Fourth Annual Report
1 July 2009 - 30 June 2010

1. Project Information

Project Title: "Tropical cyclones: current characteristics and potential changes under a warmer climate"
Project Number: CRN II -048
Principal Investigator: Graciela Binimelis de Raga
Key Words: tropical cyclones, East Pacific basin, climatology, intensification

2. Project Funding

No complementary funds were received for this project

3. Research Activities and Findings

The original work plan for the period 1 July 2009 -30 June 2010 was divided into four following categories. We report below the advances in categories *I* and *II.* The progress in category *III* is reported under **Section 7** of this report and the publications generated in this period are reported under **Section 5**.

Progress on *Data analysis*:

I.1 Climatological study from satellite data over oceans (O. Sanchez CICATA-Mexico, GB Raga and J. Zavala-Hidalgo, CCA-Mexico)

This activity was **concluded** in 2009.
The **key findings** of the study can be summarized as:

- Several cases were identified in which the sea surface height anomalies were correlated with cyclone trajectory and intensification, as was observed in other cyclonic basins
- However, the climatological results do not find a systematic increase in cyclone category with sea surface height anomaly.
- The role of the ocean eddies in the East Pacific appears to be smaller than hypothesized

The manuscript submitted was not accepted in the journal Dynamics of the Atmosphere and Oceans. The reviewers demanded quite a few changes and therefore, it was decided to hire an assistant (that recently graduated with a Master's degree under O. Sanchez) to carry out the suggested changes for a period of 3 months (August- October 2010) and then proceed to re-submit the manuscript before the end of the project.

I.2 Climatological study using NCEP-R2 and NARR data (R. Romero-Centeno and F. Oropeza, CCA-México)

The research was conducted on a case-study basis to determine the impacts of the different atmospheric conditions on the evolution of cyclones, in particular with the rapid and explosive deepening conditions. These conditions are defined by the

National Hurricane Center as a decrease in the central pressure of 1.75 and 5 hPa per hour for at least 6 hours. As seen in Figure 1, the explosive deepening condition is experienced by very few cyclones in the East Pacific basin, only twice in the last 15 years. Figure 2 shows an example of Hurricane Carlota (2000) that reached Category 4 and barely met the ED criterion. Rapid deepening is much more common that ED, but overall only about 30% of cyclones experience it. Later on we discuss the importance of the interaction with oceanic vortices in the determination of rapid/explosive deepening.

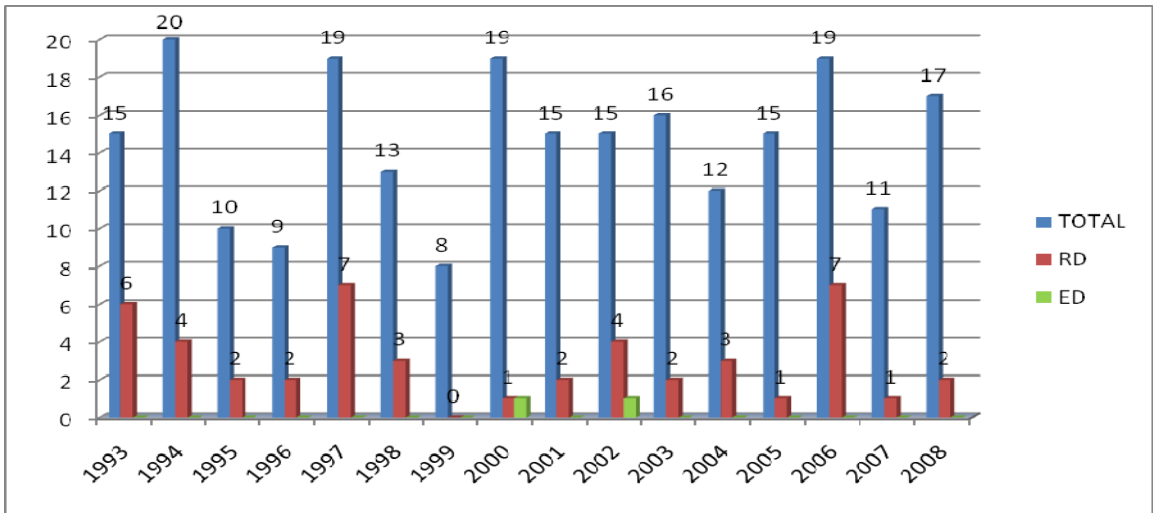


Figure 1: The total number of cyclones per season and the number of cyclones that experienced Rapid Deepening (RD) and Explosive Deepening (ED)

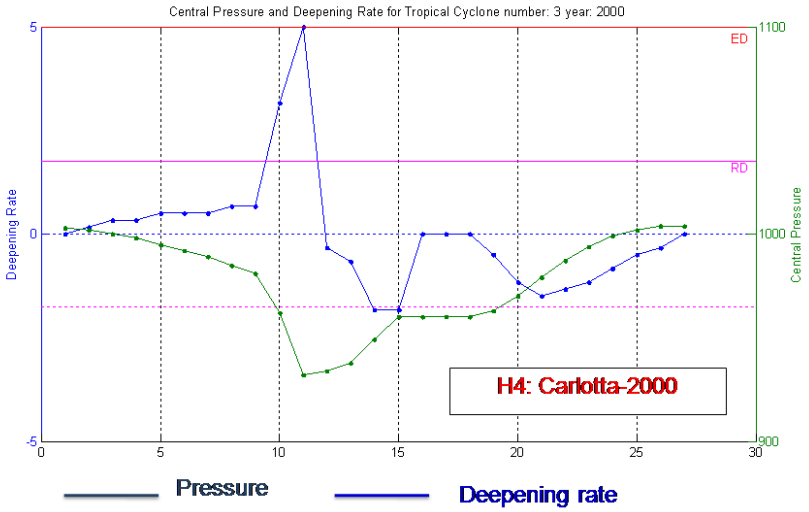


Figure 2: Time evolution of the central pressure and deepening rate of hurricane Carlota (2000)

I.2 Data analysis of selected cases that recently made landfall in Mexico (L. Farfán CICESE-Mexico; R. Romero-Centeno and GB Raga CCA-Mexico)

An observational study was carried out to determine some of the characteristics of tropical cyclones that developed in the Mexican Pacific during 2006 and 2007 and made landfall in northwestern Mexico: John, Lane, and Paul in 2006. A manuscript was submitted but the review process has been delayed, due to repeated requests for changes. The paper is still under revision.

Another study was carried out to determine the composite characteristics of the atmosphere at different altitude levels several days prior to landfall in the Mexican Pacific States. The study separated the different types of trajectories observed during the tropical cyclone season (15 May to 30 November) and utilized re-analysis data to evaluate the patterns of geopotential, low-level horizontal divergence, vertical shear of the horizontal wind, in order to extract predictive information, 2-3 days prior to landfall. Figure 3 shows the four different types of trajectories of landfalling cyclones that have been determined. The different trajectories appear to be clearly separated as a function of month within the season, with May-June-July characterized by landfalling trajectories that are not very similar, compared to those observed in August (mostly parallel and a few recurving) and October (mostly recurving). September also indicates more variability in the trajectories, with landfalling cyclones

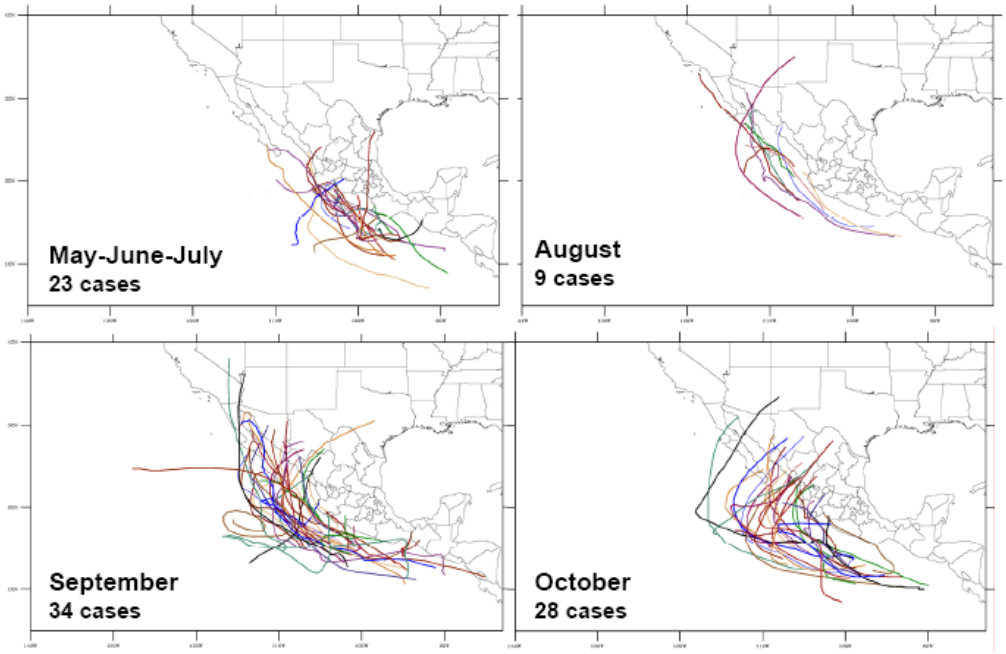


Figure 3. Categories of trajectories of landfalling cyclones

Figure 4 shows the composite of the 500 hPa geopotential heights for the same four categories. It is clear that in September and October there is an upper level trough located just West of the Baja Peninsula, that plays a role in the steering of the cyclones towards the Mexican coast. Earlier in the season, there is an intrusion of

the Atlantic anticyclonic system, that becomes more established in August, and helps to steer the cyclones parallel to the coast and to impact in the Southern parts of the Baja Peninsula.

