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Momentum budget analysis of maintenance of Arabian Sea tropical cyclone Ockhi

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सार – इस अध्ययन में कोणीय गति (एएम) बजट तकनीक का उपयोग करके अति प्रचंड चक्रवाती तूफान (वीएससीएस) ओखी के अनुरक्षण को समझाने का प्रयास किया गया है। समन्वय प्रणाली में से घिरे क्षेत्र के लिए एएम बजट समीकरण X_1 से X_2, Y_1 से Y_2 और P_1 से P_2 (x,y,p,t) का उपयोग पूर्ववर्ती अध्ययन से किया गया है। भिन्न-भिन्न शब्दों को सापेक्ष महत्व के साथ समझाया गया है। इस तकनीक का उपयोग कई लेखकों द्वारा विभिन्न छोटी, मध्यम और बड़ी मौसम प्रणालियों का पता लगाने के लिए किया जाता है। अत्यंत प्रचंड चक्रवाती तूफान (वीएससीएस) ओखी - जो अरब सागर में एक विरल स्थिति थी - का अध्ययन राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केंद्र (एनसीएमआरडब्ल्यूएफ) इंडियन मॉनसून डेटा एसिमिलेशन एंड एनालिसिस (आईएमडीएए) वेबसाइट द्वारा किया गया और सटीक चौडाई वाली जाली पाश में प्रकाशित डेटासेट के पुनः विश्लेषण की मदद से किया गया। एएम बजट समीकरण में भिन्न-भिन्न शब्दों के मूल्यों की गणना दबाव स्तर -1000, 800, 500, 200, 100 एचपीए और चार दिन की अवधि जैसे 30 नवंबर, 01 दिसंबर, 02 दिसंबर और 03 दिसंबर 2017 के लिए किया गया। एएम बजट प्रत्येक दिन के लिए 0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 यूटीसी पर आठ प्रेक्षण समय के लिए तैयार किया गया। चयनित क्षेत्र 5.04° N - 19.2° N, 60° E - 77° E है जहां अति प्रचंड चक्रवाती तूफान उष्ण कटिबंधीय चक्रवात ओखी बना, मजबूती से तीव्र और परिपक्व हुआ। सिंक और स्रोत शब्दों की तुलना की जाती है और चार्ट की मदद से परिणाम को सहसंबद्ध किया जाता है। परिणाम चार्ट में दर्शाए गए हैं और परिणामों की तुलना सिस्टम के देखे गए सिनॉप्टिक परिस्थितियों से की गई है। सतह पर घर्षण बलाघूर्ण मान दर्शाता है कि पहले दिन (प्रारंभिक) में, यह बढा (सकारात्मक) है और चौथे दिन (परिपक्व) में यह कम (नकारात्मक) हुआ है। वायुमंडल (जिसमें उष्ण कटिबंधीय चक्रवात ओखी प्रणाली शामिल है) को आरआई चरणों में अर्थात दूसरे दिन और तीसरे दिन के दौरान घर्षण के माध्यम से 2100 यूटीसी- 0300 यूटीसी (06 घंटे का समय) के बाद समुद्र से कुछ सकारात्मक प्रतिक्रिया मिल सकती है। ज़ोनल प्रेशर ग्रेडिएंट शब्द, वायुमंडल क्षेत्र की गति का एकल स्रोत (सकारात्मक मान) है, जिसमें यह प्रणाली होती है और हमेशा सकारात्मक और विचाराधीन अन्य शब्दों की तुलना में कई अर्थों में अधिक होते हैं और यह प्रणाली के जीवन चक्र के दौरान मुख्य्य अवयव होता है। सभी चार दिनों में टॉप बॉटम टर्म स्रोत से सिंक टर्म पर बहुत तेजी से स्विच करता है और मानों (कमी) को 1800 UTC तक कम करने की एक समग्र सामान्य प्रवृत्ति होती है और उच्च सकारात्मक (वृद्धि) मान सभी दिनों में 0000 UTC पर पाए जाते हैं।

ABSTRACT. In this study an effort is done to explain the maintenance of the Very Severe Cyclonic Storm (VSCS) Ockhi using the angular momentum (AM) budget technique. The AM budget equation for a region bounded by X_1 to X_2, Y_1 to Y_2 and P_1 to P_2 in (x, y, p, t) co-ordinate system is used from an earlier study. The different terms are explained with relative importance. This technique is used to the diagnosis of different small, medium and large weather systems by several authors. The Very Severe Cyclonic Storm (VSCS) Ockhi - a rare situation in Arabian Sea- is studied with the help of reanalyzed National Centre for Medium Range Weather Forecast (NCMRWF) Indian Monsoon Data Assimilation and Analysis (IMDAA) website published dataset in a fine mesh width. The values of different terms in the AM budget equation are calculated for pressure levels-1000, 800, 500, 200, 100 hPa's and for four day periods, *viz.*, 30 Nov, 01 Dec, 02 Dec and 03 Dec, 2017. The AM budget was prepared for the eight observation time periods of 0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 UTC for each day. The area selected is 5.04° N - 19.2° N, 60° E - 77° E where VSCS TC Ockhi formed, rigorously intensified and matured. The sink and source terms are compared and the results are correlated with the help of charts. The results are depicted in charts and results are compared with the observed synoptic behavior of the system. The Frictional torque values at the surface indicate that on day 1 (Initial), it is a gain (positive) and on day 4 (Mature), a loss (negative). The atmosphere (which contains TC Ockhi system) can have some positive feedback from the Sea after 2100 UTC - 0300 UTC (06 hours' time) during the RI stages, *viz.*, day 2 and day 3 through friction. Zonal Pressure Gradient term, is the single source (positive value) of the momentum of the atmosphere area, which contains the system and always positive and several orders higher than other terms under consideration and is the main player during the life cycle of the system. The top bottom term switch from source to sink term very rapidly on all four days and there is an overall general trend of decreasing the values (loss) up to 1800 UTC and high positive (gain) values are found at 0000 UTC on all days.

Key words – Angular momentum budget, Equation, Source/Sink term, VSCS Ockhi-diagnosis.

