RAPID DEEPENING OF TROPICAL CYCLONES IN THE NORTHEASTERN TROPICAL PACIFIC: THE RELATIONSHIP WITH OCEAN EDDIES

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1. INTRODUCTION

During the 1995 North Atlantic tropical cyclone season, hurricane Opal (the most intense in that season) experienced a sudden and unpredicted intensification 24 h before its landfall. During the rapid deepening from 965 hPa to 916 hPa over 14 h, Opal moved over an Anticyclonic Ocean Eddy (AOE) that had been shed from the Loop Current in the Gulf of Mexico (Hong et al. 2000). During this event the 1-min surface winds, estimated from reconnaissance flights, increased from 35 to more than 60 ms-1, and the radius of maximum wind decreased from 40 to 25 km (Shay et al., 2000).

During the 2003 western North Pacific tropical cyclone season, Supertyphoon Maemi (the most intense of the season) intensified (in 1-min sustained wind) from 41 to its peak of 77 ms-1 during its 36 h interaction with an AOE. Based on results from the Coupled Hurricane Intensity Prediction System (CHIPS) and satellite microwave sea surface temperature observations, Lin et al. (2005) demonstrated that the AOE acts as an effective insulator between typhoon and the deeper ocean cold water, inhibiting the effect of negative feedback (originally discussed by Chang and Anthes, 1978) between the ocean and the typhoon.

During the 2005 North Atlantic tropical cyclone season, Katrina and Rita (the third and second most intense cyclones of that season) experimented rapid deepening during its encounter with an AOE in the Gulf of Mexico. Jaimes and Shay (2009) have studied these cases using airborne measurements deployed from four aircraft flights during September 2005; moored Acoustic Doppler Current Profiler (ADCP) and Conductivity, Temperature, Depth (CTD) data; wind stress evaluation; geostrophic circulation evaluation and isotherm depth estimated from sea surface height anomaly satellite-based radar altimetry, to evaluate the rapid increase in intensity experimented by Katrina and Rita during their passages over mesoscale ocean features like an AOE and the Loop Current. They conclude that in each case the hurricane central pressure decreases correlated better with the depth of the 26°C isotherm and the oceanic heat content than with the sea surface temperature (SST).

Previous studies have shown that the generation of AOE off the Mexican coast over the Gulf of Tehuantepec (GT) is due to intermittent strong offshore winds in that region, mainly during the boreal cold season (fall–winter) (Clarke, 1998; McCreary et al., 1989; Lavin et al., 1992; Giese et al., 1994; Müller-Karger and Fuentes-Yaco, 2000) cited by Zamudio et al. (2006). Those winds reach the Pacific Ocean at the GT with gusts of 35 m/s (Romero-Centeno et al., 2003). Zamudio et al. (2006) performed an analysis of satellite altimeter observations and Naval Research Laboratory Layered Ocean Model simulations to study the interannual variability of eddies in the GT., Their results suggest that coastally trapped waves, which are generated in the equatorial Pacific, play a crucial role in the modulation and generation of Tehuantepec eddies and a dominant role in Tehuantepec eddy interannual variability.

In this study we address the following questions:

1. Is this interaction between hurricanes and AOE occurring in the northeastern Tropical Pacific (NETP) basin?

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2. Is that interaction a necessary condition in order for rapid or explosive deepening to occur during the evolution of tropical cyclones in the region?
3. Is that interaction important to produce major hurricanes (3, 4 and 5) in the region?

The use of best-track information from the National Hurricane Center (NHC) to identify tropical cyclones that reached the criteria of Rapid Deepening or Explosive Deepening in the NETP (1993-2008) is discussed in Section 2, in Section 3 we discuss the use of altimetry data from Ssalto/Duacs-AVISO to investigate the interaction of those tropical cyclones with an AOE.

The evaluation of the relative contribution of mesoscale oceanic features and of atmospheric processes to hurricane intensity fluctuations using the North American Regional Reanalysis (NARR) and Simple Ocean Data Assimilation (SODA) are discussed in Section 4. Final remarks and conclusions are presented in Section 5.

2. SELECTION CRITERIA FOR CASE STUDIES

The glossary of the National Hurricane Center (NHC) defines the terms Rapid Deepening (RD) and Explosive Deepening (ED) as a decrease in the minimum sea-level pressure of a tropical cyclone of 1.75 mb/hr or 42 mb for 24 hours; and 2.5mb/hr for at least twelfth hours or 5 mb/hr for at least six hours, respectively. (http://www.nhc.noaa.gov/aboutgloss.shtml).

The deepening rate (dp/dt) was calculated from the NHC Best-Track (BT) dataset for each named tropical cyclone between 1993 and 2008. Forty two tropical cyclones were found to reach the RD criteria and two the ED one. The two ED cases were hurricane Carlotta in 2000 and hurricane Elida in 2002, and both of them reached category four in the Saffir-Simpson scale. In Figure 1 the evolution of central pressure and deepening rate are shown for hurricane Carlotta (Fig. 1a) and hurricane Elida (Fig. 1b).