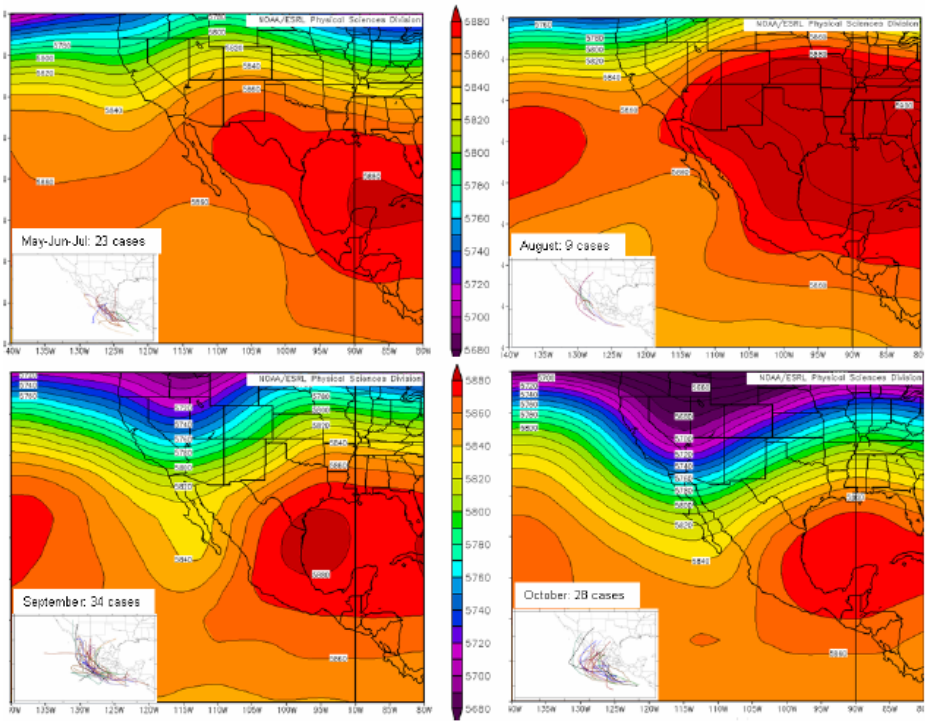


Figure 4. Composite 500 HPa geopotential heights corresponding to the 3 categories of trajectories of landfalling cyclones shown in Fig. 3.

Individual case studies have been performed (as seen in Figure 5) to identify the steering level of landfalling cyclones.

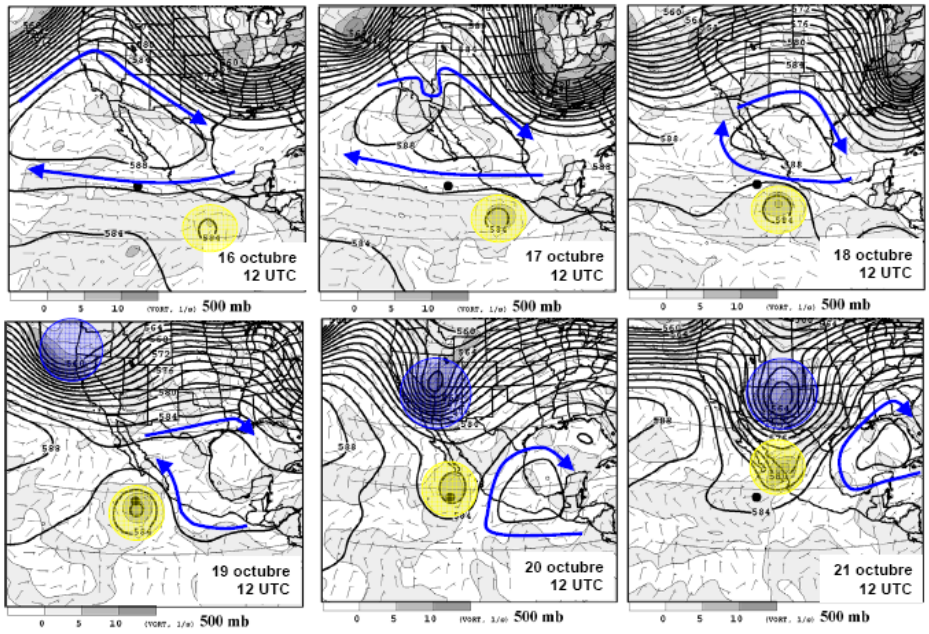


Figure 5. 500hPa geopotential heights and wind fields corresponding to hurricane Rick (2009)

Figure 6 shows the mid-troposphere patterns associated with mainland landfall (lower panel) and landfall on the Baja Peninsula (upper panel). The upper level trough at the West of the Baja Peninsula is much more pronounced in mainland landfall cases.

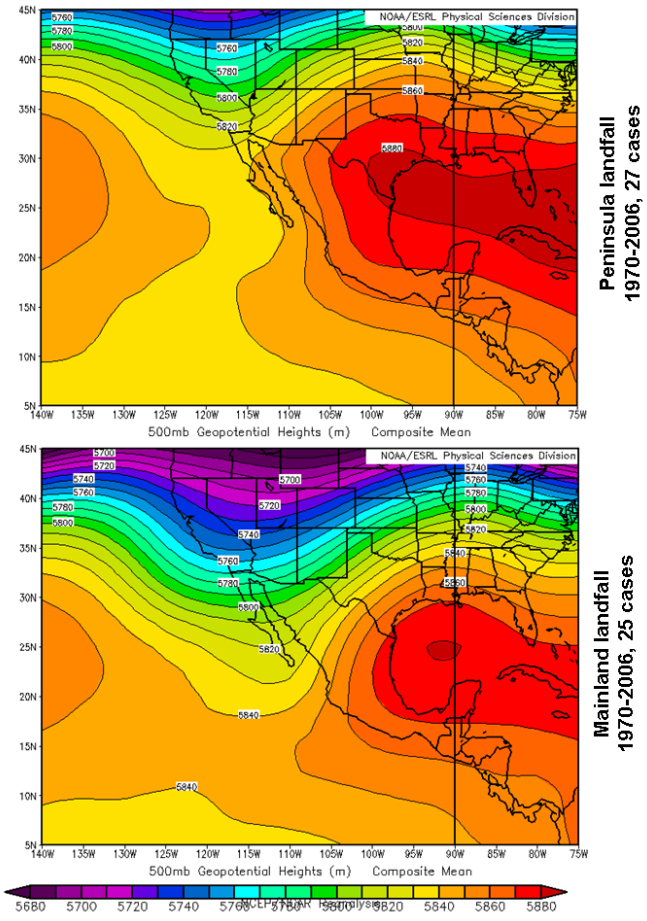


Figure 6. 500hPa composite geopotential heights corresponding to landfall in the main land (lower panel) and landfall in the Baja Peninsula (upper panel)

This task has now been **completed** and a manuscript is almost ready for publication. The **key findings** from the study are the following:

- Trajectories of landfalling cyclones have a clear seasonal distribution
- Mid-troposphere conditions (geopotential heights and winds) clearly indicate different patterns to discriminate the categories of trajectories.
- Composites of atmospheric conditions for 1, 2 and 3 days prior to landfall are suitable to be used as predictors of landfalling regions.

These results will be made available to the Mexican National Weather Service, to provide more information on the potential landfalling systems onto the Pacific coast

I.3 Data analysis from TCSP/IFEX (J Marin and GB Raga, CCA-Mexico; J. Cisneros and D. Raymond, NMT-USA)

This task was **concluded** in 2009, and J. Marín obtained his PhD in April 2009. Even though this task as stated had been completed, D. Raymond, J Cisneros and C. Lopez-Carrillo participated in the field project TPARC during September - October 2009, to continue to elucidate the important atmospheric factors leading to tropical cyclone intensification.

Raymond's group at New Mexico Tech was originally going to analyze airborne dropsonde and Doppler radar data from NOAA's IFEX study of east Pacific tropical cyclones, which took place in the summer of 2005. Unfortunately, nature did not cooperate, with most of the storms developing in the Atlantic basin in 2005. Our group, consisting of graduate student Jorge Cisneros, research physicist Carlos López Carrillo, and PI David Raymond, analyzed the little east Pacific data that were available, but we were unable to extract significant science from them. However, we participated in an alternative program, TPARC/TCS-08 (Thorpex Pacific Area Regional Campaign/Tropical Cyclone Structure 2008). This program was funded by the US National Science Foundation and the Office of Naval Research. Both Jorge Cisneros and Carlos López received partial support from the IAI grant at various times while working on TPARC/TCS-08. Since TPARC/TCS-08 had many of the same goals as IFEX, we felt that this allocation of IAI support was reasonable.

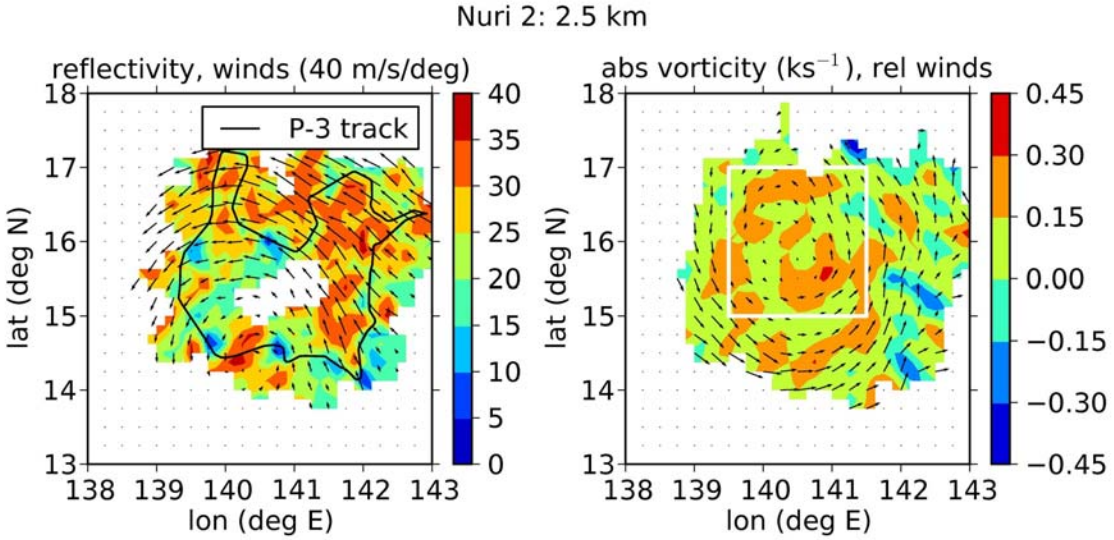


Figure 7. Results from Tifoon Nuri observed during T-PARC

In TPARC/TCS-08 we observed the formation and development of several typhoons in the tropical west Pacific. The primary work accomplished so far is the evaluation of all terms in the vorticity equation during the intensification of typhoon Nuri from a tropical wave to typhoon strength. These missions involved the use of dropsondes deployed from Air Force Reserve WC-130J aircraft and airborne Doppler radar data

from the ELDORA radar, which was mounted on the Naval Research Laboratory P-3 aircraft. Figure 7 shows the winds, reflectivity, and absolute vorticity at an elevation of 2.5 km obtained from a three-dimensional variational analysis (3D-VAR) of the data. At this stage Nuri was a tropical depression with no central vorticity maximum, but with signs of the development of banding structure in the vorticity field. Carlos López created the 3D-VAR analysis scheme, and Jorge Cisneros is expected to receive his PhD in 2010 from an analysis of data from this project. Three papers are under preparation for this project and three presentations were made at a TCS-08 workshop in October 2009.

