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Cloud Streets Occurrence over the Arabian Sea during Summer Monsoon Season

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ABSTRACT: Cloud streets occurrence over the Arabian sea during the summer monsoon season of June to September is documented in this study using meteorological satellite imageries. Mostly cloud streets are documented in the planetary boundary layer of the cold air outbreak regions of mid- and high-latitudes. Possible reasons for the formation of cloud streets over the Arabian sea located within the tropical belt is examined using satellite and atmospheric reanalysis data. Due to unavailability of high resolution in-situ observations over the Arabian sea, cloud streets were not studied in detail earlier.

Strong Indian summer monsoon winds near the surface cause upwelling of the Arabian sea near the horn of Africa which brings cold water from below to the surface. When cold and strong monsoon winds of this upwelling region blow over the remaining parts of the Arabian sea with relatively warmer air, alters thermal stability of the atmosphere. Thermal stability of the atmospheric layer below the cold air tongue (900 hPa – 1000 hPa) is low whereas above the cold air tongue (800 hPa - 900 hPa) is relatively higher. Vertically rising moist air near the surface due to weak thermal stability may hit the stable atmospheric barrier above and return back. In this process, parallel cylinders of rotating air called roll vortices may be generated. Clouds are expected to form over the ascending regions whereas clear-sky conditions are expected over the descending regions. These cloud streets are aligned along the wind flow direction near the surface. Cloud streets are well developed when the low level winds are strong and steady. Width of the cloud streets appears to vary if the altitude of the thermal inversion varies.

Keywords: Cloud streets, Arabian Sea, Indian Summer Monsoon season, satellite, Thermal stability, Outbreak.

I. INTRODUCTION

Occurrence of long and straight lines of clouds aligned in rows in the planetary boundary layer was noticed by meteorologists from satellite imageries. They called these cloud rows with different names such as cloud streets, roll clouds, horizontal convective clouds, etc. Impressive formation of cloud streets is found to occur over the cold air outbreak regions of the high and middle latitude seas and lakes [12, 19, 22, 26, 27, 35, 39]. Number of earlier studies have documented the cloud streets occurrence over different parts of the middle and high latitude regions during cold air outbreaks. Occurrence of cloud streets caused by the passage of northerly cold continental air from the Alaskan interior to the relatively warm Bering sea was studied using NOAA-4 satellite imageries [39]. Climatology of winter time cloud streets occurrence over Greenland and Barents Sea regions was studied by Brümmer and Pohlmann (2000) [2] using NOAA satellite imageries of ten winter seasons for the years from 1985/1986 to 1994/1995. Kelly (1984) studied the characteristics of cloud streets observed over the Michigan lake using airplanes and radars during 1981 winter season. Bands of cumuliform clouds over the Caribbean Sea was observed [12] and studied by Schuetz and Fritz (1961) using TIROS-1 satellite imageries [30]. LeMone and Meitin (1984) [17] provided evidences of fair-weather cumulus to towering cumulus clouds organized into bands over the East Atlantic Ocean during GATE. Cloud streets are found to occur over land region as well [15]. Prior to satellite observations, glider and aircraft pilots were aware of the cloud streets. Glider pilots called them as ‘wind thermals’ and used the upward motion associated with them for long-distance soaring [15, 16]. Observations even suggested that the birds prefer to travel beneath these cloud streets [16].

Formation of cloud streets associated with cold air outbreaks in the planetary boundary layer can be explained by the presence of counter rotating wind rolls or roll vortices along the wind flow direction. Clouds form over the ascending region whereas clear-sky conditions prevail over the descending region of the counter rotation [38]. Cloud streets are aligned along the wind flow direction and they are confined to the planetary boundary layer due to the presence of stable atmospheric cap. They typically have a width of tens of kilometres and stretch for hundreds of kilometres along the wind flow direction. They persist for about few hours to a day. As the cloud streets are most often noticed during cold air outbreaks over ocean or land, studies suggested that the roll vortices and associated cloud streets are formed due to thermal instability caused by the passage of cold air over the warm earth/ocean surface in the boundary layer combined with stable atmospheric cap [5, 15].

Efforts were made in the past to simulate cloud streets of the cold air outbreaks [1, 3, 5, 8, 18, 21]. Roll vortices are found over the cloud free atmospheric planetary boundary layer also Kropfli & Kohn (1978) [14]. Roll vortices induced heating and wind shear is appearing to be responsible for crown-street formations caused by crown fires [9]. Roll vortices similar to that form roll clouds are even observed over the ocean boundary layer. They are called as Langmuir circulation [37]. Dedicated field experiments were conducted in the past to understand the cloud streets. For BOMEX [7], MIZEX [39], GALE [4] were in part devoted to the study of cloud streets. They collected meteorological data at different levels of the planetary boundary layer over large horizontal extent.