1. Introduction

In this study an effort is made to understand the VSCS Ockhi using AM budget technique. It is noted by many authors that Arabian Sea (ARB) is witnessing unusual phenomenon of increased cyclonic activity in frequency and intensity during the past few years. Many authors applied this technique to know more about the various weather systems around the globe during the past. Piexoto and Oort (1984) uses 15 years of more complete data set over the entire globe and evaluated the global budgets. Keshava (1968) studied on the maintenance of mean zonal motion in the Indian summer region. The maintenance of the westerlies in the lower troposphere and the easterlies in the upper troposphere in the Indian southwest monsoon is studied by considering the angular momentum balance of the region. The main source term for the zonal angular momentum is found to be Coriolis or Ω-transport term. Josan (1995) studied about the low level westerly jet during the onset of monsoon 10 to 17 of June 1979. He pointed out for the time averaged momentum budget for the box considered in the region suggests that the maximum contribution for the maintenance of westerly jet is due to transient north-south term and the Coriolis force term is a sink term for the momentum along with transient top-bottom and frictional force terms. The acceleration and deceleration of the jet was depicted with the values of source and sink terms of momentum. Joseph *et al*., (2012) studied with data of storms with 34 knots or more at the North Indian Ocean for the period of 1979-2008. The study showed enhanced convection of MJO over maritime continent and adjoining eastern Indian Ocean are the highest favorable environment for cyclogenesis in the Bay of Bengal. Geetha B., *et al*., (2020) points out that the rapid intensification phase of TC Ockhi was associated with vertical non-uniform heating with upper and lower tropospheric warming associated with latent heat release in convection. Bala Subrahamanyam D., *et al*., (2020) investigated the impact of a very severe cyclonic storm 'Ockhi' on the marine atmospheric boundary layer using a regional numerical weather prediction model and found a huge rise in the magnitude of sensible and latent heat fluxes during the period with a decline in the mixed layer height during the passage of storm.

2. Objectives

There are a few number of studies on Tropical Cyclones (TC) of the North Indian Ocean (NIO) especially the Arabian Sea (ARB). The very rare Very Severe Cyclonic Storm (VSCS) Ockhi over the NIO in the Sea area during 29/Nov-05/Dec/2017 shows rapid development and intensification. Fig. 1 and Table 6 shows the life cycle (courtesy India Meteorological Department, New Delhi). Before TC Ockhi only three numbers of TCs were formed in the ARB area. But now it shows a sudden increase in the number and intensity of TCs in the ARB. This AM budget study is intended to provide certain insights, *viz*., which are the factors that influence the TC system by finding out the source and sink terms for the maintenance of TC Ockhi especially during the four days of Initial (30 Nov, 2017), Rigorous Intensification (RI) (01, 02 Dec, 2017) and Mature (03 Dec, 2017).

3.1. *Data and methodology*

Momentum Budget Per Unit Mass	BUDGET EQUATION IN (X, Y, P, T) SYSTEM USED
Pressure Levels (5 Levels)	1000 hPa-100 hPa (1000, 800, 500, 200, 100)
Meridional Boundary	5.04° N - 19.2° N
Zonal Boundary	60° E - 77° E
Date	30 Nov (DAY1), 01 Dec (DAY2), 02 Dec (DAY3), 03 Dec 2017 (DAY4)
Time Of Observation	0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 UTC
Data Set	NCMRWF IMDAA 3 HOURLY PRESSURE LEVEL DATASET (0.12° × 0.12°) - Reanalysed Web Site data
Variables Used	U-COMPONENT OF WIND M/S
	V-COMPONENT OF WIND M/S
	Z-GEOPOTENTIAL HEIGHT METRES

3.2. *Budget equation used*

Here the area is a small box very near to the Equator, the effect due to the curvature of the Earth's surface can be neglected. Thus, the momentum budget equation per unit mass in Cartesian system (x, y, p, t) given by [Josan (1995)] is used.

$$\frac{1}{M}\left[\frac{1}{g}\int_{x_1}^{x_2}\int_{y_1}^{y_2}\int_{p_1}^{p_2}\frac{\partial u}{\partial t}\,dx\,dy\,dp\right] = +\frac{1}{M}\left[\frac{2\Omega}{g}\int_{x_1}^{x_2}\int_{y_1}^{y_2}\int_{p_1}^{p_2} v\sin\phi\,dx\,dy\,dp\right] \qquad \text{(T1)}$$

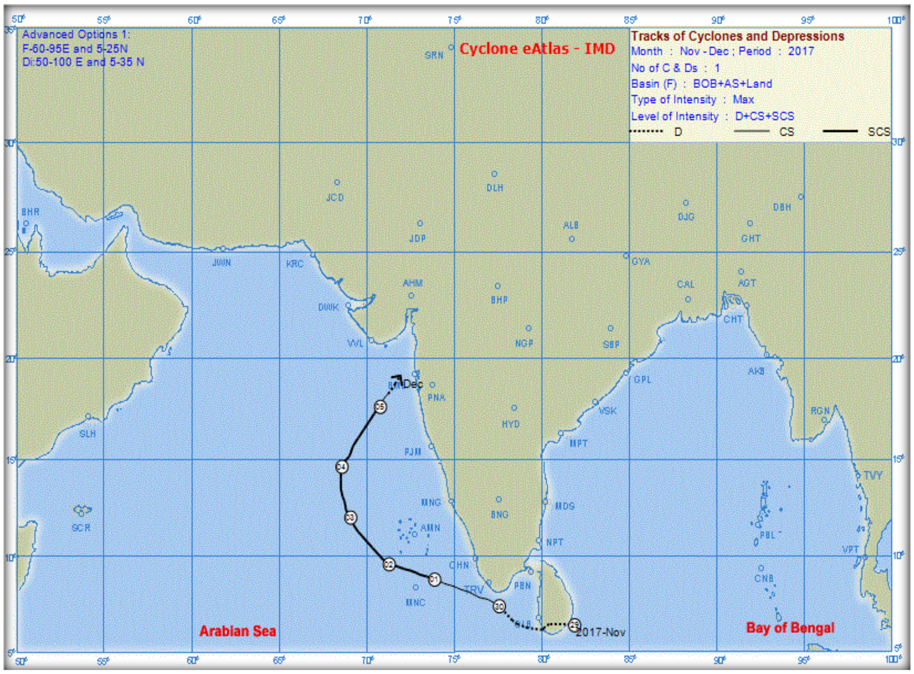

Fig. 1. Track of TC Ockhi (*Courtesy* : IMD, New Delhi)