I.4 Data analysis using the NARR and SODA databases (F. Oropeza and GB Raga, CCA-Mexico)

This task is part of the research for the doctoral thesis of F. Oropeza y has progressed very well. He presented results at the AGU Ocean Sciences Meeting (February 2010) and at 29th Conference on Hurricanes and Tropical Meteorology (May2010). The databases used are the North American Regional Re-analysis (NARR) and the Simple Ocean Data Assimilation (SODA). This task is still **ongoing** but will be completed in the next few months. A manuscript will be submitted at the end of September, and its acceptance is the only requisite missing for F. Oropeza to obtain his PhD, expected by December 2010.

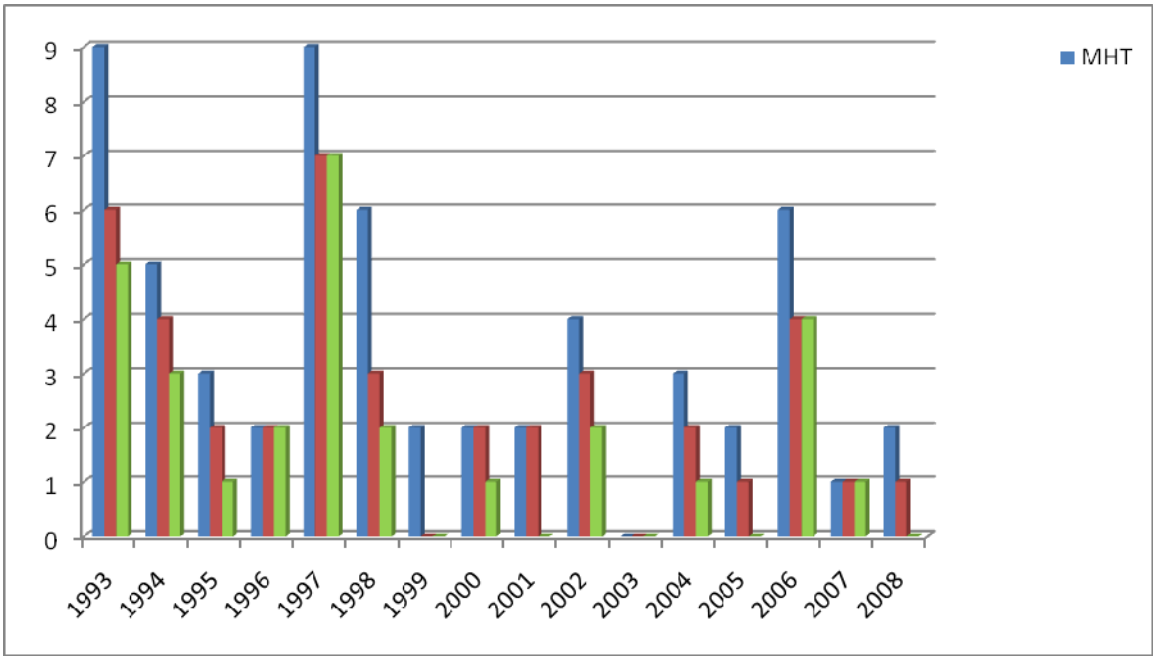


Figure 8. Number of major hurricanes per season (blue) that experienced rapid deepening (red) and those with rapid deepening that interacted with a positive sea surface height anomaly (green)

A total of 44 cyclones between 1993 and 2008 experienced rapid or explosive deepening and 30 of those (68%) had an interaction with a sea surface height

anomaly that had enhanced ocean heat content, as seen in Figure 8. The Gray parameters have been estimated in a box following each cyclone (as was described in previous reports) and are followed in time to determine their relative importance. As an example, in Figure 9, the different parameters are presented for tropical cyclone Lane (1994) that indicate that the increasing wind shear (WS), decreasing relative humidity (HR) as well as the decreasing ocean thermal energy (OTE) all contributed to the decline of the cyclone

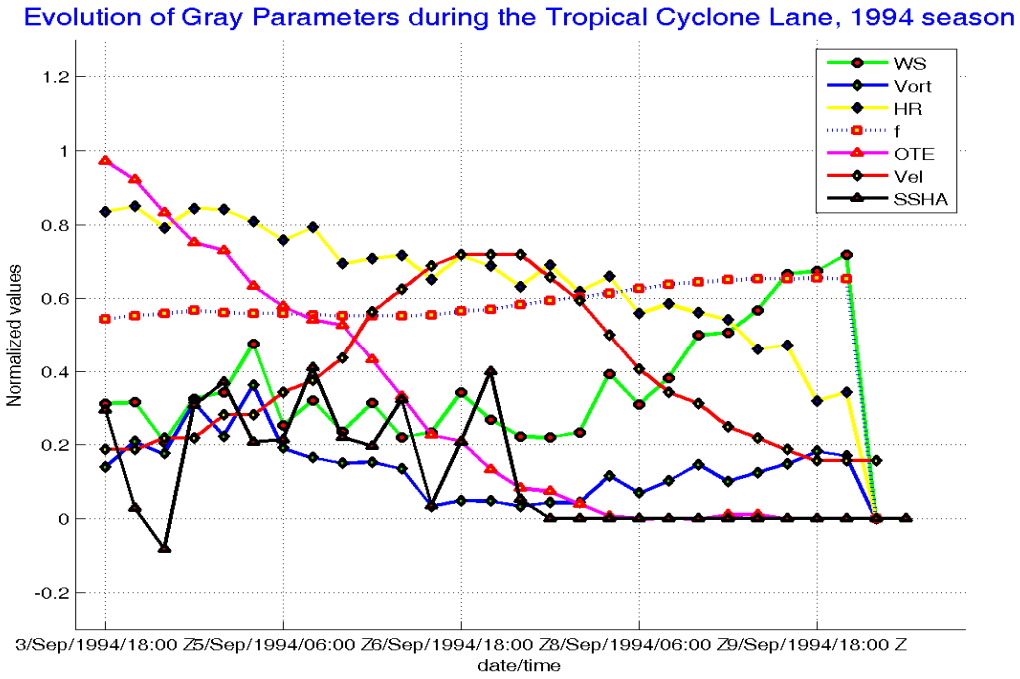


Figure 9. Time evolution of the Gray parameters fro cyclone Lane (1994)

Progress on *Modeling:*

II.1 Hindsight modeling with WRF (L. Farfan CICESE-Mexico; D. Pozo and GB Raga, CCA-Mexico)

The modeling activity reported earlier with the Weather Research and Forecasting (WRF) model, indicated that the deepening of the modeled systems was always much less that the observed intensity of the cyclones. Therefore, we pursued the tackle of including a vortex into the simulations once a tropical depression was identified by the National Hurricane Center. We present here a few results from the simulation of Hurricane Jimena, that made landfall in the Pacific coast of the Baja California peninsula, causing large devastation in some coastal communities in 2009 (Figure 10, from the official NHC track dataset).

Simulations with the WRF model included 2 nested grids (20 and 5 km resolution) and were performed for 4 days. The Final (FNL) analyses from the Global Data

Assimilation System provided the initial and lateral boundary conditions for simulations every six hours. The Mellor-Yamada parameterization was selected for the boundary layer processes and Monin-Obukhov describes those in the surface layer. The Kain-Fritsch cumulus parameterization was used in the external domain and the microphysics scheme of Lin et al. (1983) was used in the inner one. Simulations using the Thompson et al. (2004) microphysics scheme in the inner domain and the simplified Arakawa-Schubert cumulus parameterization in the outer one were performed to test sensitivity. Given the high spatial resolution used in the simulations, an adaptive time step had to be implemented, since otherwise the runs experienced numerical instability. This of course translates into a higher computational costs and longer times to obtain the results.

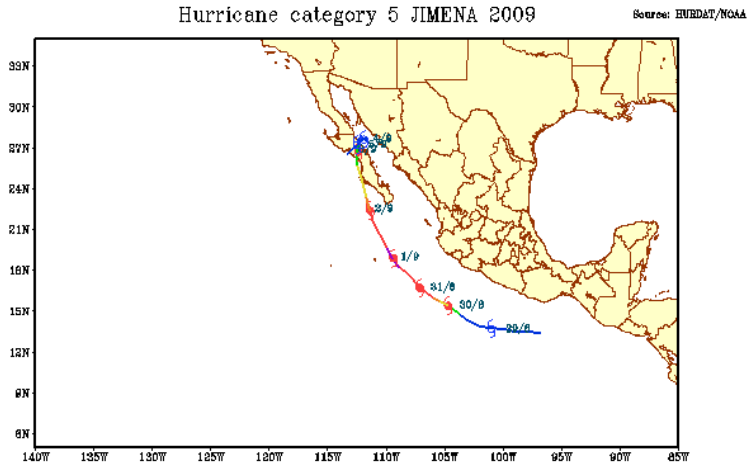


Figure 10. Official trajectory followed by hurricane Jimena in 2009

Figure 11 shows the low-level (10m) wind field at the time of the inclusion on the vortex on 29 August 2009 and Figure 12 shows the corresponding sea surface pressure.

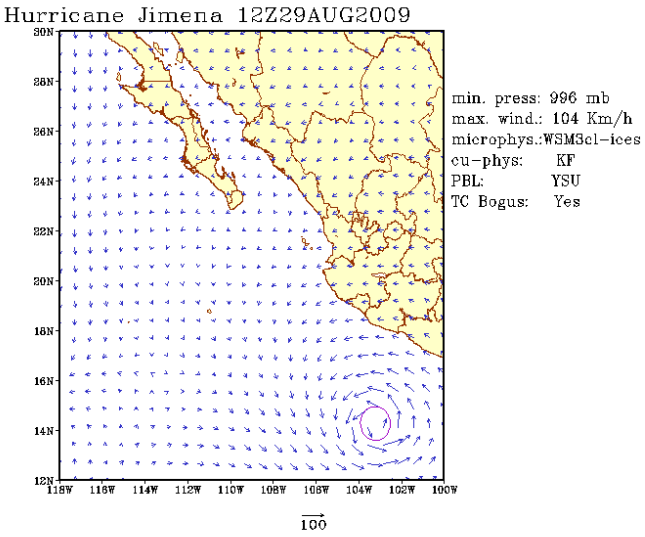


Figure 11. Low- level winds at the initiation of the simulation of hurricane Jimena in 2009. Also seen is the circle that represents the vortex

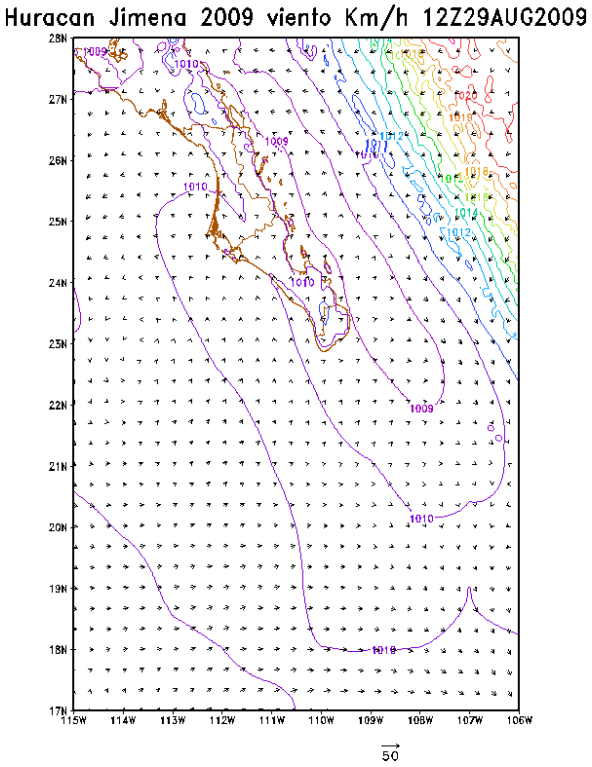


Figure 12. Sea level pressure of hurricane Jimena in 2009, at the initiation of the simulation.