For practical reasons we will consider the RD and ED criteria together as Deepening Criteria (DC). Out of the sixteen seasons analysed, fifteen presented at least one tropical cyclone reaching the DC. The only season with no tropical cyclone reaching the DC was 1999, the most inactive season on record in terms of total number of tropical cyclones, with only eight (Fig. 2).

a)

b)

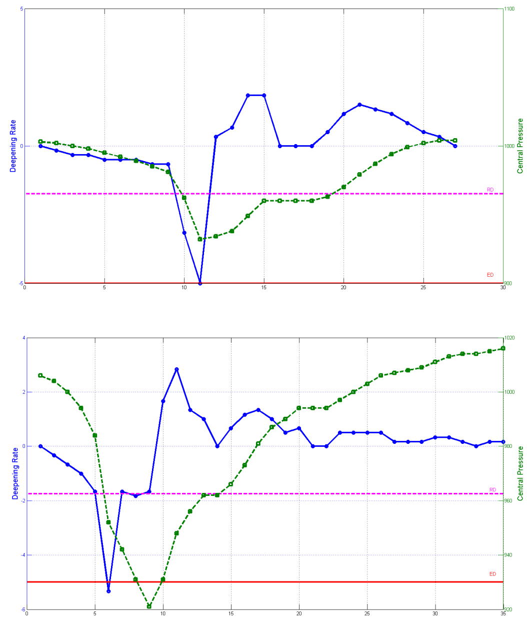

Figure 1. Central pressure (dashed green line, right size scale) and deepening rate (solid blue line, left size scale) evolution for tropical cyclones a) Carlotta-2000, and b) Elida-2002. The dashed magenta horizontal line is indicating the RD criteria threshold and the solid horizontal red line de ED criteria threshold.

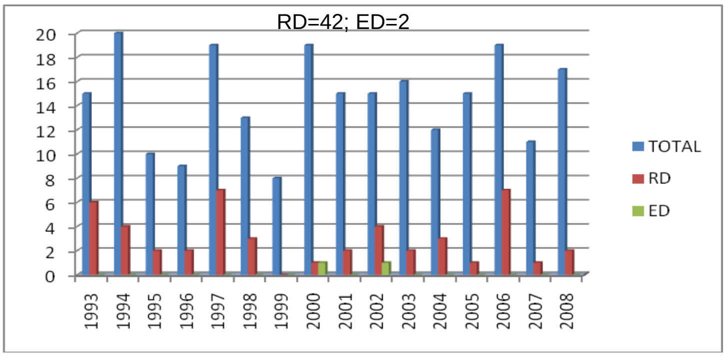

Figure 2. Frequency distribution of total number of tropical cyclones (blue), number of tropical cyclones reaching the RD criteria (red), number of tropical cyclones reaching the ED criteria (green).

3. TROPICAL CYCLONE-ANTICYCLONIC OCEAN EDDIES INTERACTION

3.1 OCEAN EDDIES INTERNAL CIRCULATION AND ITS IMPLICATIONS

Figure 3 shows a sketch of the horizontal and vertical views of a) AOE's circulation and b) Cyclonic Ocean Eddie's circulation.

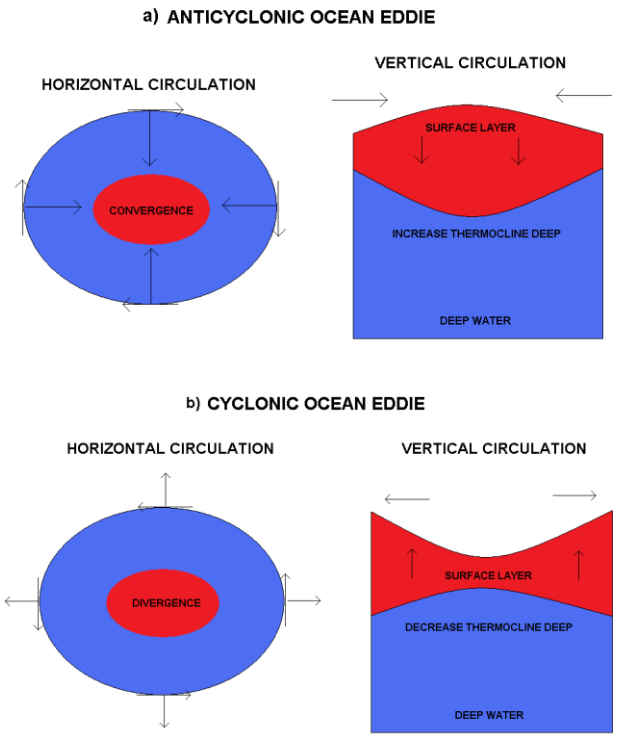

Figure 3. Horizontal and vertical views of a sketched internal dynamics of a) Anticyclonic Ocean Eddie and b) Cyclonic Ocean Eddie.

In the northern hemisphere, anticyclonic horizontal flow (cyclonic horizontal flow) induces a secondary circulation directed to the centre of the gyre (to the periphery of the gyre). In the vertical, this convergence (divergence) must be balanced by a downward (upward) motion. Because the water near the surface (far away from the surface) is warmer (cooler), and the secondary downward flow increases (decrease) the thermocline depth, the result is a local pool of warm (cool) water. This local pool of warm (cool) water would constitute a heat source (sink) to hurricanes in the vicinity. In this work we only focus on the interactions between AOE and hurricanes interactions. These warm features are characterized by a deepening of several meters of the isotherms towards their centres (in regions like the Gulf of Mexico could be several tens of meters) and with different temperature and salinity structure than the surrounding waters.

3.1.1 LOCATING OCEAN EDDIES IN THE ALTIMETRY DATA

The presence of an AOE in the Sea Surface Height Anomaly (SSHA) product is identified by a positive anomaly (dome) and it is possible to calculate its associated surface geostrophic circulation. Figure 4 shows an instantaneous SSHA map from AVISO and its related geostrophic circulation for 27th of April 2005.

