Construction of Vertical Wind Profile from Satellite–Derived Winds for Objective Analysis of Wind Field

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ABSTRACT

During summer Monex–79, a variety of observing systems viz. research ships, research aircrafts, constant pressure balloons and geostationary satellite etc. were deployed, besides the regular conventional observations. The purpose of these additional systems was to make the best possible data for the studies on various aspects of monsoon circulation. The present study is aimed at the construction of vertical wind profile using cloud motion vectors obtained from GOES (I–O) satellite and to examine whether the constructed wind profiles improves the representation of the monsoon system, flow pattern etc. in the objective analysis. For this purpose, climatological normals of the wind field are considered as the initial guess and the objective analyses of the wind field are made with, first using only data from conventional observations over land areas, subsequently including the constructed winds from cloud motion vectors. These analyses are then compared with the standard analyses of wind field obtained from Quick Look Atlas by T. N. Krishnamurti et al. (1979).

It is inferred that satellite estimated mean wind profiles show good agreement with the mean wind profiles of the research ships with RMS errors less than 5 mps below 500 hPa and less than 8 mps above 500 hPa. It is further inferred that the inclusion of constructed winds shows a positive impact on the objective analysis and improvement is seen to be more marked in the data–sparse region of the Arabian sea. Analyses which include the constructed winds show better agreement with the standard analysis, than the analyses obtained using only conventional winds. Thus, results of our study suggest that the wind profiles constructed using cloud motion vectors are of potential use in objective analysis to depict the major circulation features over the Indian region.

I. INTRODUCTION

India is surrounded by vast oceanic areas such as the Arabian sea, the Bay of Bengal and the Indian ocean. Wind observations over these areas are only feasible through cloud tracked winds from geostationary satellites. Winds observed by geostationary meteorological satellites are based on the cloud motions, and are, therefore, restricted to cloudy areas. Cloud motion winds are generally obtained at two levels in the vertical. Satellite–derived winds at low–level are mainly concentrated at about 900 / 850 hPa, where the base of cumulus is formed and at highy level it is mostly confined at about 250 / 200 hPa, where layered cirrus clouds are generally formed. Detail prospects of satellite wind sensing system in the years 1995–2000 have been studied by Hamda (1988) over the oceanic regions. It is shown that the technological development such as the Doppler lidar system onboard the satellite would estimate the winds even over cloud free zones and for more levels. Wind is one of the most important meteorological parameters, particularly over the tropical ocean regions and hence till such time that the new technology provides wind field at all levels, we have to develop techniques to construct vertical wind profile using low and high level cloud motion winds available from geostationary satellites over the tropical regions for NWP models.

Some of the investigators (Mahajan et al., 1986; Yadao and Kelkar, 1989; Mahajan, 1987; Mahajan et al., 1989) have used cloud motion vectors for various atmospheric studies over the Indian region. A best match for satellite–derived low–level winds is shown against the observed winds at 900 hPa over the Indian seas (Mahajan and Deshpande, 1986). A relationship between satellite–derived low lever winds and surface winds is established over the tropical Indian ocean (Simon and Desai, 1986; Mahajan and Nagar, 1987). An expression for both u and v components relating 900 hPa winds to various other pressure levels is obtained for the oceanidc regions surrounding India (Begum and Datta, 1986; Begum, 1986). Impact study of various data sets has been made using Monex–79 data for regional circulation (Rajamani et al., 1982; Joshi et al., 1986).

Winds at all the standard pressure levels are very much required as an input to Numerical Weather Prediction models, especially over the global tropics where wind data are more reliable than the geopotential height fields. Since the data coverage over the tropical region is poor due to large oceanic regions, it is important to obtain winds through nonconventional means. Therefore, in this paper an attempt has been made to construct vertical wind profile from surface–100 hPa, using satellite–derived cloud motion vectors. For this purpose, linear regression equations are developed between satellite–derived cloud motion vectors obtained from GOES (I–O) satellite and conventional winds reported by USSR research ships during summer Monex–1979. Verification experiment is performed for a case of depression making the use of constructed winds in objective analysis over the Indian region.

