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Seasonal prediction of cyclonic disturbances over the Bay of Bengal during summer monsoon season : Identification of potential predictors

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सार – बंगाल की खाड़ी में आने वाले चक्रवातीय विक्षोभ (सी. डी.) मानसून ऋतु के दौरान भारत में होने वाली वर्षा को काफी प्रभावित करते हैं। इस ऋतु के दौरान कई बार इनके कारण बाढ़ आ जाती है जिससे जान व माल की क्षति होती है। अतः आपदा प्रबंधकों और योजनाकारों को ऐसे विक्षोभों की घटनाओं के बारम्बारता के बारे में पहले से सूचना होने से काफी मदद मिल सकेगी परन्तु विश्व की अन्य समुद्री द्रोणियों के विपरीत बंगाल की खाड़ी में चक्रवातीय विक्षोभों के मौसमी पूर्वानुमान तक ही ये अध्ययन सीमित रहे हैं। अतः मानसून ऋतु (जून–सितम्बर) के दौरान बंगाल की खाड़ी में चक्रवातीय विक्षोभों की बारंबारता का पूर्वानुमान करने के लिए अप्रैल और मई के महीनों में संभावित पूर्वसूचकों का पता लगाने हेतु एक अध्ययन किया गया है। इस कार्य के लिए 1948 से 2007 तक की अवधि के भारत मौसम विज्ञान विभाग के विशेष रूप से तैयार किए गए आँकड़ों तथा एन. सी. ई. पी. / एन. सी. ए. आर. के पुनः विश्लेषित आँकड़ों के आधार पर बड़े पैमाने के क्षेत्रीय प्राचलों का शोध पत्र में विश्लेषण किया गया है। संभावित पूर्वसूचकों का पता लगाने के लिए, चक्रवातीय विक्षोभों की बारंबारता और एन. सी. ई. पी. / एन. सी. ए. आर. में पुनः विश्लेषित आँकड़ों के आधार पर बड़े पैमाने के क्षेत्रीय प्राचलों के बीच रैखिक सहसंबंध विश्लेषण का प्रयोग किया गया है।

भूमध्यरेखीय हिन्द महासागर में विशेष रूप से पश्चिमी भूमध्यरेखीय हिन्द महासागर और उसके समीपवर्ती अरब सागर के क्षेत्रों (15° उत्तर तक) में उत्तरवर्ती मानसून ऋतु के दौरान चक्रवातीय विक्षोभों की अधिक बारंबारता के लिए ऊपरी स्तर में प्रबलतर उत्तराभिमुखी पवनों के साथ, निम्नतर माध्य समुद्रतल दाब (एम. एस. एल. पी.), निम्नतर जियोपोटेंशियल ऊचाई तथा मध्य स्तरों में प्रबलतर दक्षिणाभिमुखी पवनों के साथ अप्रैल और मई के महीनों के दौरान क्षेत्रीय प्राचल बड़े पैमाने पर अनुकूल होने चहिए। परिणामस्वरूप उत्तरवर्ती मानसून ऋतु में चक्रवातीय विक्षोभों की अधिक बारंबारता से अप्रैल और मई में इस क्षेत्र में निचले स्तरों पर सापेक्ष आर्द्रता (आर. एच.) और वर्षणीय जल अवयव में वृद्धि तथा बहिर्गामी दीर्घ तरंग विकिरण (ओ. एल. आर.) और तापमान में कमी होगी। अप्रैल से सितम्बर तक चक्रवातीय विक्षोभों की बारंबारता और बड़े पैमान पर क्षेत्रीय प्राचलों तथा उनकी स्थिरता के बीच महत्वपूर्ण सहसंबंध के क्षेत्र की तुलना करने पर यह पता चला है कि ओ. एल. आर. समुद्र सतह तापमान, हवा का तापमान और 850 हेक्टापास्कल स्तर पर सापेक्ष आर्द्रता के बाद एम. एस. एल. पी. और भूविभव ऊँचाईयाँ सबसे अधिक प्रभावी प्राचल हैं।

ABSTRACT. The cyclonic disturbances (CD) over the Bay of Bengal during monsoon season have significant impact on rainfall over India. On many occasions, they cause flood leading to loss of lives and properties. Hence, any early information about the frequency of occurrence of such disturbances will help immensely the disaster managers and planners. However, the studies are limited on the seasonal prediction of CD over the Bay of Bengal unlike other Ocean basins of the world. Hence, a study has been undertaken to find out the potential predictors during the months of April and May for prediction of frequency of cyclonic disturbances over the Bay of Bengal during monsoon season (June – September). For this purpose, best track data of India Meteorological Department and large scale field parameters based on NCEP/NCAR reanalysis data have been analyzed for the period of 1948 – 2007. The linear correlation analysis has been applied between frequency of CD and large scale field parameters based on NCEP/NCAR reanalysis data to find out the potential predictors.

The large scale field parameters over the equatorial Indian Ocean, especially over west equatorial Indian Ocean and adjoining Arabian Sea (up to 15° N) should be favourable in April and May with lower mean sea level pressure (MSLP), lower geopotential heights and stronger southerlies in lower and middle levels, along with stronger northerly components at upper level for higher frequency of CD during subsequent monsoon season. Consequently, there should be increase in relative humidity (RH) and precipitable water content and decrease in outgoing longwave radiation (OLR) and temperature at lower levels over this region during April and May for higher frequency of CD during subsequent monsoon season. Comparing the area of significant correlation between frequency of CD and large scale field parameters and its stability from April to September, MSLP and geopotential heights are most influencing parameters followed by OLR, sea surface temperature, air temperature and RH at 850 hPa level.

Key words – Seasonal prediction, Cyclonic disturbance, Monsoon, Correlation, Bay of Bengal.

1. Introduction

The first attempt in seasonal forecast of cyclonic disturbances over various ocean basins was made in early 1980s by Neville Nicholls (1979) for Australian region and William Gray (1984 a,b) for the north Atlantic region. Since then forecast for different regions, using different methodologies have been developed. Tourism, insurance and re-insurance companies make use of seasonal forecasts in their policy decision. The disaster managers and planners also use these forecasts. A detailed review of the seasonal tropical cyclone forecasts over the globe has been given by Camargo *et al*., (2007). Colorado State University, USA and Cuban Meteorological Institute issue seasonal forecast for cyclonic disturbances for Atlantic. City University of Hongkong, China issues such forecast for western north Pacific; European Centre for Medium Range Weather Forecasts (ECMWF) for Atlantic, Australia, eastern north Pacific, north and south Indian Ocean, south Pacific and western north Pacific; International Research Institute for Climate and Society (IRICS) for Atlantic, Australia, eastern north Pacific, western north Pacific and south Pacific; Macquerie University, Australia for Australia/southwest Pacific; United Kingdom Meteorological Office (UKMO) for north Atlantic; National Meteorological Service, Mexico for eastern north Pacific; National Climate Centre, China for western north Pacific; National Ocean and Atmospheric Administration (NOAA) issues hurricane outlooks for Atlantic, eastern north Pacific and central north Pacific and Tropical Storm Risk (TSR) for Atlantic, western north Pacific and Australian region. All the above forecasts are based on statistical techniques except ECMWF, IRICS and UKMO forecasts which are based on dynamical methods. However, the skill of dynamical methods is lower compared to statistical methods.

For the north Atlantic Ocean basin, seasonal forecast for hurricane season (July – December) was originally issued in early June and updated in early August. Research in 1980s and 1990s led to the development of an early December forecast (Gray *et al*., 1992). More recently, Klotzbach and Gray (2004) developed a new December statistical hindcast scheme utilizing National Centre for Environment Prediction / National Centre for Atmospheric Research (NCEP/NCAR) reanalysis data (Kistler *et al*., 2001). This prediction scheme utilized a total of six predictors and attempted to hindcast several forecast metrics including named storms. Although this scheme showed considerable hindcast skill, it did not show real time forecast skills from 2003 to 2007. Additional revisions to the early December forecast schemes have recently been made. They involve simplifying the statistical scheme and including more robust statistical tests for prediction significance (Klotzbach and Philip, 2008), based on data of 1950 to 2007. Predictors are selected based on how much variance is explained over the period of 1950-1989 using stepwise regression. It could explain 54% of the total variance of seasonal net tropical cyclone activity. The predictors include tropical Atlantic wind shear, sea level pressure change and ENSO phase changes in the month of October and November to issue forecast in early December for the hurricane season commencing from next year July. The NCEP/NCAR reanalysis fields of mean sea level pressure, sea surface temperature and 500 hPa geopotential height were correlated with north Atlantic tropical cyclone activity for the purpose of the study.