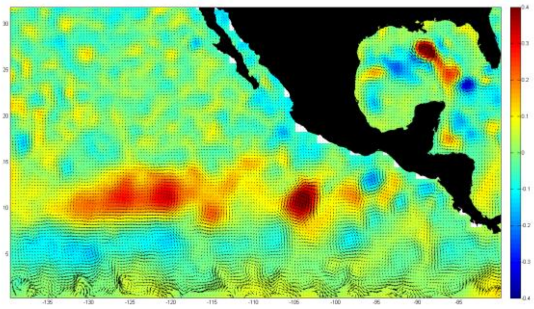

Figure 4. SSH anomaly (m) from AVISO and their associated surface geostrophic circulation for 27th of April 2005, showing a very well developed Anticyclonic Ocean Eddy at 105 W and 10 N .

The presence of an AOE in the NETP near (105W, 10N) location is clearly visible. Satellite altimeter data from Ssalto/Duacs-AVISO combined with BT-NHC information where used to identify the tropical cyclones that moved over an AOE during their evolution. The delayed time merged data product from the AVISO project was used, with a time resolution of 7 days and spatial resolution of about 20 arc minutes with global geographical coverage.
(http://opendap.aviso.oceanobs.com/thredds/dodsC)

Figure 5 a) shows an interpolated instantaneous SSHA map with the partial trajectory of hurricane Fausto at 00 UTC hrs on 12 September 1996, it also shows tree time series of: b) the deepening rate and thresholds for the two deepening criteria, c) the minimum central pressure, and d) the evolution of the SSHA calculated in a square area of 1° by 1° centred in the hurricane current position.

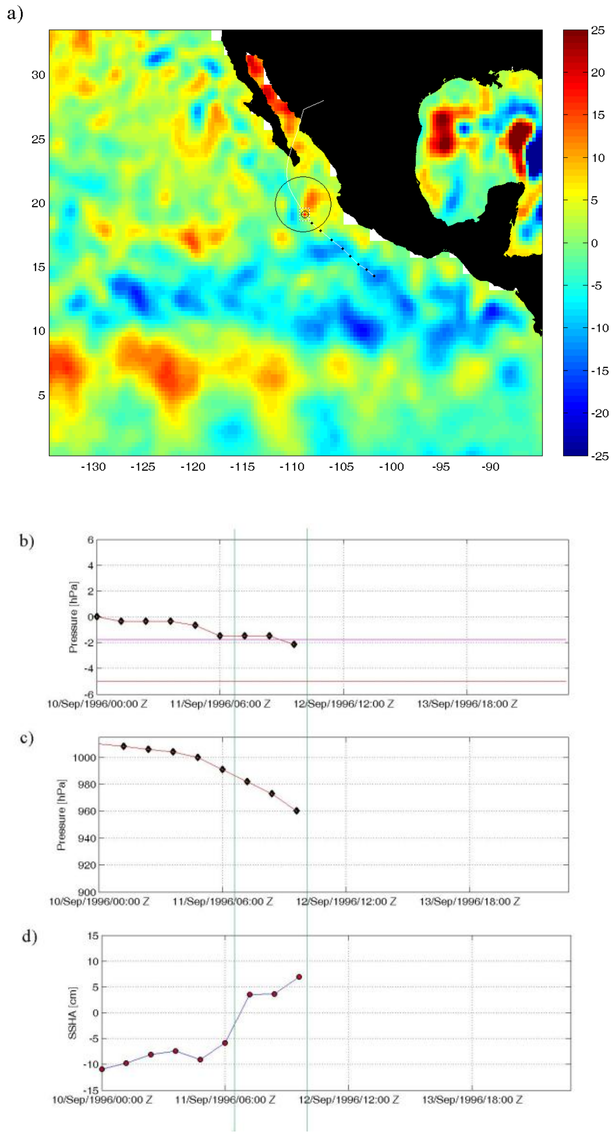

Figure 5. a) SSHA instant map (cm) interpolated from AVISO for 00 hrs UTC of 12th of September 1996 and partial Best-Track trajectory for hurricane Fausto at the same time, b) deepening rate (dp/dt) evolution, the magenta line indicates the threshold for Rapid Deepening Criteria and the red line indicates the threshold for Explosive Deepening Criteria, c) Minimal central pressure evolution taken from the NHC-Best-Track, d) Sea Surface Height Anomaly evolution calculated from interpolated maps for each Best-Track hurricane position. Circle and green vertical lines highlights the moment of hurricane-AOE interaction.

Note that in Fig. 5, the time when the Rapid Deepening threshold is exceeded coincides with the hurricane-AOE interaction. In this particular case, the DC was satisfied during only 6 hours and the peak intensity of the cyclone occurs about 6 hours after this interaction with the SSHA. The maximum magnitude of the SSHA is about 7 cm and the horizontal extent of the positive anomaly is small (we classify small=250 km, medium=300 km, and Large=800 km of mean ratio for positive anomalies). This is a category 3 hurricane and the interaction with the AOE occurs during its intensification stage. Since the hurricane was already intensifying when it encountered the AEO the atmospheric conditions were favourable for intensification. We apply this methodology to each tropical cyclone in the NETP basin from 1993 to 2008, in order to evaluate which cases presented an interaction with AEOs. Figure 6 is similar to Fig. 5a for a sub-set of twelve hurricanes from 1993 to 2008, highlighting the co-location of hurricanes and AOE.