Twelve hours after the inclusion of the bogus vortex, the sea level pressure has decreased significantly and the winds have strengthen accordingly (Figure 13)

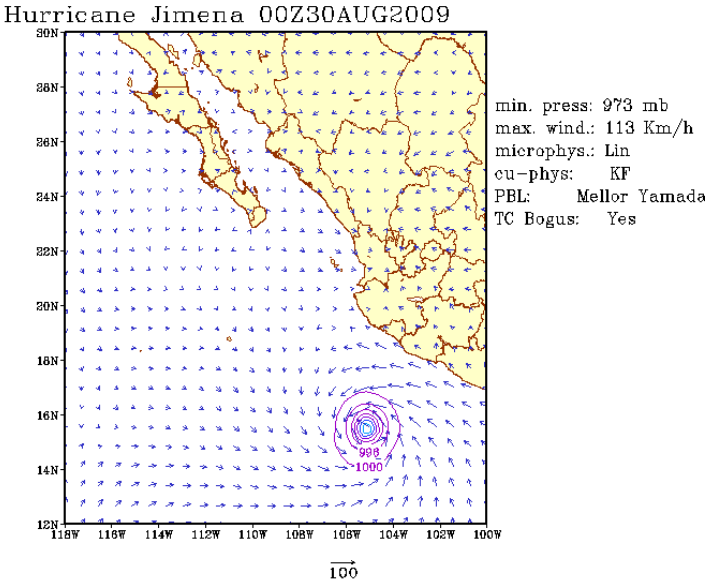


Figure 13. Low- level winds 12 hours after the initiation of the simulation of hurricane Jimena with a bogus vortex.

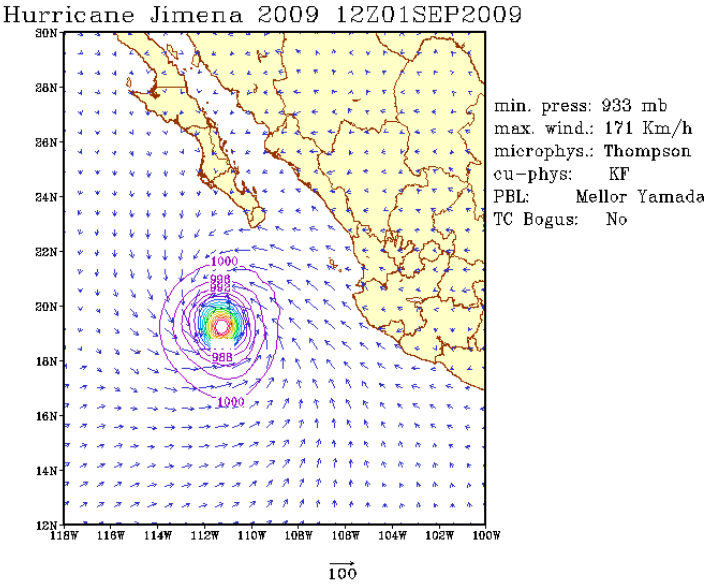


Figure 14. Low- level winds 124 hours after the initiation of the simulation of hurricane Jimena with a bogus vortex.

The simulations with the inclusion of the vortex led to more intensification of the cyclone as seen in Figure 14. The Table I indicates just how much more intense the

resulting simulation was. However, we still need to note that the simulations with the bogus cyclone were not able to fully reproduce the official intensity reported by the National Hurricane Center (NHC)

Table I

External domain	Central pressure (mb)	Maximum wind (Km/h)
NHC	970	166
Control run	1003	46
TC bogus run	973	113

The sensitivity to the different parameterizations of the microphysical processes are summarized in the following Table II, were it is evident that the more complex microphysical parameterization with 5 categories of hydrometeors results in a simulation with a deeper cyclone (even deeper that observed central pressure). However the maximum winds observed were higher than the simulations with the bogus cyclone.

Table II

Internal domain	Central Pressure (mb)	Maximum wind (Km/h)
NHC	940	231
Control run	907	232
TC bogus LKF	932	186
TC bogus WSM-KF	942	185

LKF: Lin (5 categories) and Kain-Fricht parameterizations
WSM-KF: Simple 3 categories and Kain-Fricht parameterizations

The **key findings** of the modeling study are:

- The AWR-core was implemented, with the inclusion of a bogus vortex to simulate the cyclone evolution in a 2-domain simulation with fairly high resolution (20 and 5km, respectively)
- Because numerical simulations kept becoming unstable, an adaptive time step was implemented, which resulted in much higher computational costs.
- The inclusion of the bogus vortex resulted in a much more intense cyclone, comparable in central pressure with the observations.
- The maximum winds were not well reproduced, with the simulations underestimating the observations by about 25%.
- The sensitivity test of the microphysical parameterizations indicates that the more complex one (5 categories of hydrometeors versus 3) results in a more intense cyclone.

These results will be made available to the Mexican National Weather Service, to provide more information on the potential landfalling systems onto the Pacific coast . In the following months, an effort will be made to try to put this modeling system in a semi-operational fashion, to provide more accurate forecast of the trajectory and intensity of cyclones that may potentially affect the Mexican coastline.

II.2 Ocean modeling for the EPAC region (F. Oropeza and GB Raga, CCA-Mexico)
F. Oropeza visited the Institute of Marine and Coastal Sciences at Rutgers University for 4 weeks in August 2008. His visit was very successful and he was able to implement the regional ocean model for the East Pacific. He has carried out exploratory simulations, whose results clearly indicate the presence of warm anticyclonic ocean eddies as observed. However, the exact timing of these eddies does not correspond exactly to the location of the observed ones on specific cases, related to particular tropical cyclones. It was therefore decided that a somewhat different approach would be explored. The database SODA has been used instead of the numerical simulations to estimate the ocean heat content that would be available for developing tropical cyclones. This task is now **completed.**

II.3 Analysis of results from "Hurricane" model (Emanuel, 2003) (F. Oropeza and GB Raga, CCA-Mexico)
A few selected cases were simulated with the Hurricane model of Emanuel,, and the interaction with the anticyclonic oceanic vortex led to slightly more intense modeled hurricane. In particular, the case of observed category 5 hurricane Linda (1997) shown in Figure 15, reached category 5 in the simulation with the interaction and did not reach such high winds without the interaction. Currently, simulations of all cyclones that had interaction are being carried out, to establish statistically, what is the effect of the interaction with oceanic vortices on the intensification of East Pacific cyclones.

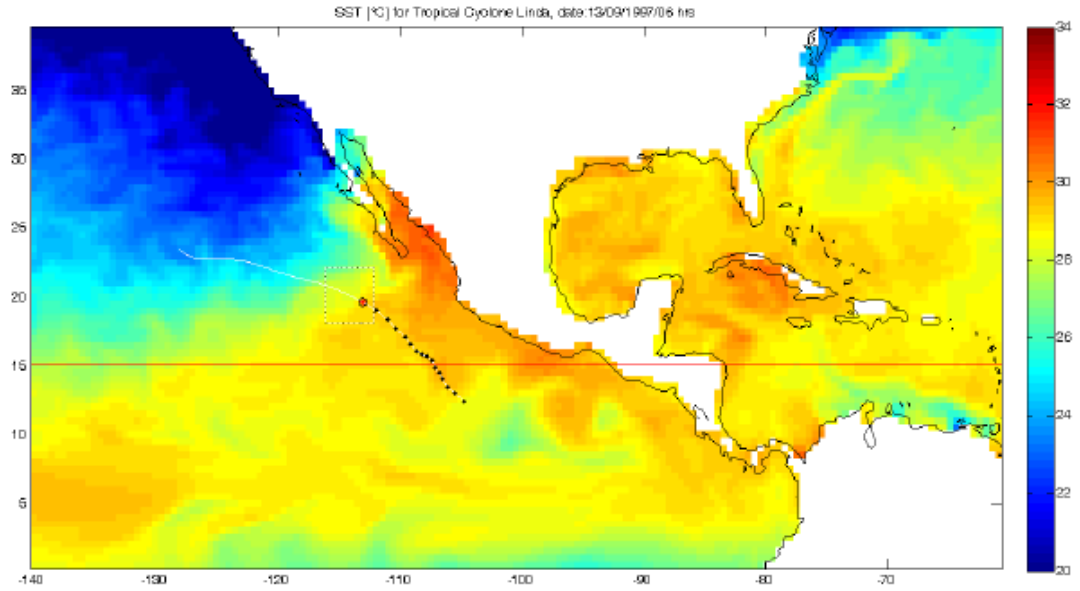


Figure 15 SST and track of Linda (1997)

The model was implemented to simulate Linda (Category 5) as it encountered the sea surface temperature observed in Figure 15. The results are shown in Figure 16,

where it is clear that the simulated maximum winds underestimate the observed winds, by about 17%. The simulations including a ocean heat content positive anomaly resulted in very similar results, with the underestimation being 15%.

