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ARTICLE

Development and Rapid Intensification of Tropical Cyclone OCKHI (2017) over the North Indian Ocean

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ABSTRACT

Tropical Cyclone OCKHI over the North Indian Ocean during 2017 underwent dramatic development and rapid intensification very close to the land - Sri Lanka, extreme South Indian coast and Lakshadweep area during its initial developmental stage and caused extensive damages over these areas. On examining the physical and structural mechanism involved in such development, it is observed that the initial development was associated with axi-symmetrisation of the vortex that could be associated with Vortex Rossby waves near the eyewall. Associated with the expulsion of high vorticity from the centre during asymmetry mixing, there was outward propagation of eddy angular momentum flux in the lower levels that strengthened a low level anticyclone to the northeast of the TC centre which in turn enhanced the cyclonic inflow near the TC centre. The rapid intensification phase was associated with vertical non-uniform heating with upper and lower tropospheric warming associated with latent heat release in convection. During the mature phase, the system sustained 'very severe' intensity even under increasing vertical shear and lower ocean heat flux under the influence of a break in the sub tropical ridge to the north of the system centre that enhanced the poleward outflow in the upper troposphere.

1. Introduction

Tropical cyclone (TC) intensity changes occur through complex interaction of multi-scale physical and dynamical processes. Ocean heat fluxes, especially the latent heat flux (LHF) transfer at the sea-air interface, have long been recognized as important factors for the generation and maintenance of TCs [1]. Several studies have brought out the role of environment in TC intensity changes [2], DeMaria et al [3]). Rhome and Sethuraman [4] made a review of the processes identified to be associated with TC intensity change such as vertical wind shear (VWS), sea surface temperature (SST), upper level divergence, land interactions, eddy angular momentum fluxes etc. Some studies have also shown that even though environmental properties are important, they alone do not explain the intensity change problem. Hendricks et al. [5] found that the environments of rapid and slow intensification cases are similar and hence concluded that the rate of intensification may be only weakly dependent on environmental condition. Several studies have examined the role of storm-scale processes which are associated with the precipitation properties of TCs [6]. Bosart et al [7] have shown that TCs

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undergo intensity changes under complex interaction between the large-scale environment, storm-scale processes and ocean-atmosphere coupling. Knaff et al. [8] found that the development of annular hurricanes was systematically preceded by a dramatic asymmetric mixing event between the eye and the eyewall involving one or more mesovortices. Montgomery and Enagonio [9] demonstrated the role of axi-symmetrisation mechanism in the development of a warm-core vortex and clarified the significance of axi-symmetrisation for tropical cyclogenesis. Corbaseiro et al [10] suggested that Vortex Rossby Waves (VRW) could result from expulsion of high vorticity from the eye during the asymmetry mixing and vorticity rearrangement in the vortex (axi-symmetrisation) and such VRWs could accelerate the tangential winds near the eye leading to inward shift of the radius of maximum wind and cause TC intensification. Such studies throw light on the TC processes and evolution. However, there are only limited studies on such processes for the TCs of the North Indian Ocean (NIO).

The very severe cyclonic storm (VSCS) OCKHI over the NIO during 29th November - 05th December 2017 underwent dramatic development and rapid intensification very close to Sri Lanka, Tamil Nadu-Kerala coasts (Comorin area) and Lakshadweep area during its initial developmental stage from 29th November/0300 UTC to 02nd December/0000 UTC and caused extensive damages over these areas. Subsequently, during its mature stage, it maintained VSCS intensity even under unfavourable environmental conditions. The Comorin area has been affected by only three cyclones in the past - during the period 1891-2016 and hence it is of scientific interest to understand the physical and structural mechanism involved in the development and intensification of TC OCKHI over the NIO during 29th November - 05th December 2017. Results of such studies, especially the present one regarding its initial development near the coast and rapid intensification during the formative stages, would help in improving our forecasting capabilities. Section 2 briefly describes the data and methodology used for analysis and Section 3 presents the results and discussions. Section 4 summarises the results.

2. Data and Methodology

The best track data from IMD, Ocean latent heat flux data fromWoodshole Oceanographic Institution [11], VWS product of Colorado State University - NOAA-NESDIS-CIRA based on AMSU, Low level convergence (LLConv), Upper level divergence (ULDiv) and Relative vorticity (RVor) from University of Wisconsin - CIMSS NCEP-FNL, 6-hrly, 1°x1° dataset are utilised for the present study. Using these datasets the environmental features, synoptic scale eddy interactions, dynamical parameter, convective structural asymmetries and thermo-dynamical features related VSCS OCKHI are analysed.

Synoptic scale eddy forcings have been shown to influence the intensification of TC MADI (2013) over the NIO [12]. For the present case, the role of synoptic scale eddy interactions is examined by computing Eddy angular momentum flux convergence (EFC) using NCEP-FNL, 6-hrly, 1°x1° dataset. The computation methodology adopted by Molinari and Vollaro [13] is used and is given by:

$$EFC = -\frac{1}{r^2}\frac{\partial}{\partial r}r^2\overline{u'v'} \qquad (1)$$

where u and v refer to storm relative radial and tangential velocities and prime refers to the deviations from the azimuthal mean; r is the radial distance from the TC centre. Computations are in storm relative cylindrical co-ordinate system up to 12˚ from the centre with radial interval Δr = 1°and azimuthal interval Δϕ = 15° using bilinear interpolation.