$$+\frac{1}{M}\left[\int_{x_1}^{x_2}\int_{y_1}^{y_2}(\Gamma_{zx})_{p1}\,dx\,dy\right] \qquad \text{(T2)}$$

$$-\frac{1}{M}\left[\int_{y_1}^{y_2}\int_{p_1}^{p_2}(z)\Big|_{x_1}^{x_2}\,dy\,dp\right] \qquad \text{(T3)}$$

$$-\frac{1}{M}\left[\frac{1}{g}\int_{y_1}^{y_2}\int_{p_1}^{p_2}\left(u^2\right)_{x_1}^{x_2}\,dy\,dp\right] \qquad \text{(T4)}$$

$$-\frac{1}{M}\left[\frac{1}{g}\int_{x_1}^{x_2}\int_{p_1}^{p_2}(uv)_{y_1}^{y_2}\,dx\,dp\right] \qquad \text{(T5)}$$

$$-\frac{1}{M}\left[\frac{1}{g}\int_{x_1}^{x_2}\int_{y_1}^{y_2}(uw)_{p_1}^{p_2}\,dx\,dy\right] \qquad \text{(T6)}$$

The LHS of the equation is the rate of change of relative angular momentum for the region. Where M = $\left|\frac{(x2-x1)(y2-y1)(p2-p1)}{g}\right|$, modulus of entire mass of the box considered.

Term T1 (CF) is the Ω or Coriolis transport term. Term T2 (FRICN) is the frictional torque at the surface or skin friction. Term T3 (ZPG) is the zonal pressure gradient term. Term T4 (EW) is the east-west flux divergence. Terms T5 (NS) and T6 (TB) are the north-south and top-bottom flux divergence terms.

Where Ω = Angular velocity of earth, ϕ = any arbitrary latitude, u = zonal component of wind, v = meridional component of wind, P = any arbitrary pressure level, t = any arbitrary time, ω = Vertical velocity (is computed by kinematic method from u and v data on a regular grid array), z = geo potential height, V = horizontal velocity, g = acceleration due to gravity, ρ = density of air, x_1 = western boundary, x_2 = eastern boundary, y_1 = southern boundary, y_2 = northern boundary, P_1 = lower pressure level, P_2 = upper pressure level, τ_{zx} = eddy stress due to zonal motion, $\tau_{zx} = C_D = \rho V u$, is the eddy stress due to zonal motion. $V = (u^2 + v^2)^{1/2}$ is the horizontal velocity. $C_D = C_{D0}$ (0.94 + 0.034 V) for V >16.8 m s^{-1} (This is used in this study) are used where $C_{D0} = 1.1 \times 10^{-3}$ is the average nondimensional drag coefficient, u and v are the zonal and meridional wind speeds [after Krishnamurti (1980)] and is considered for pressure levels from 1000 hPa and 800 hPa. This is taken as the total frictional force term value for the entire box 1000 hPa - 100 hPa here.

3.3. *Method*

The evaluation of integrals are done with the help of Trapezoidal rule. FORTRAN programming language is used for computation.

4. Result and discussion

There are mainly three results, (*i*) Momentum budget term values for 8 observations each day (Tables 1-4) and charts 1-6. (*ii*) Table 5 and Charts 7-10 show the total

TABLE 1

Momentum budget term values for eight observations provided by NCMRWF IMDAA for the area (5.04° N - 19.2° N, 60° E- 77° E) on 30/11/2017(day1)-all values are in SI unit (Newton per Unitmass)

Time	TM (CF)	T2(FRICN)	T3(ZPG)	T4(EW)	T5(NS)	T6 (TB)	Total
0000 UTC	-1.2391E-06	-3.9086E-07	1.0510E-04	1.7347E-07	-9.2195E-06	1.4156E-12	9.4424E-05
0300 UTC	-1.0842E-06	-4.9639E-07	1.0519E-04	1.4370E-07	-1.4740E-05	2.2562E-12	9.4424E-05
0600 UTC	-8.7838E-07	-5.1363E-07	1.0546E-04	-4.3184E-08	-1.7003E-05	-6.5630E-12	8.9013E-05
0900 UTC	-9.8380E-07	-3.8685E-07	1.0527E-04	-7.6941E-08	-1.6410E-05	5.6527E-12	8.7022E-05
1200 UTC	-1.1383E-06	2.1887E-07	1.0520E-04	1.3911E-08	-9.3356E-06	-2.5965E-12	8.7413E-05
1500 UTC	-1.0535E-06	7.6122E-07	1.0526E-04	8.2718E-08	-1.0312E-05	3.4851E-12	9.4959E-05
1800 UTC	-7.8430E-07	6.6053E-07	1.0517E-04	-1.4932E-08	-1.1413E-05	-2.1106E-12	9.4738E-05
2100 UTC	-7.2260E-07	7.1087E-07	10530E-04	-1.7944E-07	-1.2345E-05	-2.0712E-12	9.3618E-05
Total	-7.8842E-06	5.6376E-07	8.4195E-04	9.9302E-08	-1.0078E-04	-5.3170E-13	7.3561E-04

TABLE 2

Momentum budget term values for eight observations provided by NCMRWF IMDAA for the area (5.04° N - 19.2° N, 60° E- 77° E) on 01/12/2017(DAY2)-all values are in SI unit (Newton per Unit mass)

Time	T1(CF)	T2(FRICN)	T3(ZPG)	T4(EW)	T5(NS)	T6(TB)	Total
0000 UTC	-1.0514E-06	6.7346E-07	1.0535SE-04	-1.7146E-07	-3.3384E-06	-4.2752E-12	1.0146E-04
0300 UTC	-1.1369E-06	-1.1431E-07	1.0538E-04	-2.1365E-07	-6.5596E-06	5.8750E-12	9.7356E-05
0600 UTC	-8.7717E-07	-4.1151E-07	1.0531E-04	-2.4908E-07	-1.8319E-06	4.9992E-12	1.0194E-04
0900 UTC	-8.1360E-07	-4.9871E-07	1.0532E-04	-2.6779E-07	-3.8280E-06	-8.8917E-12	9.9912E-05
1200 UTC	-7.6804E-07	-3.7662E-07	1.0535E-04	-1.8225E-07	-8.9274E-06	-6.3463E-12	9.5096E-05
1500 UTC	-7.6848E-07	-5.4325E-07	1.0544E-04	-3.8756E-07	-1.3777E-05	1.2380E-12	8.9964E-05
1800 UTC	-5.8076E-07	-3.4303E-07	1.0543E-04	-6.9532E-07	-1.3972E-05	-1.2738E-12	8.9839E-05
2100 UTC	-5.0799E-07	-3.8115E-07	1.0560E-04	-8.3881E-07	-1.8412E-05	5.7815E-12	8.5460E-05
Total	-6.5043E-06	-1.9951E-06	8.4318E-04	-3.0059E-06	-7.0646E-05	-2.8933E-12	7.6103E-04