Considering the north Indian Ocean, which consists of Bay of Bengal and Arabian Sea, the frequency of cyclonic storms are less compared to other basins, only about 7% of total global tropical cyclones develop over north Indian Ocean. Only about five cyclones develop per year over the north Indian Ocean including four in the Bay of Bengal and one in the Arabian Sea [India Meteorological Department (IMD, 2008)]. Further they show large inter-seasonal variations with primary peak occurring in November and secondary peak in May. Perhaps due to these reasons, much effort has not been made for seasonal prediction of cyclones over the north Indian Ocean. About 7 cyclonic disturbances (CD) occur over the north Indian Ocean during summer monsoon season (June – September). Most of these develop over the Bay of Bengal and move northwestward along the monsoon trough (Rao, 1976). They cause heavy to extremely heavy rainfall leading to flood over various river catchments along their paths. Mooley and Shukla (1989), Mohapatra and Mohanty (2007) and Mohapatra (2008) have shown that the rainfall over some meteorological subdivisions, especially in central India is dependent on the westward moving low pressure systems including CDs which form over the Bay of Bengal. According to Dhar and Nandergi (1993 a,b) most of the rain storms in India occur during monsoon season and are due to low pressure systems including CDs. The floods and droughts are very often related with these CDs. These CDs also cause marine hazards and affect coastal areas due to squally/gale winds.

Considering all the above facts, a study has been undertaken to find out the potential predictors for seasonal prediction of frequency of CDs over the Bay of Bengal during the monsoon season (June – September). For this purpose, the large scale fields based on NCEP/NCAR reanalysis during 1948 – 2007 have been considered. The predictors have been selected through linear correlation technique applied to the frequency of CDs and the large scale fields.

TABLE 1

Large scale field parameters under consideration

	Parameter	Level (hPa)
	Dynamical Parameters	
1.	Mean Sea level pressure	Surface
2.	Geopotential Height	1000, 850, 700, 500, 400, 300, 200
3.	Horizontal component of wind (*u*)	Surface, 1000, 850, 700, 500, 400, 300, 200
4.	Vertical component of wind (*v*)	Surface, 1000, 850, 700, 500, 400, 300, 200
5.	Vertical velocity	1000, 850
6.	Momentum Flux (MF) of horizontal component of wind(*u*)	Surface
7.	MF of vertical component of wind (*v*)	Surface
8.	Relative vorticity	850
9.	Divergence	200
10.	Convergence	850
11.	Vertical wind shear of horizontal wind	200 – 850
	Thermo dynamical parameters	
12.	Sea surface temperature (SST)	Surface
13.	Air temperature	Surface, 1000, 850, 700, 500, 400, 300, 200
14.	Relative humidity (RH)	Surface, 1000, 850, 700, 500, 400, 300, 200
15.	Outgoing longwave radiation (OLR)	Surface
16.	Precipitation rate	Surface
17.	Precipitable water content (PWC)	Surface

2. Data and methodology

The statistics of CDs over the Bay of Bengal during the monsoon season (June – September) have been taken from the best track data set published as Cyclone e-Atlas by IMD (2008). From these dataset a time series of the frequency of CDs (depression and above) during the monsoon season have been prepared for the period of 1948 – 2007 (60 years).

Over the sea, wind strength at the surface level is used as a criterion for classification of different intensities of CDs. As per the criteria of IMD, a CD is a depression if the wind speed is 17 – 27 kt, a deep depression if the wind speed is 28 – 33 kt, a cyclonic storm if the wind speed is 34 – 47 kt, a severe cyclonic storm if the wind speed is 48 – 63 kt, a very severe cyclonic storm if the wind speed is 64 – 119 kt and a super cyclonic storm if the wind speed is 120 kt or more. During monsoon season, mostly depression, deep depression and marginal cyclones (up to cyclonic storm intensity) develop over the Bay of Bengal.

Though the use of satellite for the monitoring of cyclonic disturbances (Dvorak, 1975) came into existence in 1970s, the whole period under study may be considered to be a good qualitative data set as most of the CDs develop over the north and adjoining central Bay of Bengal (IMD, 2008) and their existence is supported by the coastal observatories from India, Bangladesh and Myanmar. The missing disturbances during the period could have been negligible, though there might have been variation in the intensity estimates during the pre-satellite era as in north Atlantic Ocean (Landsea, 2005). Since in the present study, we are dealing with the frequency of CDs, the error due to variation in intensity will have no impact on the analysis.

The NCEP/NCAR reanalysis (Kistler *et al*., 2001) is utilized to search the predictors. The reanalysis product provides global data on a 2.5° latitude and 2.5° longitude grid for a large number of dynamical and thermodynamical parameters including zonal and meridional wind, mean sea level pressure (MSLP),

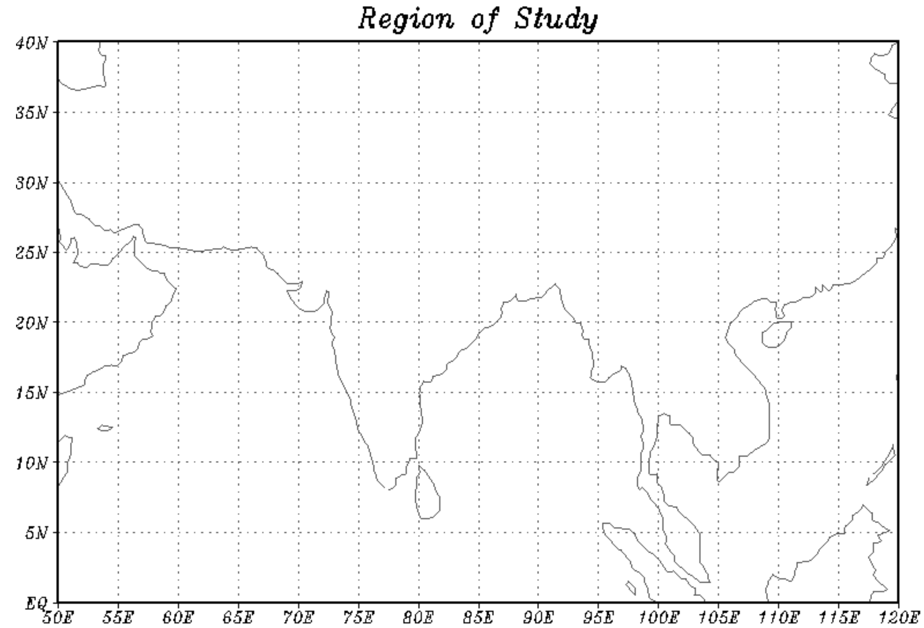


Fig. 1. Region of study under consideration

geopotential height, sea surface temperature (SST) etc. The reanalysis products are a combination of assimilated observations along with model derived approximations. The parameters considered in this study are shown in Table 1. The region of study has been taken as 50° E to 120^0 E and equator to 40° N (Fig. 1), which is reasonably large to take into account the physical relationship between the cyclogenesis and the large scale field parameters. The zonal westerlies and meridional southerlies are considered as positive in the study. The easterlies and northerlies are considered as negative.

Predictors are selected from the NCEP/NCAR reanalysis using linear correlation technique. The NCEP/NCAR reanalysis fields of different parameters as mentioned in Table 1 during April and May are correlated with the frequency of CDs during monsoon season (June – September) over the period of 1948 – 2007. The correlation significant at 99% level of confidence ($r \geq |0.30|$) have been analysed in details. Areas of significant correlation have been demarketed for each parameter. Significance is determined by using a two tailed student's *t*-test and assuming that each monsoon represents one degree of freedom. The areas selected should have fairly large spatial extent (at least 10° latitude and 15° longitude) in order to avoid selecting correlation bulls-eyes which sometimes exists in NCEP/NCAR reanalysis (Klotzbach adn Philip 2008). In order to remain in the predictor pool, several additional criteria have to be met. First, the predictors should have persistence *i.e.* the correlation of predictor parameters during April with that in subsequent months till the end of monsoon season should be statistically significant. Similar should be the case for the predictor parameters in the month of May. Second, these predictors should have the physical relationship with the cyclogenesis parameter during monsoon season. Third, the correlation between the parameters and the frequency of cyclonic disturbances should be stable over the period of time (for the whole period of study). Fourth, the NCEP/NCAR reanalysis fields should represent the climatology of the region.

