Atmospheric stability estimation using radio occultation data over India and surrounding region

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The paper presents analysis of occurrence and intensity of rainfall with the lifted index (LI), total precipitable water (TPW), average relative humidity (ARH) and average refractivity (RI) derived from radio occultation (RO) data. Constellation Observing System has been used for meteorology, ionosphere and climate (COSMIC) refraction index 1-d variational assimilation retrievals of pressure, temperature and water vapour pressure during May-August 2007 over India and the surrounding region. The results mainly indicate that RO data can be a sensitive measure of rainfall. LI, TPW and ARH together are linked to give 90% probability of occurrence of rainfall events. Almost similar probability of rainfall occurrence and its intensity is captured when RI is used in place of LI. The results emphasize that RO average refractivity (above a certain threshold) is a measure of instability of the atmosphere and can be used as stability index instead of LI. RI in combination with moisture indices is able to give potential signature of rainfall occurrence and its intensity.

Keywords: Radio occultation data, Atmospheric stability indices, Refractivity index, Rainfall intensity

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1 Introduction

The radio occultation (RO) technique provides atmospheric refractivity profile which in turn is related to temperature, pressure and water vapour pressure. The RO method for obtaining atmospheric sounding is summarized by Kursinski et al. 1. The radio occultation technique gives very good estimation of water vapour in the atmosphere 2-6. The currently operational RO mission COSMIC gives around 1500-2000 profiles of temperature, humidity, and pressure per day distributed over the globe 7. How useful are these profiles? It is shown that assimilating radio occultation refractivity in numerical weather prediction models improved the weather forecasts significantly 8-17. One can see the impact of radio occultation derived temperature and humidity profiles using atmospheric stability and moisture indices. Currently operational mission COSMIC is able to give profiles down to ~ 2 km or less from the surface. Major global weather prediction centers, including European Centre for Medium-Range Weather Forecast (ECMWF), National Centre for Environmental Prediction (NCEP), UK Met Office and Meteo France are using COSMIC data for their operations 18-20. One can easily calculate average refractivity; atmospheric stability indices like lifted index; and moisture parameters like column precipitable water, average relative humidity, etc. and compare with daily rainfall estimates. Such a study may indicate short term forecast potential for rainfall from radio occultation refractivity and derived temperature and humidity profiles. Forthcoming Indian missions, Megha-Tropiques and Oceansat-2, are scheduled to have global positioning system radio occultation (GPS RO) receivers. Megha-Tropiques is a cooperative experimental mission of ISRO and CNES, the space agencies of India and France. The ISRO mission Ocean Sat-2 would be the first mission in India that will embark Radio Occultation Sounder of Atmosphere (ROSA). ROSA is a space instrument, which uses the RO technique to provide highly accurate measurements of the atmospheric refractivity. Thus, the main focus of the present study is how RO refractivity can be used as an indicator of atmospheric instability. In the present study, stability and moisture parameters are observed from COSMIC refractivity and derived temperature and humidity profiles over India and the surrounding region during May-August 2007. These parameters have been analyzed with collocated three hourly rainfall estimates from the Tropical Rainfall Measurement Mission (TRMM) 21-22 and found that stability and
moisture parameters can be associated with different degrees of probability of rainfall. The results are concluded with the importance of atmospheric refractivity and moisture parameters for the prediction of rainfall occurrence.

2 Data and methodology

In the present study, COSMIC radio occultation refractivity and derived temperature and humidity profiles of India and surrounding regions during May-August 2007 have been used (http://tacc.cwb.gov.tw). The geographic distribution of the tangent points of occultation events used in the present study is shown in Fig. 1. Collocated three hourly rain rate estimates are obtained from TRMM Online Visualization and Analysis System (TOVAS) website of NASA (http://lake.nascom.nasa.gov/tovas).

Stability refers to the tendency of the atmosphere to either resist or enhance small-scale vertical displacement due to buoyancy forces arising from temperature difference between ambient air and displaced parcel. Stability influences vertically all weather phenomena and its assessment is an integral part of operational forecasting. Many indices are known that represent stability as a numerical field. These mainly depend upon the temperature difference between two or more levels in the troposphere to assess the potential for convection based on a set of empirical threshold values. Among presently existing stability indices, lifted index (LI) is an index which accounts other effect such as parcel lift. Lifted index (LI), total precipitable water (TPW), and average relative humidity (ARH) indices describe the thermodynamic state of the atmosphere, and help to identify the pre-convective state of the atmosphere. Traditionally, these indices are calculated from temperature, humidity sounding by the radio sonde. Nowadays, LI, TPW and relative humidity can also be calculated from presently operational radio sonde measurements. But radio occultation is a limb sounding technique that provides integral information about the refractivity field along the line of sight, which is totally different from the point measurement of other sounders data.

Currently COSMIC is using 1-d variational assimilation technique for retrieval of pressure (P), temperature (T) and water vapour pressure (e) from radio occultation refractivity. The lifted index, total precipitable water and average relative humidity have been calculated by using these temperature and humidity profiles. In addition to stability and moisture parameters, the average refractivity is also calculated, termed as average refractivity index (RI), which is used as a new index for the determination of

Fig. 1 — Locations of 1623 COSMIC 1-d var temperature and humidity profiles for May-June 2007 used in the study
atmospheric instability. The importance of RI stability index is that it is directly calculated from the refractivity. This signifies that RO refractivity itself is able to give some degree of probability of rainfall without retrieving temperature, pressure and water vapour pressure. All the above mentioned indices are calculated from 950 hPa to the water vapour point height which is defined as the height below tropopause when dry temperature reaches ~230°C. This is because even if the atmosphere is saturated at temperature of 250°C or lower, the resulting water vapour do not affect the dry retrieval and hence dry temperatures may be approximated as actual temperature within 2°C (ref. 28).