II. DATA

1. *Satellite Data*

During summer monsoon 1979, a special campaign was organised for intensive data collection from variety of platforms viz. satellites, research ships, research aircrafts, constant pressure balloons etc., besides the regular convectional resources. One of the U.S. geostationary satellites, GOES, was specially brought from the Atlantic ocean over the Indian ocean and positioned at about 60°E for monitoring the monsoon circulation, particularly in terms of wind observations. GOES measurements were ideal because they possessed both high spatial and high temporal resolutions i.e., 1 km in visible, 8 km in infrared and half hourly sampling frequency. The satellite had produced images of the earth and its cloud cover in the spectral bands 0.5–0.9 μm (visible) and 11–12 μm (infrared) respectively. Based on the sequences of cloud photographs transmitted by GOES satellite between 09:30 to 10:30 UTC wind vectors at two levels in the troposphere were determined by several groups in USA and France. Wind data produced by these groups have been utilized in the study.

2. *Research Ship Data*

Russian research ships, taking part in Monex programme were recording upper air observations, two to four times a day at their stationary positions and during their transit over the Indian ocean. Wind data available from Russian research ships at their stationary positions 6.3°N, 59.1°E (UHQS); 6.5°N, 54.5°E (UMAY); 8.7°N, 57.0°E (EREB); 3.9°N, 57.1°E (EREC) for the period 16–29 May 1979; 7.0°N, 69.0°E (UHQS); 7.0°N, 64.5°E (UMAY); 9.2°N, 66.7°E (EREB); 4.7°N, 66.7°E (EREC); 6.9°N, 66.3°E (EREH); for the period 2–12 June 1979; and 18.0°N, 89.5°E (UHQS); 16.1°N, 91.0°E (UMAY); 16.2°N, 87.7°E (EREC); 14.4°N, 89.5°E (EREH); for the period 11–23 July 1979 have been used in the study (Fig.1). Wind data at 12 UTC recorded by these research ships at the surface, (deck level of the ship

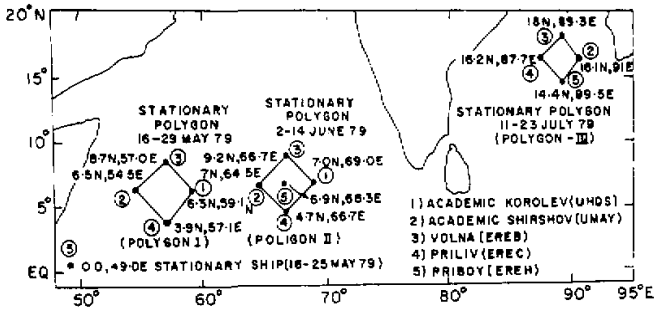

Fig.1. Stationary positions of Russian research ships over the Indian ocean during May–July 1979.

i.e., ~ 10 m) 1000, 950, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150 and 100 hPa are utilized. 12 UTC timing of the ship observations is considered since it is very close to the timings of satellite wind observations.

3. *Climatological and Conventional Data*

Monthly climatological normals of the wind field obtained from I. I. O.E. atlas for the month of June in the domain 0–25°N and 48–80°E are utilized as initial guess field for the objective analysis made in the experiment. Similarly conventional wind data over only land areas in the above domain are also utilized.

4. *Objectively Analysed Data*

Objectively analysed wind data at 850 and 200 hPa obtained from Quick Look Summer Monex Atlas have been utilized (Krishnamurti et al., 1979). These analyses have been considered as standard one because the analyses were made very carefully and also they were based on all available conventional data including additional observations from research ships, research aircrafts, satellites, constant level balloons etc. This wind field is used for comparison with the wind analyses obtained in our experiment.