Forty-nine tropical cyclones reached the deepening criteria between 1993 and 2008 in the NETP basin. However, five of them were removed from the dataset since their trajectories started to the west of 140 W, so the final data set used for this study is based on forty-four tropical cyclones. The results of this evaluation are summarized in Table 1. Thirty cyclones (68%) presented a clear interaction with AOE (indicated by the red rows in table 1), or at least with a positive SSHA (in some cases, the horizontal circulation of the AOE is not very well defined, or the positive SSHA is related with other oceanic features). Note that 28 (93%) of those are major hurricanes (cat 3, 4 and 5). Fourteen cyclones (32%) did not present a clear interaction with positive SSHA (indicated by the blue rows in table 1), and some of them had a clear interaction with a negative SSHA, mostly related with Cyclonic Ocean Eddies. Such interactions are related in the literature with rapid weakening (Emanuel, 2004; Jaimes and Shay, 2009) but we did not find any evidence of that effect in this analysis.

The mean value of the magnitude of the SSHA in the set was about 7 cm and the standard deviation was 3.7cm. The maximum SSHA value was 15 cm and it was observed in two interaction cases: Lane (2006), and Linda (1997). There are 14 cases in which hurricanes interacted with ocean features that had SSHA larger or equal to the mean value , 93% of them were major hurricanes (3, 4 y 5) and 71% were categories 4 and 5.

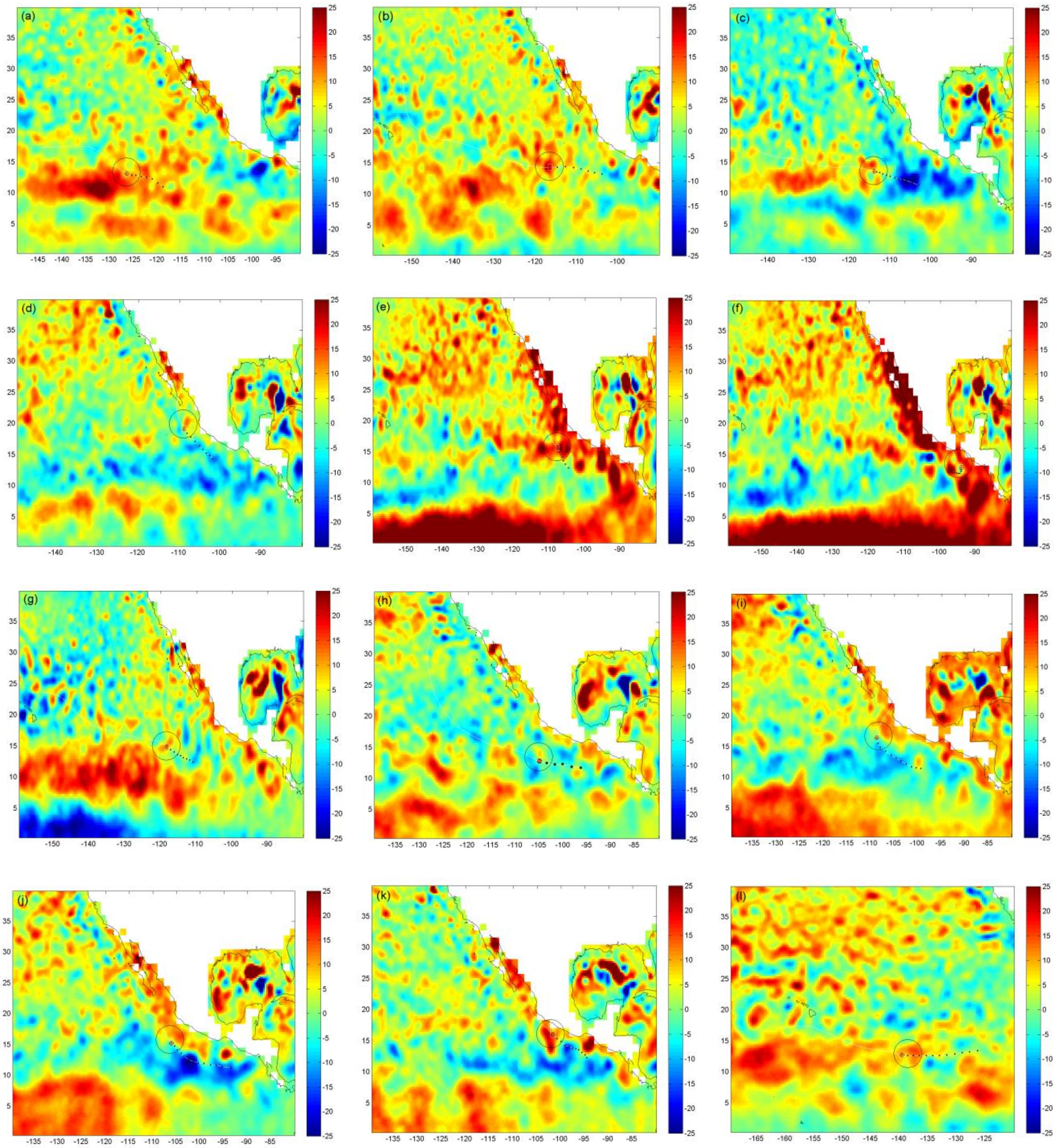

Figure 6. Interpolated instant field of SSHA and Best-Track trajectory in UTC for 12 hurricanes: a) Dora (16/07/1993/06 hrs), b) Fernanda (11/08/1993/00 hrs), c) Barbara (10/07/1995/12 hrs), d) Fausto (12/09/1996/00 hrs), e) Linda (11/09/1997/06 hrs), f) Pauline (07/10/1997/06 hrs), g) Darby (25/07/1998/00 hrs), h) Elida (24/07/2002/12 hrs), i) Kenna (24/10/2002/12 hrs), j) Javier (13/09/2004/18 hrs), k) John (30/08/2006/12 hrs), l) Flossie (11/08/2007/12 hrs)

