

Estimation of tropical cyclone heat potential in the Bay of Bengal and its role in the genesis and intensification of storms

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Received 27 December 2004, revised 31 January 2006

In the present study, cyclone heat potential (CHP) in the Bay of Bengal has been estimated for different seasons using Levitus climatology. A good association was noticed between CHP and the efficiency of intensification (i.e the ratio between severe storms to total number of storms (in $5^{\circ} \times 5^{\circ}$ grid), for the period, 1877-1977. CHP has been estimated using CTD data collected along the transects 88° E (4° - 20° N) and 11.5° N (81° - 92° E) during 1993-96 under pre-, during and post- SW monsoon seasons. These estimates are compared with those obtained from TOPEX/Poseidon sea surface height anomalies (SSHA) and TMI (Tropical Rainfall Measuring Mission Microwave Imager) SST using a two layer gravity model. The above estimates are also compared in the Andaman Sea for the 1996 post- SW monsoon season. It appears that the later method underestimates the CHP in the regions of anti cyclonic gyre (ACG). A relation between CHP and SSHA is proposed for the Bay of Bengal which shows a high correlation of 0.79 (N= 67; significant at > 99% level) using the CTD data.

[Key words: Cyclones, Bay of Bengal, cyclone heat potential, sea surface height, SST, storms, heat potential]

Introduction

Tropical cyclones originate in the oceanic regions where the sea surface temperature (SST) is above 26°C . About 87% of the tropical cyclones occur in the latitudinal belt between 20°N and 20°S and two third of all tropical cyclones occur in the Northern Hemisphere. In the Southern Hemisphere, most of the tropical cyclones form between 5° - 15° latitudes and rarely beyond 22°S , whereas in the Northern Hemisphere they form at latitudes up to 36°N . In the meridional direction, there are three favoured locations: 90°E , 140°E and 150°W . The western part of the North Pacific Ocean accounts for about one third of all the tropical cyclones. Generally, summer is the favourable season, especially in the North Pacific Ocean¹.

In the north Indian Ocean during spring (April-May) and fall (October-December) seasons, the

region between 10° and 15° N gives rise to several depressions, some develop into storms, while few even intensify into severe storms. Usually they move towards northwest and strike the coasts of Andhra Pradesh and Orissa. However, some of them recurve in the Bay of Bengal and hit north coast of the Bay¹. Almost all the storms crossing north of 17°N move north to north east during post-monsoon season. It is observed that 33 out of 38 storms (about 87%) formed during the El-Nino years have not recurved and crossed the coast south of 17°N whereas 38 out of 48 storms (79%) formed during the year previous to the El-Nino either recurved or crossed north of 17°N . During severe El-Nino years 15 out of 16 storms (about 94%) have crossed south of 17°N whereas during the year previous to severe El-Nino years 17 out of 19 (about 89%) have either recurved or crossed north of 17°N . The above points indicate the strong link between El-Nino and storm tracks in the Bay of Bengal.¹

It is known that the frequency of occurrence of cyclones is 3 to 4 times higher in Bay of Bengal as

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compared to the Arabian Sea². The favourable conditions for the formation of cyclone are low level vorticity, coriolis parameter, the inverse of the vertical shear of the horizontal wind between the lower and upper Troposphere, ocean thermal energy, sea temperature in excess of 26°C to a depth of 60 m, vertical gradient of temperature between the surface and 500 mb and mid Troposphere relative humidity.

It is not exactly known which one of the above parameters is playing a key role in Bay of Bengal. The ocean thermal energy is referred to as “hurricane heat potential”³ or cyclone heat potential (CHP), which is defined as the integrated temperature in excess of 26°C up to the depth of 26°C isotherm. This value represents a threshold temperature suggested for hurricane genesis by Palmen⁴. Presumably, the surface fluxes would be small below this value. In the Bay of Bengal, SST is more than 26°C most of the year except in winter (December-February). The depth of 26°C isotherm (D26) is also more than 60 m in most parts of the Bay except in winter. Maximum values of D26 are observed in the western Bay during April-May.⁵

Distribution of CHP during SW monsoon (July-September) and fall (October-December) was reported earlier⁶. Seasonal variability of CHP and its role in the intensification of storms in the Bay of Bengal have been reported by Sadhuram *et al.*⁵. The seasonal variability of Effective Oceanic Layer for Cyclogenesis (EOLC) and the associated effective heat potential, the parameters representing the thermohaline regime of the near surface stratified layer, were reported⁷ in relation to seasonal cyclogenesis over the Bay.