For the above purpose, the mean climatology of the region of study has been analysed for different NCEP/NCAR fields under consideration and the same

TABLE 2

Mean frequency of CD over the Bay of Bengal during (a) 1948 – 2007 and (b) 1891 – 2007

Period	(a) 1948 – 2007	(b) 1891 – 2007
June	0.90	0.92
July	0.90	1.23
August	1.37	1.52
September	1.13	1.38
Season (JJAS)	4.30	5.05

TABLE 3

Mean values of large scale field parameters over the region

Parameter	Level (hPa)	Month						Season
		April	May	June	July	August	September	
MSLP		1010.73	1008.50	1006.14	1005.48	1006.57	1009.58	1006.94
Geopotential	850	1497.19	1486.48	1469.15	1462.66	1470.45	1491.61	1473.46
height	500	5808.67	5828.55	5835.29	5840.43	5843.32	5839.85	5839.72
	200	12286.6	12368.9	12438.9	12472.2	12467.6	12420.8	12449.9
u	Surface	0.53	1.47	2.16	2.24	2.02	1.31	1.93
	850	0.87	2.39	4.17	4.44	3.85	2.17	3.66
	500	4.93	3.58	2.71	1.62	1.29	1.79	1.85
	200	16.07	9.26	-0.20	-6.81	-6.85	-0.88	-3.69
v	Surface	0.34	1.15	2.15	2.40	2.12	1.25	1.98
	850	0.30	0.36	0.96	1.28	0.94	0.35	0.88
	500	-0.21	-0.44	-0.31	-0.13	-0.19	-0.19	-0.21
	200	1.56	0.37	-1.72	-2.18	-1.74	-0.74	-1.59
RH	Surface	65.81	66.35	68.77	72.44	73.35	72.61	71.79
	850	53.76	54.43	58.27	62.44	63.48	62.41	61.65
	500	36.30	40.32	47.87	53.02	52.63	48.29	50.45
PWC	Surface	27.03	30.94	35.46	38.52	38.23	34.69	36.73
Temperature	Surface	21.31	23.56	24.75	24.83	24.30	22.75	24.16
	850	17.21	19.50	20.84	21.08	20.55	18.73	20.30
	500	-8.75	-6.85	-5.26	-4.37	-4.51	-5.75	-4.97
	200	-53.39	-51.56	-49.62	-49.04	-49.40	-50.81	-49.72
MF-U	Surface	-19.86	-29.97	-45.10	-45.99	-35.73	-15.08	-35.47
MF-V	Surface	-9.63	-16.57	-35.87	-41.84	-30.58	-12.19	-30.12

have been compared with the existing climatology. The inter-correlation coefficients (CC) of different months during April to September for different field parameters have been calculated and analysed to find out the stability of the parameters. To test the stability of the correlation between the frequency of CDs and the field parameters, the correlation coefficients of the frequency of CDs during monsoon season with the field parameters in different months from April to September have been calculated and analysed. The maps of correlation of frequency of CDs during the monsoon season with the large scale fields during April and May have been developed and analysed with demarcation of areas of significant correlation. The physical relationship of the predictors with the frequency of CDs have been analysed and presented.

3. Results and discussion

3.1. *Mean pattern of CD over the Bay of Bengal and the large scale field parameters*

The mean frequency of CDs is higher in August followed by September (Table 2). It further supports the earlier findings of Mohapatra and Mohanty (2004) that compared to long period average based on data of 1891 – 2007, the frequency of CDs have reduced significantly during recent years, especially in July. Considering the interannual variation, the frequency of CDs varies from 0 to 4 in June, July and September, from 0 to 5 in August during the period of study (not shown) and from 0 to 8 in the season as a whole.

TABLE 4

Inter-correlation coefficients (CC) of large scale field parameters over the region during April to September

Parameter	Level (hPa)	CC of parameters in April with that in					CC of parameters in May with that in			
		May	Jun	Jul	Aug	Sep	Jun	Jul	Aug	Sep
MSLP	Surface	**0.78**	**0.68**	**0.68**	**0.72**	**0.67**	**0.80**	**0.80**	**0.81**	**0.84**
Geopotential	850	**0.85**	**0.79**	**0.79**	**0.78**	**0.76**	**0.86**	**0.86**	**0.87**	**0.88**
height	500	**0.82**	**0.81**	**0.78**	**0.72**	**0.72**	**0.91**	**0.88**	**0.89**	**0.85**
	200	**0.73**	**0.66**	**0.49**	**0.45**	**0.56**	**0.69**	**0.56**	**0.58**	**0.54**
u	Surface	**0.43**	**0.30**	0.00	**0.30**	0.17	**0.38**	0.08	**0.32**	0.21
	850	**0.37**	**0.27**	**0.05**	**0.30**	0.19	**0.37**	0.24	**0.30**	**0.30**
	500	0.22	**0.33**	**0.41**	0.26	**0.41**	**0.35**	**0.44**	**0.41**	**0.34**
	200	**0.72**	**0.69**	**0.60**	**0.65**	**0.59**	**0.74**	**0.61**	**0.58**	**0.49**
v	Surface	**0.72**	**0.66**	**0.64**	**0.58**	**0.46**	**0.69**	**0.62**	**0.50**	**0.55**
	850	**0.62**	**0.42**	**0.65**	**0.59**	**0.45**	**0.47**	**0.60**	**0.63**	**0.61**
	500	**0.30**	0.00	0.22	0.29	0.06	0.26	**0.32**	0.27	0.28
	200	0.07	-0.17	-0.11	-0.06	-0.08	-0.01	-0.17	0.08	0.18
RH	Surface	**0.76**	**0.53**	**0.38**	**0.37**	**0.49**	**0.54**	**0.43**	**0.42**	**0.65**
	850	**0.90**	**0.70**	**0.76**	**0.72**	**0.78**	**0.78**	**0.79**	**0.78**	**0.86**
	500	**0.75**	**0.64**	**0.64**	**0.63**	**0.69**	**0.67**	**0.65**	**0.63**	**0.77**
PWC	Surface	**0.75**	**0.35**	**0.46**	**0.36**	**0.37**	**0.43**	**0.51**	**0.53**	**0.65**
Temperature	Surface	**0.63**	**0.52**	**0.38**	**0.42**	**0.41**	**0.69**	**0.68**	**0.68**	**0.51**
	850	**0.74**	**0.60**	**0.47**	**0.50**	**0.48**	**0.73**	**0.68**	**0.67**	**0.56**
	500	**0.61**	**0.33**	0.28	0.24	**0.38**	**0.55**	**0.50**	**0.47**	**0.34**
	200	**0.54**	**0.43**	0.15	0.21	**0.30**	**0.39**	0.27	0.21	**0.37**
MF-U	Surface	**0.62**	**0.50**	0.26	**0.41**	**0.51**	**0.61**	**0.47**	**0.50**	**0.60**
MF-V	Surface	**0.82**	**0.72**	**0.81**	**0.76**	**0.73**	**0.78**	**0.79**	**0.77**	**0.80**

CCs significant at 99% level of confidence are highlighted

The mean values of large scale field parameters over the region under consideration are shown in Table 3. The MSLP over the region gradually decreases from April to July and then increases. Similar is the case with Geopotential height at 850 hPa level. The geopotential height at 500 hPa level increases from April to August and then decreases. The geopotential height at 200 hPa level increases from April to July and then decreases. Accordingly, the zonal westerly wind increases in lower level from April to July and then decreases whereas the zonal westerly wind in middle and upper levels decreases till August and then increases. Similar is the case with meridional southerly wind in lower levels which increases from April to July and then decreases. It decreases in middle and upper levels from April to July and then increases. Considering the vector wind, the southwesterlies prevail in lower level with increase in strength from April to July and decrease thereafter. The northwesterlies prevail in middle levels. Initially southwesterly wind prevails in upper troposphere in April. It decreases in strength in May and becomes northeasterly from June. The strength of northeasterlies increases from June to July, remains almost same in August and then decreases in September. All these results endorse the earlier findings of characteristic flow pattern of southwest monsoon by Rao (1976).

With the increase in south-westerlies, the relative humidity (RH) in lower and middle levels also increases from April to August/July and then slightly decreases. The precipitable water content (PWC) also increases from

TABLE 5

Correlation coefficients (CC) of the frequency of CD over the Bay of Bengal during the monsoon season (June – September) with the monthly mean values of the large scale field parameters over the region under consideration