It has been shown that increase of diabatic heating with height near the TC centre in the mid-to-upper troposphere and increase of vertical inhomogeneous heating near the TC centre in the lower troposphere are favourable for RI and absence of upper tropospheric warming is a feature associated with rapid weakening (RW) [11,14]. The latent heat release associated with intense eyewall convection enhances the upper tropospheric warming of the core and lowers the central sea level pressure of the TC during the RI phase [15]. For examining this aspect in the present case, vertical profiles of apparent heat source and moisture sink are studied using NCEP-FNL 6-hrly, 1°x1° dataset based on the following heat and moisture budget equations [16]:

$$Q_1 = C_P\left[\frac{\partial T}{\partial t} + V.\nabla T + \left(\frac{p}{p_0}\right)^k \omega\frac{\partial \theta}{\partial p}\right] \quad Q_2 = -L\left[\frac{\partial q}{\partial t} + V.\nabla q + \omega\frac{\partial q}{\partial p}\right] \qquad (2)$$

C_p is the specific heat capacity of air at const pressure, *T*: Temperature; *V*: Horizontal wind velocity, *P*: Pressure; *ω*: pressure vertical velocity, *Θ*: Potential temperature, *k*=R/C_p, *L*: Latent heat of condensation and *q*: mixing ratio of water vapour.

Under the influence of VWS and TC motion, it has been shown that there is a pronounced front-back asymmetry in TC convective structures [17]. It has also been shown that asymmetry maximum shifts cyclonically inwards during the intensification phase [12] and the asymmetry amplitude in the inner core is lower during RI events but, quite high during RW events [14]. As in these studies, asymmetry analysis for VSCS OCKHI is carried out based on Fourier first order wave number-1 asymmetry using TRMM based

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0.25° x 0.25° rain rate data at 3-houly intervals (3B42v7) using the method followed by Lonfat et al. [18]. First, the mean rain rate in each 0.1° wide annulus (≈10 km) around the TC centre is computed up to 5° radial distance (50 annuli). For each annulus, the first order Fourier coefficients are computed using all individual rain rates as

$$a_1 = \sum_i [R_i \cos\theta_i] \,,\; b_1 = \sum_i [R_i \sin\theta_i] \qquad (3)$$

where R_i represents individual rain rates and θ_i, the phase angle of the corresponding grid point relative to the direction of motion of the TC. The spatial structure of the first order asymmetry can then be represented by

$$M_1 = \frac{\left[a_1 \cos\theta + b_1 \sin\theta\right]}{R} \qquad (4)$$

where R is the mean rain rate calculated over the entire annulus. The asymmetry amplitudes are then normalised to the ambient mean rain rate of each annulus so that amplitude near unity implies that the wave number signal at that point is as strong as the axi-symmetric average.

3. Results and Discussions

Evolution of TC OCKHI under the influence of various oceanic and atmospheric environmental features and other large scale and storm scale dynamical processes are discussed below.

3.1 Synoptic History of VSCS OCKHI

The TC OCKHI formed as a low pressure area over southwest Bay of Bengal (BOB) and adjoining areas of south Sri Lanka on 28th November /0300 UTC and became well marked on 29th /0000 UTC over the same region. Under favourable environmental conditions, it concentrated into a Depression (D) over southwest BOB off southeast Sri Lanka coast on 29th / 0300 UTC. Moving westwards, it crossed Sri Lanka and emerged into Comorin area by 29th /1200 UTC. It intensified into a Deep Depression (DD) on 29th/2100 UTC. Moving northwestwards it intensified into a Cyclonic Storm (CS) on 30th / 0300 UTC over the Comorin area, into a Severe Cyclonic Storm (SCS) over Lakshadweep area on 01st December / 0000 UTC and further into a Very Severe Cyclonic Storm over southeast Arabian Sea (AS) to the west of Lakshadweep by 01st / 0900 UTC. Generally, for the NIO basin, TCs are considered to have undergone rapid intensification (RI)/ rapid weakening (RW) whenever there is 30 knots increase/decrease in maximum sustained surface wind speed (MWS; V_{max}) in 24 hrs [19]. In the present case OCKHI underwent RI during 01st/0000 UTC to 02nd 0000 UTC and attained its peak intensity of 150-160 kmph gusting to 180 kmph on 2nd /0900 UTC with lowest central pressure of 976 hPa over the AS. It then gradually recurved north-northeastwards, maintained its VSCS intensity till 04th / 1200 UTC and then weakened gradually. It crossed south Gujarat coast as a well marked low on 06th/0000 UTC. The system caused extensive damages over extreme south Tamil Nadu and south Kerala during its developmental stages on 29th-30th November. The system centre was about 60 km from Kanyakumari (Tamil Nadu), the southern most tip of peninsular India on 30th November / 0300 UTC when it intensified from DD to CS stage (as per IMD's best track data). Even though the system centre did not cross the coast and move inland, Kanyakumari and Thiruvananthapuram (Kerala) bore the brunt of the fury of the eye-wall region of the TC during 29th night-30th morning. The dynamical features and precipitation structures are analysed with regards to its initial developmental phase during 29th/0300 UTC to 30th/0300 UTC, rapid intensification phase during 01st/0000 UTC to 02nd 0000 UTC and its mature stage 03rd/1200 UTC to 04th/1200 UTC. The track of OCKHI as per the IMD's best track data is given in Figure 1.

