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## **Upper air thermal inversion and their impact on the summer monsoon rainfall over Goa – A case study**

**Swathi, M.S., Muraleedharan, P.M\*., Ramaswamy, V., Rameshkumar, M.R., Aswini, Anirudhan**

CSIR-National Institute of Oceanography, Dona Paula, Goa 403004, India

\*Corresponding author (mpm84521@gmail.com)

### **Abstract**

Profiles of periodic GPS Radiosonde ascends collected from a station at the west coast of India (Goa) during summer monsoon months (June to September) of 2009 and 2013 have been used to analyze the thermal inversion statistics at various heights and their repercussions on the regional weatheris studied. The interaction of contrasting air masses over the northern Arabian Sea often produces a two layer structure in the lower 5000 m close to the coastal stationwith warm and dusty air (Summer Shamal) occupying the space above the cool and moist Low Level Jet (LLJ) by virtue of their density differences. The warm air intrusion creates low lapse rate pockets above LLJ and modifies the gravitational stability strong enough to inhibit convection. It is observed that the inversion occurring in the lower 3000 m layer with an optimum layer thickness of 100-200 m has profound influence on the weather beneath it. We demonstrated the validity of the proposed hypothesis by analyzing the collocated data from radiosonde, lidar and the rain gauge during 16<sup>th</sup> July 2013as a case study. The lidar depolarization ratio provides evidence to support the two layer structure in the lidar backscatter image. The presence of dust noticed in the two layer interface hints the intrusion of warm air that makes the atmosphere stable enough to suppress convection. The daily rainfall record of 2013 surprisingly coincides with the patterns of a regional break like situation centered at 16<sup>th</sup> July 2013 in Goa.

**Keywords:** Warm air intrusion, Low Level Jet, Two layer structure, Thermal Inversion, Monsoon

## Introduction

Indian summer monsoon is a unique weather phenomenon of the south-east Asian region that critically affects India's agriculture and economy and is considered as an important component of global climate system. Because of the ongoing modern anthropogenic activities and global warming, several inconsistencies in the Indian Summer Monsoon have been noticed, such as delayed onset of monsoon, increased numbers and duration of break spells during the monsoon period and increased frequency of abnormally high rain events causing floods (Ashfaq, et al., 2009, Goswami, et al., 2006, Kumar, et al., 2009)

The meridional oscillation of Inter Tropical Convergence Zone (ITCZ) during summer monsoon generate monsoon trough in the northern latitudes that drives the low level jet (often referred to as Findlater Jet) bringing moisture from south to the peninsular India and their variability plays a vital role in modulating the Indian Summer Monsoon (Joseph and Sijikumar, 2004). The mineral dust hotspots over the Middle-East (Fig.1a) have been shown to affect not only the monsoon precipitation over India, but it also modifies the ecosystems located far away from the source region (Vinoj et al., 2014; Johnson et al., 2003). The interaction of LLJ with the northerly Summer Shamal often make the dynamics more complex as these two air masses have contrasting characteristics (Aboobacker, et al., 2011), the former being cold and moist due to its oceanic origin and the later warm and dusty as it originate from arid regions of the Middle-East (Fig.1b). These two air masses appears to meet at 65° E in the northern Arabian Sea and by virtue of buoyancy the warm dusty Shamal wind slide over the moist and cold LLJ to form a two layer structure as it approaches the coast of Goa (Ramaswamy et al., 2017).

It has been observed that the warm air intrusion often create thermal inversions in the north western Arabian Sea that inhibit convection and precipitation thereby retaining moisture in the LLJ before it strike the western coast line. The thermal inversion in the troposphere refers to intermittent increase of temperature with height and the layer is often called inversion layer. Similar inversion and the associated stability occurring over Goa appears to inhibit vertical movement of convective clouds promoting a break like situation or a transition from active to break phase of the monsoon (regional scale) at Goa as demonstrated by Muraleedharan, et al., (2013) using the observations from Autonomous Weather Station (AWS) and GPS Vaisalaradiosonde sounding during monsoon months.

The origin of thermal inversion above LLJ is attributed to the advection of warm air from west (Abish and Mohanakumar, 2011, Nair, et al., 2004). In an earlier study, McBride and Frank (1999) had also attributed the middle and upper tropospheric drying over Arabian Sea to lateral advection

rather than subsidence emphasizing the transport of mineral aerosol and dust from the Middle East terrains.

Some of the recent studies (Hazra, et al., 2013, Lau, 2014, Vinoj, et al., 2014) have highlighted the impact of natural dust originating from Arabian territories on the Indian summer monsoon rainfall. Vinoj, et al., (2014) have provided evidences for the existence of a positive relationship between natural (mostly dust) aerosol and monsoon precipitation. Manoj, et al., (2011) also have shown the role of absorbing aerosols in modifying the large-scale circulation and moisture transport through direct radiative effect leading to transition from a break to an active condition.

In this paper we discuss the implications of warm air advection on the regional rainfall patterns as a case study to demonstrate their potential to influence the monsoon in a much wider sense.

## 2. Data and Methodology

An upper air laboratory has been set up at the CSIR-National Institute of Oceanography, Goa (15.5°N; 74°E) in 2008 by installing a GPS VaisalaRadiosonde system alongside an Autonomous Weather Station to monitor the upper atmospheric processes and surface weather. Details of the instruments and sensor specifications are given by Muraleedharan, et al., (2011). The facility has been upgraded by the installation of Micro Pulse Lidar (MPL) in July 2013 to supplement the information on the aerosol distribution in the atmospheric column. The MPL installed at the Institute has the distinction of all weather capability by means of a protection shield (air conditioned environment chamber and optical grade glass window) to provide uninterrupted data availability irrespective of seasons. This seems to be the first instrument of this kind compared to other similar instruments in the network spread over the country. TheLidar – GPS radio sonde combination is effective and well-tested in studying upper atmospheric dynamics (Brian et al., 2004).

The depolarization ratio time series derived from MPL, provides information on the vertical distribution of spherical and non-spherical particles in the lower troposphere. Most lasers in Lidar inherently produce linearly polarized radiation of light. When the light is backscattered by particles in the atmosphere, the backscattered signal is received in two channels; the plane of polarization parallel to the laser and plane of polarization perpendicular to the laser. To analyze the polarization effects of the backscatter, a quantity called the linear depolarization ratio ( $\delta$ ) is defined(Schotland, et al., 1971)in equation (1) below.

$$\delta(r) = \frac{P_{\perp}}{P_{\parallel}} \text{-----} (1)$$

Where  $P_{\perp}$  and  $P_{\parallel}$  are the backscatter intensities perpendicular and parallel to the plane of polarization of the laser. The  $\delta$  is a very useful quantity in determining the type and characteristics of aerosols and clouds.