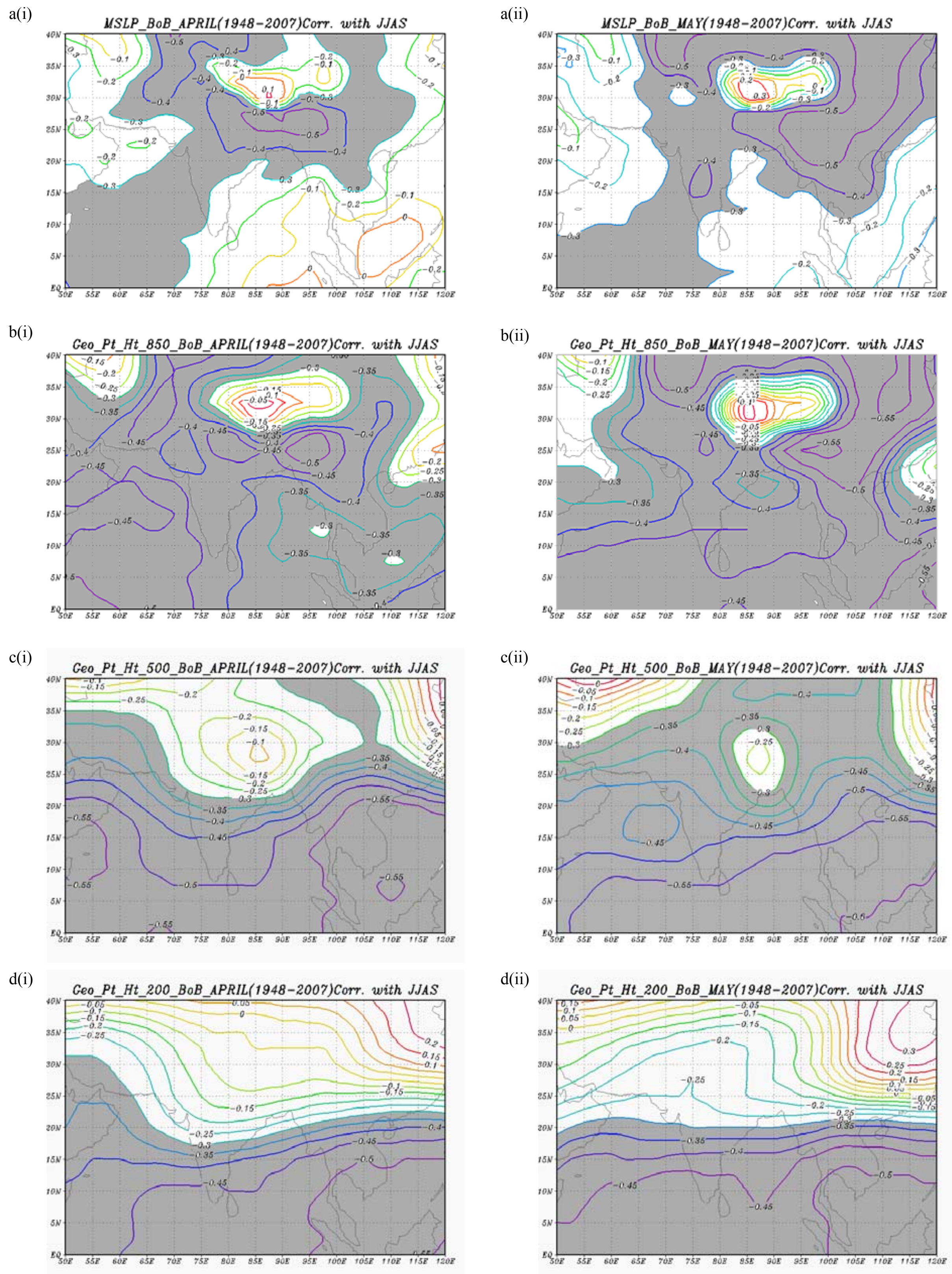
Parameter	Level (hPa)	Month					
		April	May	June	July	August	September
MSLP		**-0.39**	**-0.47**	**-0.49**	**-0.55**	**-0.65**	**-0.51**
Geopotential height	850	**-0.45**	**-0.50**	**-0.51**	**-0.56**	**-0.64**	**-0.53**
	500	**-0.49**	**-0.52**	**-0.51**	**-0.50**	**-0.61**	**-0.53**
	200	**-0.33**	**-0.31**	**-0.40**	-0.25	**-0.35**	-0.26
u	Surface	0.21	0.25	0.13	0.06	0.16	**0.32**
	850	0.14	**0.30**	0.24	**0.34**	**0.45**	**0.47**
	500	-0.10	0.01	0.08	0.14	0.22	0.27
	200	**-0.40**	**-0.43**	-0.29	**-0.43**	**-0.50**	**-0.37**
v	Surface	**0.52**	**0.49**	**0.55**	**0.59**	**0.63**	**0.50**
	850	**0.39**	**0.40**	**0.44**	**0.49**	**0.40**	**0.49**
	500	**0.40**	0.21	0.02	0.20	0.25	0.24
	200	-0.15	-0.05	0.29	-0.05	**0.36**	0.07
RH	Surface	**0.34**	**0.41**	0.22	0.14	0.02	**0.34**
	850	**0.52**	**0.58**	**0.56**	**0.54**	**0.45**	**0.59**
	500	**0.58**	**0.53**	**0.44**	**0.57**	**0.47**	**0.56**
PWC	Surface	0.28	0.28	0.05	0.20	0.05	0.23
Temperature	Surface	-0.22	**-0.38**	**-0.35**	**-0.30**	-0.25	-0.28
	850	**-0.38**	**-0.45**	**-0.46**	**-0.34**	**-0.30**	**-0.32**
	500	-0.17	-0.16	-0.23	0.08	0.06	0.09
	200	-0.17	0.00	0.00	0.13	0.22	0.16
MF-U	Surface	**-0.39**	**-0.44**	**-0.38**	**-0.33**	**-0.35**	**-0.42**
MF-V	Surface	**-0.51**	**-0.48**	**-0.52**	**-0.57**	**-0.56**	**-0.49**
OLR	Surface	**-0.59**	**-0.56**	**-0.37**	**-0.42**	**-0.46**	**-0.60**

CCs significant at 99% level of confidence are highlighted.

April to July, remains almost same in August and then decreases. The Atmospheric temperature in lower and middle levels gradually increases from April to July and then decreases like RH. The air temperature at 200 hPa level also increases from April to July and then gradually decreases. The momentum flux (MF) also increases from April to July and then decreases like lower level southwesterlies. All these are typical climatological characteristics associated with southwest monsoon as discussed in Rao (1976). Comparing with the frequency of cyclonic disturbances, while southwest monsoon current is stronger in July and August, the frequency of cyclonic disturbances is higher in August and September. Hence, the mean flow pattern can not explain the variation of frequency of cyclonic disturbances over the region.

3.2. *Inter-correlation in the monthly mean values of the large scale parameters*

The significant inter CCs between the monthly mean values of the parameters are presented in Table 4. The significant CC values in April extend up to the end of monsoon season in case of OLR and RH at 850, 500 and 200 hPa levels, PWC, MSLP and geopotential heights at 850, 500 and 200 hPa levels, *u* component of wind at 200 hPa level and *v* component of MF. Hence, the



Figs. 2(a-d). The CC of frequency of CD over the Bay of Bengal during monsoon season with (a) MSLP and (b-d) geopotential height during (i) April and (ii) May. The area of CCs significant at 99% level of confidence are highlighted above mentioned parameters may be considered as stable parameters for use as predictors of monsoon circulations over the region based on the data of April.

Considering significant CC values in May, the SST, OLR and RH at 850, 500 and 200 hPa levels, PWC and air temperature at surface and 850 hPa level, MSLP and geopotential heights at 850, 500 and 200 hPa levels and v-component of MF show stability from May to September. So, these parameters can be considered as potential predictors of monsoon circulation and hence CDs. Comparison of the CCs of large scale field parameters during June to September with that in April and May indicates that correlation is more significant in May than in April.

3.3. *Frequency of CD in relation to large scale parameters*

Table 5 presents correlation significant at 99 % level of confidence between the mean large scale field parameters over the region as a whole under consideration during April to September and frequency of CDs during the monsoon season (June – September). It is found that most of the parameters like MSLP, geopotential height, *u* and *v* components of wind, MF, SST, air temperature, OLR and RH show stable relationship with the frequency of CD. Many of these parameters show significant relationship with effect from the pre-monsoon months of April and May till September. Hence these parameters during April and May could be the potential predictors for the frequency of CDs over Bay of Bengal during monsoon season.

Considering only stable CCs up to September, the frequency of CDs during monsoon season increases with (*i*) decrease in MSLP and geopotential height at 850, 500 and 200 hPa levels, (*ii*) increase in easterlies at 200 hPa level, (*iii*) increase in southerlies at surface and 850 hPa levels, (*iv*) increase in RH at 850 and 500 hPa levels, decrease in temperature at 850 hPa level, (*v*) increase in both components of MF at surface level and (*vi*) decrease in OLR at surface level. All the above mentioned conditions present an active monsoon condition over the region with strong cross equatorial flow in lower levels, strong tropical easterly jet (TEJ) at 200 hPa level and increased convection over the region. The cyclogenesis over the Bay of Bengal is favoured with strong southerly surge over the south Bay of Bengal, persistant convection, increased RH and stronger TEJ. Due to increasing and persisting cross equatorial flow over the region during monsoon months, cyclonic vorticity over the northern part of the Bay of Bengal increases leading to the favorable conditions for cyclogenesis over the Bay of Bengal along the monsoon trough (Sikka, 1980). The occurrence of low level asymmetric wind surge on one side of the tropical disturbance is helpful in intensification of the system (Gray *et al*., 1992).

As the cross equatorial flow increases leading to strong southwesterlies over the north Indian Ocean, the relative humidity in the troposphere increases over the region. Hence, the frequency of CDs over the Bay of Bengal increases with increase in RH during April to September. Considering the cyclogenesis parameters suggested by Gray (1968), the region with low RH in mid-tropospheric level are unfavorable for cyclogenesis for the reasons *viz*., (*i*) convective winds which originates in the boundary layer are eroded by entrainment of dry air as they rise through the middle troposphere, (*ii*) much of the mass convergence takes place above boundary layer. Less mass convergence in middle layer leads to less latent heat release and hence less growth of convection. However, according to McBride (1979), the RH does not differ significantly in convective systems which intensify into cyclone and those which do not. However the Gray parameters including RH work better for North Indian Ocean according to Kalsi (2002).