It is now realized that upper ocean thermal structure plays a vital role in the intensification of a storm. Warm layers of 26°C extended at least 100 m beneath the surface in these oceanic features which represent high heat potential (> 90 kJ/cm²) in the western Gulf of Mexico^{8,9}. Monitoring of warm and cold core eddies and the regions of high heat potential have become important to predict the intensification of a storm. A few studies¹⁰⁻¹³ reported the existence of meso scale eddies and their seasonal variability in the Bay of Bengal using hydrographic observations and sea surface height anomalies (SSHA) derived from altimeter. Exact role of these eddies in the distribution of CHP and intensification of the storm is not known. In the present study, role of CHP in the genesis and intensification of storms is studied. Estimates of CHP obtained from *in situ* observations

are compared with those derived from satellite altimeter and TMI (Tropical Rainfall Measuring Mission Microwave Imager) SST.

Data and Methodology

CHP estimated from Levitus climatology¹⁴ and CTD data

CHP is estimated from the equation,

$$CHP = \rho C_p \int_0^{D26} (\bar{T} - 26) dz \quad \dots (1)$$

where ρ is the density of seawater, C_p is the specific heat of seawater at constant pressure; \bar{T} is the average temperature of the layer dz . Levitus climatology data¹⁴ at 1°×1° grids have been used to compute CHP for the Bay of Bengal from April to December. These values are averaged for 5°×5° grids for the seasons, April-May; June-September; October-December and the annual mean value. Data on Efficiency of Intensification (EI) (i.e., the ratio between the severe storms to the total number of storms in that grid) for the period, 1877-1977 have been taken from earlier studies^{15,16}. Relationship between CHP and EI for the above seasons has been discussed.

Variability of CHP along the transects 88°E (4°-20°N) and 11.5°N (81°-92°E) and the distribution in the Andaman Sea during 1996 post-SW monsoon season have been presented using the CTD data collected during 1993-96..

CHP estimated from altimeter and TMI SST data

The close relationship that exists between the dynamic height and the mass field of the ocean allows these two parameters to be used within a two layer reduced gravity model to monitor the upper layer thickness⁸. The temperature profiles are estimated using the parameters: (a) TMI SST, (b) altimeter estimates of 20°C within a two layer reduced gravity model⁸, (c) the depth of 26°C isotherm from the climatological relationship between the depth of 20°C and 26°C. Here, the tropical cyclone heat potential (TCHP) is defined as the measure of integrated vertical value from surface to the depth of 26°C. Using this methodology, near real time TCHP for the Global Ocean and 7 basins are prepared by Gustov Goni, NOAA/AOML and Joaquin Trinanes, CIMAS/UM and the weekly maps from 1992 and daily maps from June, 2003 are available from their web site (www.aoml.noaa.gov/phod/cyclone/data). In

addition to this, maps on sea surface height anomalies, SST; altimeter estimates of the depth of 26°C and 20°C are also available on the internet. The authors attempt to obtain the estimates which could be updated after the validation scheme is applied and the fields are computed”.

In this study, the nearest weekly data on TCHP has been chosen corresponding to the time of data collection along the transects (88°E and 11.5°N) and the estimates are compared with those obtained from CTD data.

Estimation of CHP from SSHA

Earlier studies¹⁰⁻¹² reported meso scale eddies in Bay of Bengal using hydrographic measurements and SSHA fields obtained from altimeter. Intra seasonal and inter annual variability of circulation in the Bay of Bengal has been reported¹³ using SSHA for the period, 1992-97. Here, a case study is presented for 1996 pre- SW monsoon season. Dynamic topography obtained from CTD measurements during 23 May-21 June, 1996; indicate a large scale anti cyclonic gyre (ACG) in the central Bay and a cyclonic gyre (CG) west of Andaman Sea. These features could be seen up to 100 m depth. Impact of these gyres could be seen in the thermal structure plotted along 88°E and 11.5°N. To identify these features, SSHA fields are plotted for the dates ending with 23 May, 2 June, 12 June and 22 June, 1996. The ACG and its growth with time could be seen clearly while CG is not visible. The reason may be due to the fact that the southern stations are covered during 5-10 June, 1996 (not shown). These observations^{5,17} suggest that the thermal structure of the top layer will be reflected in SSHA field. Keeping this in view, a direct relation between CHP and SSHA is proposed here. A total number of 67 values covering pre-SW monsoon, SW monsoon and post-SW monsoon along the transects 88°E and 11.5°N are used. Details of processing of SSHA were reported earlier¹³. The errors involved in obtaining SSHA from altimeter were described by Ali¹⁸. Very low values (-2 to 2 cm) are avoided for the analysis. A polynomial fit between SSHA and CHP gave a high correlation of 0.79 for 67 values (significant at > 99% level) and the equation is