Occurrence of cloud streets over the tropical region during summer season is rare due to the pole ward shifting of mid-latitude cold weather systems and absence of intense cold air intrusions to tropical belt. But the Arabian sea, located within the tropical belt, is an exception. Cloud streets do occur over the Arabian sea during summer monsoon season of June to September. Sathiyamoorthy *et al.*, (2013) noticed that cloud streets are present during two third days of the peak monsoon season of 2012 over the central, north and eastern parts of the Arabian sea [31]. It is interesting to know the cause behind the formation clouds streets over the Arabian sea during summer season. Though studies are available in literature about the clouds over the Indian region [6, 20, 23, 25 30, 32] they did not focus on the Arabian sea cloud streets possibly due to the unavailability of high-resolution atmospheric data. We present observational evidences from satellite and reanalysis data to show the occurrence of cloud streets over the Arabian sea.

II. DATA USED

The visible (0.55–0.75 µm) channel radiometric count data from INSAT-3D geostationary satellite were obtained from the website of Meteorological & Oceanographic Satellite Data Archival Centre (MOSDAC), http://www.mosdac.gov.in. The range of visible channel counts is in between 0 to 65535 (16-bit unsigned integer), which provides 2^{16} or 65536 levels of luminance per pixel in INSAT-3D Imager [28]. Luminance is also described as brightness or intensity, which can be measured on a scale from low count value (zero intensity) to high count value (full intensity).

Daily horizontal wind (zonal and meridional components), air temperature and sea surface temperature data from ECMWF reanalysis (ERA) interim global atmospheric reanalysis are downloaded from the website of ECMWF, https://www.ecmwf.int. These data are available at 0.25° latitude × 0.25° longitude resolution at every 6 hourly (0000 UTC, 0600 UTC, 1200 UTC and 1800 UTC) interval. Gridded daily rainfall data of India meteorological department (IMD) generated using observations from 1803 rain gauges well distributed across India is used [24]. This rainfall data is available at a horizontal resolution of 0.25° latitude × 0.25° longitude since 1901.

III. RESULTS AND DISCUSSION

A. Cloud streets over the Arabian sea in satellite imageries

Every year, Indian subcontinent and the oceanic region surrounding it are covered by monsoon clouds during the summer season of June to September. INSAT-3D visible radiometric counts for two typical monsoon days viz., 01 July 2015 and 17 July 2015 at 0630 UTC are shown in Fig. 1.

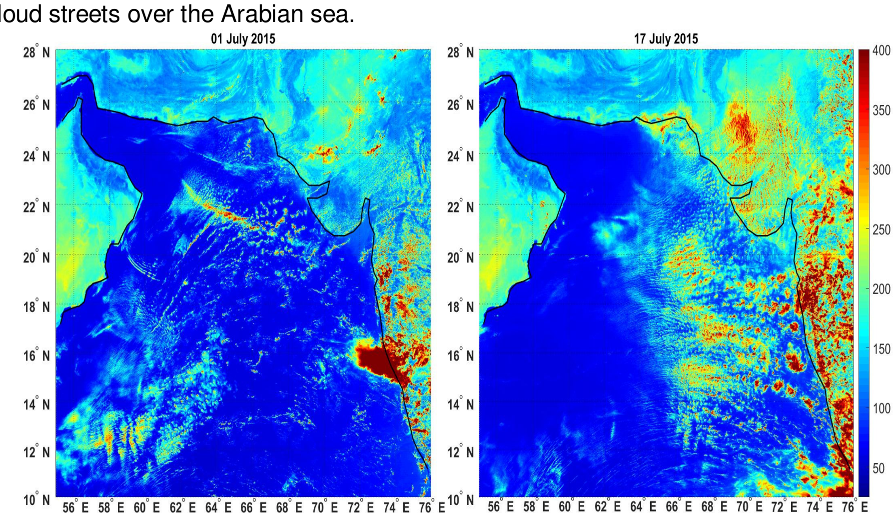

Fig. 1. INSAT-3D visible channel radiometric counts over the Arabian Sea and the adjoining land region at 0630 UTC for (left) 01 July 2015 and (right)17 July 2015.

On 01 July 2015, clouds are sparse but found over most parts of the Arabian sea whereas on 17 July 2015 clouds are dense but confined to the central, eastern and north-eastern parts of the Arabian sea. It is interesting to note that the clouds are aligned as straight lines over the northern and central parts of the Arabian sea on 01 July 2015 and over the entire cloudy region on 17 July 2015 similar to what is observed during cold air outbreaks over the high/middle latitude ocean surfaces. On 01 July 2015, cloud streets are oriented from southwest to northeast direction whereas on 17 July 2015, cloud streets are oriented both west to east and southwest to northeast directions. The cloud streets are closer and well developed on 17 July 2015 than on 01 July 2015. Upon reaching the coast, cloud streets lose their straight-line structure. Examination of INSAT-

3D visible imageries during peak summer monsoon months of July and August suggests that cloud streets are seen during most days of the peak monsoon season (July-August months) over north, central and eastern parts of the Arabian sea. Cloud streets with different width and length are found over different regions on different days of the peak monsoon season. Cloud streets are absent when organized deep convection associated with monsoon depression, mid-tropospheric cyclone, etc., form/move over the Arabian Sea. Life span of the Arabian sea cloud streets is about few hours to a day.