The dynamics of the prevailing wind systems over northern latitudes and their interaction is more or less replicated in the back trajectory derived from NOAA HysplitModel (Stein et al., 2015) during 1<sup>st</sup> July 2013 (Fig.2). The mixed core of the air mass over the coast of Goa is sourced from two geographical regions of distinct characteristics. The warm and dusty air appears to be originated from the arid regions of the Middle East and the northeast African terrain often funneled along the narrow boundaries of the Red Sea and Persian Gulf while the cold and moist air mass originates from the deep oceanic region far south. The geography of the hot northern terrain allows the turbulent air to lift the mineral dust to the atmosphere and move towards south-east to meet the LLJ at 60° E and by virtue of buoyancy, slide over it and occupy the space above LLJ as it reaches the west coast (Ramaswamy et al., 2017). The oceanic branch trajectory, on the other hand, sourced back to the southern latitudes close to the Mascarene high.

The dynamics of the interaction of two contrasting air masses in the northern Arabian Sea is demonstrated by computing temperature lapse rate and virtual potential temperature anomaly during monsoon months. The temperature lapse rate is computed as the temperature (°C) drop in every 100m in the vertical. The thermal inversion in the layer often decreases the lapse rate thereby highlighting the warm air pockets in the atmospheric column. The gravitational stability of the atmosphere is best represented through examining the vertical stratification of the density field, thereby plotting the vertical profiles of virtual potential temperature (Betts, 1974, Cohen and Frank, 1989). The virtual potential temperature ( $\theta_v$ ) is on the other hand is the measure of buoyancy attained by virtue of temperature and humidity in the air mass. It is defined as the theoretical potential temperature of dry air that would have the same density as moist air and is often derived from the following equation (2).

$$\theta_v = \theta(1 + 0.61q_v - q_l) \text{-----} (2)$$

Where  $\theta$  is potential temperature,  $q_v$  is specific humidity of water vapor, and  $q_l$  is liquid water specific humidity. Here  $q_l$  is set to zero for the calculations, as it is poorly observed and tends to be small when averaged over the time and space scales studied here.

The virtual potential temperature anomaly (VPTA) is then computed by subtracting the mean VPT of the respective layers from the individual value. It virtually separates the dusty warm air and moist

cold air in the northern Arabian Sea and highlight their interaction while it meet each other at 60°E (Ramaswamy et al., 2017). This parameter is used to separate the contribution of moist and cold oceanic air mass from the warm dusty continental air in the well mixed core noticed in the lower troposphere at Goa.

### **3. Results and Discussion**

#### **3.1. Characterization of thermal inversion in the troposphere during two contrasting years.**

It was noticed from the radio sonde ascends that the thermal inversions do occur at all heights in varying intensity and thickness throughout the troposphere over Goa. An effort has been put in to analyze these inversions based on their gradient, inversion layer thickness and the percentage of occurrence to ascertain their impact on the atmospheric stability leading to convection and precipitation. We have categorized these inversion statistics to fall in five inversion layer thickness windows (<100 m; 100-200m, 200-300m, 300-500m and >500m) averaged over the entire tropospheric height taken here as 12 km. The exercise is again repeated by averaging over sub-partitioned atmospheric columns viz: <3000m, 3000-6000m, 6000-9000m, 9000-12000m to check the consistency in the percentage of occurrence of various designated inversion layer thickness as shown in Table 1. In order to gauge the impact of these inversions on the convective precipitation, two contrasting years of 2009 and 2013 have been selected to test our hypothesis. During the period of observations the year 2009 is considered as the drought year and 2013 as the higher than normal monsoon year with percentage of long time average rainfall of 78 and 106 mm respectively. The average values of temperature difference, thermal gradient and the percentage of occurrence in each window for various atmospheric columns during 2009 and 2013 are given in table 1.

It is interesting to note that the percentage of occurrence of small scale thermal inversions less than 100m thickness varies from 92% to 98% in various columns of atmosphere selected of which majority of them falls below 50m thickness. The percentage of occurrence of such inversion often higher in 2013 than 2009 displaying its insignificant role on suppressing convection in relatively unstable atmosphere as in the former case. It is, therefore, assumed that such inversions could be either due to the uncertainties associated with ascending speed and sensor response time or it is not strong enough to modify the stability criteria and hence ignored from the ensuing discussion. It is not surprising that such inversions occur more in 2013 (higher than normal monsoon year) than 2009 (drought year) defying the conventional concept of atmospheric stability thereby justifying the exclusion of such inversions (Table 1). A close examination of mean T-difference and mean T-gradient over various cases indicate that about 1°C T-difference (in the inversion layer) occurring in

100-200 m layer thickness with more periodicity appears to affect the stability of the column (Table 1). The percentage of occurrence of such inversion varies from 6% to 8% in the case of 2009 and 3% to 7% in the case of 2013 probably make the atmospheric column more stable in 2009 than in 2013, suppressing convection leading to less rainfall in Goa during 2009 compared to 2013. The percentage of occurrence of inversions with similar intensity is negligibly small in other higher windows and has insignificant effect on the atmospheric stability.

It is worth noting that the inversion does occur in the higher windows (>100m and <500m) in the lowest 6000m column especially during 2009 and such vertical spreading is not observed in 2013 precisely highlighting the direct implication of stability in suppressing convective precipitation (Table 1). However, such inversions are unlikely to be present in the upper half of the troposphere.

