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A Study on Winter-time Roll Clouds over the Arabian Sea using INSAT-3D Satellite Observations

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ABSTRACT: Roll clouds are a special type of boundary layer clouds aligned as parallel lines along wind flow direction. They are commonly found over the cold air outbreak regions of the extra-tropics. Roll cloud occurrences are relatively less over the tropics. In this paper, we report the occurrence of roll clouds during the winter seasons of 2013-2017 over the Arabian sea using INSAT-3D satellite data. These clouds occur during cold air outbreak conditions and they were not studied extensively. This is due to the unavailability of high resolution meteorological observations over the Arabian sea. The European Center for Medium Range Weather Forecast (ECMWF) reanalysis data is used to study the atmospheric condition. The cold air intrusion around 900 hPa level reduces the thermal stability of the atmospheric layer just below it and increases the stability just above it. Reduced thermal stability favours low level cloud formation whereas stable atmospheric condition around 850 hPa unfavours vertical cloud growth. Strong and steady winds and favourable changes in atmospheric stability are conducive for the formation of roll clouds. Roll clouds are aligned along the wind flow direction. Eighteen roll cloud episodes were observed during December-January months of 2014-2016. Once the strength of cold-air outbreak weakens, roll clouds disintegrate. These small-scale cloud processes should be captured well by the Numerical Weather Prediction (NWP) models in order to simulate the winter monsoon more realistically.

Keywords: Roll clouds, winter, Arabian sea, INSAT-3D Satellite Observations, Numerical Weather Prediction (NWP)

I. INTRODUCTION

Roll clouds are a special type of shallow planetary boundary layer clouds aligned as parallel lines along the wind flow direction. They are observed mostly over the cold air outbreak regions of the extra-tropical latitudes. The roll clouds extend as long as few tens to a hundred kilometers along the wind flow direction. These clouds are known by different names such as cloud streets, roll clouds, horizontal convective rolls, etc. Many of the researchers studied the roll clouds and observed that the atmospheric thermal instability close to the surface along with the presence of vertical wind shear helps the formation roll clouds [1, 5, 6, 8, 11, 12, 15, 16, 27, 29].
Formation of roll cloud associated with cold air outbreaks can be explained by the presence of counter rotating roll vortices along the wind flow direction in the boundary layer. Clouds are expected to form over the ascending regions and cloud-free conditions are expected to form over the descending regions of the roll vortices [29].
Researchers used satellite imageries to study the occurrence of roll clouds in the extra-tropics as the satellite imageries provide a synoptic view of a larger region at any point of time [3, 22]. The NOAA satellite imageries used to study the occurrence of roll clouds over the Greenland and Barents Sea regions during winter season [3]. Renfrew & Moore (1999) used satellite based AVHRR infrared imageries and in-situ data to study the characteristics of roll clouds over the Labrador Sea [20]. Numerical models were used to understand the structure and dynamics of the roll clouds [15, 17, 18, 19, 28].
Liu *et al*., (2004) used numerical modelling method over a large domain at high spatial resolution and successfully captured the transition of two-dimensional roll clouds to three-dimensional convection [13]. Various field studies also have been carried out by researchers at different parts of the world to understand the roll clouds [2, 7, 10, 23].
Occasionally roll clouds form over the tropical region also when extra-tropical cold air intrudes to relatively warmer tropical region. Frequency and intensity of mid-latitude cold air intrusion to tropics are pronounced during the winter season. Roll clouds do occur over the Arabian sea during the winter when cold continental air intrudes to the Arabian sea similar to the extra-tropical cold air outbreaks. No dedicated study was made to understand the occurrence of roll clouds over the Arabian sea. In this work, possible reasons behind the roll cloud formation over the Arabian sea and its influence on top of atmosphere radiation balance are presented. In this work 3-year (2014-2016) INSAT-3D geostationary meteorological satellite data are used to study the roll clouds and their characteristics over the Arabian sea during winter season.

II. DATA AND METHODOLOGY

The present study is focusing on the Arabian sea region in north Indian ocean. The visible (0.55μm–0.75 μm) channel radiometric count data from INSAT-3D Indian geostationary satellite have been used to identify the roll clouds (Rana & Sathiyamoorthy, 2018 [22]).