Table 1. Summary of selected case studies from 1993 to 2008, and its relevant information related with the interaction of each cyclone with AOE

YEAR	NAME	I-AOE	SSHA	IDIP	H-TMI	ANOM. HORIZONTAL EXTENSION	DURATION OF DC	CATEGORY
1993	Dora	Y	+8	Y	24	L	6	H-4
	Fernanda	Y	+13	Y	12	L	12	H-4
	Greg	Y	+5	Y	0	L	12, 6	H-4
	Kenneth	Y	+8	Y	6	L	18	H-4
	Lidia	N	-4	Y	0	M		H-4
1994	Emilia	Y	+5	Y	30	L	6, 12	H-5
	Gilma	Y	+10	Y	12	L	12	H-5
	John	Y	+10	Y	72	L	6	H-5
	Olivia	Y	+2.5	Y	0	M	30	H-4
1995	Barbara	Y	+6	Y	6	M	6, 6	H-4
	Juliette	N	-2.5	Y	6	S		H-4
1996	Douglas	Y	+4	Y	90	S	6	H-4
	Fausto	Y	+6	Y	6	S	6	H-3
1997	Felicia	Y	+3	Y	24	S	6	H-4
	Guillermo	Y	+7	Y	36	M	12	H-5
	Jimena	Y	+7	Y	0	M	12	H-4
	Linda	Y	+15	Y	6	L	24	H-5
	Nora	Y	+12	Y	0	L	6	H-3
	Pauline	Y	+5	Y	6	L	12	H-4
	Rick	Y	+10	Y	0	M	6	H-1
1998	Darby	Y	+10	Y	6	M	6, 6	H-3
	Estelle	Y	+5	Y	0	M	6	H-4
	Howard	N	-5	Y	0	S		H-4
1999	No cases were found							
2000	Carlotta	N	-5	Y	0	S		H-4
	Daniel	Y	+3	Y	12	M	6	H-3

Table 1. Summary of selected case studies from 1993 to 2008, and its relevant information related with the interaction of each cyclone with AOE (cont.).

YEAR	NAME	I-AOE	SSHA	IDIP	H-TMI	ANOM. HORIZONTAL EXTENSION	DURATION OF DC	CATEGORY
2001	Adolph	N	-10	Y	24	M		H-4
	Juliette	N	-10	Y	12	S		H-4
2002	Elida	Y	+3	Y	6	S	6, 6	H-4
	Kenna	Y	+5	Y	6	L	18	H-5
2003	Ignacio	N	-1	Y	0	M		H-2
	Nora	N	-5	Y	0	M		H-2
2004	Frank	Y	+3	Y	12	S	6	H-1
	Howard	N	-3	Y	0	S		H-4
	Javier	Y	+3	Y	0	L	18	H-4
2005	Kenneth	N	-6	Y	30	L		H-4
2006	Daniel	Y	+6	Y	30	S	6	H-4
	Ileana	Y	+2	Y	6	S	6	H-3
	John	Y	+10	Y	24	M	6, 6	H-4
	Lane	Y	+15	Y	6	M	6	H-3
	Paul	N	-8	Y	12	S		H-2
	Sergio	N	-15	Y	0	S		H-2
2007	Flossie	Y	+10	Y	0	M	6	H-4
2008	Elida	N	-3	Y	0	S		H-2
	Hernan	N	-10	Y	0	S		H-3

Notation for Table I Heading

I-AOE = Interaction with Anticyclonic Ocean Eddie

SSHA = Sea Surface High Anomaly

IDIP = Intensification during the Intensification Period

H-TMI = Hours before Time of Maximum Intensity

ANOM. HORIZONTAL EXTENSION: S≈250 Km, M≈300 Km, L≈ 800 km

Another measure of the evolution of the intensity of a tropical cyclone is the duration of the period during which the deepening criteria were satisfied. The mean value of the duration in the set was 10 hours and the standard deviation, 6.1 hours. The maximum value calculated was 30 hours in the case of hurricane Olivia-1994 (cat 4) and the second longest was 24 hours (Linda-1997). There are 12 cases with the duration of the period in which the deepening criteria was satisfied, larger than the mean value and all of them developed into hurricanes with categories 4 and 5.

Within the set, we observed six cases that presented more than one period in which the DC was satisfied, and those are marked in the Table 1 with two numbers in the column labelled “Duration of DC”. Linda (1997) is the most intense hurricane in the basin record, it presented AOE-interaction and deepening criteria were satisfied during at least 24 hours, its trajectory moved over a SSHA with magnitude larger than the mean value, and while it was co-located with this ocean feature, Linda experienced its lowest translation speed (between 8 and 12 km/h), likely maximizing the impact of the AOE on its deepening.

4. EVALUATING THE ENVIRONMENTAL PARAMETERS

4.1 ATMOSPHERIC PARAMETERS

North American Regional Reanalysis (NARR) data were used to analyze atmospheric environmental parameters, similar to those originally calculated from Gray (1975):

1) Low level relative vorticity
2) Vertical shear of the zonal wind between lower and upper troposphere
3) Middle troposphere relative humidity

The data are available through an Open-source Project for a Network Data Access Protocol (OpenDap) server (http://nomads.ncdc.noaa.gov/dods/NCEP_NARR_DAILY) and have a spatial resolution of 32 km and a time resolution of 3 h, in 29 vertical levels (Mesinger, 2005).