3.4. *Frequency of CD in relation to gridded monthly mean values of field parameters*

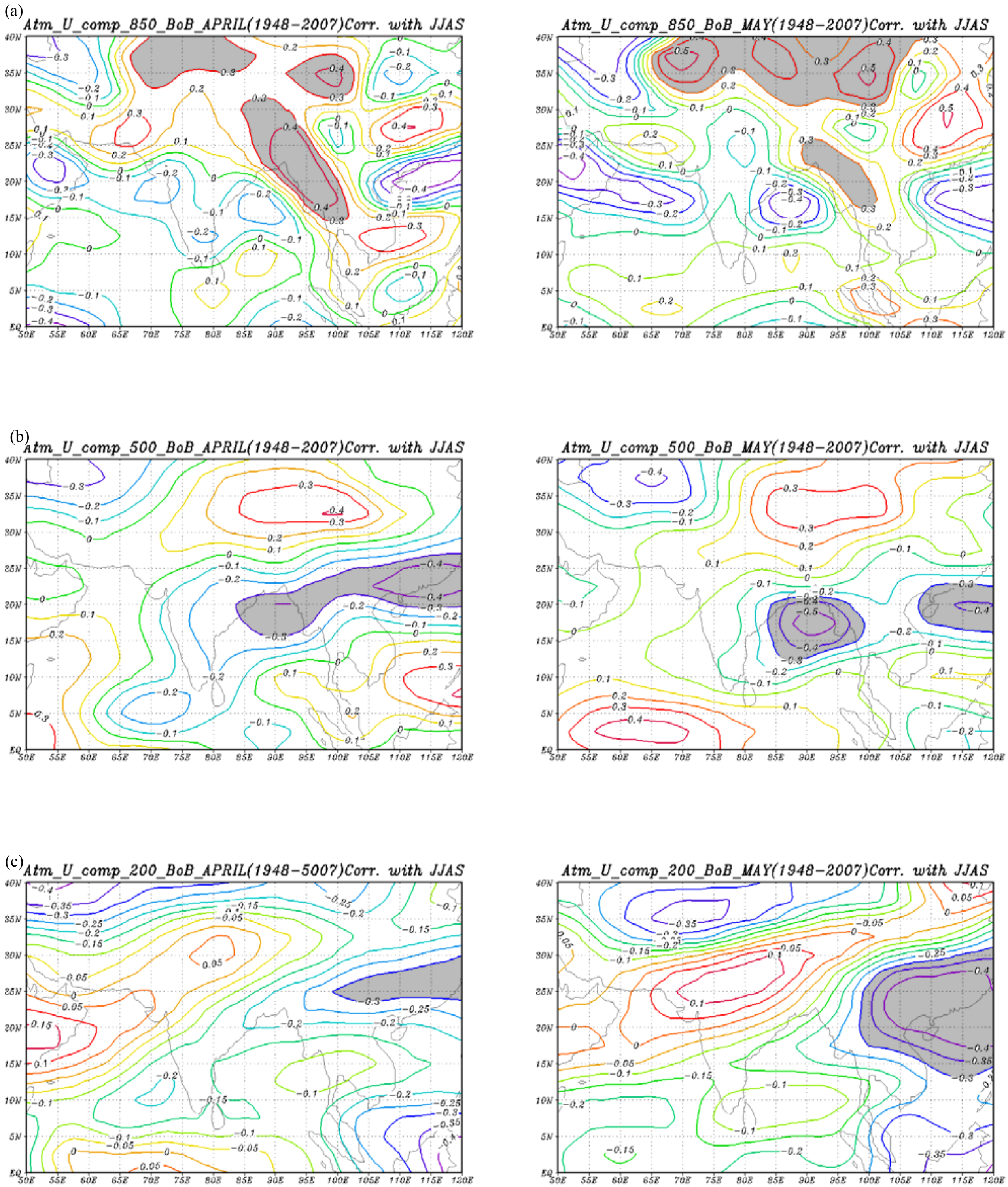
3.4.1. *Frequency of CD in relation to MSLP and geo potential height*

The frequency of CD increases with significant decrease in MSLP over the northeastern part of the region consisting of Tibet and adjoining areas and over major part of the Arabian Sea and India [Figs. 2(a-d)]. It may be due to the fact that the higher heating over the region which leads to the fall of pressure triggers the cross equatorial flow off Arabian-Africa coast. Similar is the case considering lower level geopotential height with increase in area of correlation covering the Bay of Bengal. The frequency of CD increases with decrease in geopotential height in middle and upper troposphere to the south of 20° N in both the months. All these indicate that MSLP and geopotential height over the shaded region can be used as precursors for the frequency of CD over the Bay of Bengal.

3.4.2. *Frequency of CD in relation to zonal wind*

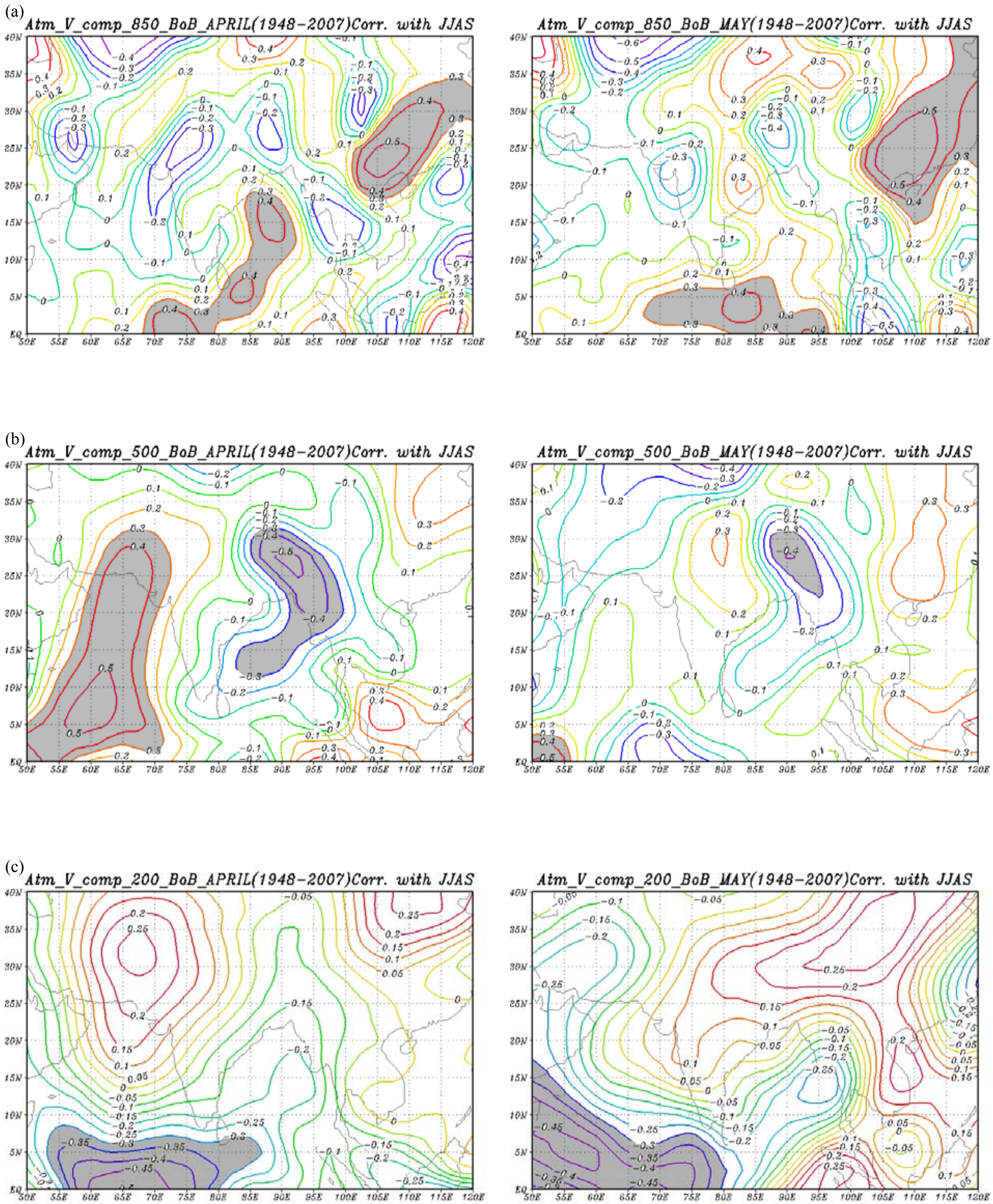
The CC between zonal wind and frequency of CD is presented in Figs. 3 (a-c). The frequency of CD increases with increase in zonal westerlies over the northeastern India, Bangladesh, Myanmar and adjoining Bay of Bengal at 850 hPa level in April. It also increases with increase in westerlies over these regions with reduced area extent and excluding Bay of Bengal in May.