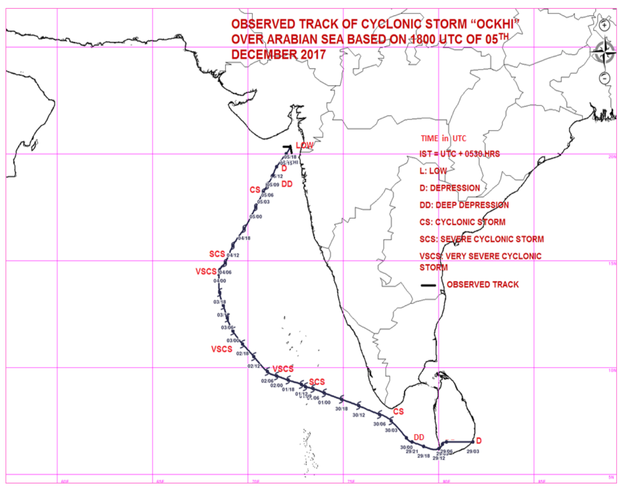

Figure 1. Track of TC OCKHI over the NIO during 29 Nov - 05 Dec 2017

3.2 Development and RI Phase

(1) Ocean-air latent heat flux and intensification of TC OCKHI

Figure 2a presents the time series of ocean-air LHF averaged over 6° lat/lon box centred at OCKHI's centre for 6-hrly positions and the MWS of TC OCKHI during the period 29th November - 05th December 2017. It is observed that LHF around the TC centre was >100 W/m^2 during its formative period (29th/0300 UTC to 30/0600 UTC) when its MWS increased from 25 kt to 40 kt. However, there was a steady decrease in the LHF in the vicinity of the TC centre (up to about 300 km from the centre) from 135 W/m^2 to70 W/ m^2 during the period 30th/0600 UTC to 02nd December/0000 UTC when the MWS increased from 40 kt to 80 kt (pink box in Figure 2a). The TC also underwent RI during 01st/0000 UTC to 02nd/0000 UTC (yellow box in Figure 2a) even though, there was persistent decrease in the LHF around its centre. This suggests that the initial stages of development of the TC OCKHI was under the favourable influence of the LHF; however, the ocean-air LHF did not play any role in the system's further development and RI during the period 30th/0600 UTC to 02nd December/0000 UTC.

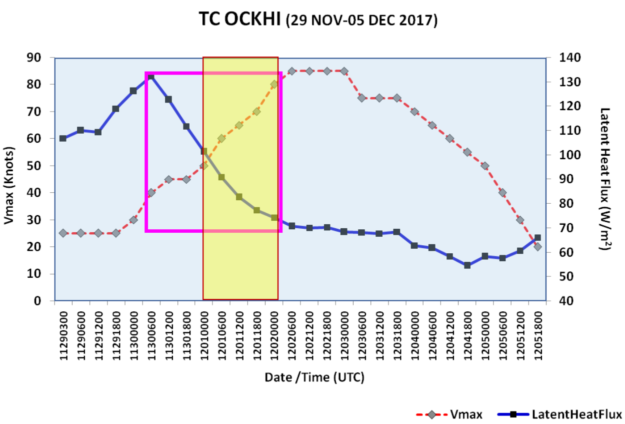

Figure 2a. Ocean-air latent heat flux (W/m2) and maximum sustained surface wind speed (Vmax in knots) during the life period of TC OCKHI over the NIO

(2) Vertical wind shear

Area averaged wind shear product for the 850-200 hPa layer as well as 850-500 hPa layer over 0-600 km from the TC centre taken from the real-time TC products of NOAA-NESDIS-CIRA is presented in Figure 2b. It is observed that during the initial period of formation from 29th November/1200 UTC to about 01st December/0000 UTC, there was a slight increase in the VWS around the TC centre from 10 kt to about 20 kt which decreased back to 10 kt during the RI phase (01st-02nd December / 0000 UTC). The system continued to be under low VWS of about 10 kt till 03rd / 0000 UTC after which, the VWS started to increase gradually. As such, the low VWS around the TC centre was favourable for its development and intensification.

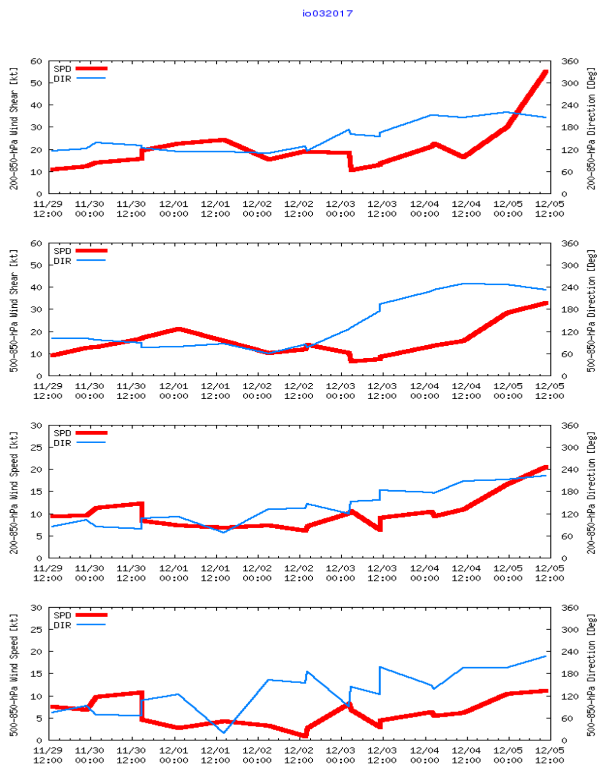

Figure 2b. Area averaged wind shear in the 850-200 hPa layer & 850-500 hPa layer over 0-600 km from the TC centre (Source: NOAA-NESDIS-CIRA TC products based on JTWC best track data)