III. METHODOLOGY

1. *Regression Analysis*

Satellite–derived low and high level winds are noted at the exact geographic locations of the stationary positions of the Russian research ships. There were a very few occasions when the satellite–derived winds were not available exactly overhead the ship locations. In such cases the mean wind in a 5° quadrangle was computed centering the ship position in that grid and this mean wind was considered as the satellite–derived wind at the ship location. This procedure was adopted because it was shown that auto–correlation coefficients of satellite wind measurements were highly significant within 5 degree square (Wylie et al., 1981). Considering satellite–derived winds at low and high level as an independent variable and ship winds at all standard pressure levels as the dependent variable, linear regression equations and correlation coefficients are derived for both u and v components. These equations are statistically tested and RMS errors are computed. Table 1 gives the values of correlation coefficients and RMS errors for satellite–derived low and high level winds. A plot of correlation coefficients and rms errors is made for both u amd v components. Fig.2 depicts these

Table 1. Statistical Relationship between Conventional and Satellite-derived Low and High-level Winds

Level		Sat-derived low-level wind				Sat-derived high-level wind			
		u	v	u	v	u	v	u	v
hPa	n	RMS error (mps)	RMS error (mps)	r	r	RMS error (mps)	RMS error (mps)	r	r
Surface	166	2.5	2.9	0.78	0.58	3.7	3.6	−0.36	−0.02
1000	166	2.4	2.7	0.80	0.63	3.7	3.5	−0.37	−0.03
950	166	2.6	2.4	0.83	0.72	4.5	3.4	−0.32	−0.05
900	166	2.7	1.9	0.85	0.76	4.9	2.9	−0.27	−0.12
850	166	3.5	2.3	0.76	0.64	5.4	2.9	−0.19	−0.10
800	166	3.9	2.9	0.71	0.45	5.6	3.3	−0.13	−0.15
700	166	4.8	3.3	0.53	0.33	5.7	3.4	−0.04	−0.19
600	166	4.7	3.6	0.49	0.21	5.3	3.7	−0.19	−0.16
500	166	4.9	3.8	0.33	0.09	5.4	3.7	−0.12	0.05
400	166	5.1	2.4	−0.24	−0.11	4.9	3.8	0.36	0.26
300	166	7.5	5.0	−0.31	−0.07	5.1	3.8	0.77	0.65
250	166	8.8	4.9	−0.39	−0.09	4.7	3.3	0.87	0.73
200	166	11.0	7.1	−0.37	−0.24	7.2	6.3	0.79	0.49
150	166	12.1	7.2	−0.45	−0.36	7.8	6.9	0.82	0.45
100	166	11.2	6.7	−0.48	−0.21	7.9	6.5	0.71	0.23

Where

r = Correlation coefficient

n = Number of observations

Table 2. Results of Regression Analysis

Level hPa	n	u Component	r	vc Component	r
Surface	166	$Y = 0.71X_1 + 0.76$	0.78	$Y = 0.59X_1 + 0.65$	0.58
1000	166	$Y = -0.1X_1 + 1.41$	0.80	$Y = 0.65X_1 + 0.63$	0.63
950	166	$Y = 0.91X_1 + 0.42$	0.83	$Y = 0.71X_1 + 0.62$	0.72
900	166	$Y = 0.99X_1 + 0.08$	0.85	$Y = 0.66X_1 - 0.35$	0.76
850	166	$Y = 0.95X_1 - 0.18$	0.76	$Y = 0.55X_1 - 0.83$	0.64
800	166	$Y = 0.92X_1 - 0.7$	0.71	$Y = 0.44X_1 - 1.1$	0.45
700	166	$Y = 0.68X_1 - 1.1$	0.53	$Y = 0.33X_1 - 0.41$	0.33
600	166	$Y = 0.59X_1 - 3.5$	0.49	$Y = 0.23X_1 - 0.41$	0.21
500	166	$Y = 0.46X_1 - 5.3$	0.33	$Y = 0.09X_1 - 0.39$	0.09
400	166	$Y = 0.02X_2 - 5.3$	0.36	$Y = 0.19X_2 - 0.45$	2.26
300	166	$Y = 0.75X_2 - 0.75$	0.77	$Y = 0.6X_2 - 0.34$	0.65
250	166	$Y = 1.04X_2 + 0.28$	0.87	$Y = 0.67X_2 - 0.1$	0.73
200	166	$Y = 1.15X_2 - 0.85$	0.79	$Y = 0.65X_2 - 0.47$	0.49
150	166	$Y = 1.36X_2 - 5.33$	0.82	$Y = 0.64X_2 - 1.70$	0.45
100	166	$Y = 1.12X_2 - 12.42$	0.71	$Y = 0.17X_2 - 0.88$	0.23