(i) April (ii) May



Figs. 3 (a-c). Same as Fig. 2, but with *u* component of wind at (a) 850, (b) 500 and (c) 200 hPa levels

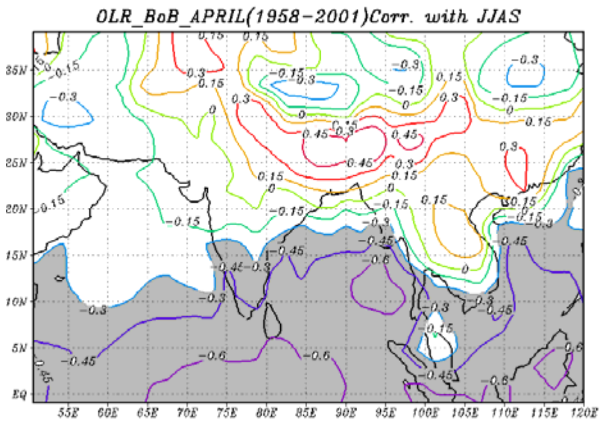
(i) April (ii) May



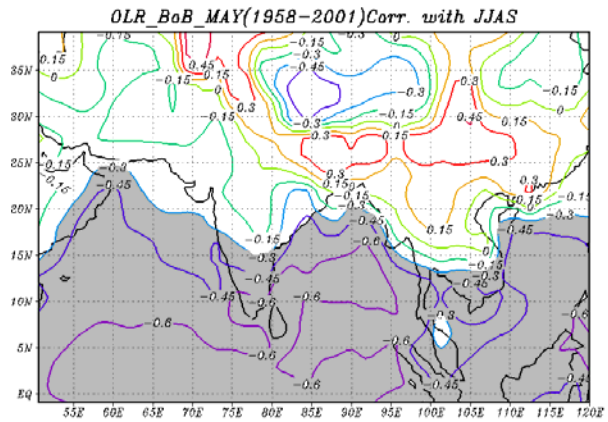
Figs. 4(a-c). Same as Fig. 3, but with *v*-component of wind at (a) 850, (b) 500 and (c) 200 hPa levels

(i) April (ii) May

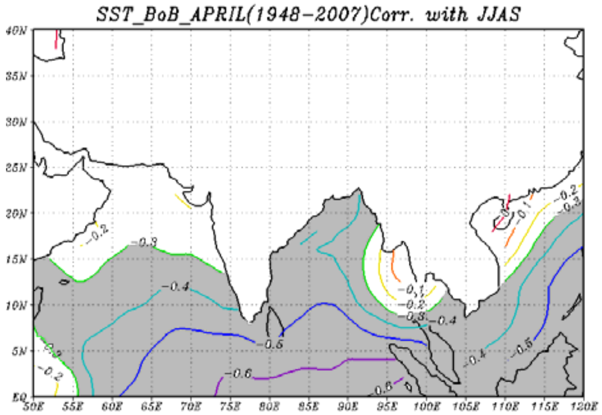
a(i)



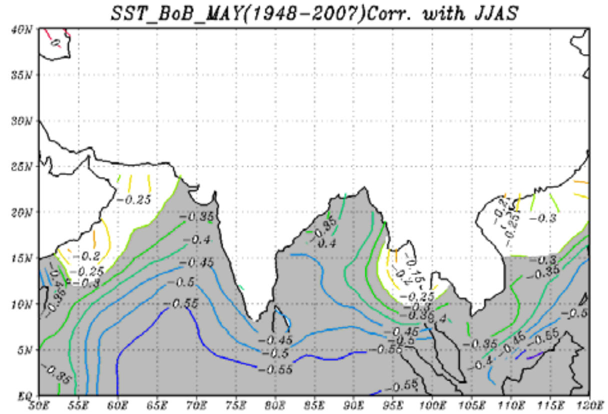
a(ii)



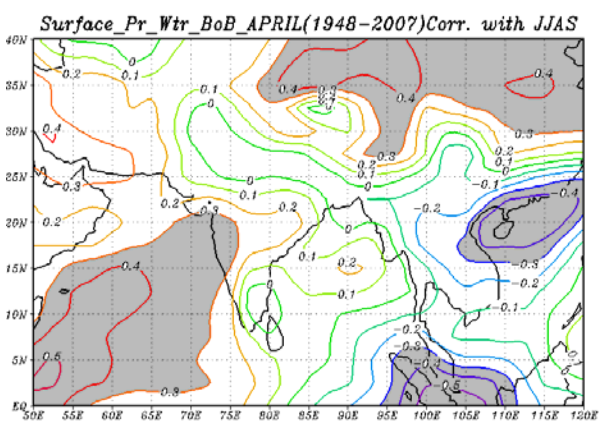
b(i)



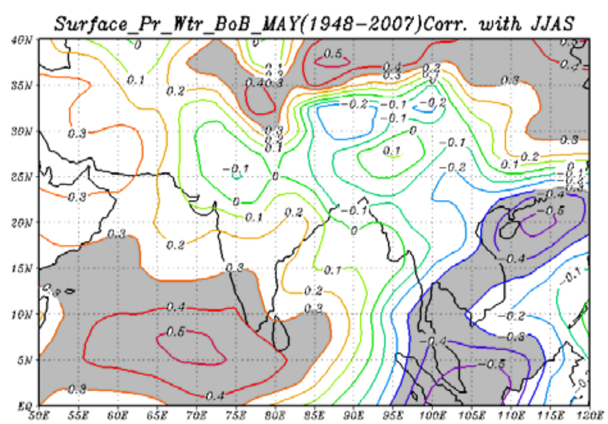
b(ii)



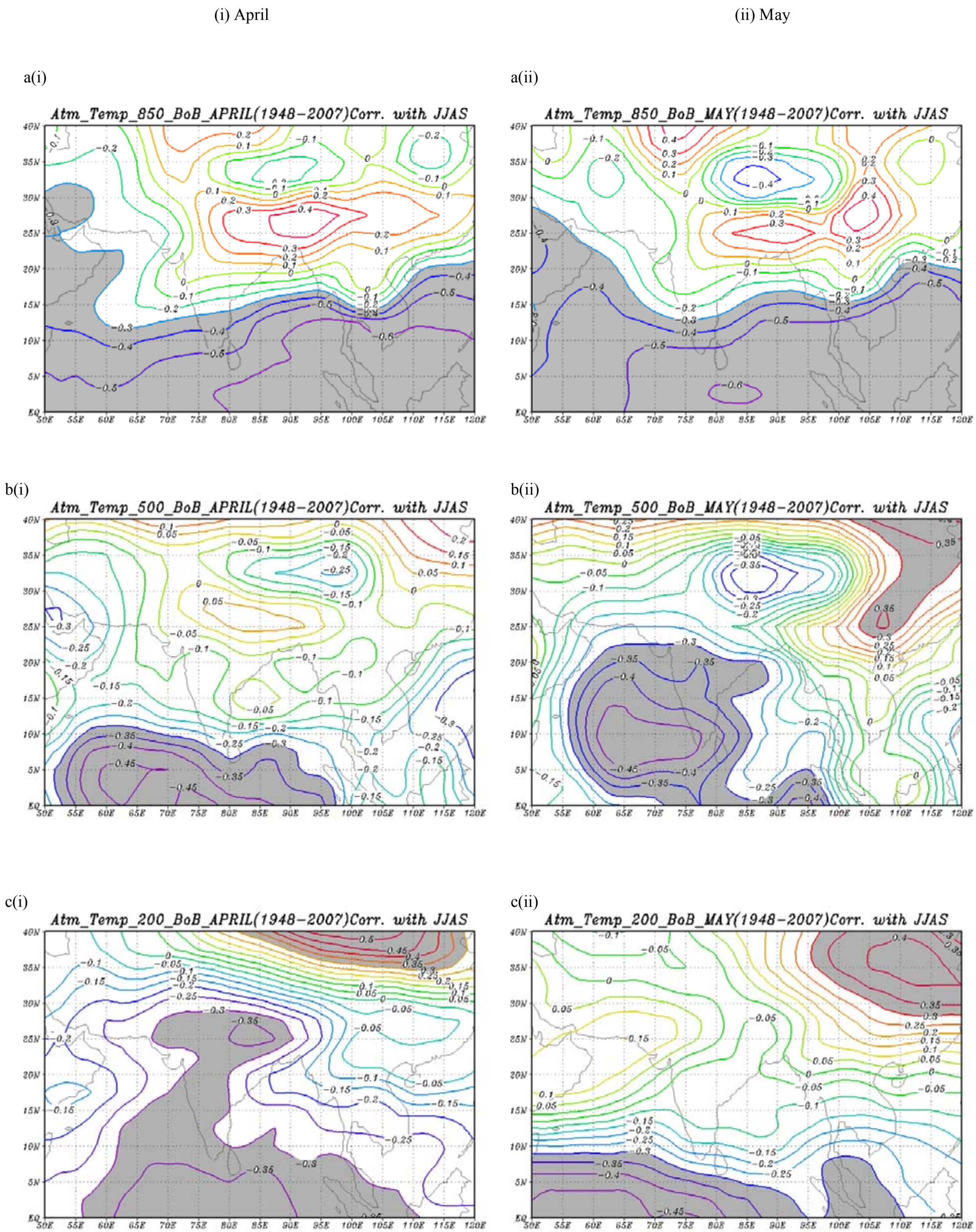
c(i)



c(ii)