(3) Synoptic scale eddy interaction

As detailed in Sec.2, the synoptic scale eddy forcings on the TC intensity changes is examined at the lower and the upper levels by computing the EFC at 850 hPa and 200 hPa levels up to about 1100 km from the TC centre. Figure 3a represents the EFC at 850 hPa during the initial development and RI phase of the TC OCKHI and Figure 3b, the radial velocity at 850 hPa during this period. It is observed that there was negative EFC in the inner core region (up to about 200 km from the TC centre) during the period 29th/1200 UTC to 29th/1800 UTC after which, there was outward propagation of EFC of 15-20 m/sec/day from about 300 km to 500 km during 30th/0000 UTC to 30th/1200 UTC. Even during the RI phase (01st/0000 UTC to 02nd/0000 UTC), there was some outward propagation of EFC (10-15 m/sec/day) at the outer radii (700 km -1000 km). The negative EFC during the initial stages indicates that there was no synoptic scale eddy forcing at the lower levels (i.e.) the system was not interacting with its environment during this period (29th/1200-1800 UTC). Such situations of the system not interacting with the environment can arise when the system's internal dynamics are very strong and do not allow the

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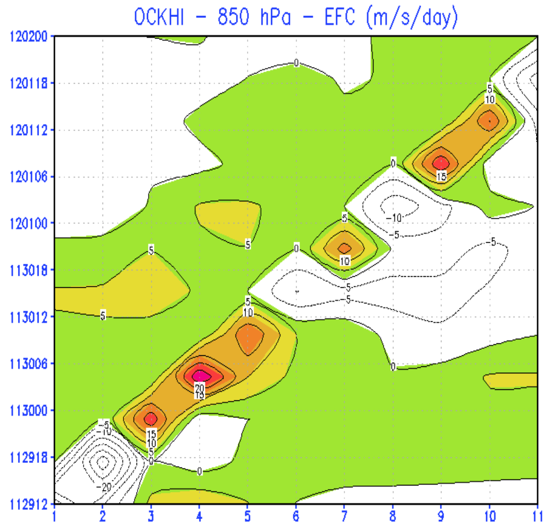
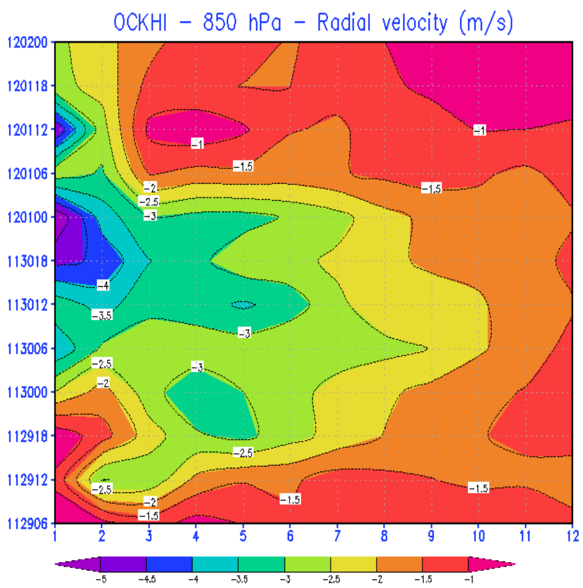
environment to influence it. The enhanced low level convergence from 20 to 60 (x10^{-5} s^{-1}), relative vorticity from about 150 to 250 (x10^{-6} s^{-1}) at 850 hPa (Figure 3c&d) and enhancement of inward radial velocity from 29th/1800 UTC onwards (Figure 3b) are supportive of the indication that meso-scale processes at the inner core could be associated with the development of the system from the depression to CS stage.



(a)



(b)

Figure 3a&b. 850 hPa Eddy Flux Convergence ($ms^{-1}day^{-1}$) (a) and Radial velocity (ms^{-1}) (b) from 100 km to 1100 km from the TC centre during the initial development and RI phase of TC OCKHI. x-axis represents the distance (in °lat/lon) from the TC centre and y-axis represents the date and time in mmddhh format