### **3.2. Formation of a two layer structure over Goa**

The figures of Ramaswamy et al., (2017) very clearly shows converging cores of LLJ and westerly component of the Red Sea jet (embedded in the summer shamal) on their course from 40°E to 60° E, meet each other at 60°E where the warm and dusty shamal (positive VPTA) slide over the moist LLJ (negative VPTA) by virtue of its buoyancy and forms a mixed core before arriving the Goa coast (Fig.3). The ECMWF ERA-40 gridded reanalysis data(zonal wind component) at various levels are used to construct the vertical sections across 40°E (Fig.3a), 50°E (Fig.3b), 60°E (Fig.3c) and 70°E (Fig.3d) stretching from 10°S to 30°N to demonstrate the advection of the contrasting lower tropospheric wind systems over the Arabian Sea during the summer monsoon month. The radiosonde ascends at Goa during July 2013 show a larger core of an easterly wind component spreading from 1000 m to about 6000 m often tend to misinterpret this as the core of LLJ which is otherwise occur only below 2000m(Fig.4). Two typical cases of extended core of a westerly wind component during the summer months of 2013 spreading beyond 3000m well above the expected altitude of the LLJ is discernible from the July profiles. However the humidity profile indicates sandwich of dry air between layers of humid air in the lower 10000m column precisely exhibit the presence of warm air above the LLJ (Fig.4). This two layer structure is further supported by the temperature lapse rate time series profiles derived from the radiosonde data from June to September 2013 wherein the intrusion of warm air above LLJ is spotted as pockets of low temperature lapse rate(Fig. 5). A clear demarcation of warm continental air mass from the clean oceanic air mass is visible as two discrete layers lying one above the other during the summer monsoon months.

The separation of moist/cold air mass (carried by LLJ) from the surrounding warm/dusty air (carried by summer Shamal wind) is possible by virtue of their buoyancy difference and the same is

demonstrated by superimposing Virtual Potential Temperature Anomaly (VPTA) over the zonal wind component time series profiles (Fig.6).As we know water vapor is less dense than dry air, humid air has warmer virtual potential temperature than dry air at the same pressure and temperature. Over Arabian Sea, the temperature effect dominates the moisture effect and hence negative and positive virtual potential temperature anomaly signifies moist and dry air respectively. Increasing (decreasing) potential temperature anomaly with altitude represents stable (unstable) condition of the atmosphere. The negative VPTA represents the oceanic air mass transported by the LLJ while the positive VPTA refers to the warm/dusty air carried by the summer Shamal thereby demonstrating the perfect situation of a two layer structure just above the boundary layer during monsoon months over Goa. The Lidar depolarization ratio during August 2013 reemphasizes the presence of mineral dust (ratio varies from 0.08 to 0.27) at about 2-5km with cold and moist air beneath it (Fig 7). Figure 7 explains the evolution of the two layer system. June 2013 data is not available as the Lidar was installed at the site in the first week of July 2013. As shown in the figure the depolarization ratio (mineral dust path ways) takes shape in July and become distinctly visible in August and started dissipating in September. Ramaswamy, et al., (2017) have reported the presence of mineral dust at Goa by analyzing daily wet depositcollected during the monsoon months since 2000 and found that it very closely resembles the characteristics of the dust produced at the arid terrains of Middle East and Northeast-African countries. It is, therefore, convincingly clear that a two layer structure develop in the lower troposphere due to the interaction of two contrasting air masses (warm and dusty air from north and cool and humid air from south) during monsoon months at the west coast more precisely over Goa. The significance of such two layer system and their influence on the weather below is to be ascertained.

### **3.3 Implications of the two layer structure on the regional weather - A case study.**

It has been observed from the inversion statistics that the thermal inversion with 100-200 m layer thickness observed in the first 3000m layer of the troposphere more often modify the gravitational stability to suppress the convection before the air gets saturated (before attaining dew point temperature). The temperature lapse rate superimposed by the lidar depolarization ratio highlight the intrusion of mineral dust (as a proxy to warm air) carried by the Shamal winds. The warmer and dusty Shamal often occupy the upper layer, by virtue of its density, above LLJ over Goa(Fig.8a). The presence of warm air triggers thermal inversion resulting in increased gravitational stability of the air column.The daily rainfall estimate derived from autonomous rain gauge corresponding to the period of the upper atmospheric profiles is also presented to make the discussion more meaningful (Fig 8b). It is worth noticing that the co-occurrence of mineral dust clusters (in the effective

inversion domain) in the two layer interface and the subdued/no-rainfall events at the surface unambiguously indicate the inhibition of convective precipitation.

In order to get a clue on the interrelationship of inversion and the regional weather, collocated profiles of Vaisalaradiosonde and Micro Pulse Lidar during 16<sup>th</sup> July 2013 has been taken as a case study to understand the structure of lower troposphere and their expected impact on the daily rainfall estimate. The profile of temperature in the first 1 km of the boundary layer shows a well-defined thermal inversion with layer thickness close to 100m with drastic decrease in humidity prescribe a stable atmosphere supported by the peak in the stability function (Fig. 4, inset). The presence of mineral dust at altitude as low as 500m is discernible in the lidar depolarization ratios on 16<sup>th</sup> July 2013 (Fig.8a) and is taken as a proxy for warm air intrusion that modify the stability. Although the intrusion of warm air does not show any signs of modification of lapse rate in the boundary layer in the middle of July, it did indicate the pathway opened up by virtue of buoyancy difference through the bottom 700m (Figure 6). In short, the increased gravitational stability above the convective regime (negative VPT anomaly) inhibits vertical movements of convective clouds resulting in subdued rainfall activity. The daily rainfall estimates in the monsoon months of 2013 shows a break like situation in the middle of July unambiguously explain the inter-relationship. Recently Muraleedharan, et al., (2013) reported that inversion induced stability during 2009 suppressed the convection resulting in weak troposphere-stratosphere interaction compared to the year 2010. They have demonstrated the defused (enhanced) convection in 2009 (2010) through the vertical oscillation of the zone of no divergence.

#### **4. Conclusion**

In this paper we discuss the significance of warm air advection on the regional rainfall patterns as a case study, to demonstrate their influence on the summer monsoon. The geography of the hot northern terrain allows the turbulent air(warm air) to lift the mineral dust to the atmosphere and advect towards south-east (as summer Shamal wind) to meet the LLJ at 60<sup>o</sup> E and by virtue of buoyancy, slide over it and occupy the space above LLJ, as it reaches the west coast of India (Ramaswamy, 2017). It has been observed that the warm air intrusion often creates thermal inversions that modify the gravitational stability of the atmosphere which in turn suppress convection (Muraleedharan et al., 2013). It is noticed from the Vaisalaradiosonde ascends that the thermal inversions do occur throughout the troposphere over Goa. We have categorized the inversion statistics of two contrasting summer monsoons (drought year of 2009 and wet year of 2013) in order to understand the optimum situation of inversion related dynamics that effectively suppress the convection in the lower troposphere and subsequent modification of the surface weather pattern. It is



worth noticing that the thermal inversion with 100-200 m layer thickness observed in the first 3000m layer of the troposphere is found to be effective to modify the gravitational stability and suppress the convection that often lead to subdued rainfall activity as in the case of 2009 compared to the year 2013. The drought year 2009 witnessed a very weak LLJ and hence has less interaction with the Shamal wind to build up the two layer structure. In order to have further insight into the interaction of two contrasting air masses and the subsequent dynamics and weather modification, the collocated data from radiosonde, lidar and rain gauge during the year 2013 has been analyzed as a case study.