$$\text{CHP}=6.41+0.141 \text{SSHA} + 0.008 \text{SSHA}^2 \quad \dots (2)$$

where SSHA is in cm and CHP is in 10^8 J/m^2 . A good correlation ($r=0.76$; $N=67$) is also noticed between SSHA and D26 for the polynomial fit and the equation is:

$$\text{D26}=63.84+1.39 \text{SSHA} + 0.044 \text{SSHA}^2 \quad \dots (3)$$

where SSHA is in cm and D26 is in m

A comparison among the estimates obtained from the above three methods has been made for the transects along 88°E and 11.5°N. The quantities are referred as CHP1, CHP2 and CHP3 respectively. These are also compared for the Andaman Sea during 1996 post-monsoon season.

Results and Discussion

CHP and the efficiency of intensification (EI)

Mooley^{15,16} presented the efficiency of intensification (EI) for different grids ($5^\circ \times 5^\circ$) in the Bay of Bengal for different seasons for the period, 1877-1977. Out of 453 storms, 169 were severe storms during the above period. Values of CHP in each grid are presented along with EI in Fig.1. During April-May, CHP is > 5.5 units (1 unit = 10^8 J/m^2) while the EI varied from 0.35-0.5. During SW monsoon season (June-September) CHP varied from 5.5-6.8 units while EI varied from 0.16- 0.27. During NE monsoon (October-December), CHP varied from 3.7-6.7 while EI varied from 0.07-0.39. For the whole year, CHP varied from 5.1-6.8 while EI varied from 0.05-0.50 (Fig.1). A high correlation ($r=0.75$; $N=10$) between CHP and EI was observed for the whole year. It may be noted that a total number of 453 storms are included in this analysis. It is a well known fact that cyclones mostly form in the North Bay during pre-SW monsoon (April-May) and in south Bay during post Sw monsoon season (October-December). Monsoon depressions form in the head Bay during SW monsoon season. Hence, averaging over $5^\circ \times 5^\circ$ grids may not affect the results. Since the origin and intensification of cyclones depend upon a number of parameters in addition to CHP, it is not possible to have a direct relationship between EI and CHP. The correlation between EI and CHP for the whole year indicates the importance of the ocean's role in the genesis and intensification of cyclones in the Bay of Bengal.

Seasonal variability of SST, SSHA, D26 and D20

Figure 2 shows the seasonal variability of the above parameters along 88°E (4° - 20° N) and 11.5°N (81° - 92° E) under pre-SW monsoon, SW monsoon and post-SW monsoon seasons. SST was 29°C during pre and post-SW monsoon seasons while it was 27.5-28.5°C during SW monsoon. Along 88°E (Fig.2A),