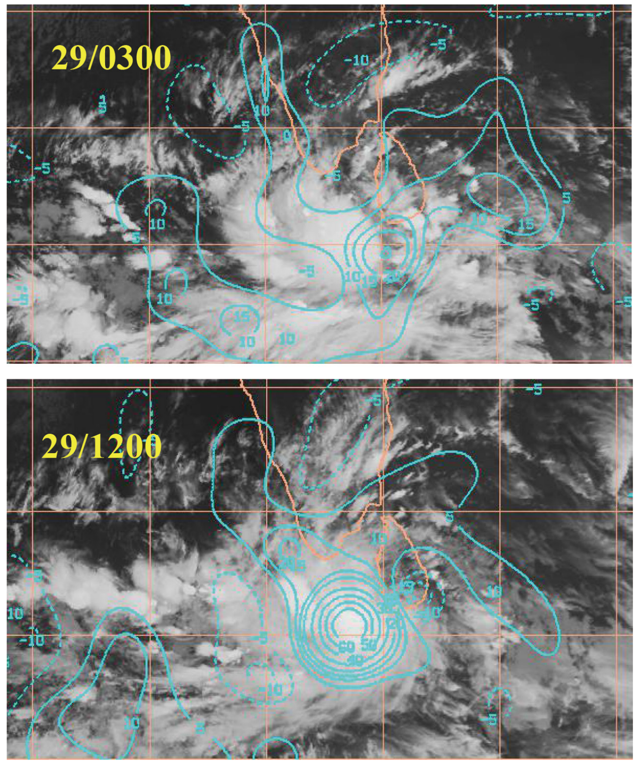


Figure 3c. NOAA-CIMSS product on low level convergence (x10-5 s-1) near the TC centre during 29th/0300 UTC and 29th/1200 UTC

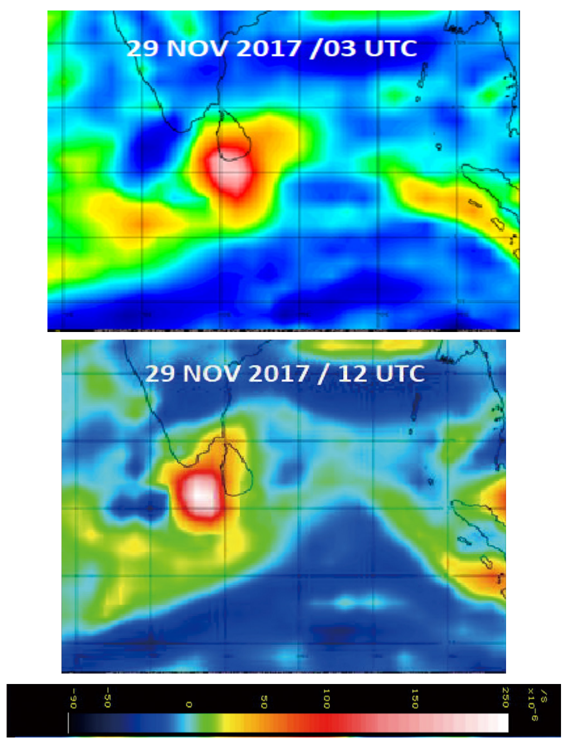


Figure 3d. NOAA-CIMSS product on relative vorticity (x10^{-6} s^{-1}) near the TC centre during 29th/0300 UTC and 29th/1200 UTC

(4) Storm-scale processes

Several modelling and observational studies on meso-scale processes have examined the convective asymmetries in the context of axi-symmetrisation that leads to vortex intensification [20]. Interaction between asymmetries and their parent vortices has been advanced using potential vorticity (PV) dynamics and the recognition that PV (or Rossby type) waves exist in the vortex core.

Hence, the TC convective structure up to about 300 km from the centre is examined using Fourier first order wave number-1 asymmetry analysis as detailed in Sec.2. Figure 4a(1) presents the asymmetric structure associated with the TC during its development from depression to a CS. It is observed that large asymmetry is present in the inner core region (up to about 100 km from the centre) of the system on 29th/0600 UTC. Subsequently, by 29th/1200 UTC, the asymmetry maxima are pushed outwards and at 1800 UTC, it is pushed further outwards which is speculated as indication that asymmetry mixing leading to axi-symmetrisation of the vortex would have taken place in the inner core. By 30th/0600 UTC asymmetry maxima appear again in the inner core. However, symmetrisation of the vortex occurs again during the RI phase [Figure 4a(2), 01st December/1800 UTC].

The outward propagation of eddy angular momentum flux convergence (>10 m/sec/day which is taken as threshold for eddy interaction, DeMaria et al [3]) at 850 hPa level from 30th November/0000 UTC onwards (including the RI phase) from about 300 km from the TC centre up to about 1000 km from the centre could be envisaged as due to generation of VRWs . Such development of VRW could be verified through numerical experiments with very high resolution observational data in the vortex region.

Associated with the outward propagation of EFC, there was strengthening of a low level anti-cyclonic flow to the northeast of the system centre which in turn enhanced the cyclonic inflow into the system core (Figure 4b). This is supported by the sharp increase in inward radial velocity at 850 hPa from 3 m/sec to 5 m/sec near the inner core during 30th November, 1200 UTC to 01st December 0600 UTC (Figure 3b). The Windsat (37 GHz) microwave imagery depicting the low-mid level circulation as on 30th November / 0000 UTC shows a distinct centre (Figure 4c). Appearance of the nearly closed cyan + pink ring in the Windsat composite product is indicative of RI [21].