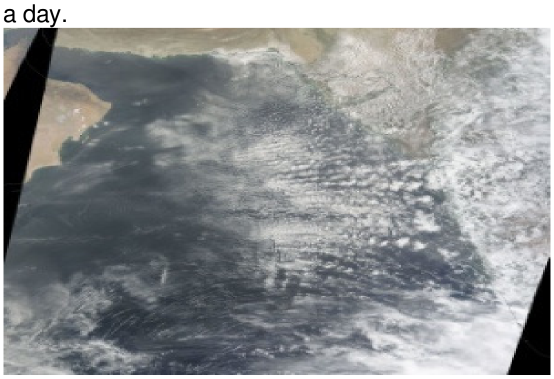

Fig. 2. True colour (band-1, band-4, and band-3) imagery of MODIS on board Terra satellite for the 17 July 2015 at 10:30 UTC over the Arabian sea.

In Fig. 2, relatively zoomed version of the MODIS True Colour (RGB) corrected reflectance images obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra satellite for 17 July 2015 at 10:30 UTC is shown. The cloud streets pattern and it's characteristics are clearly seen in this Fig.

B. Atmospheric condition during cloud streets formation

As stated earlier, a common environmental condition observed during mid/high latitude cloud streets formation is the passage of strong cold air current (outbreak) over relatively warmer ocean surface. But as stated earlier cold air outbreak is rare in the tropical belt during the summer season. So, it is important to examine, how cold air outbreak occurs over the Arabian sea during summer season. It is well known that the lower atmosphere of the Indian monsoon region is dominated by southwesterly monsoon wind current. This current originates from the Mascarene high situated near Madagascar in the southern hemisphere, crosses the equator, turns to its right due to Coriolis force and flows toward the Indian landmass as westerly/south westerly winds. This current is popularly known as monsoon low level jet (LLJ). The LLJ is found between surface to about 700 hPa with its core located at 850 hPa [11]. Climatologically, axis of the LLJ's core is found at 850 hPa and oriented west to east direction and passes along 15ºN latitude over India. But at lower levels, close to the surface, axis of the LLJ is oriented southwest to northeast, pointing towards the Gulf of Kutch [31]. Horizontal winds at 975 hPa level for 01 July 2015 and 17 July 2015 obtained from ERA are shown for the Arabian sea in Fig. 3. The LLJ is clearly seen in these two figures with jet core lying over the southwest Arabian sea with winds oriented southwest to northeast. Peak wind speed over the core region is 20 ms^{-1} and more. The core is found to cover relatively larger region with stronger winds on 17 July 2015 than on 01 July 2015.

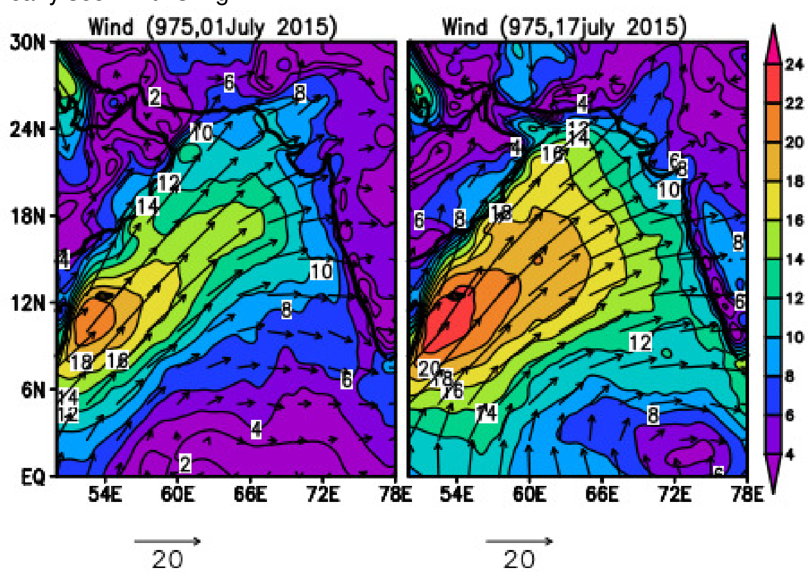

Fig. 3. Daily winds (ms^{-1}) at 975 hPa from ERA for (left) 01 July 2015 and (right) 17 July 2015.

During its course, LLJ continuously drives away the surface water off the Horn of Africa and Saudi Arabian Peninsula, which leads to upwelling of cold water from below the sea surface. Hence sea surface temperature is low in the western/southwestern parts of the Arabian sea where LLJ's core is located. When LLJ flows over the Arabian sea, surface level wind acquires cold temperature due to the exchange of sensible heat flux. In Fig. 4, daily sea surface temperature (SST) from ERA data is shown for the Arabian sea for 01 July 2015 and 17 July 2015. Relatively colder SST is seen over the LLJ core region when compared to the central and eastern parts of the Arabian sea. The SST is as low as 22°C off Horn of Africa and more than 27°C in the north, central and east Arabian sea. Flow of relatively colder wind from the LLJ core region to the central, north and east Arabian sea with relatively warm SST is analogous to what is occurring over the cold air outbreak regions of the mid/high latitudes. So, a cold air outbreak condition occurs over the Arabian sea without mid/high latitude cold air intrusion. As the winds are stronger on 17 July 2015 than 01 July 2015 spatial extent of cold SST is more on 17 July 2015.