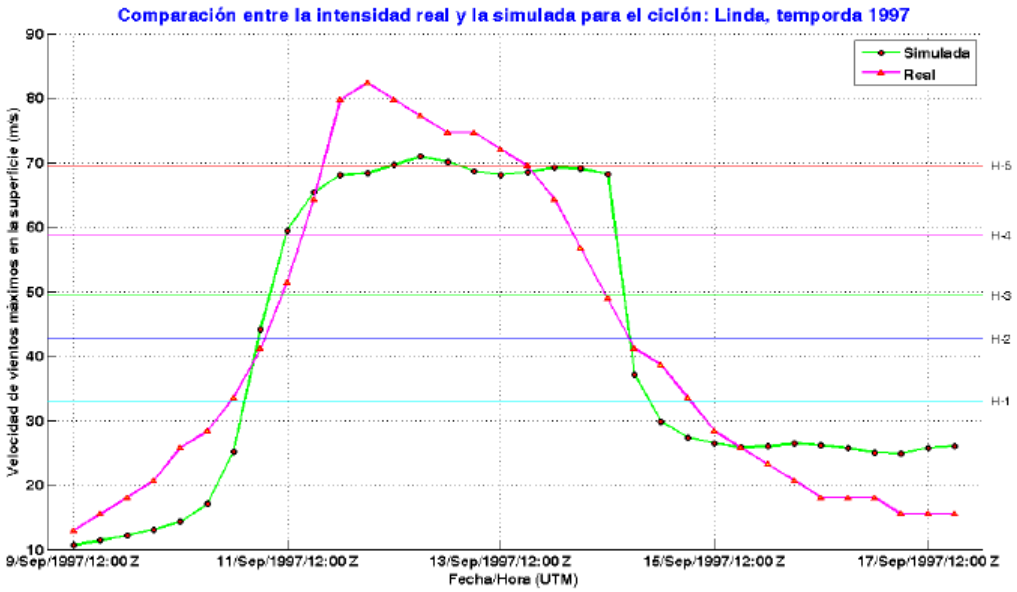


Figure 16. Time evolution of simulated maximum wind speeds (green) for Linda compared with the observations (magenta)

II.4 Analysis of results from coupled ocean-atmosphere global climate models runs (R. Romero-Centeno and GB Raga, CCA-Mexico, L. Farfán, CICESE).

This task has not started yet and since Dr. R. Romero-Centeno has taken on a faculty position after her post-doc, she will not be able to be involved in this task. Talks have been initiated with a researcher at the Mexican Institute for Water Technology that may be able to work part-time on this task in the next few months. More details can be found below on this activity.

II.5 Coastal wave modeling

The original work was going to be carried out by the co-PI from Costa Rica, but due to the departure of Dr. Lizano from the team, the Cuban component assumed the responsibility to perform simulations with the costal wave model. The objective was to try to predict the wave activity close to shore, using the winds simulated from the atmospheric simulations carried out using WRF for those same cyclones. The co-PIs from Cuba visited CCA-UNAM in September 2009 to make progress on this task which has not been **completed**. The work was carried out by Dr. Ida Mitrani Arenal, Dr. Daniel Martínez Castro, Lic. Yoandy Alonso Díaz and Msc. Oscar Onoe Díaz Rodríguez, all from INSMET-Cuba.

The model Wave Watch III (WW3, version 2.22, available on line from the NCEP/NOAA web page) was implemented in the domain shown in Figure 17. This model assumes that the ocean currents and sea level height and the wave field all are variable in time. The bathymetry for the simulations was obtained from the GEBCO DIGITAL ATLAS-2003 (that was purchased for this task). Input fields to WW3 were obtained from the atmospheric simulations performed with WRF for cyclones John, Paul and Lane in 2006. The horizontal resolution was varied in sensitivity runs from 10, 15, 20 to 25km, on a grid of 102x102 points and variable time step.

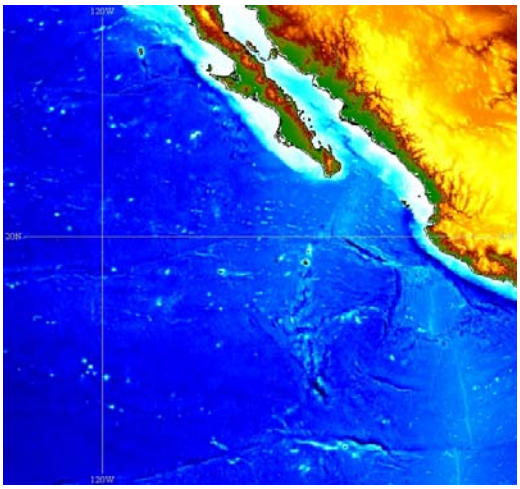
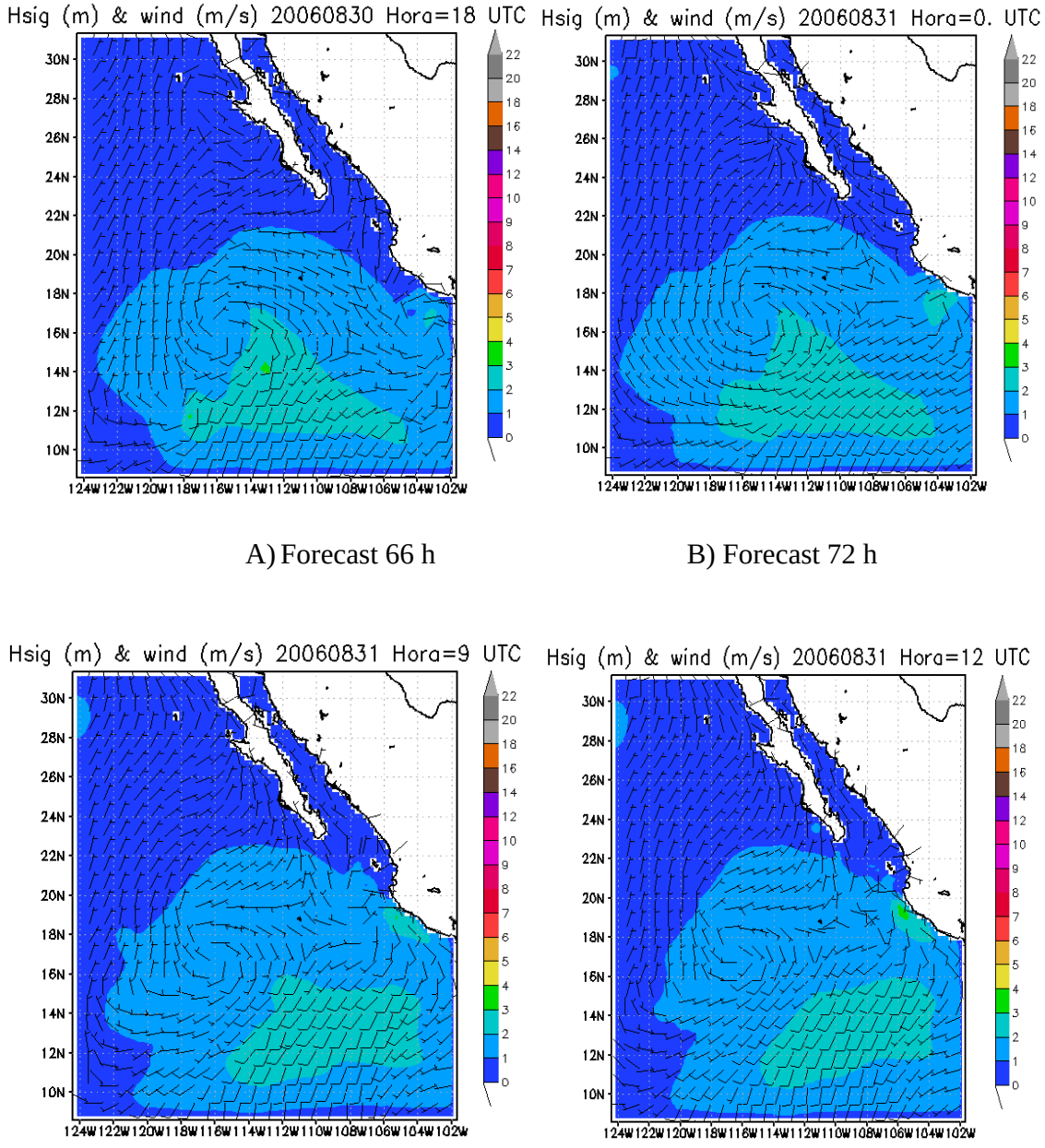


Figure 17. East Pacific region covering the domain for the WRF-WW3 study.

We describe here only the results of the simulation that correspond to hurricane John. Figures 18 a-d and 19 a-d show the results for different forecast times: 66, 72, 81, 84, 96,108 and 120 hours. Noting that the waves are generated by the persistent winds, reasonable wave hights are simulated and the best certainty is found in the region of the hurricane, when it is completely located within the domain. While the maximum winds were observed on 30 August at 18 UTC, the maximum wave heights were simulated later. At that time, heights of less than 3m were simulated, since the full cyclonic circulation was not fully within the WW3 domain. As the cyclone proceeded towards the NNW, persistent winds were experienced for over 12 hours, resulting in a larger fetch and favoring wave development up to 4m in coastal regions. The **key findings** are:

- The domain selected is adequate for the simulations as long as the tropical cyclones is completely located within it, since the fetch is important for the wave height prediction
- Computational stability was achieved using 25km for horizontal resolution and 900s for the time step.
- The results appear to be acceptable for forecast periods of up to 72 hours.
- A couple of the simulated cyclones underwent variations in their intensity, which resulted in a corresponding wave height evolution.
- A couple of simulated cases included the presence of other tropical cyclones further away from the coast and the interaction between wind vortices has to be simulated correctly in order to predict adequately the associated wave fields.



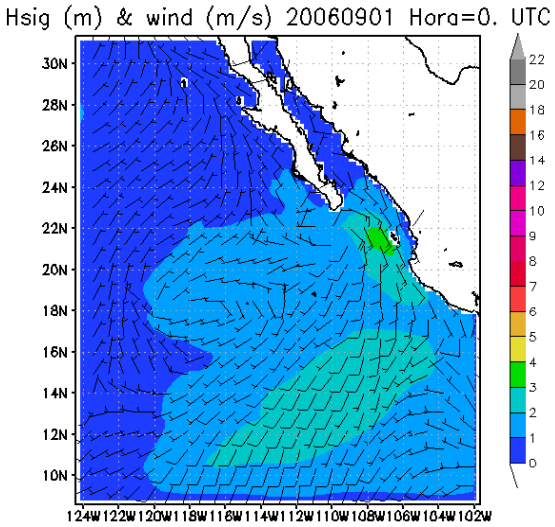
A) Forecast 66 h

B) Forecast 72 h

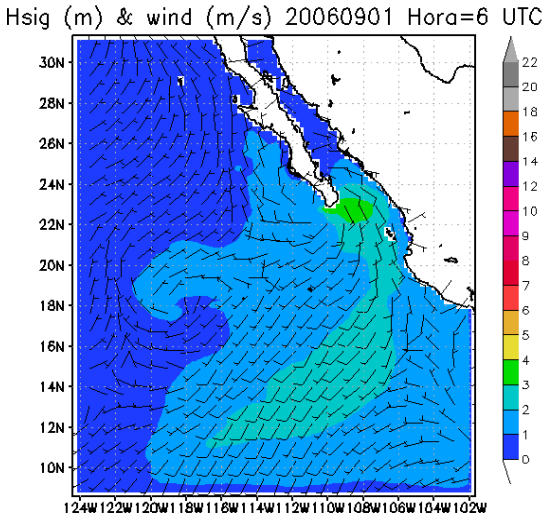
C) Forecast81 h

D) Forecast 84 h

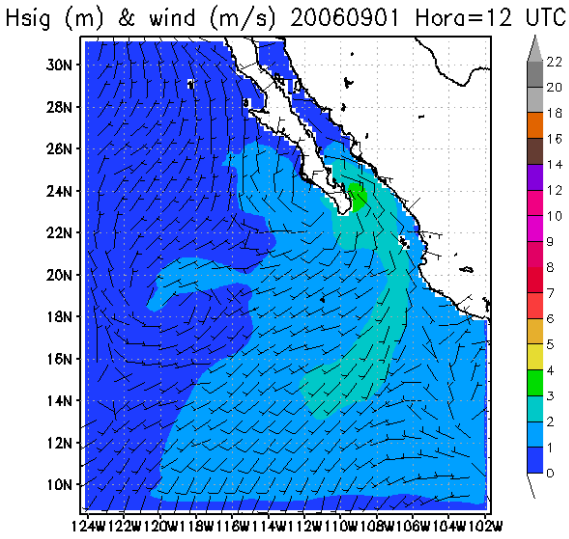
Figure 18. Simulated winds and wave height, using WRF-WW3 for hurricane John (2006), for coastal regions of the Tropical Pacific, from 30/08 18 UTC to 31/08 12 UTC. Note the presence of hurricane Kristy farther off the coast.