The temperature lapse rate time series and superimposed virtual potential temperature anomaly (VPTA) over the zonal wind component time series profiles during summer months of 2013 convincingly demonstrate the two layer structure developed over Goa, due to the interaction of two contrasting air masses of oceanic and continental origin. This is re-emphasized by the depolarization ratio profiles provided by Micro Pulse Lidar (MPL) installed at the point of observation. The Temperature lapse rate (GPS radio sonde) time series superimposed by the chosen depolarization ratio (Micro Pulse Lidar) along with the daily rainfall estimate (Automatic rain gauge) depicts the co-occurrence of mineral dust clusters and subdued rainfall events. Here the mineral dust carried by the Shamal wind acts as a proxy for the warm air intrusion during the monsoon months and their implications on the atmospheric stability and convection are visible in the rainfall pattern at the surface. The collocated profiles of Vaisalaradiosonde and Micro Pulse Lidar during 16<sup>th</sup> July 2013 emphasize the inter-relationship of inversion and regional weather with a well-defined thermal inversion of layer thickness close to 100 m within the lower boundary layer, which can be attributed to the presence of dust at 500 m. This thermal inversion increases the gravitational stability and inhibits convection resulting into a break like situation during July 2013. The impact is expected to be restricted to the regional scale as it is based on observation from a single station representing 3500 sq.km area (Goa).

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## Legends to Figures

**Figure1** (a) EUMETSAT dust product satellite image of 1<sup>st</sup> July 2013 06:00 hrs UTC showing the Lower tropospheric winds at 10 m above sea level over the northern Arabian Sea and over the Middle East terrain. Summer Shamal wind brings dust (pink color) to the northern Arabian Sea. Low Level Jet (South Westerly) is also seen south of it. The figure has been downloaded from the Eumetrain web site ([http://www.eumetrain.org/eport/tsms\\_12.php?width=1920&height=1080&date=2013070106](http://www.eumetrain.org/eport/tsms_12.php?width=1920&height=1080&date=2013070106)). The winds are provided to Eumetrain by the European Centre for Medium-Range Weather Forecasts Numerical Weather Prediction (ECMWF -NWP). The Infrared channels (8.7- $\mu\text{m}$  IR; 10.8- $\mu\text{m}$  IR; 12.0- $\mu\text{m}$  IR) have been enhanced for dust detection with the color of dust varying from red for very high-level dust (quite rare), to bright magenta for low-level dust during daytime, to dark magenta for low-level dust at night. (b) Horizontal wind vectors (ERA INTERIM REANALYSIS) plotted over the Arabian Sea, Indian Subcontinent and the adjoining land masses during July 2013 are displayed. The Low Level Jet and the Shamal wind are seen interact each other.

- Figure 2** NOAA Air Resource Laboratory (ARL) HYSPLIT transport and dispersion Model from READY website (<http://www.ready.noaa.gov>). The back trajectories of the continental wind (Shamal, green line) and maritime wind (LLJ, blue) and surface wind (red) on 1<sup>st</sup> July 2013 at the West coast of India at (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC and (d) 1800 UTC are displayed
- Figure 3** Zonal wind component (m/s) (color shaded) superimposed by the virtual potential temperature anomaly ( $^{\circ}\text{K}$ , contoured) across the longitudes (a)  $40^{\circ}\text{E}$ , (b)  $50^{\circ}\text{E}$ , (c)  $60^{\circ}\text{E}$  and (d)  $70^{\circ}\text{E}$  stretching from  $10^{\circ}\text{S}$  to  $30^{\circ}\text{N}$  over Arabian Sea during the month of July 2013. (Reproduced from Ramaswamy et al., 2017).
- Figure4** Temperature, Relative Humidity, u & v component of the Wind Speed and Brunt vaiala frequency (stability function) profiles at Goa during 16 July 2013. Inset shows the sharp inversion observed within the boundary layer that invokes enhanced stability by way of sharp reduction of moisture.
- Figure5** Temperature lapse rate time series during monsoon months of the year 2013. Julian day 151 to Julian day 271 (from 1<sup>st</sup> June to 20<sup>th</sup> September) is given in the X-axis and height (m) in the Y-axis.
- Figure6** Time series profiles of zonal wind speed (shaded) super imposed with the virtual potential temperature anomaly (contours) during June – August 2013.
- Figure 7** Depolarization ratios computed from the Micro Pulse Lidar back scatter during a) July b) August and c) September 2013. The Depolarization ratio of mineral dust varies from 0.1 to 0.4.
- Figure8** (a) The temperature lapse rate (contour) time series superimposed with Lidar depolarization ratio (shade) profile of mineral dust. (b) The daily rainfall estimate (mm) time series during monsoon months. Julian days from 1<sup>st</sup> June to 30<sup>th</sup> September 2013 is given in the X-axis

**Table1.** Mean T-difference and T-gradient and the percentage of occurrence in various inversion layer thickness windows such as <100 m, 100-200 m and 200-300 m during 2009 and 2013. The values are averaged over various atmospheric columns such as 0 – 12000 m, 0 – 3000 m, 3000-6000 m , 6000 – 9000 m and 9000-12000 m.