In Fig. 5, longitude-height plots of daily temperature along 22° N latitude for 01 July 2015 and along 17° N latitude for 17 July 2015 are shown. Different latitudes are chosen because cloud streets are found over different parts of the Arabian sea on these two days. In fact, on individual days of the monsoon season, cloud streets occur at different parts of the Arabian sea with varying coverage. One striking feature in Fig. 5 is the west to east stretching of a cold air tongue from surface to about 900 hPa level over the Arabian sea. In the western Arabian sea, cold air tongue is close to the surface and it slopes upward with height towards the east Arabian sea. This figure clearly shows cold air advection from west to east Arabian sea. Due to the cold air advection, atmospheric column below the cold air tongue will be tending to have weak thermal stability as the cold air tongue causes rapid decrease of temperature with height. This weak stability may aid convection and cloud formation. On the other hand, atmospheric column above the cold air tongue will be thermally stable as the temperature increases with height. This stable condition may try to hinder the clouds from growing tall. Hence clouds will be restricted to lower levels of the atmosphere.

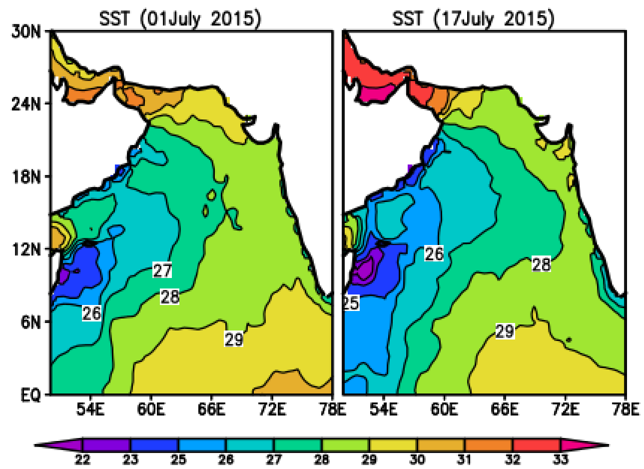

Fig. 4. Daily sea surface temperature (C) for (left) 01 July 2015 and (right) 17 July 2015 obtained from ERA data.

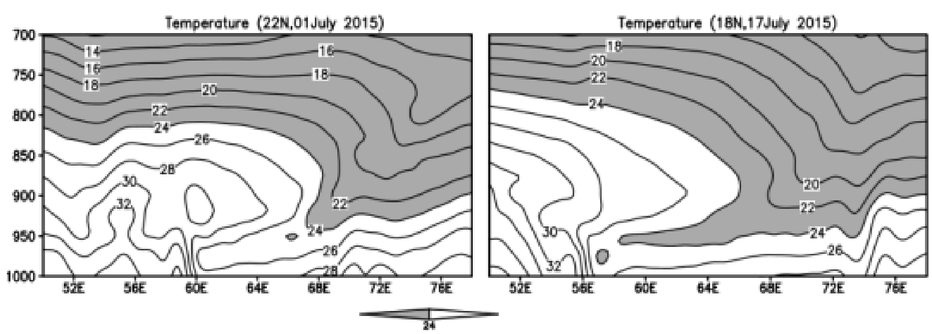

Fig. 5. Longitude-Height (Pressure – hPa) plot of the temperature (°C) for (left) 01 July 2015 along 22°N latitude and (right) 17 July 2015 along 18° N latitude. Temperature contours of 24°C and below are shaded.

The stability condition over the Arabian sea is examined further for 01 July 2015 and 17 July 2015. In Fig. 6(a-d), atmospheric stability [34, 13] computed using potential temperature (θ) difference between two levels obtained from ERA data are shown for 01 July 2015 and 17 July 2015. Fig. 6 (a) and (b) are for the lower levels of 900 hPa and 1000 hPa (θ_{900} minus θ_{1000}) for 01 July 2015 and 17 July 2015 respectively. Fig. 6(c) and (d) are for the immediate upper levels of 800 hPa and 900 hPa (θ_{800} minus θ_{900}) for 01 July 2015 and 17 July 2015 respectively. Fig. 6(c) and (d) suggest that the atmospheric layer between 900 hPa and 800 hPa is thermally stable. The stability is more over the northeast part and relatively less over the northwest part of the Arabian sea. Conversely, weak to near-zero thermal stability is seen in the lower layer between 1000 hPa and 900 hPa particularly over the central, eastern and northeast parts of the Arabian sea. Near-zero to weak thermal stability close to the surface may be conducive for the formation of cloud. But the cloud growth may be restricted by the stable atmospheric barrier found between 800 hPa and 900 hPa levels. In this process, parallel cylinders of rotating air called roll vortices may be generated. Clouds may form over the ascending regions and clear-sky conditions may prevail over the descending regions.

