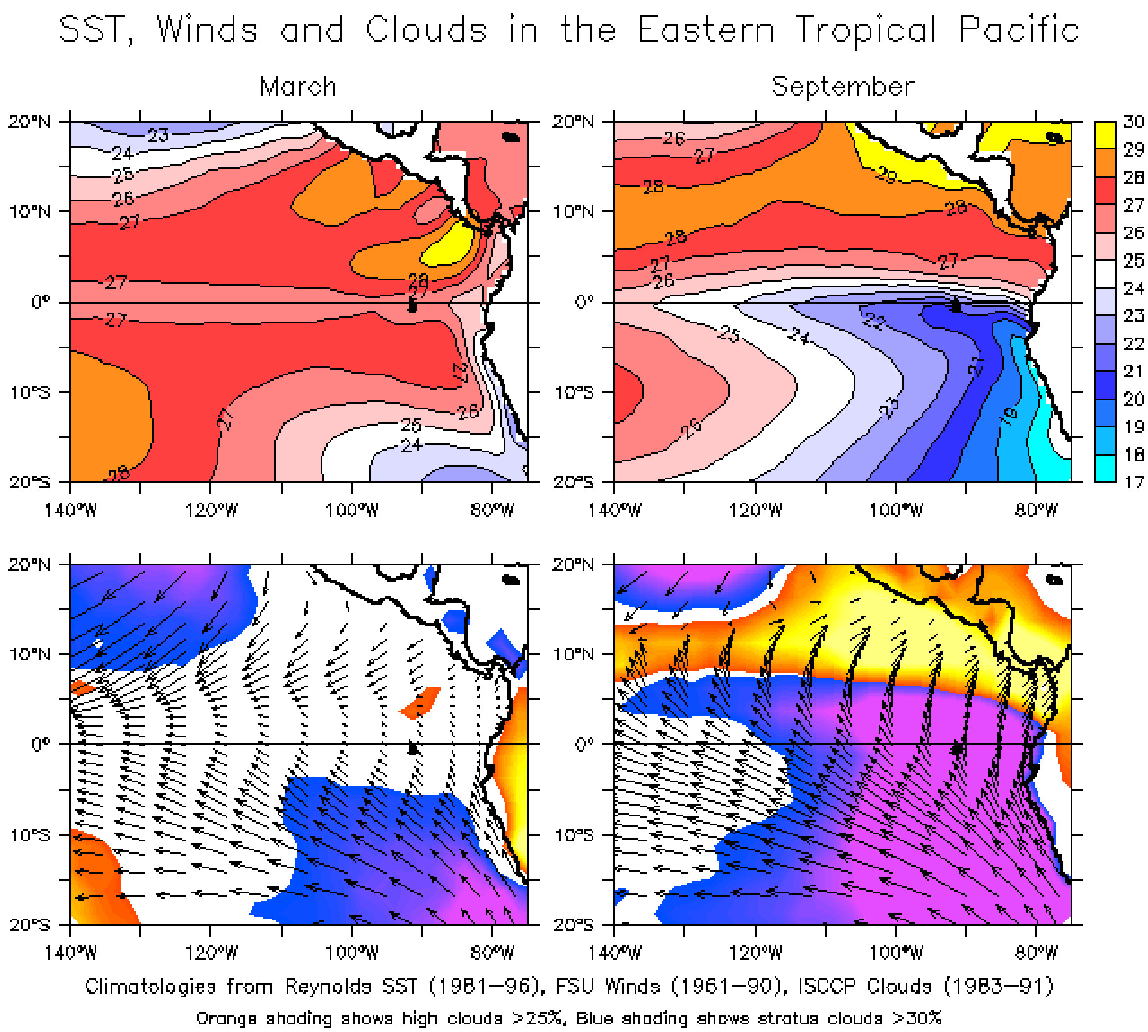

Figure 3. Seasonality in cloud cover, winds and sea-surface temperature in the Eastern Pacific Oceans. Sea-surface temperatures in the Panama Bight are among the highest in the world leading to large water vapor flux and column water vapor values resulting in copious rainfall. The unique geometry and topography of the isthmus, its location near strong sea-surface gradients in temperature make Panama ideal for examining interannual and seasonal variability in the occurrence and intensity of convective rainfall (Source: A Science and Implementation Plan for EPIC: An Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System).