Where

r = Correlation coefficient

X_1 = Satellite-derived low-level wind

X_2 = Satellite-derived high-level wind

Y = Estimated wind

n = Number of observations

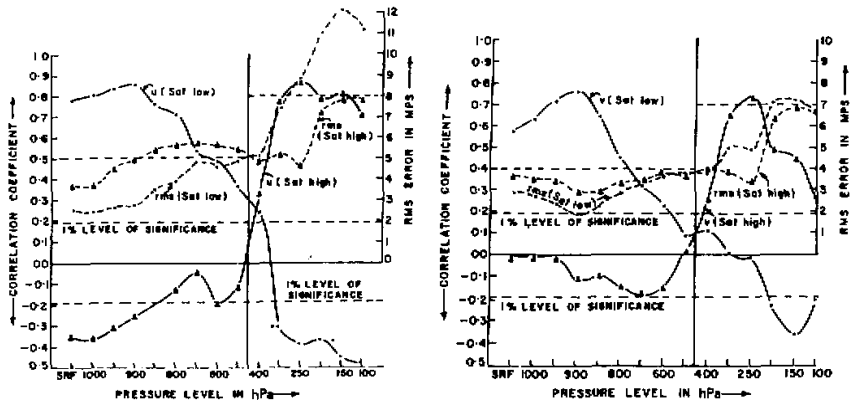

Fig.2. Plots of correlation coefficients and rms errors for u (upper panel) and v (lower panel) components.

plots. Regression equations which would be more appropriate for the construction of vertical wind profiles were decided from these plots. Based on these regression equations (Table 2) mean vertical wind profiles for both u and v components are constructed for all standard pressure levels for the stationary positions of each research ships. Three mean vertical wind profiles obtained from regression relationship alongwith the conventional wind profiles are presented in Fig.3 for three different locations of the ships during May, June and July 1979 respectively. In these figures ACE represents the vertival profiles for zonal wind component and BDF represents for the meridional wind component. Based on the equations at 850 and 200 hPa (Table 2), winds are constructed over the Arabian sea at the locations of cloud motion vectors, for a case of depression on 16 June 1979.

2. *Objecive Analysis*

The standard objective analysis scheme used in this study is based on the successive correction method after Cressman (1959). The scheme is applied to wind analysis at 850 and 200 hPa and the analysis is done over the domain equator–26°N and 48–80°E with the grid resolution 2° latitude and 2° longitude. The objective analyses are made for 16 June 1979 when a depression was formed over the Arabian sea.

In the beginning, it was thought to consider previous day's analyses as the initial guess, but these analyses have in their memory the history of the monsoon system. Hence, monthly climatological normals of wind field are used as initial guess to evaluate the real impact of constructed winds.

The analyses are performed for the following two cases.

Case A: Only conventional wind data over main land areas are used in the objective analyses.

Case B: The data of Case A are further enhanced by the inclusion of winds at 850 and 200 hPa constructed from empirical relations using cloud motion vectors.

The analyses are examined by comparing objectively analysed wind field in above two cases with the standard analysed wind fields from Quick Look Summer Monex Atlas. In addition, the vector differences of the centres of the monsoon depression are also examined.