4.1.1 LOW LEVEL RELATIVE VORTICITY

The zonal and meridional components of the wind velocity at 850 hPa from the NARR were used to calculate the relative vorticity,

$$\zeta_r = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

Figure 7 shows an example (hurricane John-2006) of the vorticity maps calculated for each time step during the life period of each hurricane in the data set. The mean value of the vorticity was estimated on a 4° by 4 ° box (indicated by the dashed line, shown centred on the hurricane current position), to generate a time series highlighting the conditions during genesis and evolution.

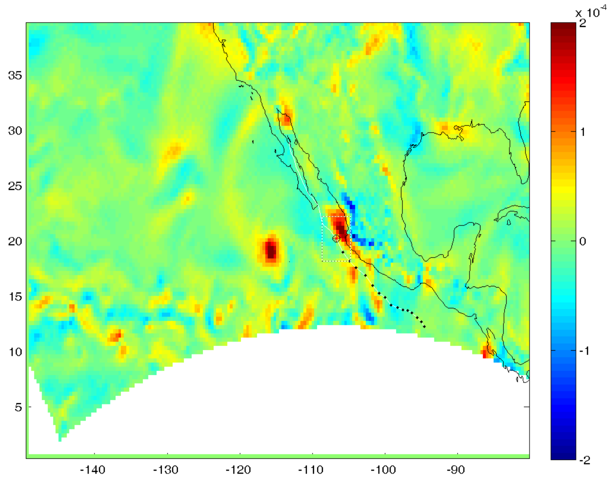

Figure 7. Vorticity field at 850 hPa (s-1), calculated from NARR wind fields for hurricane John at 31/08/2006/18 hrs

4.1.2 VERTICAL SHEAR OF THE ZONAL WIND

The zonal component of wind vector from 200 hPa was subtracted from the zonal component of wind vector at 850 hPa, to estimate the wind shear. The time evolution of the mean value in the 4°x4° box centred in the location of the cyclone can be compared against the other atmospheric and oceanic forcings. Figure 8 shows an example (John-2006) of the zonal wind shear calculated for each time step during the life period of each hurricane in the data set.

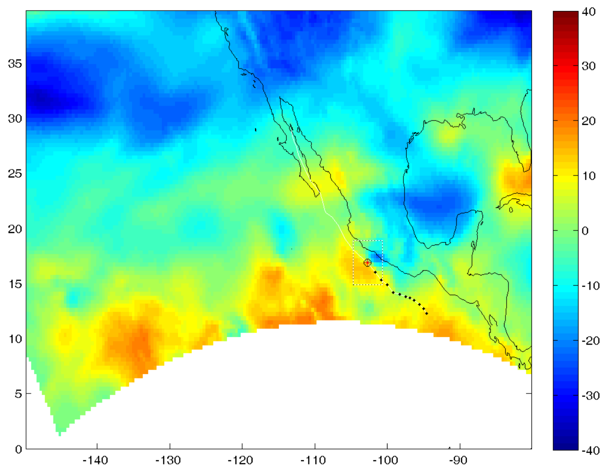

Figure 8. Zonal wind shear field (m/s) (850-200 hPa), calculated from NARR wind fields for hurricane John at 30/08/2006/18 hrs

4.1.3 MIDDLE TROPOSPHERE RELATIVE HUMIDITY

Using the specific humidity and ambient temperature data from the NARR, we calculate the vapor pressure and saturation vapor pressure in order to estimate the relative humidity for all the NARR vertical levels (29). The vertical profile was compared with the reference value of 75%, in order to estimate the vertical integral of humidity anomaly (from 1000 to 500 hPa): positive (humidity values larger than 75%) and negative (humidity values smaller than 75%). This calculation was done every 6-hours during the life period for each hurricane in the data set, and an example (John-2006) of this vertical profile and the integrated areas, representing relatively dry (red) and wet (blue) air in the environment surrounding the hurricane system, can be seen in Figure 9.

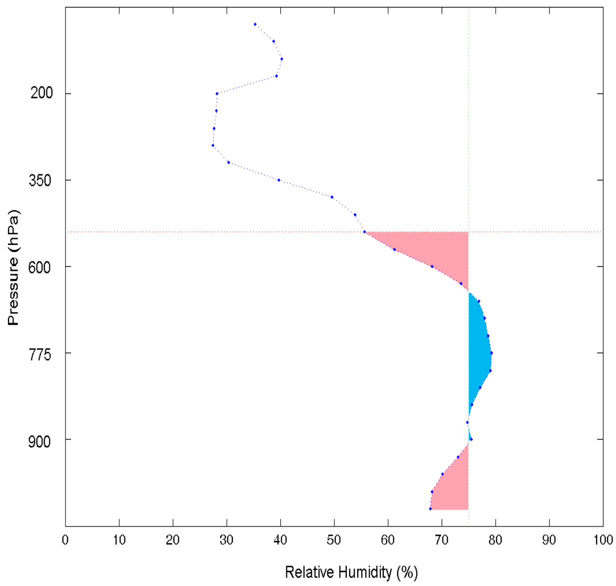

Figure 9. Relative humidity (%) profile and its integrated values from 500 to 1000 hPa levels with respect to a reference value of 75% relative humidity, calculated from NARR for hurricane John at 04/09/2006/00 hrs. Red areas indicate dry air blue areas indicates wet air in the environment surrounding the hurricane system.

4.2 OCEANIC PARAMETERS

5-day averaged 3-D fields of temperature, salinity and velocity, and surface fields of SSH from the Simple Ocean Data Assimilation (SODA) retrospective analysis were used to calculate oceanic environmental parameters a general description of this data can be found in (Carton et al. 2000a and 2000b).