TABLE 3

Momentum budget term values for eight observations provided by NCMRWF IMDAA for the area (5.04° N - 19.2° N, 60° E- 77° E) on 02/12/2017(DAY3)-all values are in SI unit (Newton per Unit mass)

Time	T1(CF)	T2(FRICN)	T3(ZPG)	T4(EW)	T5(NS)	T6(TB)	Total
0000 UTC	-1.0514E-06	6.7346E-07	1.0535E-04	-1.7146E-07	-3.3384E-06	-4.2752E-12	1.0146E-04
0300 UTC	-6.6256E-07	-1.6957E-06	1.0547E-04	-5.4569E-07	-2.6466E-05	6.6536E-12	7.6100E-05
0600 UTC	-4.4105E-07	-5.2685E-07	1.0501E-04	-2.9239E-07	-2.2503E-05	-3.0243E-12	8.1247E-05
0900 UTC	-4.1325E-07	-4.6169E-07	1.0506E-04	-2.9370E-07	-2.2162E-05	7.9904E-12	8.1729E-05
1200 UTC	-3.1504E-07	-6.9108E-07	1.0513E-04	-2.4975E-07	-2.4082E-05	-2.7161E-12	7.9792E-05
1500 UTC	-1.5463E-07	1.3683E-08	1.0509E-04	-2.0869E-07	-2.7488E-05	-1.1059E-11	7.7252E-05
1800 UTC	1.6213E-07	1.5167E-08	1.0502E-04	-2.9913E-07	-3.4809E-05	7.0508E-13	7.0089E-05
2100 UTC	2.2363E-07	-2.6315E-07	1.0489E-04	-3.6886E-07	-4.5344E-05	-2.2453E-11	5.9143E-05
Total	-2.6522E-06	-2.9362E-06	8.4102E-04	-2.4247E-06	-2.0619E-04	-2.8179E-11	6.2681E-04

TABLE 4

Momentum budget term values for eight observations provided by NCMRWF IMDAA for the area (5.04° N - 19.2° N, 60° E- 77° E) on 03/12/2017 (DAY4)-all values are in SI unit (Newton per Unit mass)

Time	T1(CF)	T2(FRICN)	T3(ZPG)	T4(EW)	T5(NS)	T6(TB)	Total
0000 UTC	3.0354E-07	-6.7756E-07	1.0507E-04	-3.8477E-07	-4.5608E-05	1.3177E-11	5.8703E-05
0300 UTC	3.7019E-07	-1.8586E-06	1.0478E-04	-4.3437E-07	-4.3120E-05	1.1539E-11	5.9737E-05
0600 UTC	5.5561E-07	-1.5163E-06	1.0477E-04	-3.9119E-07	-4.1949E-05	7.5704E-14	6.1469E-05
0900 UTC	6.3662E-07	-7.9426E-07	1.0489E-04	-5.1579E-07	-4.5863E-05	6.9244E-12	5.8354E-05
1200 UTC	5.4480E-07	-1.3938E-07	1.0478E-04	-4.5842E-07	-5.3970E-05	-1.0856E-11	5.0757E-05
1500 UTC	4.4659E-07	-6.7614E-07	1.0470E-04	-4.7182E-07	-6.1688E-05	2.1795E-12	4.2311E-05
1800 UTC	6.3193E-07	-1.1403E-06	1.0445E-04	-5.8342E-07	-6.7845E-05	-1.8453E-11	3.5513E-05
2100 UTC	8.7560E-07	-1.2710E-06	1.0425E-04	-6.4216E-07	-7.9074E-05	-1.6174E-11	2.4138E-05
Total	4.3649E-06	-8.0735E -06	8.3769E-04	-3.8819E-06	-4.3912E-04	-1.1587E-11	3.9098E-04

TABLE 5

Total Momentum budget term values for each day after adding all similar term values calculated on eight observations provided by NCMRWF IMDAA for the area (5.04° N - 19.2° N, 60° E- 77° E) on 30/11/2017(DAY1), 01/12/2017(DAY2), 02/12/2017(DAY3) & 03/12/2017(DAY4)-all values are in SI unit (Newton per Unit mass)

Date	T1(CF)ALL	T2(FRICN)ALL	T3(ZPG)ALL	T4(EW)ALL	T5(NS)ALL	T6(TB)ALL	Grand Total
DAY 1	-7.8842E-06	5.6376E-07	8.4195E-04	9.9302E-08	-1.0078E-04	-5.317E-13	7.3395E-04
DAY 2	-6.5043E-06	-1.9951E-06	8.4318E-04	-3.0059E-06	-7.0646E-05	-2.8933E -12	7.6103E-04
DAY 3	-2.6522E-06	-2.9362E-06	8.4102E-04	-2.4247E-06	-2.0619E-04	-2.8179E-11	6.2681E-04
DAY 4	4.3649E-06	-8.0735E-06	8.3769E-04	-3.8819E-06	-4.3912E-04	-1.1587E-11	3.9098E-04

budget terms for each day after adding all the same term values calculated on 8 observations. (*iii*) Table 5 and Chart 11 Grand total momentum budget for each day. All the values are in SI units, Newton per unit mass.

4.1. *Momentum budget for eight observations each day*

Charts 1-6 show the results and the fluctuations of different budget terms during the four day period on different three hour observations from 0000 to 2100 UTC. It is well explained with the observed life cycle of TC Ockhi in the Track chart (Fig. 1 and Table 6) during the period.