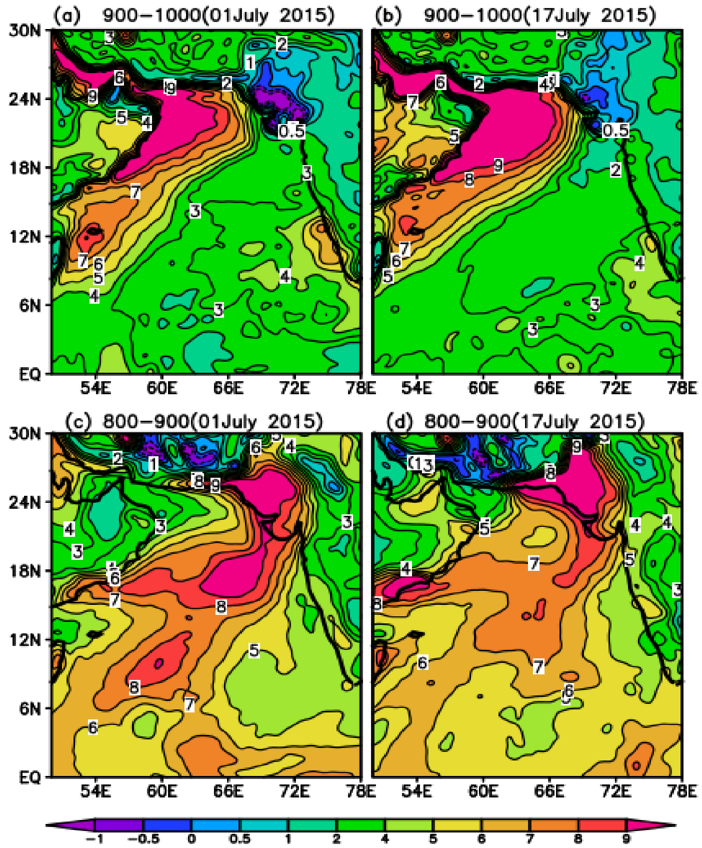

Fig. 6. Spatial plots of lower tropospheric stability (K) computed between 900 hPa and 1000 hPa levels for (a) 01 July 2015 and (b) 17 July 2015 and 800 hPa and 900 hPa levels for (c) 01 July 2015 and (d) 17 July 2015.

Another atmospheric condition that favours the cloud streets formation is low level wind shear in the planetary boundary layer (Etling and Brown, 1993) [5]. So wind shear over the Arabian sea is examined for the two days focused in this study. Difference in wind speed (wind shear) computed between 975 hPa and 1000 hPa levels obtained from ERA data is shown for 01 July 2015 and 17 July 2015 in Fig. 7. Positive wind shear is seen over the parts of the Arabian sea. Wind shear is maximum (> 5 ms^{-1}) over the LLJ core region. The cloud streets are found mainly over the mild wind shear region (<5 ms^{-1}) and absent over the high wind shear region. The low shear region is found to cover north, central and eastern Arabian sea where cloud streets are observed. By comparing Figs. 3, 6 and 7, it is clear that the cloud streets are found over the parts of the Arabian sea with lower level thermal stability caused by cold air advection, capped with stable atmospheric condition. The lower level thermal instability may initiate convection. Vertically rising air may hit the stable atmospheric barrier above and return back. In this process, parallel cylinders of rotating air called roll vortices may be generated. Clouds may form over the ascending regions and clear-sky conditions may prevail over the descending regions.

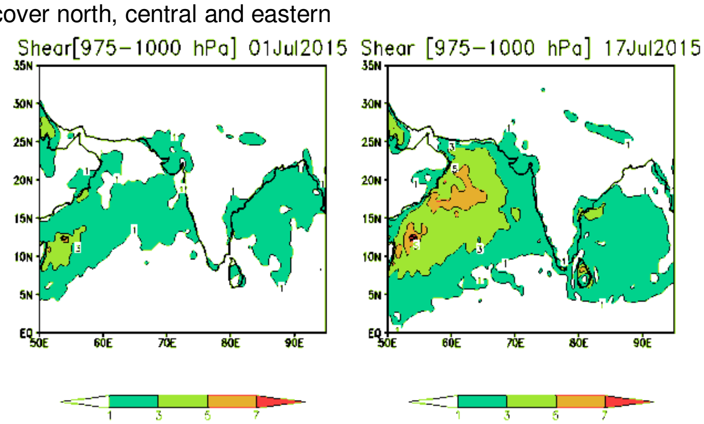

Fig. 7. Wind shear (ms^{-1}) between 975 hPa and 1000 hPa obtained from ERA data for (left) 01 July 2015 and (right) 17July 2015.