4.2.1 THE DEPTH OF THE 26°C ISOTHERM AND THE SEA SURFACE TEMPERATURE

Using 3-D fields of temperature data from SODA, we calculate the depth of the 26°C isotherm. Figure 10 shows an example (Dora-1993) of a tropical cyclone moving over a region where the depth of the 26°C isotherm is about 70 m, due to the presence of an AOE. Note that the oceanic waters surrounding the AOE has a 26°C isotherm depth of about 40 m.

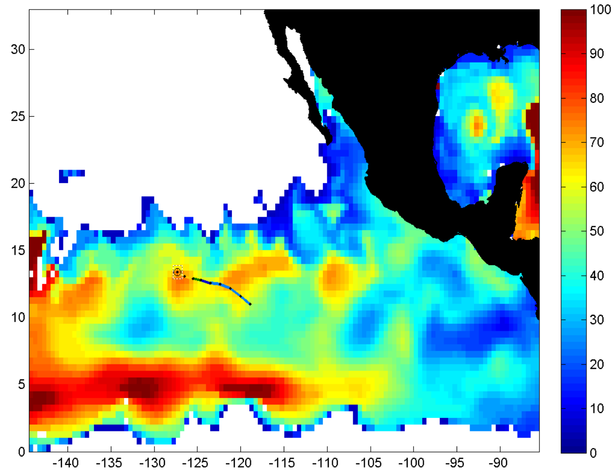

Figure 10. 26°C isotherm depth (m) instant map, calculated from SODA and Best-Track partial trajectory for hurricane Dora at July 16th, 1993 at 12 UTC.

Figure 11 shows the corresponding Sea Surface Temperature (SST), where the presence of the AOE is not at all evident. Interpolated maps were calculated for the lifetime of each tropical cyclone. The SST was calculated as the temperature from the upper most level of the SODA (5m).

4.2.2 OCEANIC HEAT CONTENT

Figure 12 shows a sketch of the concept of Ocean Heat Content (OHC) that can be we calculated as the following integral:

$$Q = \int_{Z=H_{26}}^{z=0} \rho_w C_w (T - 26)\partial z$$

Where ρ_w is the ocean water density (1026 kg/m^3) and C_w is the specific heat of ocean water (4,186 J/kgK) and T is the temperature for each of the vertical layers and dz is the depth between layers. Note that the reference temperature is 26°C (the temperature assumed for tropical cyclogenesis). Figure 13 shows a map of the OHC, calculated from the 3-D temperature field from SODA for hurricane Pauline-1997 at 12Z on 7 October. Interpolated maps were calculated covering the lifetime of each tropical cyclone.

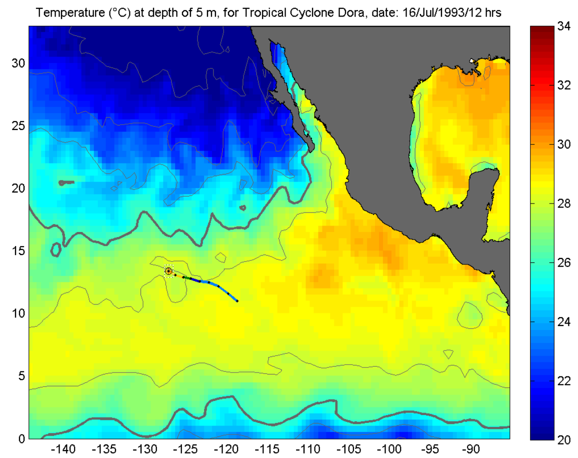

Figure 11. SST instant map and Best-Track trajectory for hurricane Dora, in July of 1993.

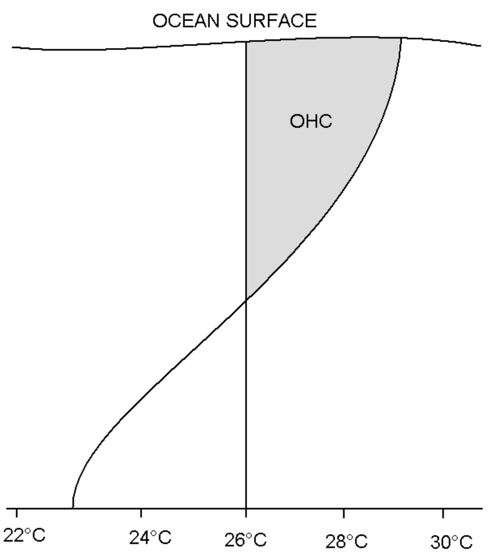

Figure 12. Sketch of the concept of Ocean Heat Content, Gray (1975).

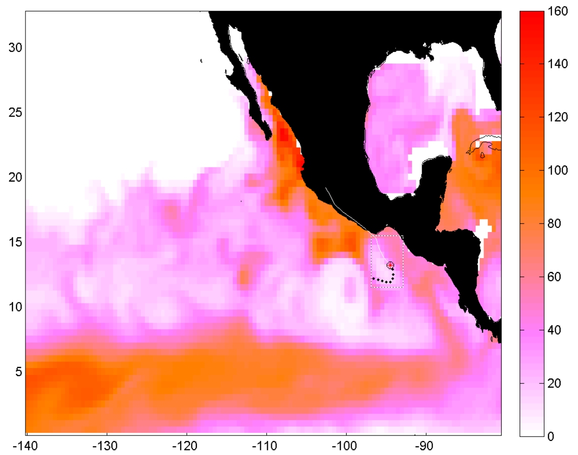

Figure 13. Ocean Heat Content (KJ/cm^2) calculated from SODA, for tropical cyclone Pauline on 7 October in 1997 at 12 hrs.