Column (m)	Inversion layer thickness (m)	T-difference (°C)		T-gradient (°C)		% of occurrence	
		2009	2013	2009	2013	2009	2013
<12000	<100	0.161	0.162	0.005	0.005	92.4	94.44
	100-200	0.655	0.675	0.0055	0.0054	6.86	5.07
	200-300	0.779	0.581	0.0032	0.0023	0.98	0.48
	300-500	1.375	-	0.004	-	0.49	-
<3000	<100	0.156	0.191	0.0051	0.006	91.61	94.94
	100-200	0.67	0.810	0.0052	0.0064	7.74	5.06
	200-300	0.704	-	0.0031	-	1.93	-
	300-500	0.75	-	0.0025	-	0.65	-
3000-6000	<100	0.168	0.1538	0.0048	0.0047	92.4	92.07
	100-200	0.963	0.599	0.0077	0.0047	6.32	6.71
	200-300	1	0.581	0.0035	0.0023	0.633	1.22
	300-500	2	-	0.0058	-	0.633	-
6000-9000	<100	0.161	0.145	0.005	0.0044	92.68	97.30
	100-200	0.4632	0.5538	0.0038	0.0052	7.31	2.70
9000-12000	<100	0.125	0.084	0.004	0.0038	100	100

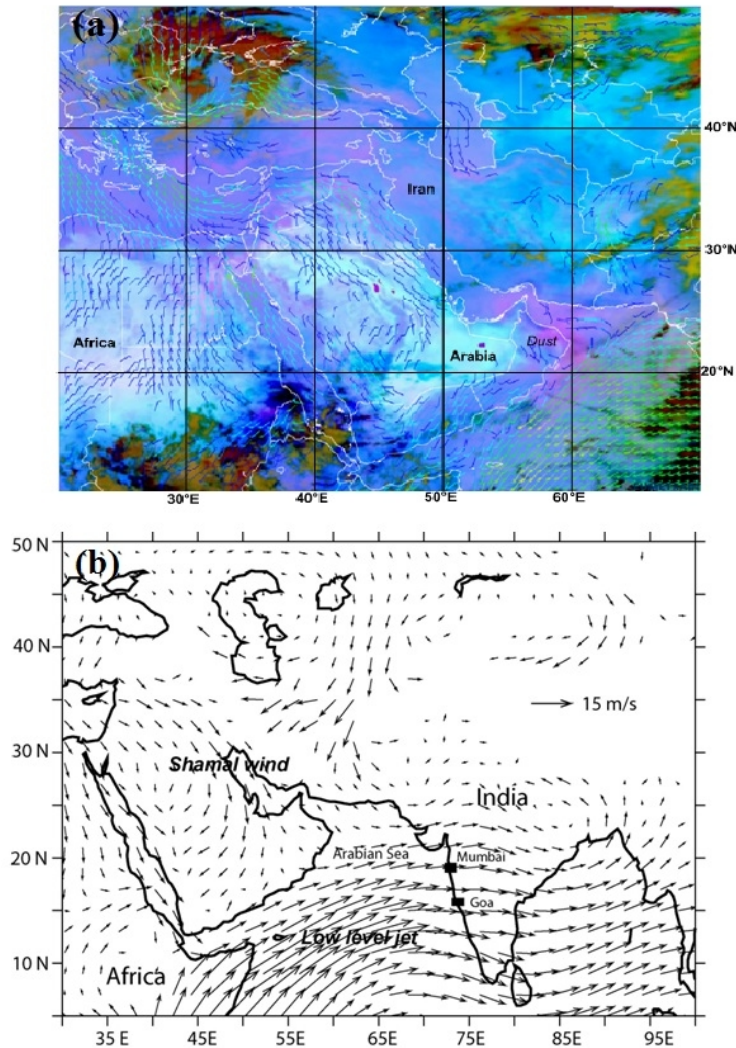


Figure 1. (a) EUMETSAT dust product satellite image of 1<sup>st</sup> July 2013 06:00 hrs UTC showing the Lower tropospheric winds at 10 m above sea level over the northern Arabian Sea and over the Middle East terrain. Summer Shamal wind brings dust (pink color) to the northern Arabian Sea. Low Level Jet (South Westerly) is also seen south of it. The figure has been downloaded from the Eumetrain web site ([http://www.eumetrain.org/eport/tsms\\_12.php?width=1920&height=1080&date=2013070106](http://www.eumetrain.org/eport/tsms_12.php?width=1920&height=1080&date=2013070106)). The winds are provided to Eumetrain by the European Centre for Medium-Range Weather Forecasts Numerical Weather Prediction (ECMWF -NWP). The Infrared channels (8.7- $\mu\text{m}$  IR; 10.8- $\mu\text{m}$  IR; 12.0- $\mu\text{m}$  IR) have been enhanced for dust detection with the color of dust varying from red for very high-level dust (quite rare), to bright magenta for low-level dust during daytime, to dark magenta for low-level dust at night. (b) Horizontal wind vectors (ERA INTERIM REANALYSIS) plotted over the Arabian Sea, Indian Subcontinent and the adjoining land masses during July 2013 are displayed. The Low Level Jet and the Shamal wind are seen interact each other.