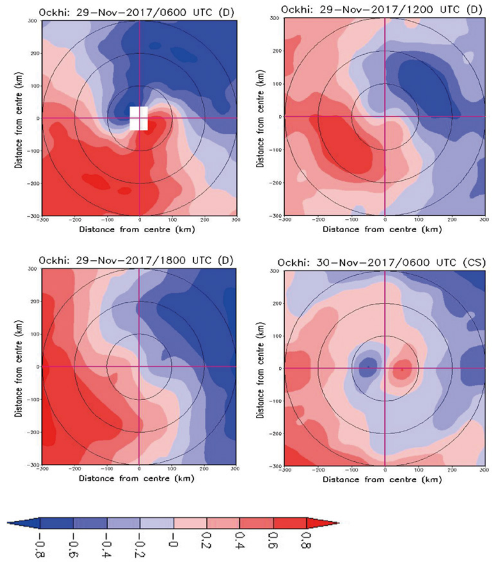


Figure 4a(1). Convective asymmetric structure up to about 300 km from the TC centre during the developmental phase of TC OCKHI - 29/0600 UTC, 1200 UTC, 1800 UTC and 30/0600 UTC, Nov 2017

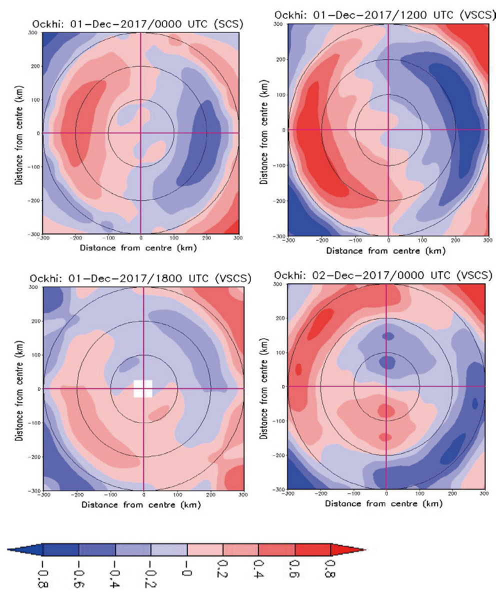


Figure 4a(2). Convective asymmetric structure up to about 300 km from the TC centre during the RI phase - 01/0000 UTC, 1200 UTC, 1800 UTC and 02/0000 UTC, Dec 2017

On examining the wind structure including the outer storm area using NOAA- NESDIS-MTCSWA data based on satellite retrievals at 6-hrly intervals during 30th November - 01st December, two azimuthal maxima (red) and minima (blue) are observed on 30th 0000 UTC and 0600 UTC in the outer storm area indicative of wave number 2 asymmetry (Figure 4d). However, this asymmetry decreases gradually during the RI phase and the system attains symmetric vortex by 01st December, 1200 UTC. In this connection, it may be mentioned that Reasor et al [22] and Corbosiero et al [10] have shown that

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wave number 2 asymmetry in the spiral reflectivity bands outside the eye wall are associated with VRWs.

Figure 5 presents the longitude-vertical cross-section and latitude-vertical cross-section of heat and moisture at the end of the RI phase (01-02 December/ 0000 UTC). As noted in the earlier studies, a double maxima, one in the lower-mid troposphere and another in the mid-upper troposphere, is observed in Q1 and Q2 both in the longitude-vertical cross-section and latitude-vertical cross-sections. However, heating rate in the longitude-vertical plane is one order higher compared to that in the latitude-vertical plane. The heat source (positive Q1) and moisture sink (positive Q2) values are of the same order in both the cross-sections indicating that heating is mainly due to latent heat release due to convection. The Q1/ Q2 maxima located by about 400 km to the south/ north of the TC centre in the latitude-vertical cross-section could be associated diabatic heating in active spiral rainbands.

It is interesting to note that, in the latitude-vertical plane, there is a mid-tropospheric cooling (heat sink: negative Q1) and a moisture source (negative Q2) in the mid levels near the centre. In this regard, it may be mentioned that a study on thermodynamic pathway leading to RI of TCs in shear by Chen et al [23] indicates cooling in the 700-400 hPa layer mainly due to enhanced convective mixing associated with increase in convective bursts and the reduction of subsidence warming as the vortex aligns.

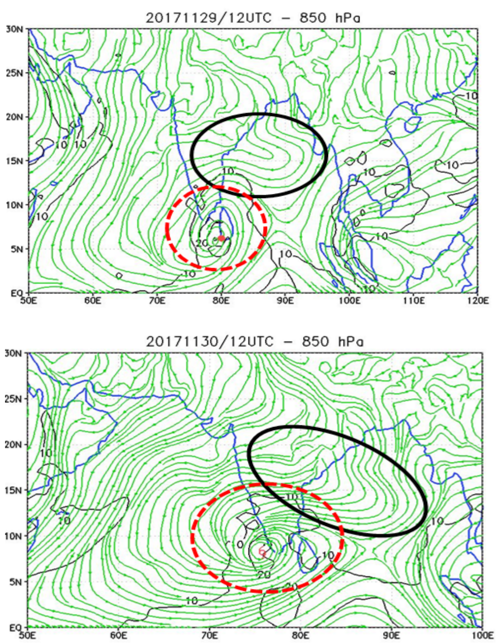


Figure 4b. 850 hPa streamline analysis for 29/1200 UTC and 30/1200 UTC, Nov 2017 (Location of TC centre is marked in red; Red dotted circle indicates the inflow region and black circle shows the anti-cyclonic circulation to the northeast of the system centre)