Figs. 5(a-c). Same as Fig. 2, but with (a) OLR and (b) SST and (c) precipitable water content at surface level



Figs. 6(a-c). Same as Fig. 3 but with air temperature at (a) 850, (b) 500 and (c) 200 hPa levels

Considering 500 hPa level, decrease in westerlies or increase in easterlies from north Bay of Bengal to southeast China in April causes increase in CD over Bay of Bengal. Similar is the case in the month of May with more significant correlation between them. Increase in easterlies over the region is possible with strengthening of anti-cyclonic circulation over southeast Asia with ridge running between 15° – 20° N during April and May. Hence stronger anti-cyclonic circulation over southeast Asia with ridge lying between 15° – 20° N during April and May is favourable for more cyclogenesis over the Bay of Bengal during monsoon season. In addition, stronger westerlies over the west equatorial north Indian Ocean are favorable for cyclogenesis over the Bay of Bengal. The stronger westerlies over this region occur in association with enhanced cross equatorial flow.

Similarly decrease in westerlies or increase in easterlies over southeast China, adjoining Myanmar and South China Sea in April and May at 200 hPa level is favourable for cyclogenesis. Comparing with 500 hPa level, this region of maximum correlation shifts northward as the anti-cyclonic circulation/ridge also shifts northward with height in April and May.

3.4.3. *Frequency of CD in relation to meridional wind*

The spatial distribution of CC of frequency of CD with the meridional southerly component of wind is presented in Figs. 4(a-c). The frequency of CD increases with increase in southerlies over the central equatorial north Indian Ocean, southwest and central Bay of Bengal in April and May. It also increases with increase in southerlies over east China at 850 hPa level in April and May. It increases with the increase in southerlies over central equatorial north Indian Ocean at 850 hPa level in May. The increase in southerlies over the equatorial Indian Ocean and the Bay of Bengal in April and May ensures availability of sufficient moisture in the subsequent monsoon months.

Considering 500 hPa level, decrease in southerlies over eastern Tibet and adjoining India and Bangladesh in April and May are favorable for cyclogenesis. The increase in southerlies over central part of Arabian Sea and adjoining Gujarat and Pakistan in April also favours cyclogenesis. The decrease in meridional southerly or increase in northerly winds at 200 hPa level over the west and central equatorial north Indian Ocean and adjoining Arabian Sea during April and May are favourable for cyclogenesis in subsequent monsoon season.

3.4.4. *Frequency of CD in relation to OLR, SST and PWC*

From correlation map [Figs. 5(a-c)], the frequency of CD in monsoon season, increases with increase in PWC over the central and south Arabian Sea and adjoining equatorial Indian Ocean during both April and May. It again indicates that strengthening of cross equatorial flow off Arabia-African coast is a prerequisite for enhanced cyclogenesis. The frequency of CD during monsoon season does not depend upon the PWC of the atmosphere over the region as a whole during monsoon months.

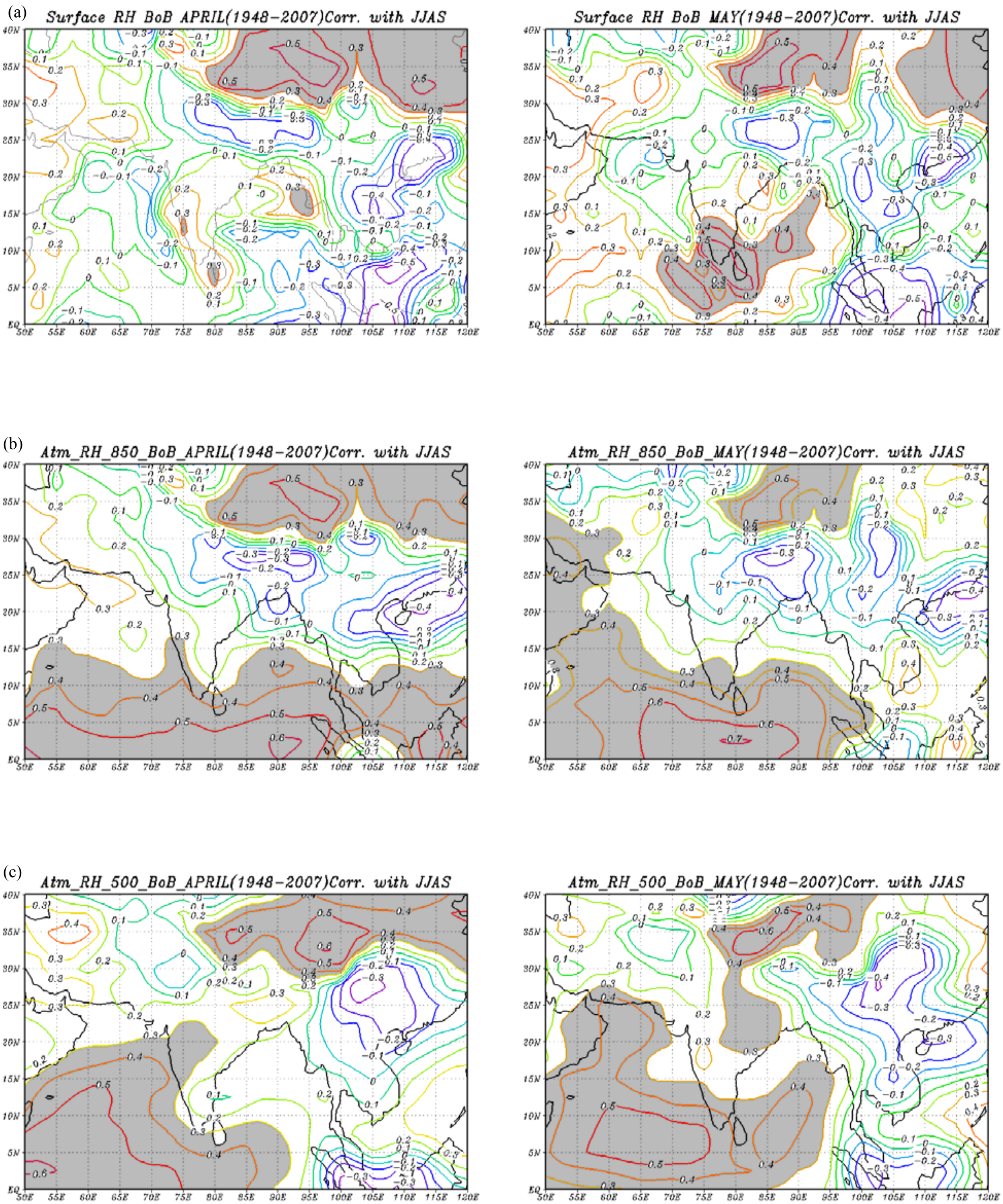
The frequency of CD during monsoon season increases with decrease in OLR leading to increase in convection over the sea region [Figs. 5(a-c)]. According to Anthes (1982), supply of energy from warm Ocean and release of latent heat in the convective elements are the main physical mechanisms for cyclogenesis.

The frequency of CD during monsoon season is inversely correlated with SST over the Bay of Bengal during April & May . Considering the spatial distributions of SST during April-May, the frequency of CD during monsoon season most significantly decreases with increase in SST over north equatorial Indian Ocean, adjoining southern part of the Bay of Bengal and the Arabian Sea. It endorses the earlier findings of Mandke and Bhide (2003). Further that the decreased cyclogenesis during monsoon season over the Bay of Bengal in recent years may be due to some other reasons and can not be attributed to SST as the frequency of CDs has decreased significantly in recently years in spite of the increase in SST over the Bay of Bengal.