C. Role of winds on cloud streets formation

On 01 July 2015 cloud streets are oriented southwest to northeast whereas on 17 July 2015 cloud streets are oriented both southwest to northeast and west to east (Fig. 1). Also, cloud streets are sparse on 01 July 2015 when compared to 17 July 2015. As seen in Fig.3, strong low level winds are directed mostly towards north-northeastward on 01 July 2015 whereas directed northeast-eastward on 17 July 2015. For e. g., spatial extent of the 16 ms^{-1} wind speed contour contour is clearly showing wider spread over the northeast-east parts of the Arabian sea on 17 July 2015. It is clear from the wind distribution that the cloud streets are aligned along the wind flow direction. If the lower level winds change their direction, cloud streets also change their orientation along the wind flow direction. Also cloud streets do not form when LLJ is weak particularly during monsoon onset and withdrawal phases and prolonged monsoon break situation. Cloud streets are not well organised when surface level wind direction is not steady like during the passage of low pressure systems. The weak surface level winds may be the reason for the sparse cloud street formation on 01 July 2015.

D. Changes in the width of the cloud streets

In Fig.1 and 2, another obvious feature seen is the broadening of cloud streets (increased width of the cloudy and cloud free regions) on 17 July 2015 as the cloud streets move eastward from central Arabian sea. Such broadening is not seen on 01 July 2015. Possible reason behind the broadening may be the upward slopping of the cold air tongue and associated thermal inversion from west to east Arabian sea. As the height of the inversion layer increases from west to east, width of the cloud streets is also increases. Such slopping of the thermal inversion does not occur in the south to north direction over the Arabian sea on 01 July 2015 (figure not shown). So it appears that the width of the cloud streets may change if the level of thermal inversion changes.

E. Influence of cloud streets on rainfall activity over the west coast of India

On 17 July 2017, six cloud streets are seen between 14°N and 20°N latitudes (Fig. 1 and 2). These six cloud streets are seen up to the west coast of India, one south of 15°N, five north of them and cloud free region around 19°N. These rolls move along with the monsoon winds and reach the west coast of India. Along the west coast, north-south oriented Western Ghats mountain chain is located parallel to the coast. On reaching the Western Ghats, cloud streets are expected to ascend over the mountain and yield rainfall. As the life span of the Arabian sea cloud streets is about a day, cloud streets are expected to rain continuously for about a day. It is interesting to examine, whether such streets like pattern is seen in rainfall [cloudy (rainy) and clear (non-rainy)] along the west coast. In Figure 8, gridded rainfall data obtained from IMD is plotted for 17 July 2017. Rainfall along the west coast exhibits cloud streets like rain - no-rain pattern. Six patches of rainfall are seen between 14°N and 20°N which is closely resembling with the cloud streets pattern. Rainfall data confirm that the cloud streets cause spatial variability in rainfall along the west the coast of India. As there are no mountains along the north-northeast coast of the Arabian sea, cloud streets do not result in rainfall. Once the cloud streets reach the north-northeast coast of the Arabian sea, their roll structure vanishes and it is difficult to trace them over the land.

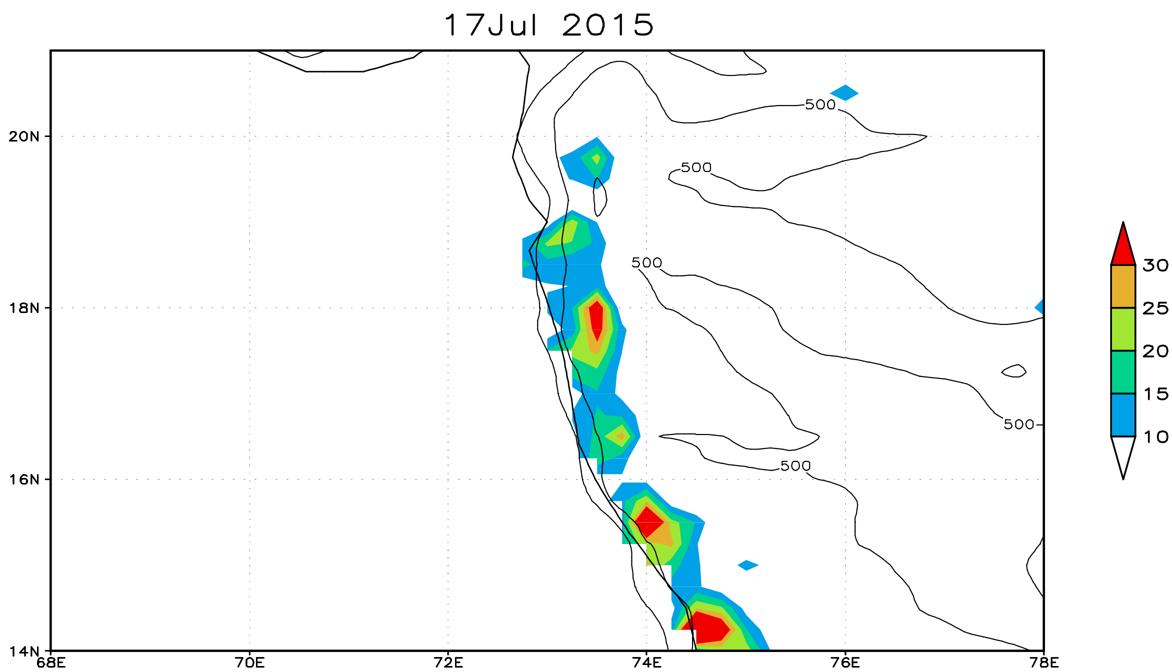

Fig. 8. Rainfall in mm (shaded) obtained from IMD data for 17 July 2015. The orographic elevation in meters is shown in contours.