The study also utilizes the high spatial resolution (0.125º latitude × 0.125º longitude) European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis (ERA) Interim surface & air temperatures, low level cloud cover amount (LCCA), temperature, humidity and wind data. Clouds are defined as low level clouds if their tops are lower than 680 hPa. Broad band top of atmosphere cloud radiative forcing data available at 1º latitude × 1º longitude resolution is obtained from Clouds and the Earth's Radiant Energy System (CERES) on board Aqua and Terra satellites for the periods of 2014-2016 [14]. The difference between top-of-atmosphere clear-sky and total-sky radiative fluxes is defined as cloud radiative forcing (CRF) [4, 21]. Shortwave cloud radiative forcing (SWCRF), long wave cloud radiative forcing (LWCRF), and net cloud radiative forcing (NCRF) are the three components of CRF. NCRF is defined as the sum of LWCRF and SWCRF. SWCRF is generally a negative quantity and LWCRF is a positive quantity. NCRF is either a negative or a positive quantity depending upon the magnitudes of SWCRF and LWCRF. The INSAT-3D visible radiometric count, ERA reanalysis and CERES cloud radiative forcing data were download from the websites of *http://*www.mosdac.gov.in, https://www.ecmwf.int and http://ceres.larc.nasa.gov respectively.

The satellite visible imageries are used to identify the roll clouds and their evolution over the Arabian during the study period. The ECMWF reanalysis data are used to understand the formation mechanism of the roll clouds. The cloud radiative forcing data are used to study the radiative forcing of roll clouds.

III. RESULTS AND DISCUSSION

A. Roll clouds observed by INSAT-3D geostationary satellite over the Arabian Sea

The Arabian sea is occasionally covered by low level clouds during the winter season when cold air intrudes from cold continental region in the north to the Arabian sea. Due to the atmospheric condition prevailing over the Arabian sea, these clouds organize as rolls, similar to the extra-tropical roll clouds. During 2013-2017, eighteen roll cloud events were noticed in the peak winter months of December and January in INSAT-3D visible radiometric count data Table 1. Out of these 26 events, three cases are considered for the detailed study to avoid repetition.INSAT-3D visible radiometric counts for these three cases viz., 12 January 2014, 10 January 2015 and 23 January 2016 at 0600 UTC are shown in Fig. 1. During these three days (referred to as case studies), clouds are seen over the southwest and central parts of the Arabian sea. These clouds are aligned as parallel lines similar to the extra-tropical roll clouds. The Arabian sea roll cloud episodes last for about a few days to a week. Roll clouds are generally well manifested in the southwest and central parts of the Arabian sea. The roll structure of the clouds is clearly manifested on 23 January 2016. On this day, roll clouds are seen to stretch horizontally about 500 km in the Arabian sea.

B. Role of atmospheric circulation on roll cloud formation

During the winter season, Asian continental region is colder than the Arabian sea in the south. Generally high pressure and subsidence prevail over the continental region. Cold air from the high-pressure region over the continent flows towards the relatively warmer Arabian sea with lower surface pressure. The northerly winds become north easterlies during their southward journey over the Arabian sea due to the deflection by Coriolis force. These lower tropospheric northeasterly winds are part of the winter monsoon or northeast monsoon circulation.