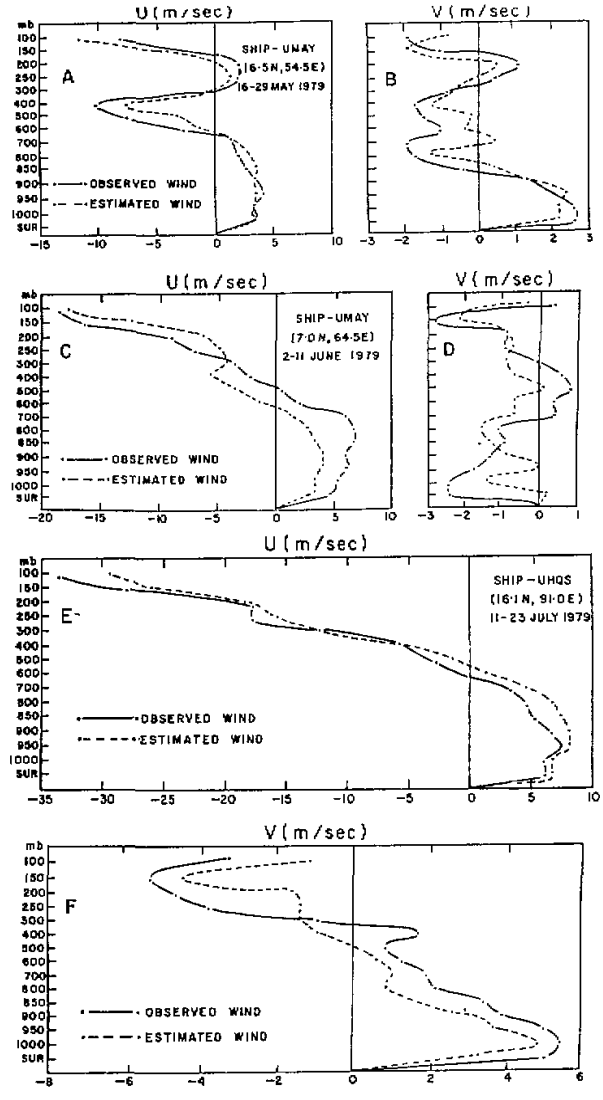

Fig.3. Observed and estimated vertical wind profiles for the stationary positions of USSR research ships during May, June and July 1979 respectively.

IV. RESULTS

The following are the major results of the study

(i) Satellite estimated mean wind profiles for both u and v components show good agreement with the mean wind profiles of the research ships with RMS errors less than 5 mps below 500 hPa and less than 8 mps above 500 hPa.

(ii) Utilization of only conventional winds in objective analysis at 850 hPa (Case A) a

fairly good cyclonic circulation and a very small area of strong winds (> 20 mps) are depicted over the southeast Arabian sea. But, with the further inclusion of constructed winds at 850 hPa (Case B), a well organized cyclonic circulation and a large area of strong westerly winds (> 20 mps) over south Arabian sea are depicted and this improvement in the analysis of Case B reflects the similar features to that of the standard analysis.

(iii) Utilization of only conventional winds in objective analysis at 200 hPa (Case A) an unorganized diffluence and no strong winds (> 20 mps) are depiced, whereas with the inclusion of constructed winds at 200 hPa (Case B), a well organized diffluence and strong easterly winds over south Arabian sea are depicted and this pattern very well resembles with the pattern of standard analysis.

(iV) The vector differences in the centres of cyclonic circulations at 850 hPa for Case A and Case B with the centres of standard analysis are 400 and 80 kms respectively.

(V) On the whole, analyses of Case B in response to the flow pattern, cyclonic circulation and centre of depression show better agreement with the standard analyses than Case A.

V. DISCUSSIONS

Satellite–derived low–level winds are first compared with the conventional winds reported by research ships at all standard pressure levels from surface–100 hPa to establish