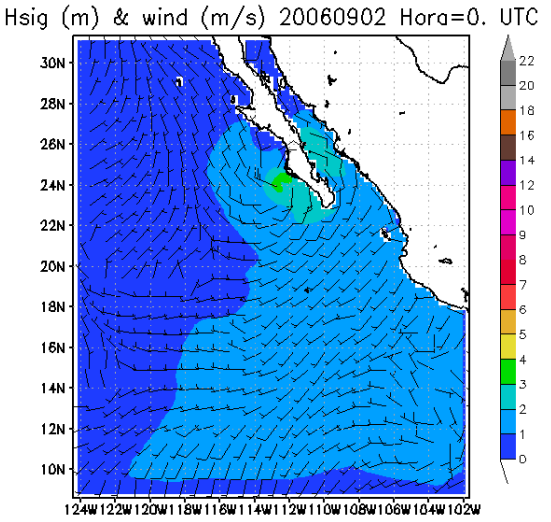
A) Forecast 96 hrs



B) Forecast 102 hrs



C) Forecast 108 hrs



D) Forecast 120 hrs

Figure 19. Simulated winds and wave height, using WRF-WW3 for hurricane John (2006), for coastal regions of the Tropical Pacific, from 01/09 00 UTC to 02/09 00 UTC. Note the presence of hurricane Kristy farther off the coast.

The results from completion of this task suggest the following recommendations:
a) Evaluation of the simulated results with instrumental data where available.
b) Use of this model in conjunction with operational prediction models for the atmospheric flows.
c) Use of combined models to model deep water waves, coastal waves and storm surge, for a better prediction in sensitive coastal regions.
There is no publication planned from this component. The model will be run semi-operationally and the results will be displayed on-line in the project web page.

Addition research not included in the original proposal

Historical record of landfalling cyclones 1850-1949
This part of the study was added to the original objectives and consisted on bibliographical research to determine the record of landfalling cyclones through newspaper reports as well as government documents. This research provides independent information valuable for the dating of sedimentary records obtained by Dr. Kam-biu Liu's team (CRN II-050), who obtained cores in several different sites of the Mexican Pacific coast. This research was considered a valuable addition to the project and provides a much closer interaction with CRN II-050.

Lic. Beatriz Bracamontes (a trained journalist) was hired for 7 months to travel to different states and research in the local libraries for the old newspapers and also to contact local government offices to request copies of annual reports, where the information about losses due to the impact of landfalling storms could have been recorded.


Los Ciclones en la memoria colectiva

Aspecto de Olas altas tras el ciclón de 1927

Figure 20: Example of newspaper report of flooding associated with the landfall of a tropical cyclone in the city of Mazatlan (Sinaloa) in the year 1927. Source: Archivo Historico Municipal de Mazatlan

She visited the cities of Chilpancingo, Guadalajara, Mazatlan, Culiacan and La Paz, as well as all the libraries in Mexico City. She was able to access old newspapers and either take digital photos of the relevant pages or request scanned version (which had to be payed for, from the project funds): Her work reported was stored in

a software called FileMaker, that allows for individual records to be classified, including links to files, such as the photos or scanned pages of documents. An example is shown in Figure 20. The information was downloaded into files using the program FileMaker, which were designed especially for this purpose. An example is seen in Figure 21, where there places to input different information on the damages of the different landfalling or land-grazing cyclones that affected coastal populations from 1850 to 1949. These files can be made available to other researchers studying the impact of tropical cyclones in Mexico.

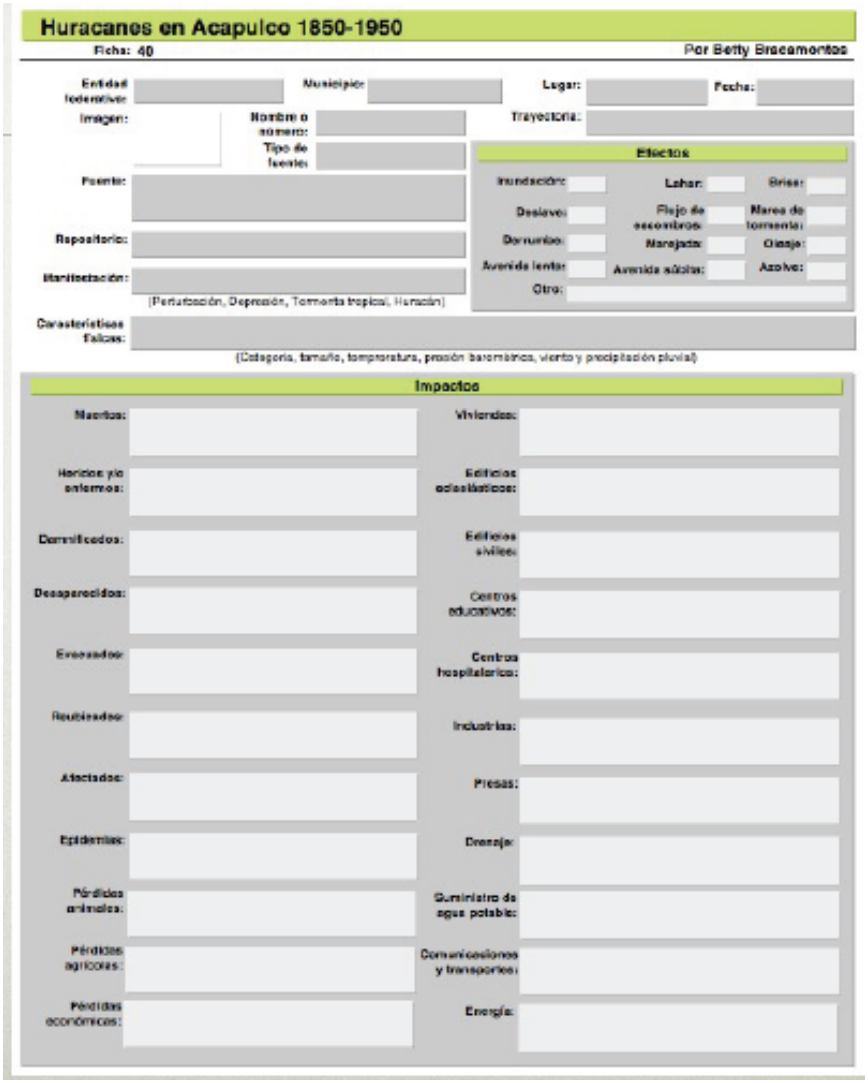


Figure 21. Example showing the design of the individual entries of the database generated. Each event found was catalogued based on its location, date and a variety of the possible effects upon landfall (e.g. deaths, injured, loss of crops, buildings, power , roads, floods, landslides, etc)

The historical results of B. Bracamontes together with the results from R. Romero-Centeno were included in Figure 22, that shows the variability in landfalling cyclones in the 4 states of the NW of Mexico. The variability observed seems to be related to the Pacific Decadal Oscillation, which is currently being explored.

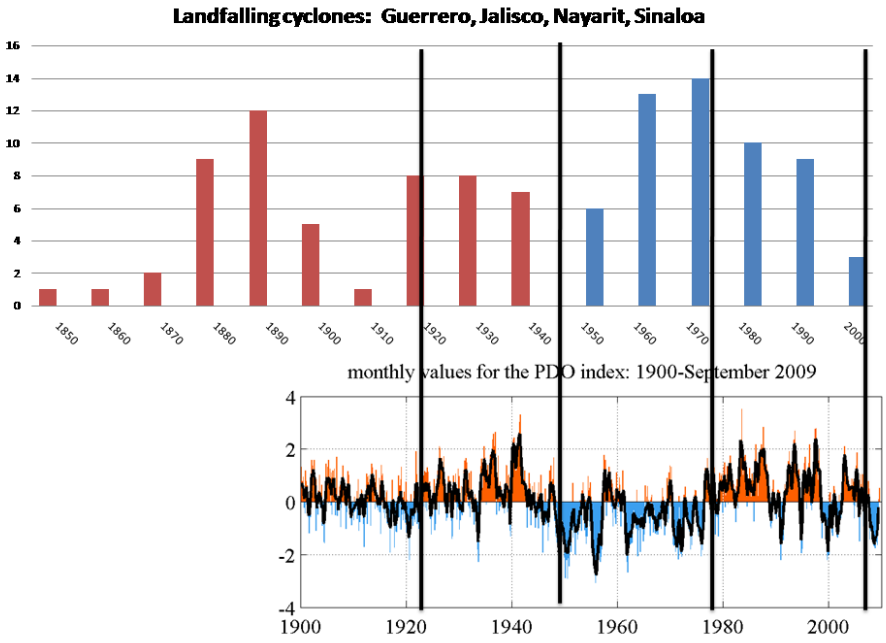


Figure 22. Decadal variability of landfalling cyclones in the Mexican Pacific, from a combination of historical sources (1850-1949) and the database of the National Hurricane Center (1949-present)

4. Contributions of Co-PIs

Costa Rica:

O. Lizano (CIGEFI) left the project in 2008.

Cuba:

I. Mitrani and D. Martínez (INSMET) were responsible for numerical simulations of ocean waves associated with cyclones and their coastal impact.

Mexico:

J. Zavala-Hidalgo and GB Raga (CCA-Mexico), together with O. Sanchez (CICATA-Mexico) concluded the analysis of the sea surface height anomaly (from satellite data Topex/Poseidon) in the region of the East Pacific, East of 120W, where the cyclones that affect Mexico are formed. A manuscript was submitted for publication and is currently under review. The reviewers suggested some more work that is underway.