IV. CONCLUSION

Cloud streets occurrence over the Arabian sea during the Indian summer monsoon season of June to September is documented in this study using high resolution meteorological satellite imageries. A cold air outbreak like situation is generated when the strong low level monsoon winds flow from cold SST pool over the southwest Arabian sea to the remaining parts of the Arabian sea. As the cold air flows over the relatively warmer air region, atmospheric layer below (around 1000 hPa to 900 hPa) will be less stable and atmospheric layer above (around 900 hPa to 800 hPa) will be more stable. The less stable air close to the surface may be conducive for cloud formation. But clouds are unable to grow tall as their growth is restricted by the stable atmospheric layer above it. In this process, parallel cylinders of rotating air called roll vortices may be generated. Clouds may form over the ascending regions and clear-sky conditions may prevail over the descending regions.

The cloud streets are aligned along the wind flow direction. Clouds streets are well developed when the low level winds are strong and steady. Width of the cloud streets appears to vary when the altitude of the thermal inversion varies. When the cloud streets are well developed up to the west coast of India, they are forced to ascend over the western ghats mountain chain located on the west coast of India and generate spatial rainfall variability.

V. FUTURE SCOPE

More study will be carried out using numerical models.

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REFERENCES

[1]. Brown, R. A. (1980). Longitudinal Instabilities and Secondary Flows in the Planetary Boundary Layer: A Review. *Rev. Geophys. Space Phys., 18,* 683-697.

[2]. Brümmer, B., & Pohlmann, S. (2000). Wintertime roll and cell convection over Greenland and Barents Sea regions: A climatology*. J. Geophys. Res., 105(D12),* 15559–15566.

[3]. Chlond, A. (1992). Three-dimensional simulation of cloud street development during a cold air outbreak. *Boundary-layer meteorology*, *58*(1-2), 161-200.

[4]. Chou, S. H., & Ferguson, M. P. (1991). Heat fluxes and roll circulations over the western Gulf Stream during an intense cold-air outbreak. *Boundary-layer meteorology*, *55*(3), 255-281.

[5]. Etling, D., & Brown, R. A. (1993). Roll vortices in the planetary boundary layer: A review. *Boundary-Layer Meteorology*, *65*(3), 215-248.

[6]. Gadgil, S., Vinayachandran, P. N., & Francis, P. A. (2003). Droughts of the Indian summer monsoon: Role of clouds over the Indian Ocean. *Current Science*, *85*(12) 1713-1719.

[7]. Grossman, R. L. (1982). An analysis of vertical velocity spectra obtained in the BOMEX fair-weather, trade-wind boundary layer. *Boundary-Layer Meteorology*, *23*(3), 323-357.

[8]. Gryschka, M., & Raasch, S. (2005). Roll convection during a cold air outbreak: A large eddy simulation with stationary model domain. *Geophysical research letters*, *32*(14). 1-5.

[9]. Haines, D. A. (1982). Horizontal roll vortices and crown fires. *Journal of Applied Meteorology*, *21*(6), 751-763.

[10]. Hartmann, J., Kottmeier, C., & Raasch, S. (1997). Roll vortices and boundary-layer development during a cold air outbreak. *Boundary-Layer Meteorology*, *84*(1), 45-65.

[11]. Joseph, P. V., & Sijikumar, S. (2004). Intraseasonal variability of the low-level jet stream of the Asian summer monsoon. *Journal of Climate*, *17*(7), 1449-1458.

[12]. Kelly, R. D. (1984). Horizontal roll and boundary-layer interrelationships observed over Lake Michigan. *Journal of the atmospheric sciences*, *41*(11), 1816-1826.

[13]. Klein, S. A. (1997). Synoptic variability of low-cloud properties and meteorological parameters in the subtropical trade wind boundary layer. *Journal of climate*, *10*(8), 2018-2039.

[14]. Kropfli, R. A., & Kohn, N. M. (1978). Persistent horizontal rolls in the urban mixed layer as revealed by dual-Doppler radar. *Journal of Applied Meteorology*, *17*(5), 669-676.

[15]. Kuettner, J. P. (1971). Cloud bands in the earth's atmosphere: Observations and theory. *Tellus*, *23*(4-5), 404-426.

[16]. Kuettner, J. (1959). The band structure of the atmosphere. *Tellus*, *11*(3), 267-294.