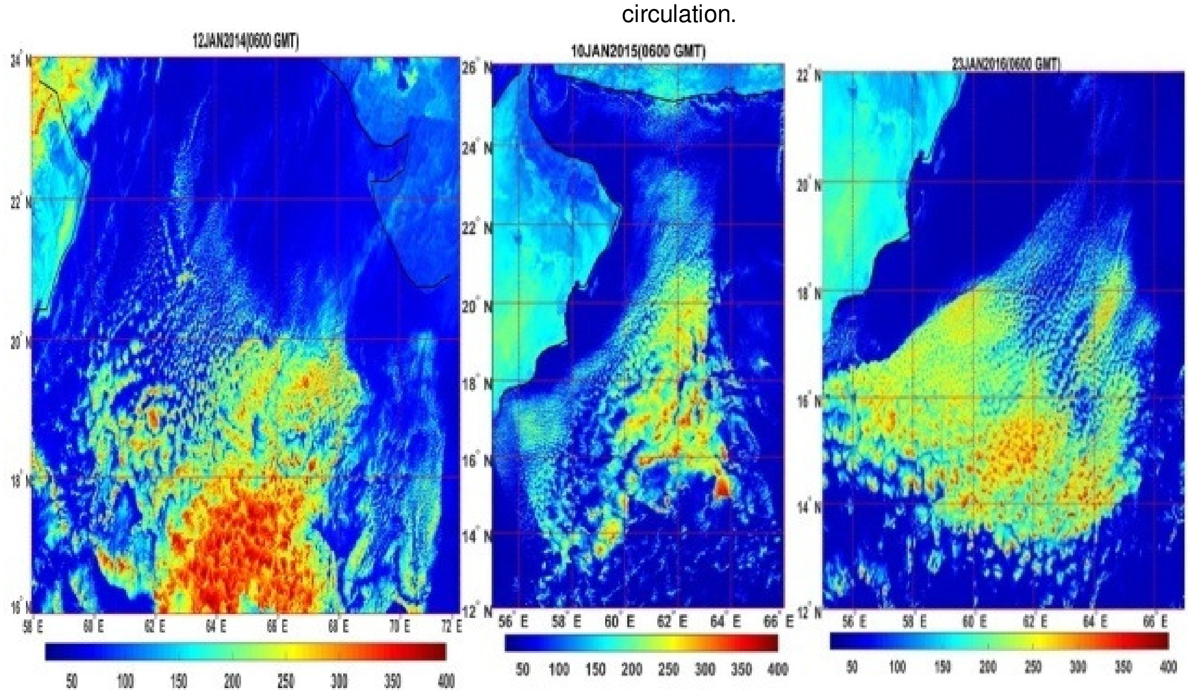

Fig. 1. INSAT-3D visible (0.55–0.75 μm) radiometric counts plotted over the Arabian sea for 12 January 2014 (left), 10 January 2015 (middle) and 23 January 2016 (right). Roll clouds are seen in these days.

Table 1: List of roll cloud episodes occurred over the Arabian sea during the winter months of December and January during 2013 to 2017. Roll cloud formations were observed in INSAT-3D visible imageries during these periods.

Year	December (Days)	January (Days)
2013-2014	10 to 12 December 2013 (3)	06 to 07 January 2014 (2)
	14 to 18 December 2013 (5)	11 to 16 January 2014 (6)
	28 to 30 December 2013 (3)	24 to 26 January 2014 (3)
2014-2015	15 to 16 December 2014 (2)	09 to 13 January 2015 (5)
	20 to 21 December 2014 (2)	27 to 29 January 2015 (3)
	24 to 25 December 2014 (2)	—
	27 to 29 December 2014 (3)	—
2015-2016	06 to 07 December 2015 (2)	21 to 26 January 2016 (6)
	13 to 14 December 2015 (2)	28 to 30 January 2016 (3)
	18 to 19 December 2015 (2)	—
	24 to 25 December 2015 (2)	—
2016-2017	01 to 03 December 2016 (3)	04 to 05 January 2017 (2)
	08 to 09 December 2016 (2)	08 to 12 January 2017 (5)
	11 to 13 December 2016 (3)	27 to 30 January 2017 (4)
	20 to 23 December 2016 (4)	—
	26 to 31 December 2016 (6)	—

In Fig. 2, surface temperature, mean sea level pressure and near-surface (900 hPa) winds are shown for the three roll cloud cases of 2014-2016. During these three case studies, low level winds are stronger (about 10ms^{-1} and above) over the Arabian sea due to the cold air intrusion to the Arabian sea.

Winds during the cold air intrusion are stronger than the prevailing northeast monsoon circulation due to the closer interaction of cold and warm air fronts. Cold air intrusion causes the interaction of cold air with warm air over the Arabian sea. From Fig. 1 and 2, it is clear that the roll clouds are aligned along the low-level wind flow direction.