GB Raga and her PhD student F. Oropeza (CCA-Mexico) have undergone an in-depth analysis of each individual cyclone case since 1970 to identify rapidly intensifying cyclones, postulating the hypothesis that those cyclones may have intensified by interacting with areas in the ocean with higher heat content. The

student presented successfully his PhC exam during the year with advances from his research. Moreover, he presented them in 2 conferences (February and May 210), in particular, he presented his results in an oral session at the Conference on Hurricanes and Tropical Meteorology (organized every 2 years by the American Meteorological Society) and they were well received. The manuscript of his paper is well advanced and will be submitted by late September. The graduate program has a requirement that the manuscript be accepted before graduation, which is planned for early 2011.

L. Farfán (CICESE-Mexico) took the lead in a manuscript based on the data analysis of the land-falling cyclone cases in 2006 and 2007, in comparison with the modeling results using WRF. This task is done in collaboration with G.B. Raga, D. Pozo, R. Romero-Centeno and J. Zavala-Hidalgo (UNAM). The results were presented at several international conferences and a manuscript is available.

R. Romero (CCA-UNAM) has carried out the estimates of several parameters from the North American Regional Re-analysis database for the selected cases that are the focus of the manuscript with Farfán as first author. She is currently preparing the manuscript on the study of the climatological conditions that are associated with land-falling cyclones in the East Pacific.

United States of America:

D. Raymond (NMT-USA) together with his PhD student J. Cisneros have continued the analysis of the airborne Doppler radar and dropsonde data from the TCSP/IFEX project, as well as participated in the T-PARC project in the Western Pacific, following the same methodology to investigate cyclogenesis and intensification.

5. Publications

Refereed publications

1. Zavala Hidalgo, J., R. de Buen Kalman,R. Romero Centeno y F. Hernández Maguey, **2010**: Tendencias del nivel del mar en las costas mexicanas. p 249-268. En Botello,A.V., S. Villanueva-Fragoso, J. Gutiérrez, y J.L. Rojas Galaviz (eds.). Vulnerabilidad de la zonas costeras mexicanas ante el cambio climático. Semarnat-INE, UNAM-ICMY, Universidad Autónoma de Campeche. 514 p.
2. Farfán, L M, Rosario Romero-Centeno, G. B. Raga, Diana Pozo and Jorge Zavala-Hidalgo, **2010**: On the landfall of Eastern Pacific Tropical Cyclones John, Lane and Paul (2006) over Northwestern Mexico. Submitted to *Natural Hazards and Earth System Sciences.*
3. Farfán, L, G. B. Raga and F. Oropeza, **2010**: Tropical Cyclone training for Latin American students. *Border Climate Summary* (in press)
4. R. Romero-Centeno, R., L. Farfán and G. B. Raga, **2010**: Tropical cyclone landfall probabilities and track analysis for the Eastern North Pacific. *To be submitted to Climate Research*.
5. Oropeza, F. and G. B. Raga, **2010**: Rapid deepening of tropical cyclones in the northeastern Tropical Pacific: The relationship with ocean eddies. *To be submitted to Atmospheric Chemistry and Physics.*

Extended Abstracts:

1. Oropeza, F. and G. B. Raga: Rapid deepening of tropical cyclones in the northeastern Tropical Pacific: The relationship with ocean eddies, 29th Conference on Hurricanes and Tropical Meteorology, 10-14 May, Tucson Az, **2010.**

Conference presentations (No extended abstracts)

1. Oropeza, F. and G. B. Raga: Intensification of Tropical Cyclones in the Eastern Pacific and its Relationship with Ocean Eddies. Joint Assembly of IAMAS-IAPSO-IACS, 19-29 July, Montreal, **2009.**
2. Raymond, D. J., C. López Carrillo, and M. Herman: Vorticity budgets in developing tropical cyclones. Tropical Cyclone Structure 2008 Science Workshop, 28-30 October, Monterey, CA., **2009**
3. López Carrillo, C., and D. J. Raymond: Wind retrieval from airborne Doppler radar and dropsondes TCS-08 field campaign. Tropical Cyclone Structure 2008 Science Workshop, 28-30 October, Monterey, CA., **2009**
4. Cisneros, J., D. J. Raymond, and C. López Carrillo: Circulations and detrained fluxes for tropical cyclones during TCS-08. Tropical Cyclone Structure 2008 Science Workshop, 28-30 October, Monterey, CA., **2009**
5 Farfán, L, R. Romero-Centeno and G. B. Raga: Characteristics of landfalling tropical cyclones in the eastern North Pacific basin. 2010 Annual Meeting of the American Association of Geographers, 14-18 April, Washington DC **2010**
6. Oropeza, F. and G. B. Raga: Intensification of tropical cyclones in the Eastern Pacific and its relationship with ocean eddies.2010 Ocean Sciences Meeting, 22-26 February, Portland, Or. **2010.**
7. Farfán, L. and G. B. Raga: Working towards increased human resources in Latin America: Short courses on tropical cyclones. The meeting of the Americas (AGU), 8-13 August, Foz do Iguassu, **2010**.

Presentations and seminars:

G. B. Raga: Cursos de primavera sobre ciclones tropicales. Reunión Anual de representantes de Organismos de Cuenca, Servicio Meteorológico Nacional, México DF, 25 de febrero **2010**.

G. B. Raga: Huracanes: Sabes qué son? Cómo afectan a México? Cinvesniños 4-2010, Mexico DF, 4 de junio **2010** (presentation made at a Science Fair organized by CINVESTAV)

6. Data

No new data has been generated in this project. A CD was generated during the spring course that contained all the course material, including all the lectures that were offered. (Note: this CD can be mailed to IAI if needed)

7. Capacity building

The ***highlights*** in this aspect during this past year are:

- 3rd Spring Course on Tropical Cyclones (1 week during early March 2010, in La Paz, BCS). This course was offered at a graduate student level and focused on the physics of different aspects of cyclone formation and evolution. More details are given below.
- 1-day Symposium on the Human Dimensions of Tropical Cyclones, incorporating the views of personnel working in civil defense agencies at different government levels (local, state, federal), same location. More details are given below.
- Third PI-workshop during to spring course, same location. More details are given below.

3rd spring course on Tropical Cyclones in La Paz, Mexico

Preparations for spring school started in December 2009, with the invitation to speakers and an open call for participants. Selection of the participants was made by the end of January, candidates were notified and arrangements were made to purchase their airline tickets when applicable. Logistical aspects (computers, internet access) and preparation of material (handout notes for students and CD) were carried out during January-February.

From 8 through 11 March, 2008, a 32-hour course was held in Acapulco and it was focused on training graduate students from Mexico, Cuba, and Argentina. A total of 33 students attended, most of them currently attending graduate programs in Atmospheric Sciences or Oceanography. Seventeen students were awarded total funding to attend, from the funds available from our IAI grant and the rest received either food and lodging (no travel support) or food. Participants also included personnel from the Mexican Ministry of Transport (Merchant Navy), Mexican Institute for Water Technology (IMTA, Spanish acronym) and from the regional office of the National Water Commission (Comisión Nacional del Agua).

A total of 11 instructors provided lectures on:

- Climatology and formation of tropical cyclones (L Farfán, CICESE)
- Dynamic and thermodynamic models (D. Raymond-NMT, S Abarca-UCLA)
- Air-sea interaction and ocean response (J. Zavala-Hidalgo-CCA)
- Ocean waves and coastal impacts (I. Mitrani-INSMET-Cuba)
- Variability of tropical cyclones (E. Romero-Vadillo, UABCS)
- Regional climate predictions (D. Martínez INSMET-Cuba and M. Montero IMTA)
- Remote sensing of atmospheric variables (R. Romero-Centeno-CCA)
- Remote sensing of oceanic variables (F. Oropeza-CCA)
- Paleotempestology (K-B Liu, LSU)

Professor Kam-biu Liu (Lead PI of CRNII-050), from Louisiana State University, offered a lecture on geologic techniques to study past activity, back to the last 5,000 years, providing the paleo-climate context of modern day observations of tropical cyclones. On Wednesday afternoon, the group attended a demonstration by Dr. Liu

and two associates (Thomas Bianchette and D. Terry McCloskey), who performed a core sampling in a near-by site.

A professor from the local university, Dr. Romero-Vadillo form Universidad Autonoma de Baja California Sur, was invited to participate as a lecturer, with the hopes that it would also attract some local students to the course and sponsor more interactions between educational and research institutions in Mexico.

The last afternoon of the course was devoted to a forum in which students divided into small groups presented to the rest of the attendants, their views on the links between tropical cyclones and climate change, based on a review of the recent literature on the topic. Students were required to review selected papers prior to attending the course, which were available through the web page for the course.

Participants at the short course offered in La Paz, BCS

Symposium on the Human Dimensions of Tropical Cyclones in Acapulco, Mexico

A one-day symposium was held on Friday 12 March, as a follow-up to the short course. The objective of this symposium was to discuss the socio-economic impacts associated with tropical cyclone landfall. Seven lecturers discussed different aspects of the environmental and societal impacts of landfalling cyclones, from landslides to the "community memory" of the events. For the first time, a video was presented based upon anthropological/historical research of survivors of a population that was heavily impacted by the landslide and flooding following a tropical cyclone in 1959 in the village of Minatitlan, in the State of Colima. There was also a presentation on the research of historical landfalling cyclones onto the Mexican Pacific states, from 1850

to 1950, that complements the modern database. And finally, as it is customary, civil defense personnel from the State of Baja California Sur, as well as representatives of the State Office of the National Water Commission (Comisión Nacional del Agua, CONAGUA), discussed preparedness and response measures.

The opening ceremony was led by Dr. Raga and Prof. José Gajón de la Toba, the Director of Civil Defense for the State of Baja California Sur.
Lecturers:
Dr. Martín Jiménez, Centro Nacional de Prevención de Desastres (CENAPRED
Lic. José de Jesús Díaz Ventura, Jefe de brigada de protección a la infraestructura y atención de emergencias (CONAGUA, BCS)
Tum. Audel Alvarez, Proteccion Civil, BCS.
Dr. Nicolás Pineda, El colegio de Sonora
Dr. Marcelo Olivera, CCA-UNAM
M. Raymundo Padilla, CIESAS and Universidad de Colima
Lic. Beatriz Bracamontes, CCA-UNAM

PI-workshop in La Paz, Mexico
The PI-meeting also took place in La Paz, during the evenings of the 3rd spring course on tropical cyclones. Time was devoted to the discussion of the research plans for the following months, with concrete contributions towards the annual repot (due in June) and the final report at the end of the year. But more importantly, a large fraction of the time was dedicated to the issue of how to make sure that the spring course can continue beyond the end of the project. It was clear to all PIs that thecourse was been the single most important contribution of the CRNII-048, since it has started to fill in the gap in capacity building that exists in the area of tropical cyclones. Dr. Raga was assigned the responsibility to look for opportunities to continue funding the course. All PIs expressed their commitment to continue participating as lecturers in future courses.