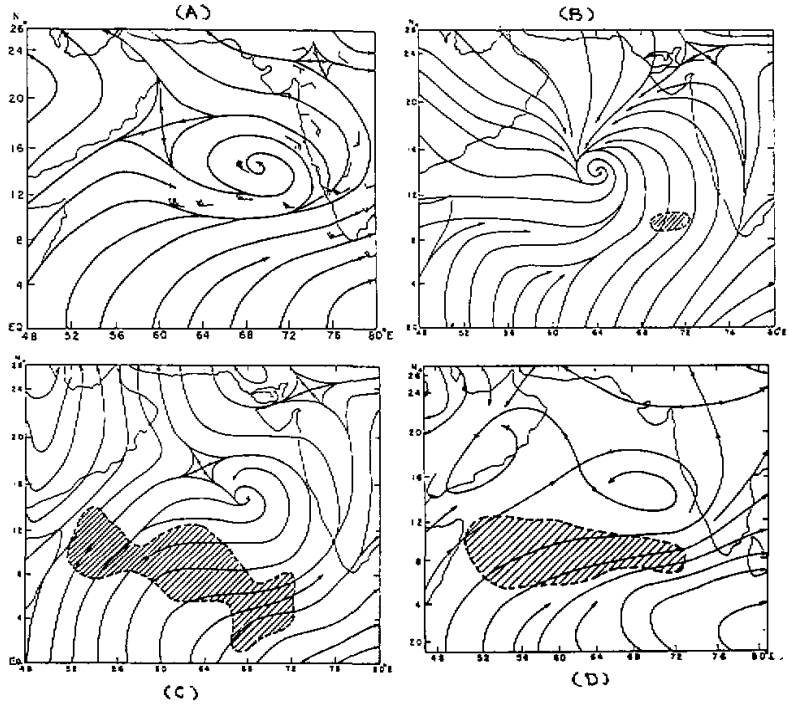

Fig.4. Wind analyses at 850 hPa for a depression on 16 June 1979. (A) Subjectively analysed wind field with all conventional wind data (B) Objectively analysed wind field with conventional wind data over only land areas (C) Objectively analysed wind field with the inclusion of constructed winds from cloud motion vectors. (D) Standard objectively analysed wind field by T. N. Krishnamurti et al.

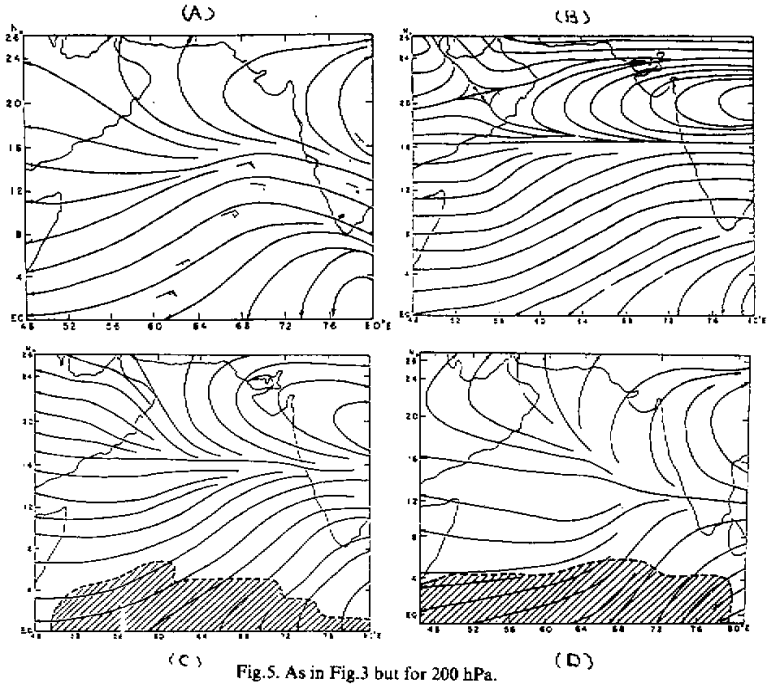

Fig.5. As in Fig.3 but for 200 hPa.

linear regression equations for each pressure level. Then, same procedure is repeated for satellite–derived high level winds. The main purpose for this was to see whether satellite–derived low–level winds alone or high–level winds alone can be used for the construction of vertical wind profile. But, from Table 1 it is seen that neither satellite–derived low–level winds nor high–level winds alone can be used for the construction of vertical wind profile. From Figs.2 and 3 it is clear that when satellite–derived low–level winds are used, significant correlation coefficients and RMS errors less than 5 mps are obtained upto 500 hPa and when satellite–derived high–level winds are used, significant correlation coefficients and RMS errors less than 8 mps are obtained above 500 hPa, for both u and v components. This suggests that satellite–derived low–level winds can be used to construct vertical wind profile upto 500 hPa and high–level winds thereafter upto 100 hPa. Regression equations which are most suitable for the construction of vertical wind profile are given in Table 2. In this table highest correlation coefficients are seen at 900 and 250 hPa where the base of cumulus clouds and layered cirrus are generally formed. Lowest correlation coefficients are seen at 500 hPa for both u and v components. During monsoon season, generally westerly wind changes to easterly at about 500 hPa and hence no specific pattern of westerly / easterly is observed at this level. Moreover there is a deficiency of linear interpolation in vertical. The level of 500 hPa is farthest level from the best match levels (900 hPa and 250 hPa). Because of these reasons, poor correlation coefficients are obtained at 500 hPa. Fig.3 depicts the comparison between estimated and conventional vertical wind profiles for the stationary positions of USSR research ships i.e., UMAY (96.5° N, 54.5° E), UMAY (7.0° N, 64.5° E) and UHQS (16.1°N, 91.0° E) for the months of May, June and July respectively. Here, estimated wind profiles show general agreement with the conventional wind profiles for both u and v components.