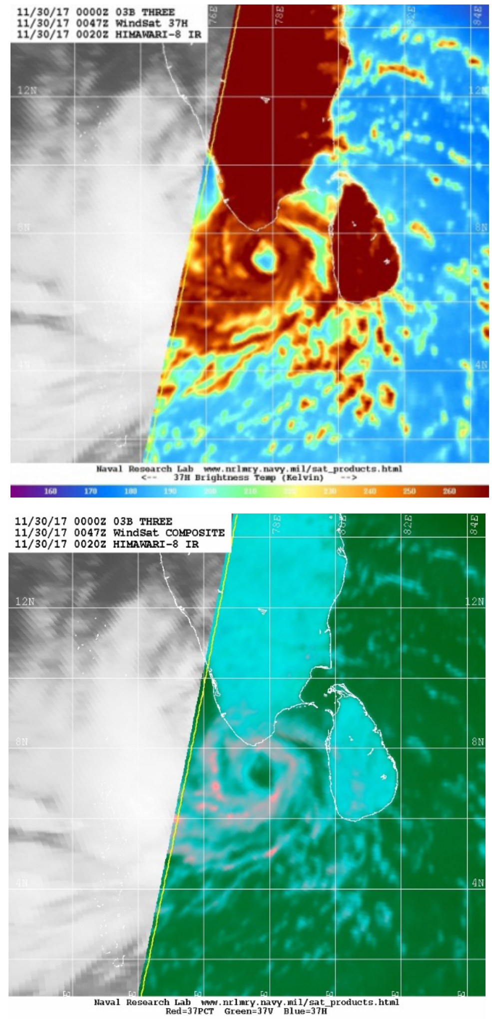


Figure 4c. Mirowave imagery of TC OCKHI as on 30 November, 00 UTC (Source: US-Naval Research Laboratory, Tropical cyclone page)

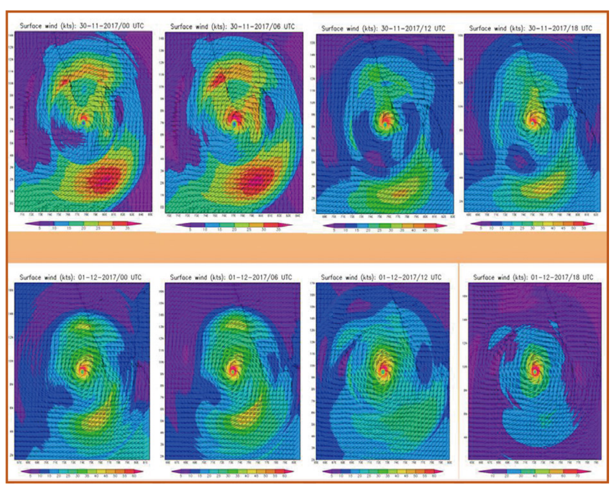


Figure 4d. Plots of satellite based NOAA-NESDIS-MTCSWA wind around the TC OCKHI at 6-hrly intervals on 30 Nov and 01 Dec 2017

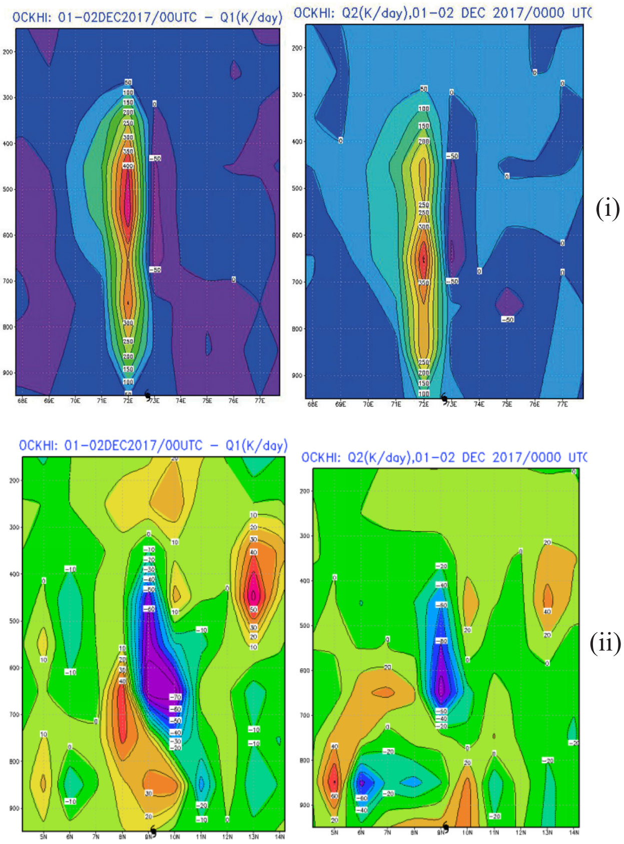
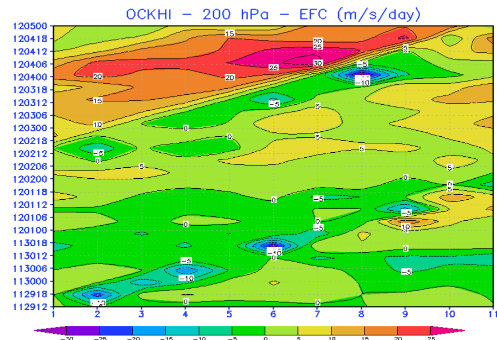