4.1.1. *Term T1 (CF) - Ω or Coriolis transport*

This term shows a steady increase throughout the four day period and on all observations (Chart 1). However, it is negative during the first two days, day 1 (Initial) and day 2 (RI) and is a sink term for the momentum of the box. The last day [day 4 (Mature)]

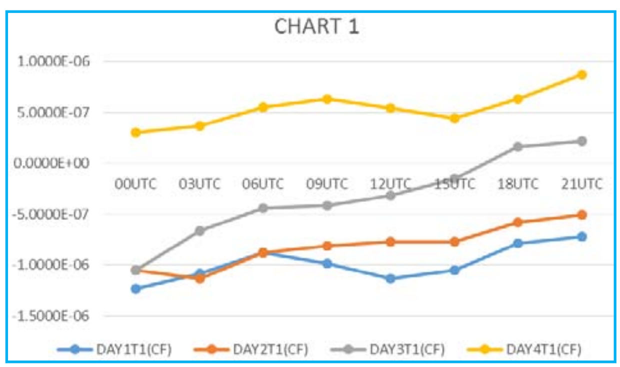

Chart 1. Shows the variation of Coriolis Force (CF) term (Y axis) with respect to time of eight observations (on X axis) for Day1(30/11/2017), Day2(01/12/2017), Day3(02/12/2017) and Day4(03/12/2017)- all values are in SI unit (Newton per Unit mass)

values show positive values and become a source for the momentum. The movement of the system from lower to higher latitudes is reflected in the values. On the third day [day 3 (RI)], the transition day, where it becomes source term from sink term at 1500 UTC.

TABLE 6

Best track positions and other parameters of the Very Severe Cyclonic Storm, 'Ockhi' over the Bay of Bengal during 30 Nov-03 Dec, 2017 (*Courtesy* : IMD, New Delhi)

Date	Time (UTC)	Centre lat.° N/ long.° E	C.I. NO.	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)	Grade
30/11/2017	0000	6.7/78.3	2.0	1000	30	6	DD
	0300	7.5/77.5	2.5	999	35	7	**CS**
	0600	7.8/76.9	2.5	998	40	8	CS
	0900	7.9/76.4	3.0	996	45	10	CS
	1200	8.2/75.8	3.0	996	45	10	CS
	1500	8.3/75.4	3.0	996	45	10	CS
	1800	8.5/74.9	3.0	994	45	12	CS
	2100	8.6/74.5	3.0	994	45	12	CS
01/12/2017	0000	8.8/74.0	3.0	992	50	14	**SCS**
	0300	8.9/73.8	3.5	990	55	16	SCS
	0600	9.0/73.4	3.5	989	60	18	SCS
	0900	9.1/73.0	4.0	988	65	21	**VSCS**
	1200	9.2/72.8	4.0	986	65	22	VSCS
	1500	9.3/72.5	4.0	984	65	24	VSCS
	1800	9.4/72.1	4.0	982	70	26	VSCS
	2100	9.5/71.8	4.0	980	75	28	VSCS
02/12/2017	0000	9.6/71.5	4.5	978	80	30	VSCS
	0300	9.7/71.2	4.5	978	80	32	VSCS
	0600	9.8/71.0	4.5	976	85	34	VSCS
	0900	10.2/70.6	4.5	976	85	34	VSCS
	1200	10.5/70.3	4.5	976	85	34	VSCS
	1500	10.8/70.0	4.5	976	85	34	VSCS
	1800	11.1/69.7	4.5	976	85	34	VSCS
	2100	11.3/69.5	4.5	976	85	34	VSCS
03/12/2017	0000	11.7/69.2	4.5	976	85	34	VSCS
	0300	12.1/69.0	4.5	977	80	32	VSCS
	0600	12.3/68.9	4.5	978	75	30	VSCS
	0900	12.4/68.8	4.5	980	75	28	VSCS
	1200	12.9/68.7	4.5	982	75	28	VSCS
	1500	13.1/68.6	4.5	982	75	28	VSCS
	1800	13.5/68.5	4.5	982	75	28	VSCS
	2100	14.0/68.5	4.5	982	75	28	VSCS

4.1.2. *Term T2 (FRICN) - The Frictional torque at the surface or skin friction*

This is the term which can give indication about air sea interaction (Chart 2) in this study. The lower level friction (1000-800 hPa) was considered for the computation of this term and some approximation was done in the drag coefficient values as given above (section 3c). From chart 2, the day 1 (Initial), a sudden increase is noted from 0900 UTC to 1500 UTC and it remains a positive (source) term for momentum. Thus, the trend of this term shows that on day1 it is a gain for the atmosphere and all the other days it is a loss as far as momentum budget is concerned. During RI stages, day 1 and day 2, the friction term shows very high positive values (source) at 0000 UTC and then it suddenly changes to sink (negative value) term after 0300 UTC onwards. The atmosphere (which contains TC Ockhi system) can have some positive feedback from the Sea after 2100 UTC - 0300 UTC (06 hours' time) during the

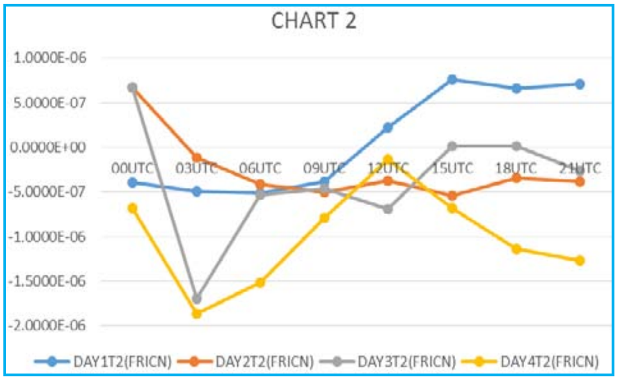

Chart 2. Shows the variation of Frictional Torque (FRICN) term (Y axis) with respect to time of eight observations (on X axis) for Day1(30/11/2017), Day2(01/12/2017), Day3(02/12/2017) and Day4(03/12/2017)- all values are in SI unit (Newton per Unit mass)

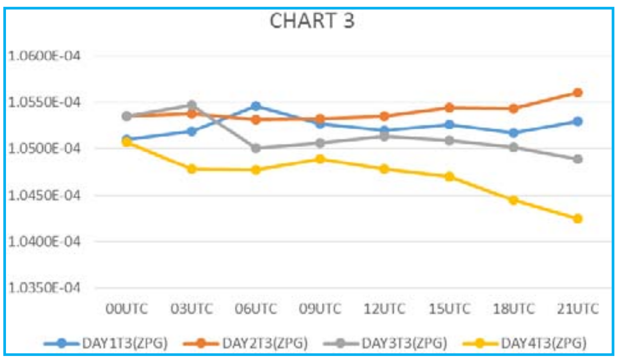

Chart 3. Shows the variation of Zonal Pressure Gradient Force (ZPG) term (Y axis) with respect to time of eight observations (on X axis) for Day1(30/11/2017), Day2(01/12/2017), Day3(02/12/2017) and Day4(03/12/2017)- all values are in SI unit (Newton per Unit mass)

RI stages. On day 4 (mature) the term is always negative (sink) and from 0000 UTC it decreases, then from 0300 UTC it increases steadily reaches highest negative value at about 1200 UTC and after that it decreases substantially.