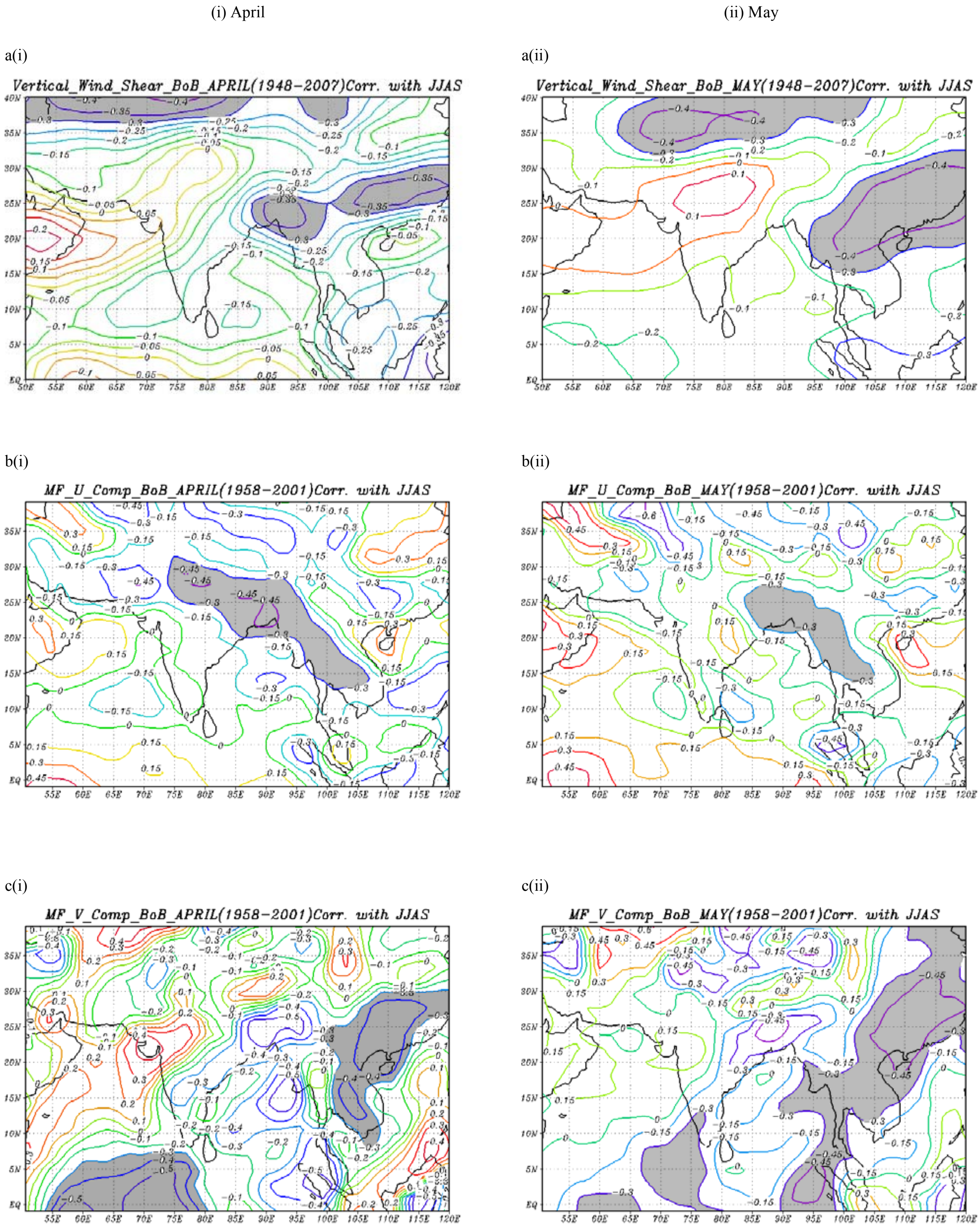
3.4.5. *Frequency of CD in relation to air temperature*

The frequency of CD increases with decrease in temperature over southern part of Bay of Bengal, Arabian Sea and equatorial north Indian Ocean at 850 hPa level in April and May [Figs. 6(a-c)]. The region of significant CC is similar to that in case of OLR as per expectation. Considering 500 hPa level, the frequency of CD increases with decrease in air temperature over north equatorial Indian Ocean, adjoining Bay of Bengal and Arabian Sea in April and over south and central Arabian Sea, south peninsula and adjoining Bay of Bengal in addition to equatorial north Indian Ocean during May. Hence colder south and central Arabian Sea, equatorial Indian Ocean, south India (south of 20° N) and adjoining Bay of Bengal during May favour cyclogenesis during the following monsoon season. It is feasible as it will enhance increased southwesterly surge over the Bay of Bengal leading to more cyclogenesis.

(i) April (ii) May



Figs. 7(a-c). Same as Fig. 3, but with RH at (a) surface, (b) 850 and (c) 500 hPa levels



Figs. 8(a-c). Same as Fig. 3, but with (a) vertical wind shear, (b) momentum flux *u*-component and (c) momentum flux *v*-component

Considering 200 hPa level, colder equatorial India Ocean and adjoining Arabian Sea during both April and May favour cyclogenesis during monsoon season. In addition, lower temperature over south Bay of Bengal during April is also favourable for cyclogenesis during the subsequent monsoon season.

Comparing with area of significant CC in case of OLR, SST, PWC and air temperature, the region of significant CC is almost identical.

3.4.6. *Frequency of CD in relation to relative humidity (RH)*

The frequency of CD increases with increase in RH over equatorial north Indian Ocean, south Bay of Bengal, south Arabian Sea and adjoining peninsula and south China Sea at 850 hPa during April [Fig. 7 (a-c)]. Similar is the case in the month of May.

Considering 500 hPa level, increase in RH over north equatorial Indian Ocean, south and central part of Arabian Sea, adjoining peninsula and northeast India in April and May are favourable for more cyclogenesis. In addition, increase in RH over south and eastcentral Bay of Bengal during May is also favourable for cyclogenesis.

3.4.7. *Frequency of CD in relation to other derived dynamical parameters*

There is no consistency in the relationship of frequency of CD with lower level convergence and upper level divergence (not shown). The frequency of CD during the monsoon season does not depend on vertical velocity and relative vorticity over the region as a whole during April and May (not shown). From Figs. 8(a-c), the frequency of CD increases with the decrease in vertical wind shear over east China, north east India and Bangladesh during April. It also increases with decrease in wind shear over the region to the north of 35° N in April and 32° N in May. The decrease of wind shear over these regions is possible with weaker and stronger extra tropical westerlies at upper & lower tropospheric levels respectively. The persistence of lower level stronger extra tropical westerlies during monsoon months over these regions with weaker westerlies over north India is favourable for good monsoon condition (Rao, 1976). The vertical wind shear is generally high over the region during the monsoon season (Rao, 1976) which is not favorable for development of the intense system. According to Gray *et al*. (1992), it is necessary for the intensification of a system to cyclonic storm stage that there exists a weak tropospheric vertical wind shear. The low vertical wind shear is essential for a disturbance to develop as the latent heat generated during the convective process is not advected away from the circulation field. However in the formative stage, the superposition of divergent portion of the upper level trough on the low level convergence region helps intensification and superposition of convergent regions of the trough weakens the system. During monsoon season the required upper level divergence over the north Bay of Bengal (region of cyclogenesis) is provided by the Tibetan anticyclone.

The increase in *v*-component of momentum flux over the west equatorial Indian Ocean and adjoining Arabian Sea during April and May favours cyclogenesis in subsequent monsoon season. The increase in U-component of momentum flux in April and May over northeast India, Bangladesh and adjoining Myanmar also favours cyclogenesis during monsoon months.

4. Major implications

Comparing all the above results, it is found that the large scale field parameters over the equatorial Indian Ocean, especially over west equatorial Indian Ocean and adjoining Arabian Sea (up to 15° N) should be favourable in April and May with lower MSLP and geopotential heights in lower and middle levels, stronger southerlies in lower and middle levels and stronger northerly components of wind at upper level for higher frequency of CD during subsequent monsoon season. Consequently, there should be increase in RH & PWC and decrease in OLR and temperature in lower levels over this region during April and May also for higher frequency of CD during subsequent monsoon season. In addition to above, stronger southeast Asian anti-cyclonic circulation at middle and upper tropospheric levels with ridge lying between 15° and 20° N are favourable for cyclogenesis during subsequent monsoon months. Comparing the area of significant CC, MSLP and geopotential heights are most influencing parameters followed by OLR, SST, air temperature and RH at 850 hPa level.

5. Conclusions

The following broad conclusions are drawn from the above results and discussion.

(*i*) The large scale field parameters over the equatorial Indian Ocean, especially over west equatorial Indian Ocean and adjoining Arabian Sea (up to 15° N) should be favourable in April and May with lower MSLP and geopotential heights in lower and middle levels, stronger southerlies in lower and middle levels and stronger northerly components of wind at upper level for higher frequency of CD during subsequent monsoon season. Consequently, there should be increase in RH and PWC and decrease in OLR and temperature in lower levels over this region during April and May also for higher frequency of CD during subsequent monsoon season.

(*ii*) Comparing the area of significant correlation between frequency of CD and large scale field parameters and its stability from April to September, MSLP and geopotential heights are most influencing parameters followed by OLR, sea surface temperature, air temperature and RH at 850 hPa level.

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