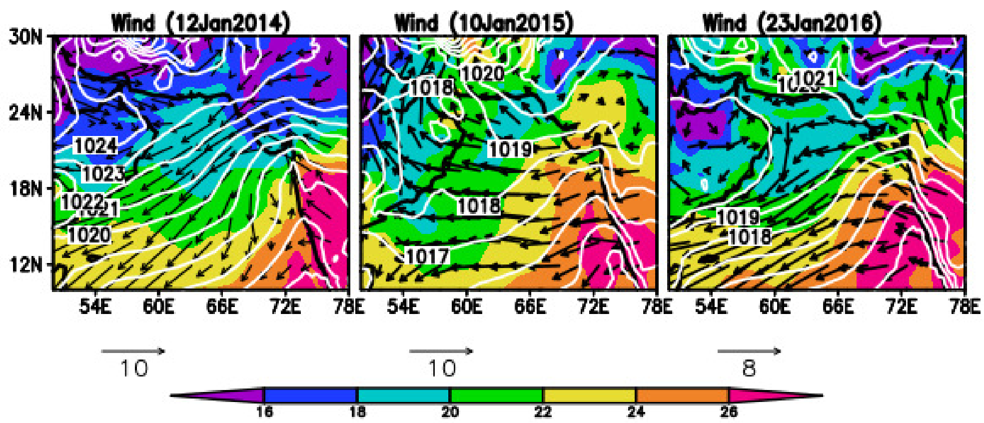

Fig. 2. Surface temperature (ºC) in shades, mean sea level pressure (hPa) in contours of 2 hPa interval and wind (ms^{-1}) vectors at 900 hPa over the Arabian sea for 12 January 2014 (left), 10 January 2015 (middle) and 23 January 2016 (right).

C. Vertical temperature distribution during roll cloud events

As suggested earlier, advection of cold air to the warmer Arabian sea causes mixing of cold air with warm air. To understand this mixing process, vertical temperature distribution during roll cloud occurrence are examined using ERA data.

In Fig. 3 vertical temperature distribution over the Arabian sea along the meridional direction is plotted for three days of anaysis, viz., 12 January 2014 along 64º E longitude, 10 January 2015 along 62ºE longitude, 23 January 2016 along 64ºE longitude. The flow of cold air from north to south is clearly seen in Fig. 4. Cold air intrusion is seen around 800 hPa - 900 hPa level. As the cold air advects, warm air over the Arabian sea is forced to ascend over the cold air.

The atmospheric layer above the cold air advection may have increased thermal stability as the temperature increases with height rather than dereasing. On the other hand, atmospheric layer below the cold air advection may have decreased thermal stabilty as the temperature decreases more drastically with height than before cold air intrusion.

In Fig. 4, vertical temperature distribution along the zonal direction obtained from ERA data is shown for same three cases, 12 January 2014 along 20ºN latitude, 10 January 2015 along 22ºN latitude, 23 January and 2016 along 15ºN latitude. Cold air advection is clearly seen over the Arabian sea in zonal direction also during these days between 800 hPa -900 hPa levels. Cold air advection is prominently seen during 12 January 2014 and 23 January 2016.

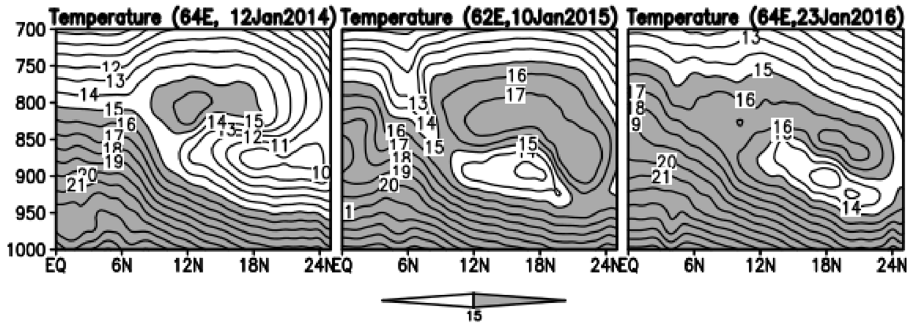

Fig. 3. Vertical distribution of temperature (°C) along the meridional direction for (left) 12 January 2014 along 64ºE longitude, (middle) 10 January 2015 along 62ºE longitude and (right) 23 January 2016 along 64ºE longitude in the ERA data.