Two experiments of objective analysis are performed for the validation of the constructed

winds, i.e., Case A and Case B. Climatological normals for the month of June are considered as the initial guess for Case A. This initial guess was considered in order to see the resl impact of constructed winds on the objective analysis. Had it been considered a previous day's analysis as the initial guess field it would have shown the better circulation features, as this initial guess field contains the history of the system. Figs.4 (ABCD) and 5 (ABCD) show wind analyses for a depression on 16 June 1979 for 850 and 200 hPa in the following respect. (i) A carefully subjectively analysed wind field with all conventional wind data, (ii) objectively analysed wind field (Case A) with conventional wind data over only land areas, (iii) objectively analysed wind field (Case B) with further inclusion of constructed winds from cloud motion vectors and (iV) a standard objectively analysed wind field by T. N. Krishnamurti et al. with input of all available data from all resources Comparison of Case A and Case B with standard analysis with respect to major circulation features i.e., cyclonic circulation, centre of depression, strong winds, flow pattern, diffluence etc. are given in Table 3. Comparison in Table 3 indicates that analyses of Case B are in better agreement in all respects with the standard analyses than the analyses of Case A.

Table 3. Comparison of Case A and Case B with Standard Analysis

Sr. No.	Major	Standard Analysis	Case A Without satellite winds	Case B With satellite winds
		850 hPa		
1.	Cyclonic circulation	Well organized cyclonic circulation is observed	A very very strong cyclonic circulation is depicted	A well organized cyclonic circulation is depicted.
2.	Centre	centre of depression is seen at 15°N, 68.8°E	Centre of depression is depicted at 14°N, 64°E	Centre of depression is depicted at 15°N, 68°E.
3.	Strong winds (> 20 mps)	Strong winds are observed over a large area over the south Arabian sea	A very small area of strong winds is depicted over southeast Arabian sea	A large area of strong winds over the south Arabian sea is depicted.
4.	Flow pattern	Flow pattern is similar to that of subjectively analysed wind pattern	Flow pattern does not show much resemblance with the subjectively analysed wind pattern	Flow pattern depicts similar features to that of subjectively analysed wind pattern.
		200 hPa		
1.	Diffluence	A well organized pattern of diffluence over southeast and adjoining central Arabian sea is seen.	Diffluence is more organized over south Arabian sea than north Arabian sea. North Arabian sea is influenced by the formation of ridge	A well organized pattern of diffluence over southeast and adjoining central Arabian sea is depicted.
2.	Strong winds (> 20 mps)	Strong winds are observed over south Arabian sea stretching from 48–80°E and Equator to 4 / 6°N	No strong winds of the order of 20 mps and above are depicted.	Strong winds over south Arabian sea are depicted stretching from 50–80°E and Equator to 4 / 6°N.
3.	Flow pattern	Flow pattern is similar to that of subjectively analysed wind pattern	Flow pattern does not resemble with the subjectively analysed wind pattern particularly over north Arabian sea	Flow pattern shows good agreement to that of subjectively analysed wind pattern.

VI. CONCLUSIONS

From the discussions made above it is inferred that vertical wind profile can be constructed over the oceanic regions using satellite–derived cloud motion vectors and, when these constructed winds are used in objective analysis it depicts the major circulation features over the Indian region. Therefore, it is suggested that the objectively analysed wind field obtained with the inclusion of constructed winds from cloud motion vectors can be used with some confidence in Numerical Weather Prediction models.

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