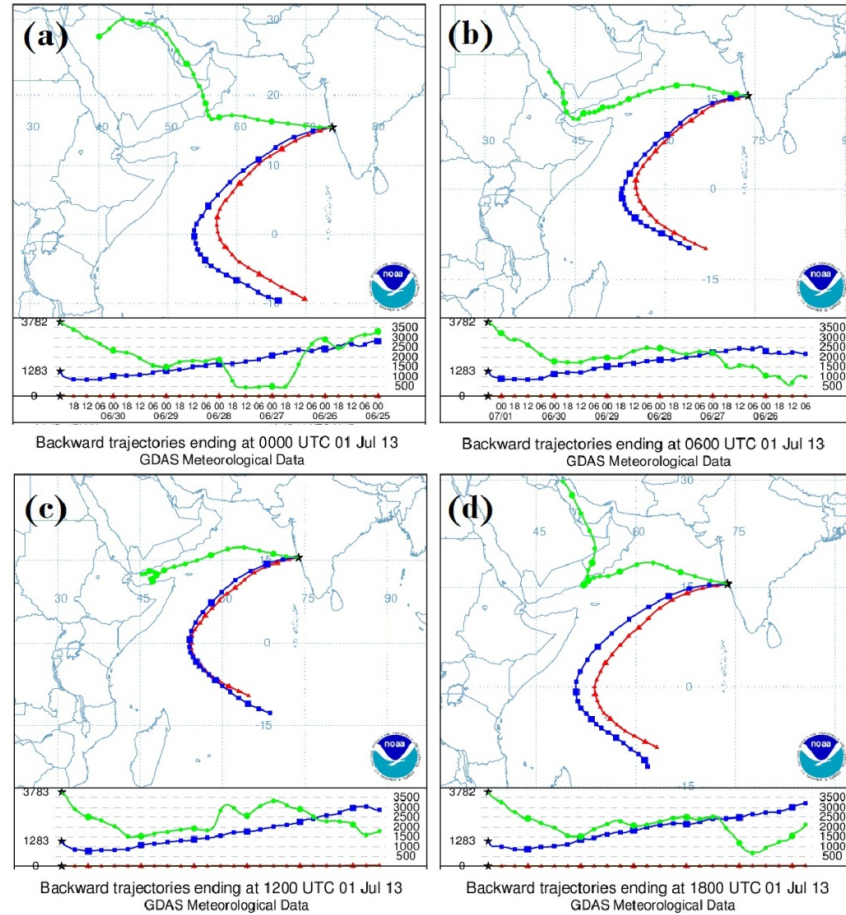


Figure 2. NOAA Air Resource Laboratory (ARL) HYSPLIT transport and dispersion Model from READY website (<http://www.ready.noaa.gov>) (Rolph et al., 2017). The back trajectories of the Continental (Shamal) wind (green line) and maritime winds (LLJ) (wind core (blue) and surface wind (Red)) on 1<sup>st</sup> July 2013 at the West coast of India at (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC and (d) 1800 UTC are displayed.

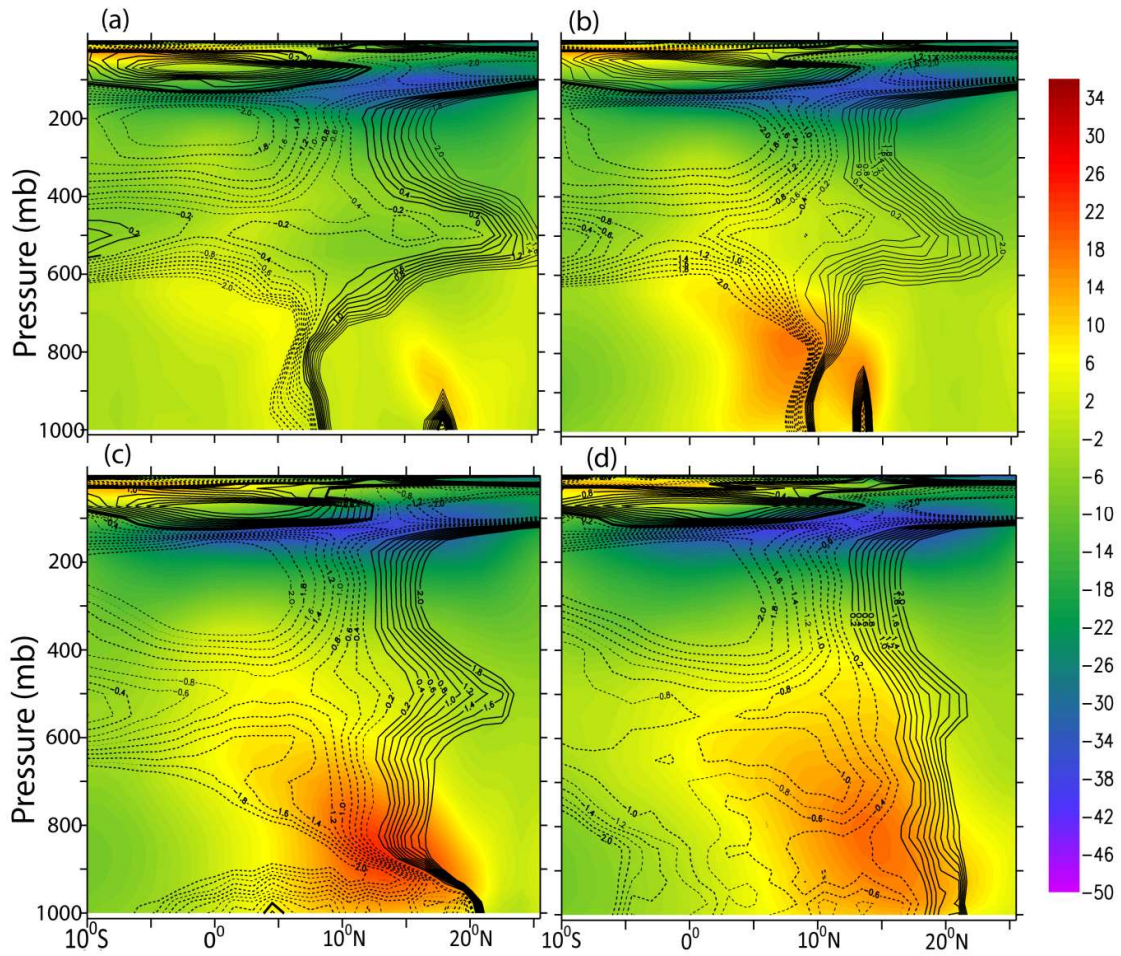


Figure 3. Zonal wind component (m/s) (color shaded) superimposed by the virtual potential temperature anomaly ( $^{\circ}\text{K}$ , contoured) across the longitudes (a)  $40^{\circ}\text{E}$ , (b)  $50^{\circ}\text{E}$ , (c)  $60^{\circ}\text{E}$  and (d)  $70^{\circ}\text{E}$  stretching from  $10^{\circ}\text{S}$  to  $30^{\circ}\text{N}$  over Arabian Sea during July 2013 (monthly average). (Reproduced from Ramaswamy et al., 2017).