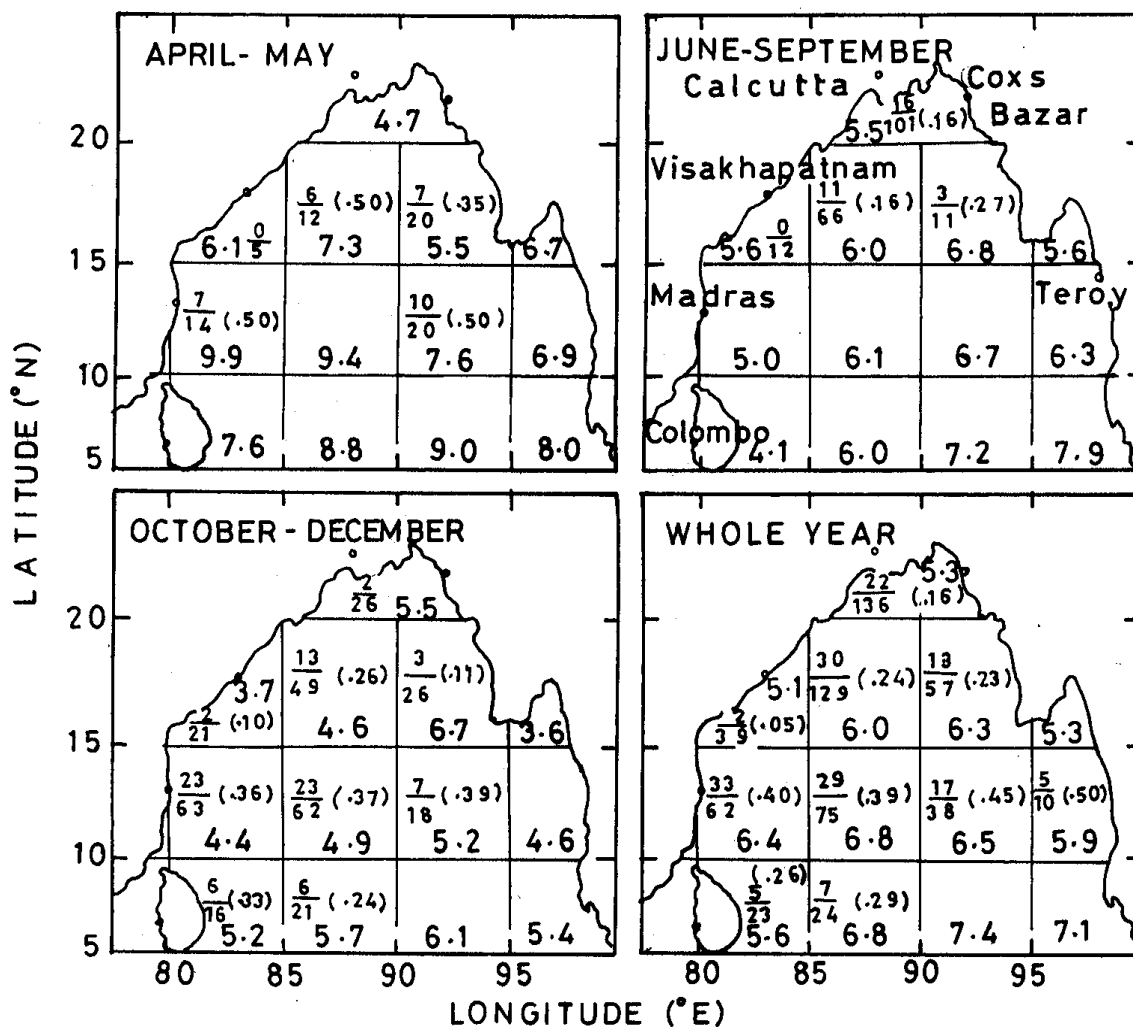


Fig. 1—Distribution of CHP and the efficiency of Intensification (in brackets) (numerator is the no. of sever storms and the denominator is the total no. of storms in that grid)

SSHA was quite high at 15-16°N which could be due to the presence of ACG and a secondary maximum was observed at 5°N during pre- SW monsoon. During the other seasons, it mostly varied between -6 to 12 cm (Fig.2 B). D26 (depth of 26°C isotherm) mostly varied between 50-100 m except during pre- SW monsoon when it exceeded 125 m at latitudes >16°N (Fig.2C). D20 (depth of 20°C isotherm) mostly varied between 100-180 m with slight variations from season to season (Fig.2D).

Along 11.5°N, SST was little above 30°C during pre-SW monsoon while it was 28.5-29°C during the other seasons (Fig.2E). SSHA was positive and varied from 1-15 cm during pre-SW monsoon, while it was negative throughout transect in the other two seasons (Fig.2F). D26 was less than 50 m during SW monsoon and over 75 m during pre- SW monsoon from 82°-

88°E while the seasonal variability is less in D26 from 88°-92° E (Fig.2G). D20 is less than 100 m during SW monsoon season while it varied between 100 and 125 m in the other two seasons. (Fig.2H).