[17]. LeMone, M. A., & Meitin, R. J. (1984). Three examples of fair-weather mesoscale boundary-layer convection in the tropics. *Monthly weather review*, *112*(10), 1985-1997.

[18]. Liu, A. Q., Moore, G. W. K., Tsuboki, K., & Renfrew, I. A. (2004). A high-resolution simulation of convective roll clouds during a cold-air outbreak. *Geophysical research letters*, *31*(3), 1-4.

[19]. Martin, T., & Bakan, S. (1991). Airplane investigation of a case of convective cloud bands over the North Sea. *Boundary-layer meteorology*, *56*(4), 359-380.

[20]. Meenu, S., Rajeev, K., Parameswaran, K., & Nair, A. K. M. (2010). Regional distribution of deep clouds and cloud top altitudes over the Indian subcontinent and

the surrounding oceans. *Journal of Geophysical Research: Atmospheres*, *115*(D5), 1-12.
[21]. Mikhajlova, L. A., & Ordanovich, A. E. (1991). Coherent Structures in the Atmospheric Boundary Layer. Izv. *Atm. Ocean Phys., 27*(6)*,* 593-613.
[22]. Miura, Y. (1986). Aspect ratios of longitudinal rolls and convection cells observed during cold air outbreaks. *Journal of the atmospheric sciences*, *43*(1), 26-39.
[23]. Padma Kumari, B., & Goswami, B. N. (2010). Seminal role of clouds on solar dimming over the Indian monsoon region. *Geophysical research letters*, *37*(6), 1-5.
[24]. Rajeevan, M., Bhate, J., Kale, J. D., & Lal, B. (2006). High resolution daily gridded rainfall data for the Indian region: Analysis of break and active. *Current Science*, *91*(3), 296-306.
[25]. Rajeevan, M., Rohini, P., Kumar, K. N., Srinivasan, J., & Unnikrishnan, C. K. (2013). A study of vertical cloud structure of the Indian summer monsoon using CloudSat data. *Climate dynamics*, *40*(3-4), 637-650.
[26]. Rana, P. (2018). Spatial Distribution of Cloud Physical Parameters and Cloud Radiative Forcing over the Indian Summer Monsoon Region. *International Journal of Scientific Research in Physics and Applied Sciences, 6*(3), 65-68.
[27]. Rana, P., & Sathiyamoorthy, V. (2018). Investigation of Clouds And Cloud Radiative Forcing on The Windward Side of the Madagascar Mountain Chains, *The International Archives of the Photogrammetry. Remote Sensing and Spatial Information Sciences, XLII-5,* 901-906.
[28]. Rana, P., & Sathiyamoorthy, V. (2018). Study of the cloud cover variability over Indian region using Geo-Stationary Satellitedata. *International Archive of Applied Sciences and Technology, 9*(3), 29-34.
[29]. Renfrew, I. A., & Moore, G. W. K. (1999). An extreme cold-air outbreak over the Labrador Sea: Roll vortices and air–sea interaction. *Monthly Weather Review*, *127*(10), 2379-2394.
[30]. Roca, R., Viollier, M., Picon, L., & Desbois, M. (2002). A multisatellite analysis of deep convection and its moist environment over the Indian Ocean during the winter monsoon. *Journal of Geophysical Research: Atmospheres*, *107*(D19), 1-25.
[31]. Sathiyamoorthy, V., Mahesh, C., Gopalan, K., Prakash, S., Shukla, B. P., & Mathur, A. K. (2013). Characteristics of low clouds over the Arabian Sea. *Journal of Geophysical Research: Atmospheres*, *118*(13), 489-513.
[32]. Sathiyamoorthy, V., Pal, P. K., & Joshi, P. C. (2004). Influence of the upper-tropospheric wind shear upon cloud radiative forcing in the Asian monsoon region. *Journal of climate*, *17*(14), 2725-2735.
[33]. Schuetz, J., & Fritz, S. (1961). Cloud streets over the Caribbean Sea. *Monthly Weather Review*, *89*(10), 375-382.
[34]. Slingo, J. M. (1987). The development and verification of a cloud prediction scheme for the ECMWF model. *Quarterly Journal of the Royal Meteorological Society*, *113*(477), 899-927.
[35]. Streten, N. A. (1975). Cloud cell size and pattern evolution in Arctic air advection over the North Pacific. *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie A.*, *24*(3), 213-228.
[36]. Sykes, R. I., Lewellen, W. S., & Henn, D. S. (1988). A Numerical Study of the Development of Claud-Street Spacing. *Journal of the Atmospheric Sciences*, *45*(18), 2556-2570.
[37]. Thorpe, S. A. (1992). The breakup of Langmuir circulation and the instability of an array of vortices. *Journal of physical oceanography*, *22*(4), 350-360.
[38]. Walter, B. A. (1980). Wintertime observations of roll clouds over the Bering Sea. *Monthly Weather Review*, *108*(12), 2024-2031.
[39]. Walter Jr, B. A., & Overland, J. E. (1984). Observations of longitudinal rolls in a near neutral atmosphere. *Monthly weather review*, *112*(1), 200-208.

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