4.1.3. *Term T3 (ZPG) - Zonal pressure gradient.*

Chart 3 shows that day 1 (initial) and day 2 (RI) a similar pattern. On day 1 and day 2 from 0900 UTC it shows a steady increase in values. On day 4 (mature) it shows a steady decrease in value from 0000 UTC to 2100 UTC. One can conclude that this term is the single source (positive value) for the momentum of the atmosphere area, which contains the system and is always positive and several orders higher than other terms under consideration. Thus, this term is the main player during the life cycle of the system.

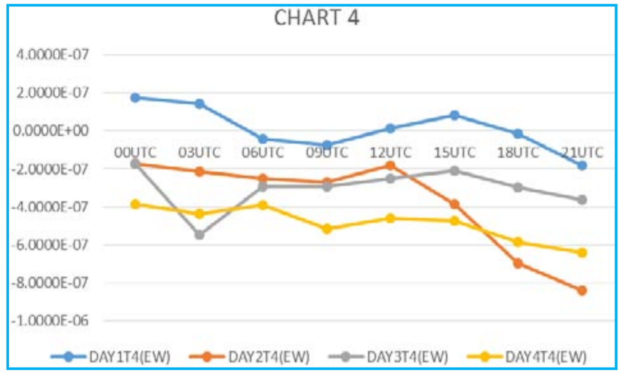

Chart 4. Shows the variation of East West Flux (EW) term (Y axis) with respect to time of eight observations (on X axis) for Day1(30/11/2017), Day2(01/12/2017), Day3(02/12/2017) and Day4(03/12/2017)- all values are in SI unit (Newton per Unit mass)

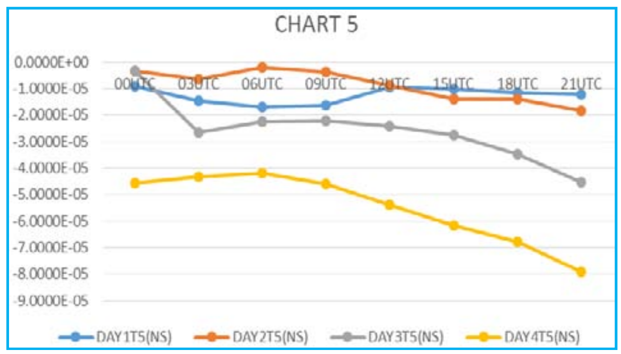

Chart 5. Shows the variation of North South Flux (NS) term (Y axis) with respect to time of eight observations (on X axis) for Day1(30/11/2017), Day2(01/12/2017), Day3(02/12/2017) and Day4(03/12/2017)- all values are in SI unit (Newton per Unit mass)

4.1.4. *T4 (EW) - East-west flux divergence.*

Chart 4 depicts the values for four days. This is a sink term except for the initial (up to 1500 UTC) stages of the system on day 1. There is a further decreasing trend after 1500 UTC on all days.

4.1.5. *T5 (NS) - North-south flux divergence*

This term is the largest sink term (negative) among all terms for all the days and shows high negative values on the last day. It shows the same pattern of further decreasing trend after 1500 UTC on all days.

4.1.6. *T6 (TB) - Top-bottom flux divergence*

This term shows an oscillation between positive and negative values (Chart 6). This is the typical area, where huge Cumulonimbus clouds with strong updrafts and

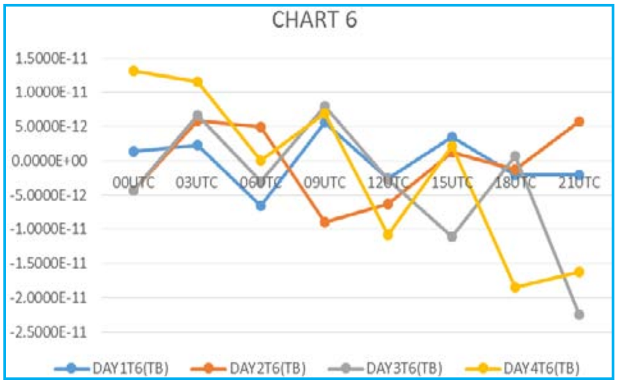

Chart 6. Shows the variation of Top Bottom Flux (TB) term (Y axis) with respect to time of eight observations (on X axis) for Day1(30/11/2017), Day2(01/12/2017), Day3(02/12/2017) and Day4(03/12/2017)- all values are in SI unit (Newton per Unit mass)

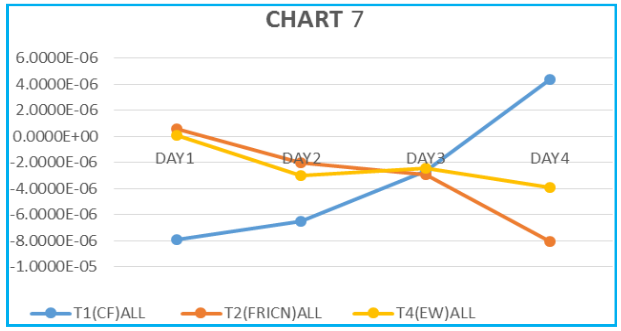

Chart 7. Shows the variation of total Momentum budget term values of Coriolis Force (T1), Frictional Torque (T2) and East West (T4) for each day (Y axis) after adding all similar term values calculated on eight observations (X axis) provided by NCMRWF IMDAA for the area (5.04N - 19.2N, 60E- 77E) on 30/11/2017(DAY1), 01/12/2017(DAY2), 02/12/2017 (DAY3) & 03/12/2017(DAY4)- all values are in SI unit (Newton per Unit mass)