8. Regional collaboration/Networking
A closer collaboration with Kam-Biu Liu, from Louisiana State University, who is the lead PI of CRNII-050 project has developed through the years. Conversations were started in May 2007 during a symposium on Tropical Cyclones held in Crete and Dr. Liu has since participated in both Spring Courses on Tropical Cyclones (La Paz 2008 and Acapulco 2009). During both trips, L. Farfan drove him to visit several sites that may be considered as potentially suitable for the drilling of sand/sediment cores that is part of his CRN II project. Dr. Liu's team collect samples in the Mexican Pacific region near Acapulco in December 2009 and in Baja California Sur in March 2010. His results would allow to put the modern record of tropical landfalls into historical perspective. Dr. L. Farfan presented a paper in the session organized by Dr. Liu in the annual meeting of the American Association of Geographers in April 2010.

The project has benefited significantly by the addition to our research group of the Lic. Beatriz Bracamontes. Her research work on the cyclones that affected Mexico between 1850 and 1950, moves back the record in the East Pacific. Moreover, the locations and time of landfall of cyclones in the last century and a half, will allow to independently date some of the sedimentary records obtained by Dr. Liu's team in the Pacific coast.

9. Media coverage and Prizes

No written reports appeared after this year's course and symposium.

10. Policy Relevance

The majority of the results obtained are too biased towards basic science to be considered relevant to policymakers. Nevertheless, the participation during the opening ceremony of the Symposium on Human Dimensions by the Director of Civil Defense for the State of Baja California Sur, indicates that there has been work by the researchers in this team towards closer relationships with administrators. Also, the interest demonstrated by the Head of the National Weather Service of Mexico (Servicio Meteorológico de México, SMN) suggests the role that the courses are playing in capacity building is acknowledged by authorities. Moreover, talks are currently taking place between SMN and CCA-UNAM to establish the spring course on tropical cyclones as a regular annual event with financial support from those 2 institutions. We consider this development a major success, one that would not have happened without the support by IAI of CRNII-048. The spring course on tropical cyclones can rightfully be considered a legacy of this project.

11. Main conclusions

We summarize here the key findings of each sub-section.

Climatological study from satellite data over oceans

- Several cases were identified in which the sea surface height anomalies were correlated with cyclone trajectory and intensification, as was observed in other cyclonic basins
- However, the climatological results do not find a systematic increase in cyclone category with sea surface height anomaly.
- The role of the ocean eddies in the East Pacific appears to be smaller than hypothesized

Data analysis from T-PARC (preliminary results)

- The circulation increases in the developing cyclones due to the mass convergence at low levels
- As it intensifies, the height of this low level convergence is reduced, confined to a shallower region.
- The surface heat fluxes are very important in the intensification of the cyclones

- The ventilation (related to the advection of air with low entropy) can cause the cyclone to decelerate and dissipate.

Data analysis of climatological database of cyclones that made landfall in Mexico

- Trajectories of landfalling cyclones have a clear seasonal distribution
- Mid-troposphere conditions (geopotential heights and winds) clearly indicate different patterns to discriminate the categories of trajectories.
- Composites of atmospheric conditions for 1, 2 and 3 days prior to landfall are suitable to be used as predictors of landfalling regions.

Modeling with WRF and comparison with observations

- The AWR-core was implemented, with the inclusion of a bogus vortex to simulate the cyclone evolution in a 2-domain simulation with fairly high resolution (20 and 5km, respectively)
- Because numerical simulations kept becoming unstable, an adaptive time step was implemented, which resulted in much higher computational costs.
- The inclusion of the bogus vortex resulted in a much more intense cyclone, comparable in central pressure with the observations.
- The maximum winds were not well reproduced, with the simulations underestimating the observations by about 25%.
- The sensitivity test of the microphysical parameterizations indicates that the more complex one (5 categories of hydrometeors versus 3) results in a more intense cyclone.

Modeling of wave height coupling WWATCH-3 with WRF simulated winds

- The domain selected is adequate for the simulations as long as the tropical cyclones is completely located within it, since the fetch is important for the wave height prediction
- Computational stability was achieved using 25km for horizontal resolution and 900s for the time step.
- The results appear to be acceptable for forecast periods of up to 72 hours.
- A couple of the simulated cyclones underwent variations in their intensity, which resulted in a corresponding wave height evolution.
- A couple of simulated cases included the presence of other tropical cyclones further away from the coast and the interaction between wind vortices has to be simulated correctly in order to predict adequately the associated wave fields.

Historical record of landfalling cyclones 1850-1949

- The research found a large number of records (mostly newspapers and annual report from government offices) in the libraries visited
- A time series of the impacts of landfalling cyclones was constructed from those records
- The variability observed in that century is similar to the one observed since 1949, which is the official record of the National Hurricane Center
- The variability appears to be linked to the Pacific decadal Oscillation, and this link is currently being explored further.
- A database of all impacts has been constructed, which will allow further research to be carried out on the societal impact of tropical cyclones.

- The database will allow the results from the team of CRNII-050 to provide independent dating for the core samples taken from 3 Mexican States in the Pacific coast.

12 Work plan for the last months with associated costs

The original project was scheduled for 3 years. However, due to the bureaucratic delays, the project formally started in January 2007, so an extension was requested and approved by IAI Directorate. The work plan proposed for the final six months (1 July 2010 - 31 December 2010) would allow all the original objectives to be fulfilled. The remainder of the work is detailed as follows:

i) Data analysis:

Analysis of results from coupled ocean-atmosphere global climate models runs (GB Raga, CCA-UNAM, L. Farfan, CICESE).

Since this proposal was funded, there have been several groups that devoted their efforts to evaluate the performance of the coupled models in the different tropical cyclone basins of the world. In particular, models seem to systematically underestimate the frequency of tropical cyclones in the East Pacific. No satisfactory explanations have been put forward for this discrepancy with the climatology of this region. Moreover, recent publications have indicated that most models provide very mixed results in the East Pacific basin in the future. Therefore, the emphasis of the activity as was originally proposed has been somewhat reduced. However it is still important to determine why the different models do not agree on their predictions. Conversations with a few of the modelers involved (at the conferences attended during the project), suggest that perhaps the ocean-atmosphere coupling in the East Pacific is not adequate (mainly the momentum transfer). The particular characteristics of the mixed layer in this region (very shallow) are not fully captured in the coupled models, and could also be responsible for the discrepancy. We plan to evaluate this particular aspect in our activity. A research assistant from IMTA has been contacted to participate in this activity in the next few months.

ii) Modelling:

The WRF model has now been used extensively to simulate past cyclones and the latest advance was the inclusion of a vortex once the National Hurricane Center names the tropical depression. The results are encouraging, because the predicted trajectories are more similar to the observed ones, than one the vortex is not included. We are currently planning having the WRF model running semi-operationally this season and expect to have it fully implemented by the end of the project.

The modeling of the wave height as the cyclone approaches the coast will also be implemented semi-operationally in the next few months. This modeling is done after the WRF results are available, since it is the winds that are forcing the waves in the models used.

iii) Publications:

- Manuscript for publication on the role of ocean eddies on cyclone

intensification in the EPAC (Oropeza and Raga)
- Manuscript for publication on the synoptic scale variability of meteorological parameters (e.g. geopotential and precipitation) during the cyclone season in the Pacific (Romero-Centeno, Farfán and Raga)
- Text book in Spanish on Tropical Cyclones, with emphasis on the EPAC (Raga and Farfán)
- Final report to IAI

It is worth mentioning here that the following activities (not planned originally) have also resulted from this project:

1. A proposal was submitted to the UC-MEXUS program between Dr. Corbosiero (UCLA) and Dr. Raga, to further study the electrification of tropical cyclones in the East Pacific. This proposal was based on the preliminary work started under this project by F. Oropeza and S. Abarca (both PhD students, currently very close to obtaining their degrees) looking at the lightning distribution in tropical cyclones as they approached land. The working hypothesis was that continental cloud condensation nuclei would be entrained into the outer bands of the cyclone by the low-level flow and would lead to more enhanced electrical activity in those bands. The preliminary work was not conclusive (in a statistical sense) but it led to the formulation of the work for the above mentioned proposal, to study the distribution of electrical activity within the cyclones, as a function of the vertical shear of the horizontal winds and as the quadrant within the cyclone, following earlier work by Corbosiero and Molinari on cyclones in the Atlantic basin as they approached the US coast.

2. Very close ties have developed with the group at the CIESAS that studies hurricanes form the past and their link to society for a historical and anthropological point of view. In particular, the ties include M. Raymundo Padilla and Lic. Beatriz Bracamontes who participated as a speakers at the Simposium on Human Dimensions in La Paz. One (RP) provides the historical perspective of how societies have responded to the threat and damage from landfalling cyclones and the other (BB)provided the perspective of a reporter. Moreover, the ties between “hard science” and social sciences developed even stronger, since M. Myriam de la Parra has been collaborating with Dr. in a project to study deaths by lightning in Mexico, but will in the following months study the deaths by the effects of landfalling cyclones (mostly due to flooding and landslides). Their work methodology has brought to this project the human dimension aspect that was missing but more importantly, it has allowed to increase our research network, that can continue in the future after this project ends.

3. Close ties have now developed with the Mexican National Weather Service, and there is interest in establishing the *Spring Course on Tropical Cyclones* as an annual event, sponsored jointly by the National Weather Service and CCA-UNAM. There is currently an agreement in the process to be signed by the parties to formalize this

and to start sponsor of the course in March 2011. Both institutions considered the great contribution that the course has made towards capacity building in the Mexico-Caribbean region. This agreement should be considered as a major success by IAI and the CRN program, because it has constituted a *seed* that now can be taken over by other programs. It is clear to this team that this course would have never been established had it not been for the support of this CRNII-0048 grant. Furthermore, the link to the National Weather Service will allow more ready communication of the results that were obtained during this project, that may help them improve their forecasts of cyclones, particularly those that threaten to make landfall onto the Pacific coast of Mexico and Central aAmerica.

4. On-line access to trajectory and intensity forecast using the model WRF in which a cyclonic vortex is included. This activity is currently underway and will be available on the project web page as well as in CICESE's web page in the next few months.

5. On-line access to wave-height prediction as the cyclones approach land using WWATCH-3 model. This activity is currently underway and will be available on the project web page in the next few months.

The detailed cost estimates for planned activities for the remainder of the project are as follows:

Expenditures @ UNAM	Cost (usd)
1 research assistant @ 1500 usd per month x 7 months	10500
3 research assistant @ 800 usd per month x 6 months	14400
Publication costs 2 @ 1500 usd	3000
Final PI meeting:	
Per diem @ 210 usd per day x 3days x 7 people	4410
Flights @1000usd x 4 people	4000
Total	**36310**