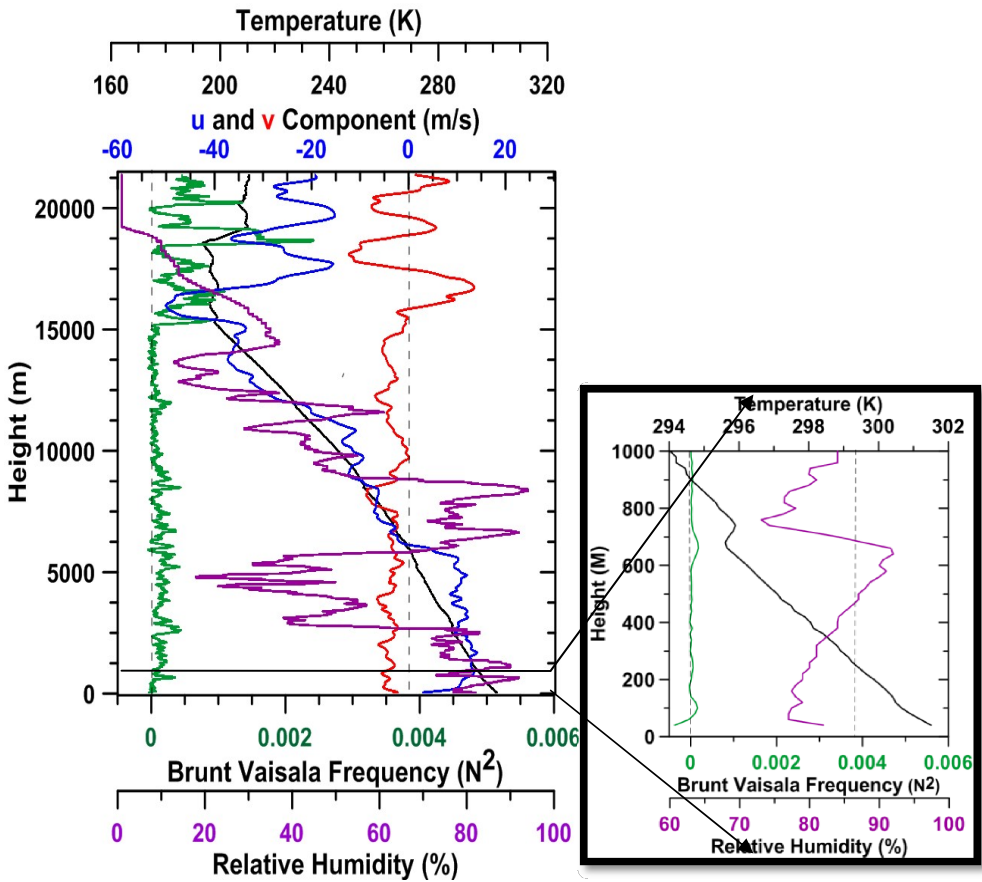


Figure 4. Temperature, Relative Humidity, u & v component of the Wind Speed and Brunt Vaisala frequency (stability function) profiles at Goa during 16 July 2013. Inset shows the sharp inversion observed within the boundary layer that invokes enhanced stability by way of sharp reduction of moisture.

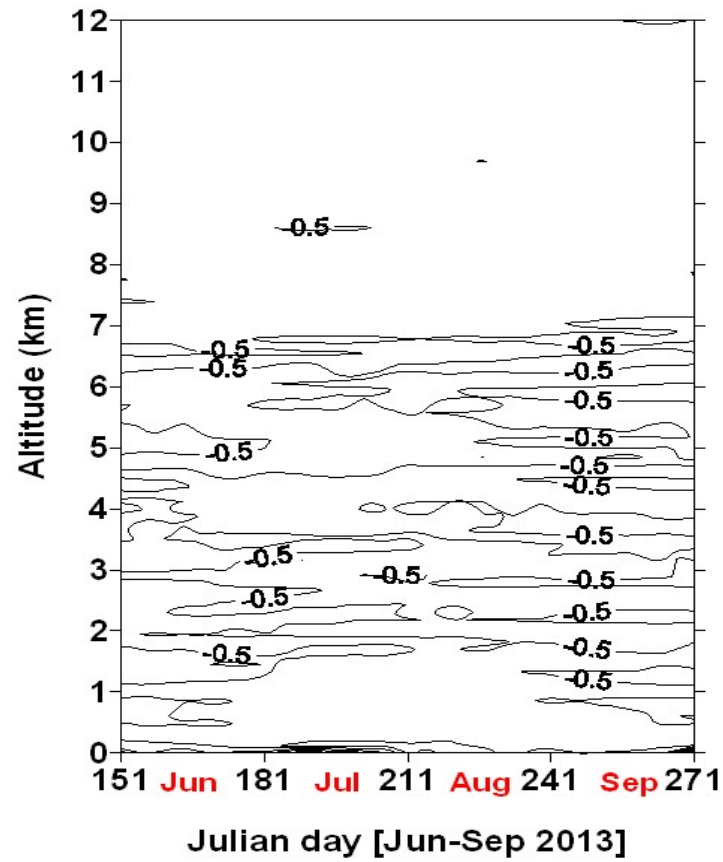


Figure 5. Temperature lapse rate time series during monsoon months of the year 2013. Julian day 151 to Julian day 271 (from 1<sup>st</sup> June to 30<sup>th</sup> September) is given in the X-axis and height (km) in the Y-axis.

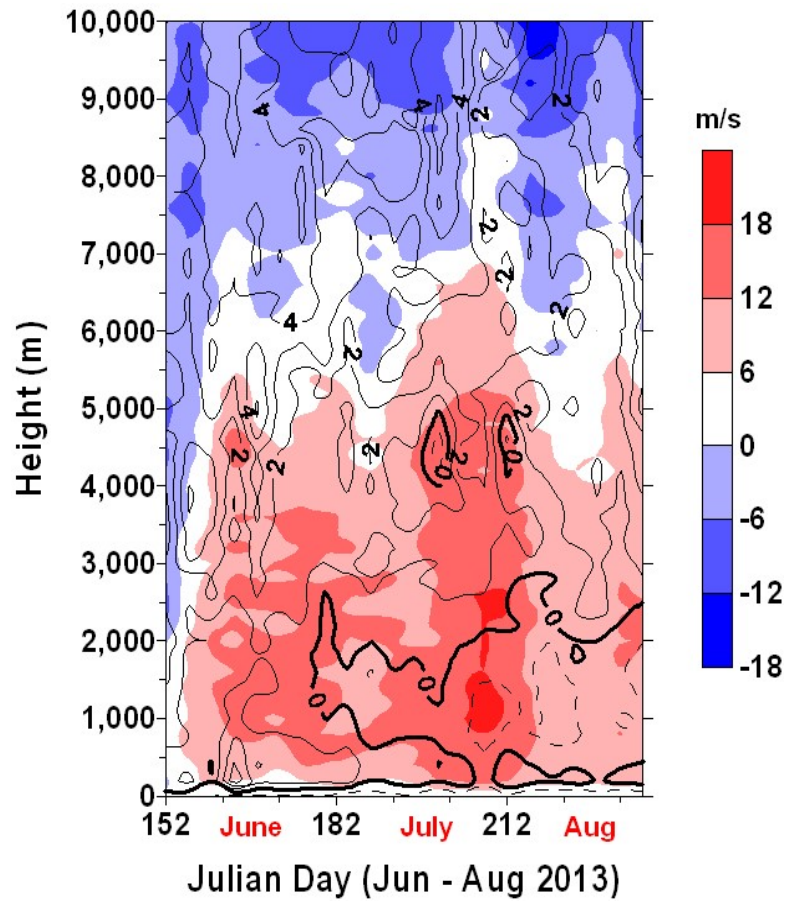


Figure.6. Time series profiles of zonal wind speed (shaded) super imposed with the virtual potential temperature anomaly (contours) during June – August 2013.