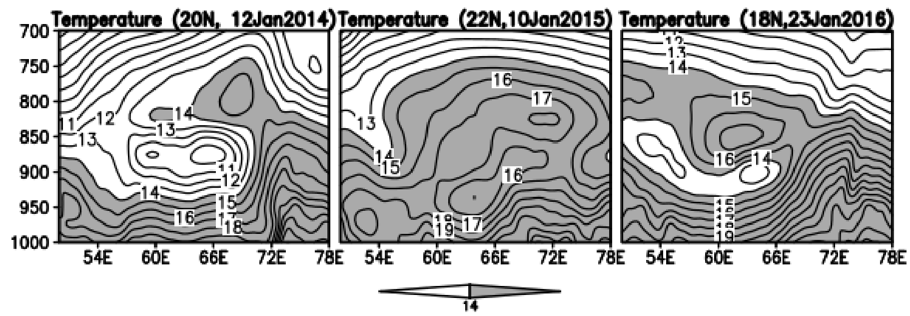

Fig. 4. Vertical distribution of temperature (°C) in zonal direction for (left) 12 January 2014 along 20ºN latitude, (middle) 10 January 2015 along 22ºN latitude and (right) 23 January 2016 along 15ºN latitude in ERA data.

D. Atmospheric stability during cold air advection

In this section, atmospheric stability is analysed for two layers, one just above the cold air advection (800 hPa – 900 hPa levels) and another just below the cold air advection (900 hPa – 1000 hPa levels) of the lower troposphere. The atmospheric stability is calculated by using potential temperature (θ) difference between 900 hPa(θ_{900}) and 1000 hPa (θ_{1000}) and the atmospheric stability calculated between 800 hPa (θ_{800}) and 900 hPa (θ_{900}) are shown in Fig. 6 and 7 respectively [9, 26]. Fig. 5 suggests that the atmospheric thermal stability is weak throughout the Arabian sea at the layer just below the cold air advection. Stability is about 2K or below over the roll cloud regions during these three days of analysis. In contrary, stability is strong in the layer just above cold air advection (Fig. 6). The magnitude of upper tropospheric stability is as high as 14K over the roll cloud occurrence region.

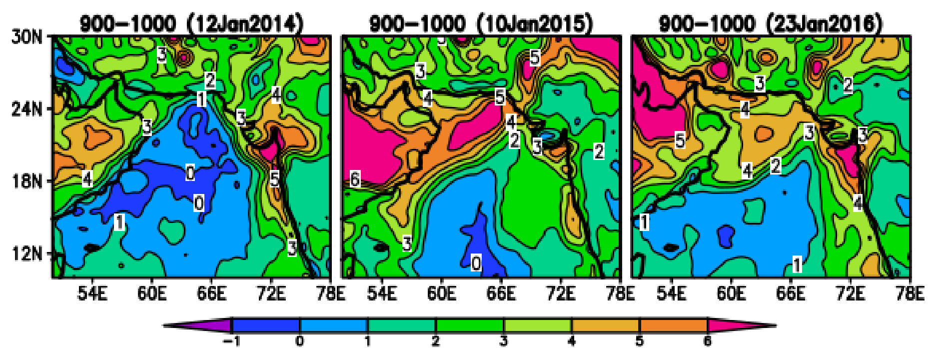

Fig. 5. Atmospheric stability (K) computed by taking the difference of potential temperature at 900 hPa and 1000 hPa levels for 12 January 2014 (left), 10 January 2015 (middle) and 23 January 2016 (right) using ERA data.

Lower level weak stability along with strong and steady winds during cold air intrusions may generate counter rotating roll vortices similar to that reported in extra-tropical latitudes. Clouds are expected to form over the ascending regions and clear-sky condition is expected over the descending regions. These clouds are unable to grow vertically due to the stable atmospheric layer present around 850 hPa. The clouds are aligned as rolls along the wind flow direction.

E. Humidity distribution during roll cloud events

In Fig. 7, daily vertical relative humidity distribution in the zonal direction during the three days of roll cloud formation discussed in this study are shown. The relative humidity profiles during cold air advection suggest that moisture laden air is trapped below 850 hPa level. The relative humidity is above 60% from the surface to about 850hPa and less than 10% above 850hPa level.