Comparison of CHP estimates (CHP1, CHP2, CHP3)

During pre- SW monsoon season, CHP1 is very high (>14 units) at 15°N; 88°E which is located in the ACG¹⁷ and the secondary maximum is noticed at 5°N (Fig.3A). CHP2 is lower than CHP1 along transect and the difference is quite high in the region of ACG. In general, there is a good agreement between CHP1 and CHP3 during SW monsoon. CHP1 and CHP2 are closer while CHP3 is higher than CHP1 in the region, 4-8°N (Fig.3B). During post- SW monsoon season, CHP2 is lower than CHP1 throughout the transect while CHP3 is fluctuating around 6 units which could

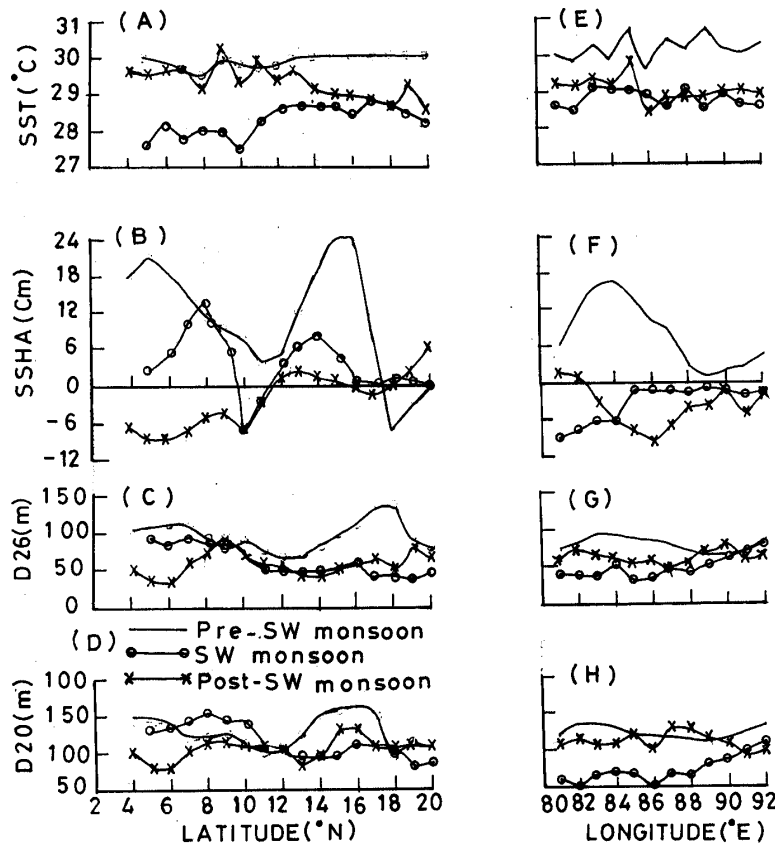


Fig. 2—Variability of SST (°C), SSHA (cm), D26 (m) and D20 (m) along the Transects 88°E and 11.5°N under pre- SW monsoon, SW monsoon and post-SW monsoon seasons