4.3 NORMALIZED TIME SERIES

In order to estimate the relative importance of the different atmospheric and oceanic environmental parameters its evolution was calculated for the case studies, an example for Hurricane Linda in 1997 is showed in figure 14, figure 14-a shows the evolution of maximum wind velocity (blue) and minimal central pressure (green), figure 14-b shows the normalized time series of Relative Humidity at 550 hPa (red), zonal wind shear in mirror-image (magenta), wet air (blue), dry air (green), and OHC (black).

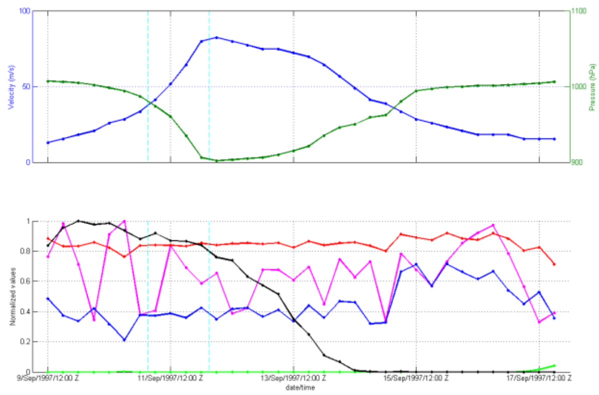

Figure 14. a) time series for wind velocity and pressure for hurricane Linda-1997, and b) Normalized time series of RH at 550 hPa, zonal wind shear in mirror-image (bigger values have positive impact in hurricane intensity), dry and wet air in the surrounding environment, and Ocean Heat Content.

5. SUMMARY AND CONCLUDING REMARKS

Energy exchange between the hurricane and the ocean in relation with Hurricane-AOE interaction appears to be the most important mechanism in order to hurricanes in the NETP to reach DC.

The analyzed cases have shown the importance of long exposure time from hurricanes to AOE in the NETP most of the cases with long exposure time (larger than the mean value of the set) are cat 5 hurricanes.

1997 was the most active season in terms of number of hurricanes that have reached the DC with 7, all of them have presented AOE interaction (6 of them are major hurricanes), the second most active season was 2006 with 6 hurricanes reaching the DC, 4 of them have presented the AOE interaction and those 4 are major hurricanes, it is possible to link this activity with El Niño?

The intensification related with Hurricane-AOE interaction always occurs during the intensification period, it means that the interaction by itself is not enough in order to increase the intensity of hurricanes in the region; Atmospheric environment has to be positive

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6. REFERENCES

Emanuel, K. A., C. DesAutels, C. Holloway, and R. Korty, 2004: Environmental control of tropical cyclone intensity. J. Atmos. Sci., 61, 843–858..

Carton, J.A., G. Chepurin, X. Cao, and B.S. Giese, 2000a: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995, Part 1: methodology, J. Phys. Oceanogr., 30, 294-309.

Carton, J.A., G. Chepurin, and X. Cao, 2000b: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950-1995 Part 2: results, J. Phys. Oceanogr., 30, 311-326.

Chang, S. and R. Anthes, 1978: Numerical simulations of the ocean's nonlinear baroclinic response to translating hurricanes. J. Phys. Oceanogr., 8, 468–480.

Gray, W. M., 1975: Tropical Cyclone genesis. Dept. of Atmos. Sci. Paper No. 234, Colorado State Univ., Ft. Collins, CO.

Hong, X., S. W. Chang, S. Raman, L. K. Shay, and R. Hodur, 2000: The interaction between Hurricane Opal (1995) and a warm core ring in the Gulf of Mexico. Mon. Wea. Rev., 128, 1347–1365.

Jaimes, B., and L. K. Shay, 2009: Mixed layer cooling in mesoscale oceanic eddies during hurricanes Katrina and Rita. Mon. Wea. Rev., 137, 4188-4207.

Jacob, S. D. and L. K. Shay, 2003: The role of mesoscale features on the tropical cyclone–induced mixed layer response: a case study. J. Phys. Oceanogr., 33, 649–676.

Marks, F., L. K. Shay, and PDT-5, 1998: Landfalling tropical cyclones: Forecast problems and associated research opportunities. Bull. Meteor. Soc., 79, 305–323.

Mesinger, F.; G. DiMego, E. Kalnay, K. Mitchell, P.C. Shafran, W. Ebisuzaky, D. Jovic, J. Woollen, E. Rogers, E.H. Berbery, M.B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish and W. Shei (2005). North American Regional Reanálisis. BAMS, 87:3, 343-360.

Romero-Centeno, R., J. Zavala-Hidalgo, A. Gallegos, and J. J. O'Brien, 2003: Tehuantepec isthmus wind climatology and ENSO signal, J. Clim., 16, 2628–2639.

Scharroo, R., W. H. F. Smith, and J. L. Lillibridge, 2005: Satellite Altimetry and the Intensification of Hurricane Katrina, Eos Trans. AGU, 86(40), doi:10.1029/2005EO400004.

Shay, L. K., G. J. Goni, and P. G. Black, 2000: Effects of a warm oceanic feature on Hurricane Opal. Mon. Wea. Rev., 128, 1366–1383.

Shay, L. K., and E. W. Uhlhorn, 2008: Loop Current response to Hurricanes Isidore and Lili. Mon. Wea. Rev., 136, 3248-3274.

Zamudio, L., H. E. Hurlburt, E. J. Metzger, S. L. Morey, J. J. O'Brien, C. E. Tilburg, and J. Zavala-Hidalgo, 2006: Interannual variability of Tehuantepec eddies, J. Geophys. Res., 111, C05001, doi:10.1029/2005JC003182.