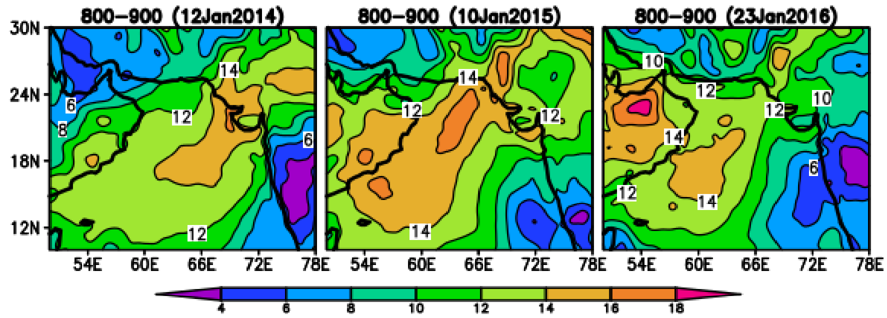

Fig. 6. Atmospheric stability (K) computed by taking the difference of potential temperature at 800 hPa - 900 hPa for 12 January 2014 (left), 10 January 2015 (middle) and 23 January 2016(right) using ERA data.

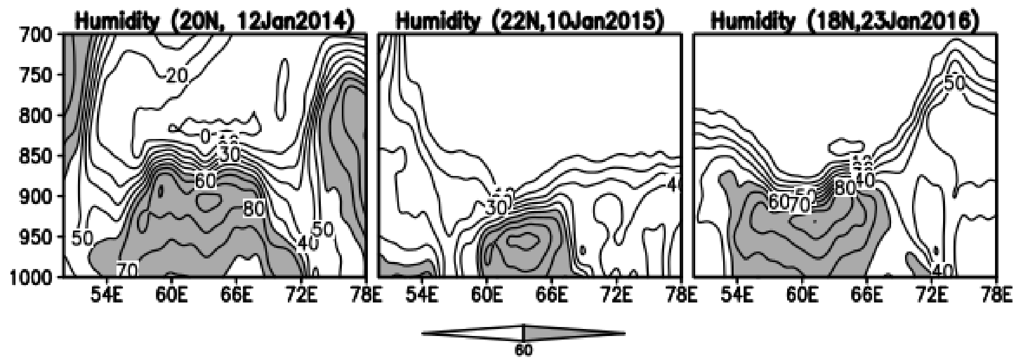

Fig. 7. Vertical distribution of relative humidity (%) in the zonal direction for (left) 12 January 2014 along 20ºN latitude (middle) 10 January 2015 along 22ºN latitude and (right) 23 January 2016 along 18ºN latitude obtained from ERA data.

As the atmosphere is stable around 850 hPa, vertical mixing of water vapour is constrained by the stable layer. Hence roll clouds are expected to be present below 850 hPa during cold air intrusion over the Arabian sea due to the presence of abundant moisture.

F. Cloud Radiative Forcing

Clouds influence the radiation balance of the earth-atmosphere system. One of the important parameters used to quantify the influence of clouds on Earth radiation balance is the cloud radiative forcing [20-21]. In this section, LCCA from ERA and top of atmosphere NCRF from CERES are examined for the winter month of January during 2014-2016. As the top of atmosphere cloud radiative forcing data from CERES are available on monthly basis, this analysis is done on monthly basis. The three-year (2014-2016) average January LCCA is shown in Fig. 8. This figure suggests that the LLCA are more over the south-west, central and southern parts of the Arabian sea where roll clouds are seen. As the roll clouds are confined below850 hPa due to the thermal inversion, they fall under low cloud category. Cold air intrusion is the dominant factor which causes cloudiness over the Arabian sea in winter. As solar heating is minimum in January, convective clouds such as cumulus and cumulonimbus are less over the central and north Arabian sea. The low-level cloud cover amount is ranging between 10% to 50% over the Arabian sea in January. In Fig. 9, 3-year average monthly NCRF for January is shown. The NCRF is negative and peaks up to -20 Wm^{-2}over the central parts of the Arabian Sea, where maximum low-level cloud coverage is seen. Negative NCRF suggests that the low-level clouds of the Arabian sea exert a net radiative cooling effect on the earth-atmosphere system.