downdrafts exists with cloud tops reaching up to tropopause level. It is clear in vertical velocity values in this area. The vertical velocity is zero beyond 200 hPa level. The vertical velocity values for the whole area other than the 100 hPa level shows a mixture of negative (ascending air associated with heavy rainfall and release of latent heat occurs) and positive (sinking air with clear skies) values. The day 1 and day 4 charts are similar with a wavy nature. The values are decreasing up to 0600 UTC and then increases to a peak positive value at 0900 UTC, then decreases for the next 3 hours and then increases to a second peak positive value at 1500 UTC and then afterwards decreases to 2100 UTC for both day 1(Initial) and day 4 (Mature). This may be due to intense internal feedback mechanisms during day time. On day 2 (RI) and day 3 (RI) there are rapid oscillations from positive and negative values and is observed an inverse correlation during observations of these days. From the above chart one can conclude that the top bottom term switch from source to sink term very rapidly on all days. There is an overall general trend of decreasing the values (loss) up to 1800 UTC and high positive (gain) values are found at 0000 UTC.

4.2. *Total budget for each day*

Table 5 and charts 7-10 show the results pictorially. The charts show the fluctuations of different terms during the four day period and values are obtained after adding the terms computed for different observations from 0000 to 2100 UTC on each day separately.

4.2.1. *T1 (CF) - Ω or Coriolis transport.*

This term show a steady increase throughout the period on all days and observations. However, it is negative during the first two days (Initial and RI) and a sink for momentum of the box. The last day (Mature) values show positive values and become a source of the momentum. The movement of the system from lower to higher latitudes is the clear indication of the values. The third day (RI), the transition day where it becomes source term from sink.

4.2.2. *T2 (FRICN) - Frictional torque at the surface or skin friction*

This is the term which gives some indication regarding air-sea interaction in the day. Here we also considered lower level friction (1000-800 hPa) with the same previously discussed approximation of the drag coefficient values. From Chart 7 only day 1 (Initial) gives a positive value (source) of the momentum. So, this day is a gain for the atmosphere and all the other days a loss, as far as momentum is concerned. During RI and mature stages (day 2, day 3 and day 4), the friction terms show overall negative values. The TC-Sea interaction is dominant through this term by exchanging momentum flux as seen in the chart. That is, on day 1 (Initial), it is a gain (positive) and on day 4 (Mature), a loss (negative) and the other two days (RI) are transition days.

4.2.3. *T3 (ZPG) - Zonal Pressure Gradient*

Chart 8 shows that it is always source (positive) term on all days. From day 1 the values increases to day 2 (RI), then observes a steady decrease in positive values through day 3 and day 4. One can conclude that this term is the single source (positive value) of the momentum of the atmospheric area, which contains the TC system and several orders higher than all other terms. And also, this term is the main player during the life cycle of the system as identified by previous genesis studies of Tropical Cyclones.

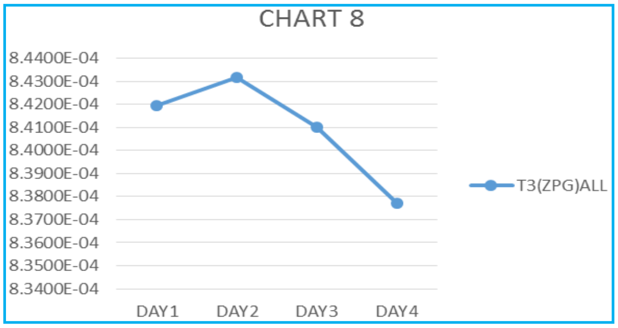

Chart 8. Shows the variation of total Momentum budget Zonal Pressure Gradient (T3) term values for each day (Y axis) after adding all similar term values calculated on eight observations and Days (X axis) provided by NCMRWF IMDAA for the area (5.04N - 19.2N, 60E- 77E) on 30/11/2017 (AY1), 01/12/2017(DAY2), 02/12/2017(DAY3) & 03/12/2017(DAY4)- all values are in SI unit (Newton per Unit mass)

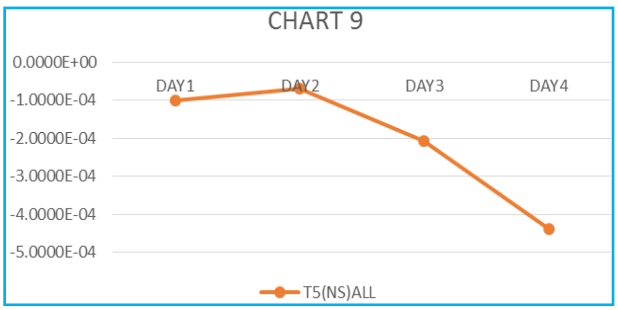

Chart 9. Shows the variation of total Momentum budget North South (T5) term values for each day (Y axis) after adding all similar term values calculated on eight observations and Days(X axis) provided by NCMRWF IMDAA for the area (5.04N - 19.2N, 60E- 77E) on 30/11/2017 (AY1), 01/12/2017(DAY2), 02/12/2017(DAY3) & 03/12/2017(DAY4)- all values are in SI unit (Newton per Unit mass)

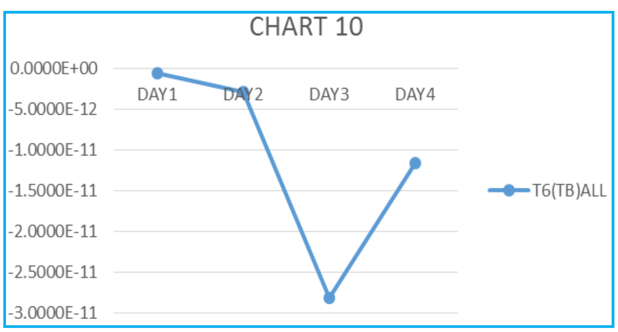

Chart 10. Shows the variation of total Momentum budget Top Bottom (T6) term values for each day (Y axis) after adding all similar term values calculated on eight observations and Days (X axis) provided by NCMRWF IMDAA for the area (5.04N - 19.2N, 60E- 77E) on 30/11/2017 (AY1), 01/12/2017(DAY2), 02/12/2017(DAY3) & 03/12/2017(DAY4)- all values are in SI unit (Newton per Unit mass)