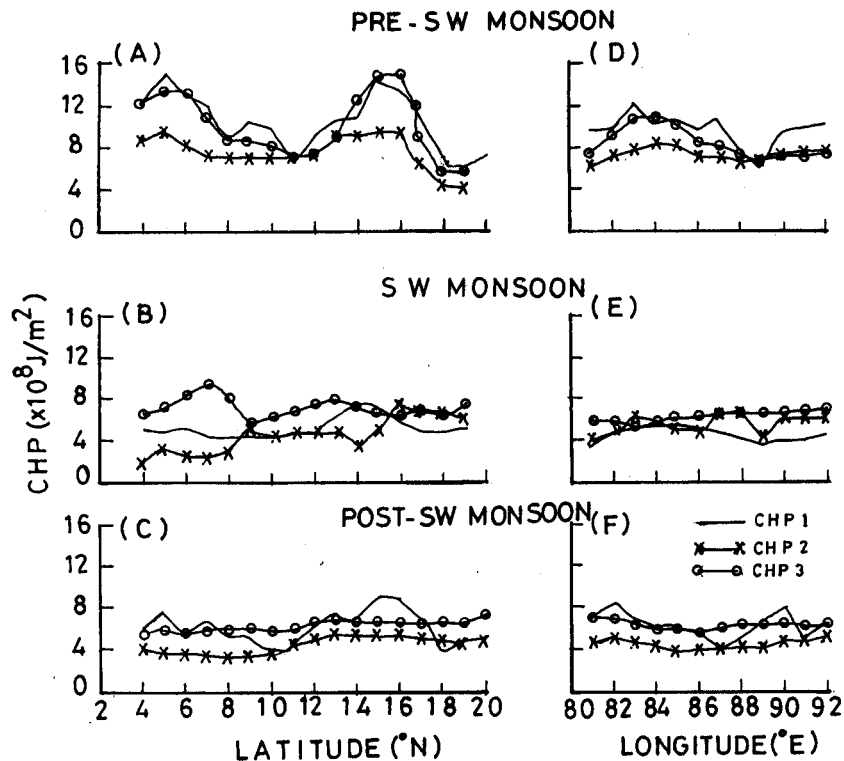


Fig. 3—Comparison of CHP obtained from the three methods (CHP1, CHP2 and CHP3)

Table 1—Comparison of CHP in the Andaman Sea during Post- SW monsoon season, 1996 (CHP in 10^8 J/m^2)

Grid No	Latitude ($^{\circ}$ N)	Longitude ($^{\circ}$ E)	CHP1	CHP2	CHP3
1	7.5	91.5	3.87	3.56	5.92
2	7.5	92.5	4.49	3.80	6.07
3	7.5	94.5	7.31	3.44	6.96
4	8.5	91.5	4.60	3.57	5.84
5	8.5	92.5	5.43	3.79	5.98
6	8.5	93.5	6.48	3.31	6.46
7	8.5	94.5	7.52	3.75	7.00
8	9.5	91.5	4.81	3.31	5.80
9	9.5	92.5	6.58	3.11	6.61
10	9.5	94.5	7.52	4.00	7.74
11	10.5	91.5	5.02	3.43	5.98
12	10.5	92.5	5.64	3.16	7.10
13	10.5	94.5	6.58	3.71	9.29
14	11.5	91.5	5.54	3.82	6.45
15	11.5	92.5	4.49	3.15	7.07
16	11.5	94.5	4.39	3.10	8.86
17	12.5	91.5	5.54	3.95	6.82
18	12.5	92.5	4.28	2.71	6.60
19	12.5	94.5	4.18	3.33	7.00
20	13.5	91.5	6.16	3.97	6.90
21	13.5	92.5	5.22	3.38	7.00
22	13.5	94.5	5.64	3.44	7.79

be due to lower SSHA values. Similar trends are observed in case of 11.5°N transect also (Figs 3 D-F). It may be mentioned here that CHP obtained from CTD data in ACG and CG are 15 and 7 units respectively during pre-SW monsoon. The corresponding values in ACG and CG obtained from the altimeter and TMI SST data are 9.4 and 6.3 respectively. This suggests that there is a possibility of underestimation of CHP in the regions of ACG.

The present method (Eq.2) is used to estimate CHP in the Andaman Sea (7° - 14° N; 91° - 95° E) during 1996 post-SW monsoon season. Please note that this data has not been included to develop the Eqs (2 and 3). It is observed that CHP1 varied from 3.87-7.52 while the range in CHP2 (2.71-4.00) is very small. CHP3 varied from 5.84- 9.29. In general there is a close agreement between CHP1 and CHP3 except in three grids (13, 15&16). The method based on SSHA and TMI SST data appears to be under estimating CHP in the Andaman Sea during post-SW monsoon season (Table 1).Though the preliminary results with Eq. (2) are encouraging, it has to be verified further

using more data sets under different months in Bay of Bengal. The data on TCHP which is available on the web site (www.aoml.noaa.gov/phod/cyclone/data) which will help to examine the role of CHP in the intensification and genesis of the storms, during the recent years. Numerical modelers may run their storm prediction models replacing SST with CHP which was found to give better results in forecasting the storm tracks in other oceanic regions¹⁹. We feel that our results will help to validate the CHP estimates derived from altimeter for the Bay of Bengal region. The data from ARGO floats will probably be available in future with more coverage, and thus help to understand the role of ocean in the intensification of cyclones in the Bay of Bengal.

Acknowledgement

Authors thank Gustov Goni, NOAA/AOML and Joaquin Trinanés, CIMAS/UM for making the TCHP data available from their web site, (www.aoml.noaa.gov/phod/cyclone/data). This is NIO contribution Number 4089.

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