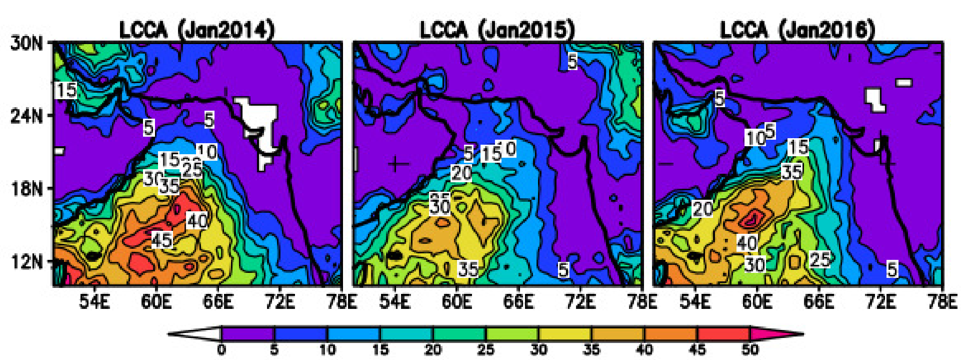

Fig. 8. Monthly average low level cloud cover amount (%) during peak winter month of January for 2014 (left), 2015 (middle) and 2016(right) obtained from ECMWF data.

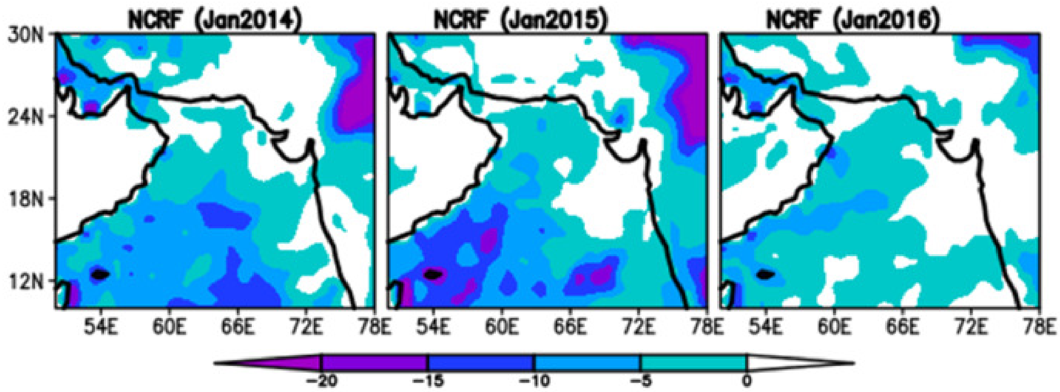

Fig. 9. Monthly averaged net cloud radiative forcing (w/m^2) during peak winter month of January for 2014 (left), 2015 (middle) and 2016 (right) obtained from CERES data.

IV. CONCLUSION

In this study, occurrence of boundary layer roll clouds over the Arabian sea during the winter season of 2013-2017 is documented using INSAT-3D visible radiometric count data. During the study period, 26 roll cloud episodes were noticed during the peak winter season. Out of the 26 episodes, three cases were considered for the analysis. Possible meteorological conditions behind the formation of roll clouds over the Arabian sea were studied in this work. These roll clouds form during cold-air intrusions over the Arabian sea. Cold air intrusion brings cold continental air to the Arabian sea around 900 hPa level. Atmospheric layer below the cold air intrusion has weak thermal stability whereas the layer above the cold air intrusion has strong thermal stability. Strong and steady winds and changes in atmospheric stability may be conducive for the formation of counter-rotating roll vortices. Clouds are expected over the ascending parts of the roll vortices and cloud-free conditions are expected to form over the descending parts. These roll clouds are confined up to 850 hPa from surface and hence falls under low cloud category. Once the cold air intrusion weakens, roll clouds disintegrate and remain as normal low-level clouds. The low-level clouds of the Arabian sea are found to exert a net radiative cooling as high as -20 Wm^{-2} in January at the top of atmosphere.

It is suggested that the small-scale processes like the roll cloud formation and their radiative forcing should be captured well by the numerical weather prediction models in order to simulate the Indian winter monsoon circulation in a more realistic way.

V. FUTURE SCOPE

Ability of the different boundary layer schemes in simulating the winter time roll clouds over the Arabian sea will be attempted using NWP model.

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