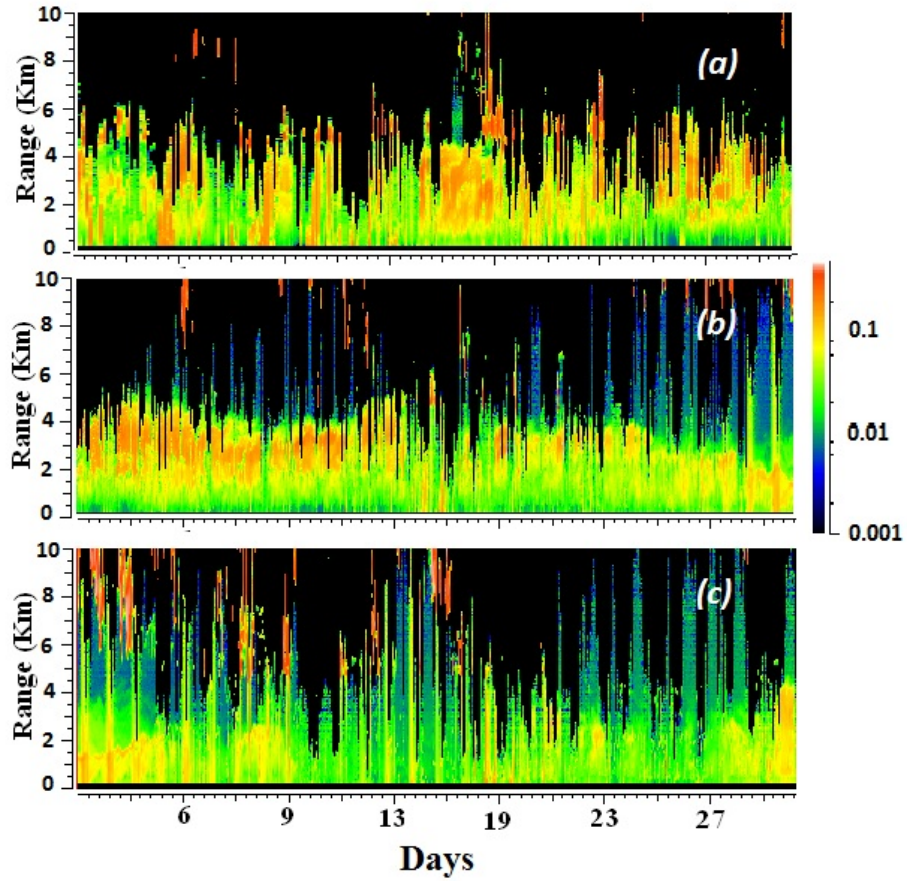


Figure 7. Depolarization ratio computed from the Micro Pulse Lidar back scatter during a) July b) August and c) September 2013. The Depolarization ratio of mineral dust varies from 0.1 to 0.4.

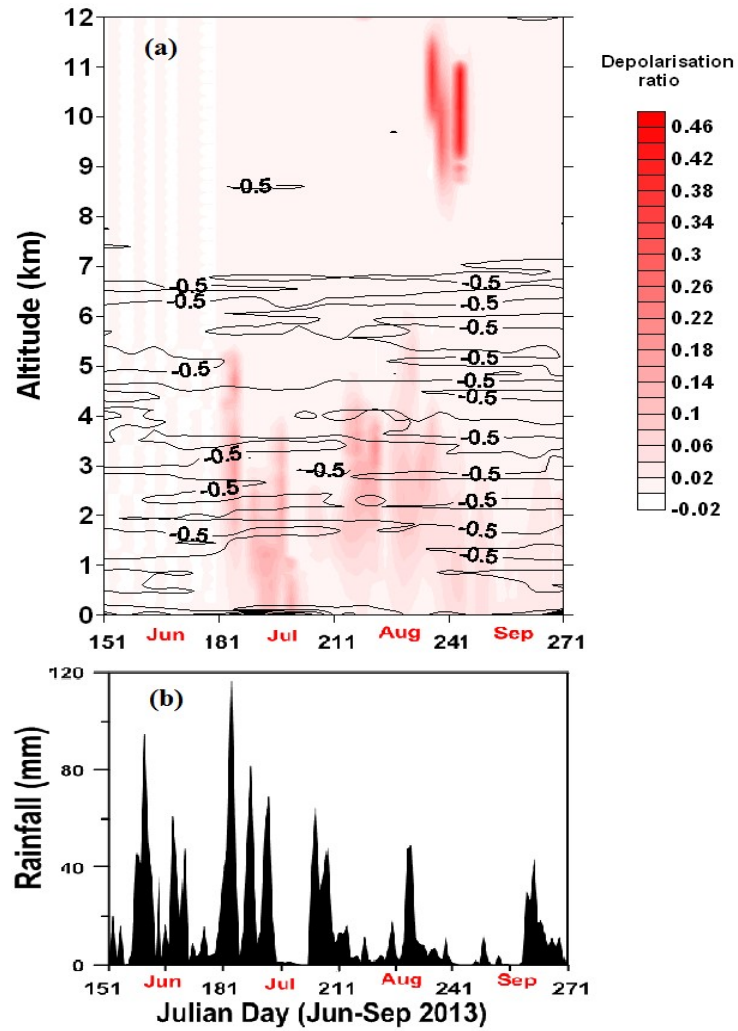


Figure8. (a) The temperature lapse rate (contour) time series superimposed with Lidar depolarization ratio (shade) profile of mineral dust. (b) The daily rainfall estimate (mm) time series during monsoon months. Julian days from 1<sup>st</sup> June to 30<sup>th</sup> September 2013 is given in the X-axis