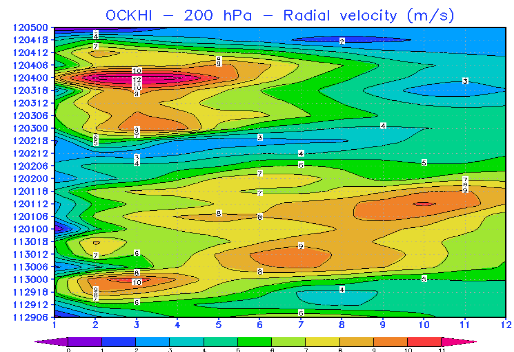
Figure 5. Vertical profiles of heat and moisture (K/day) in the (i) longitude- vertical cross-section (ii) and latitude-vertical cross-section during the RI phase of TC OCKHI

3.3 Mature Stage

During the period, 03rd December /1200 UTC to 04th/ 1200 UTC, the system maintained VSCS intensity even when the VWS was increasing and the ocean heat flux was less than 70 W/m^2 (Figure 1 & 2) under the influence of upper level eddy interactions. Figure 6(a&b) presents the 200 hPa eddy flux convergence and radial velocity during the life period of TC OCKHI. It is noted that until 03rd December / 0000 UTC there was no significant eddy interaction in the upper troposphere. Subsequently, EFC of the order of 10-20 m/sec/day is observed near the inner radii which expands outwards till 04th/1200 UTC (Figure 6a). Associated with this positive EFC, outward radial velocity at about 200-300 km from the TC centre increases from 4 m/sec to 12 m/sec during 03rd/0000 UTC to 04th/0000 UTC (Figure 6b). The eddy influence has been in the form of break in the sub tropical ridge and creation of enhanced outflow channel (Figure 6c) as observed in several earlier studies [24].



(a)



(b)

Figure 6a&b. 200 hPa eddy Flux Convergence (ms^{-1}day^{-1}) (a) and Radial velocity (ms^{-1}) (b) from 100 km to 1100 km from the TC centre during the life period of TC OCKHI. x-axis represents the distance (in °lat/lon) from the TC centre and y-axis represents the date and time in mmddhh format

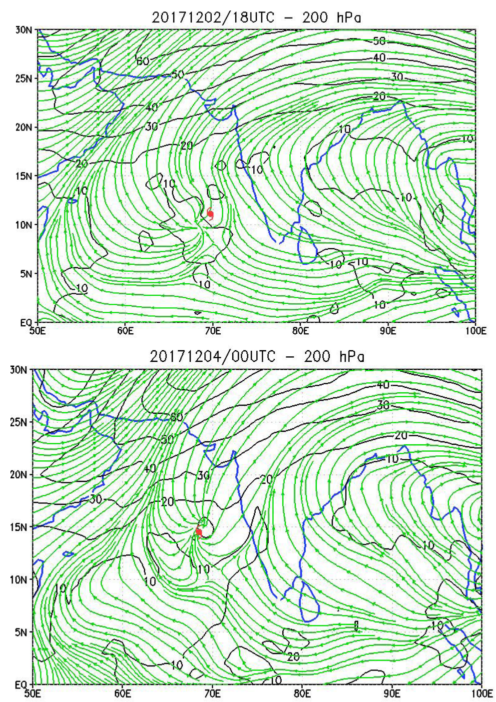


Figure 6c. 200 hPa streamline analysis as on 02nd/1800 UTC and 04th/0000 UTC, Dec 2017 (Location of TC centre is marked in red)

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4. Summary

The physical mechanisms and structural changes involved in the development and intensification of TC OCKHI over the NIO during 29th November - 05th December 2017 is studied. OCKHI underwent dramatic development and rapid intensification during the period 29th November/0300 UTC to 02nd December/0000 UTC even as the ocean heat fluxes near the TC centre decreased sharply. However, the system was in a low-moderate VWS environment and the initial development of OCKHI was associated with axi-symmetrisation of the vortex as observed in the wave number-1 asymmetry in the convective structure which could be associated with Vortex Rossby waves near the eyewall.

Wave number-2 asymmetry in the outer storm area which has been identified with VRWs in some other works is seen in the wind structure during this period. Associated with the expulsion of high vorticity from the centre during asymmetry mixing and vorticity rearrangement, there was outward propagation of eddy angular momentum flux in the lower levels. This strengthened a low level anticyclone to the northeast of the TC centre which in turn enhanced the cyclonic inflow near the TC centre. During the RI phase, there is upper and lower tropospheric warming associated with latent heat release in convection. A mid level cooling is also observed during RI which could be due to enhanced convective mixing associated with increased convective bursts during asymmetry mixing and vorticity expulsion. During the mature phase of the TC, the system sustained VSCS intensity even under increasing VWS and lower ocean heat flux under the influence of a synoptic scale eddy forcing in the upper troposphere in the form a break in the sub tropical ridge to the north of the system centre which enhanced the poleward outflow channel and maintained the system. Further studies with numerical simulation with high resolution observational data from RADAR and satellite are required to substantiate the above results.

Acknowledgments

The authors thank the Director General of Meteorology, India Meteorological Department for providing facilities to undertake this study. Use of NCEP reanalysis and FNL data, TRMM rainfall data, NOAA-CIMSS satellite based tropical cyclone products, NOAA-NESDIS MTCSWA data, Woodshole Ocenographic Institution's OAFLUX data and US-NRL microwave products are duly acknowledged.

Conflicts of Interest

The authors declare no conflict of interest.

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