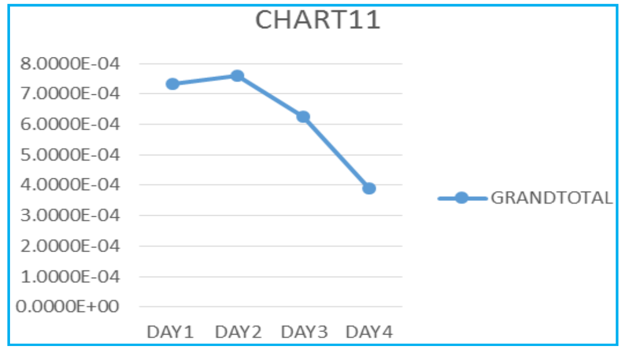

Chart 11. Shows the variation of Grand total of Momentum budget term values after adding all term values calculated on eight observations for each day (Y axis) and Days (X axis) provided by NCMRWF IMDAA for the area (5.04N - 19.2N, 60E 77E) on 30/11/2017 (AY1), 01/12/2017(DAY2), 02/12/2017(DAY3) & 03/12/2017(DAY4)- all values are in SI unit (Newton per Unit mass)

4.2.4. *T4 (EW) - East-West flux divergence*

Chart 7 depicts the values for four days. This is a sink term except for the initial stages of the system on day 1. There is a further decreasing (sink) trend after day 3 (RI).

4.2.5. *T5 (NS) - North-South flux divergence*

This term is the largest sink term (negative) among all terms for all the days and shows high negative values on the last day (Chart 9). It shows the same decreasing pattern after day 2 (RI). This term is several orders higher than other sink term like T4 (EW).

4.2.6. *T6 (TB) - Top-Bottom flux divergence*

This term shows (Chart 10) an oscillation between positive and negative values. This is typical area, where ascending and descending of air co-exists and is seen only up to 200 hPa in this study. On all days this term has negative (sink) values and the largest negative (loss) is found to be on day 3 (RI).

4.3. *Grand total momentum for each day*

Chart 11 depicts the grand total momentum budget values after adding all the terms each day for the four days [day 1 (initial), day 2 (RI), day 3 (RI) & day 4 (Mature)]. It is well explained with the observed behavior of TC Ockhi during the period. On all days, the grand total momentum for the whole box is positive. The peak positive value (gain) is observed on day 2 (RI). There is a steady decrease of total momentum up to day 4 (mature) and reaches a minimum positive value. That is the system loses momentum from day 2 onwards. Generally, due to the system, the total momentum is gained by the atmosphere on all the days and is the maximum on the second day.

5. Conclusions

The Coriolis transport term shows a steady increase throughout the four day period and on all observations in tune with the movement of TC Ockhi. The day 1 (Initial) and day 2 (RI) the Coriolis values are negative (sink) while last day (mature) it becomes a source (positive) of the momentum. This is due to the system's movement from 6.7º N/78.3º E (day 1 position) to 14.0º N/68.5º E (day 4 position) as shown in the track. The Frictional torque values at the surface indicate that on day 1 (Initial), it is a gain (positive) and on day 4 (Mature), a loss (negative). This is due to the initial days the atmosphere which contains the TC Ockhi gets the momentum through the air-sea interaction and during the mature stage a reverse process took place through hurricane wind and convective towers and subsequent release of latent heat. The other two days (RI) are transition days. The atmosphere (which contains TC Ockhi system) can have some positive feedback from the Sea after 2100 UTC-0300 UTC (06 hours' time) during the RI stages, *viz.*, day 2 and day 3 through friction. It is reported by IMD the sea surface temperature was around 28-29 °C over the region which is the one of the criterion for the genesis of TC. So the transfer of latent heat took place during the late night hours from the Sea to Atmosphere. One can conclude that the Zonal Pressure Gradient term, is the single source (positive value) of the momentum of the atmosphere area, which contains the system and always positive and several orders higher than other terms under consideration and the main player during the life cycle of the system. The East-West flux divergence and North-South flux divergence terms are sink terms, while later term is the largest sink term (negative) among all terms for all the days. From the chart of Top-Bottom flux divergence term, one can conclude that the top bottom term switch from source to sink term very rapidly on all days. There is an overall general trend of decreasing the values (loss) up to 1800 UTC and high positive (gain) values are found at 0000 UTC on all days. On all days the total momentum for the whole box is positive. This may be explained in connection with the convective tower development with strong up and down drafts around the eye wall of the system. Thus, from this momentum budget study, the observed behavior of TC Ockhi during the period is well explained.

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References

Geetha, B. and Balachandran, S., 2020, "Development and Rapid intensification of tropical cyclone OCKHI(2017) over the North Indian Ocean", *Journal of Atmospheric Science Research*, **03**, 3, 13-22. doi : https://ojs.bilpublishing.com/index.php/jasr/article/download/2177/1856.

Josan, P. S., 1995, "Momentum budget of low level westerly jet during monsoon onset", *MAUSAM*, **46**, 3, 235-244. doi : https://metnet.imd.gov.in/mausamdocs/14632_F.pdf.

Joseph, P. V., Mohankumar, K. and Krishnamohan, K. S., 2012, "The influence of Madden-Julian Oscillation in the genesis of North Indian Ocean tropical cyclones", *Theoretical and Applied Climatology*, **109**, 271-282. doi : https://link.springer.com/article/10.1007/s00704-011-0582-x.

Keshava, Murthy, R. N., 1968, "On the maintenance of mean zonal motion in the Indian summer Monsoon," *Monthly Weather Review*, **96**, 1, 23-31. doi : https://doi.org/10.1175/1520-0493(1968)096<0023:OTMOTM>2.0.CO;2.

Krishnamurti, T. N., 1980, "Work-book on Numerical Weather Prediction", *WMO Publication*, **669**, 1-2.

Piexoto, J. P. and Oort, A. H., 1984, "Physics of climate", *Reviews of Modern Physics*, **56**, 3, 365-429. doi : https://link.aps.org/doi/10.1103/RevModPhys.56.365.

Subrahamanyam, D., Bala, S. Roshny, P. Paul, Freddy, T. J., Anurose and Ramachandran, R., 2020, "Impact of very severe cyclonic storm 'OCKHI' on the vertical structure of marine atmospheric boundary layer over the Arabian Sea", *Bulletin of Atmospheric Science & Technology*, **1**, 407-431. doi : https://link.springer.com/ article/10.1007/s42865-020-00020-7.