LI is defined as the difference in temperature of an air parcel would have when lifted from a lower level (close to the surface) adiabatically until lifting condensation level (LCL), moist adiabatically from LCL to 500 hPa level and the environmental temperature at 500 hPa. The more negative the value of LI, better suited is the surrounding environment for convection. LI is a function both of low-level heat and moisture content and static stability of lower half of the atmosphere. Lifted index depends on the properties of the particular air parcel that was used.

In this study, the parcel is raised from 950 hPa level. In other words, those COSMIC profiles have been taken which reach 950 hPa or lower.

Initially, the height at which saturation just occur, i.e. LCL is calculated from Eq. (1):

$$LCL = (SP^* ((PT + 273.16) / ST)^{3.5}) / 1000 \quad \ldots (1)$$

where, $SP =$ surface pressure (hPa); $ST =$ surface temperature (K); and $PT =$ parcel temperature (°C).

The parcel temperature ($PT$) is calculated from Eq. (2):

$$PT = (1/(1/(SDP-56)+log(ST/SDP)/800))+56) \quad \ldots (2)$$

where, $SDP =$ surface dew point (here 950 hPa dew point).

$$SDP=[1 - \frac{R}{L_v} \ln \left( \frac{e}{e_o} \right)]^{-1} \quad \ldots (3)$$

where, $e_o = 0.611$ Kpa; $e =$ water vapour pressure at 950hPa; $T_o = 273°K$; and $\frac{R}{L_v} = 0.0001844K^{-1}$

In the present study, surface is approximated by 950 hPa level. It has been noted that surface temperature and water vapour do not practically represent the actual parcel though it is a good approximation. By taking 950 hPa level, one may actually be underestimating the stability indices, as the amount of moisture at 950 hPa would be comparatively less than the one present at the surface but in general, the tendency is to remain same as 950 hPa, which is well within the boundary layer. Scatter plot of lifted index for a parcel originating from 950 hPa and 1000 hPa indicates that there is a linear scaling especially when lifted index is negative (Fig. 2). Thus, in general, lifted index calculated for a parcel originating from 950 hPa is as good an indicator of atmospheric instability as the lifted index calculated for a parcel originating from 1000 hPa.

Then lifted index is found by comparing the temperature of a parcel of air raised from the 950 hPa to the 500 hPa level to that of the actual temperature at 500 hPa, i.e.

$$LI = T (500 \text{ mb envir}) - T (500 \text{ mb parcel}) \quad \ldots (4)$$

The LI will be made less stable by increasing the surface dew point, increasing the surface temperature and/or decreasing the 500 hPa temperature. If the parcel temperature is warmer than the environmental temperature, then the lifted index is negative and the troposphere is unstable relative to surface (or lower level within the boundary layer) based convection.

![Fig. 2 — Scatter plot of lifted index (LI) for a parcel originating from 950 hPa and 1000 hPa](image-url)
If the entire vapour, liquid and solid water within a column of air in the atmosphere were to precipitate out, the resulting depth of water on a square meter area is called precipitable water vapour. Total precipitable water (TPW) represents the total latent heat available in the column from the vapour, and it has the potential to provide a powerful constraint to numerical weather prediction model [1] and weather analysis. The integrated precipitable water is determined from the 950 hPa to water vapour point height level and is calculated by the Eq. (5):

$$TPW = \int_{p_1}^{p_2} \frac{q}{g} dp$$  \hspace{1cm} \ldots (5)$$

where, $q$ is the mixing ratio (kg/Kg); $g = 9.8$ ms$^{-2}$ is gravitational acceleration; $P$ is pressure (P); $p_1 = 950$ hPa; and $p_2 = $ water vapour point height level.

Along with these parameters, the average relative humidity (ARH) is also calculated between 950 hPa and water vapour point. The water vapour is a lighter gas than air at the same temperature so the humid air will tend to rise by natural convection. This mechanism is behind the thunderstorms formation and other weather phenomenon. Thus, the measure of relative humidity is an indicator of the likelihood of precipitation, dew or fog. The higher the tropospheric relative humidity, the warmer is the equilibrium temperature of the troposphere and more chance of precipitation [2]. It is also known that higher relative humidity in mid and upper troposphere is observed during active phase of the monsoon and is known to increase precipitation efficiency of clouds.

3 Results and discussion

The stability and moisture indices govern the state of the atmosphere on the synoptic scale. They also provide an initial assessment of the potential for convection. The spatial average time series of rain rate with the calculated value of LI, TPW, ARH and RI of the Indian and surrounding region during 3-7 May 2007 is shown in Fig. 3. The tangent point locations of RO data used for the calculation of moisture and stability indices during this period is shown in Fig. 4. From the figure, it is clear that the occurrences of rainfall events are generally associated with high values of ARH, TPW, RI and negative values of LI. During this period, rainy events increase when RI is greater than a threshold of 175. Thus the higher values of RI also indicate instability in atmosphere along with above calculated parameters. During total period, no rain is observed when LI is positive. The occurrence of rain and its intensity is mainly associated when atmosphere is almost completely saturated as indicated by average relative humidity values. During 3-5 May, the peak of rain is observed when ARH is greater than 85%. On 6 May, less intensity of rainfall is observed in spite of negative LI and high values of TPW and RI. This is because of low value of ARH (75%). Thus, along with LI, RI, and TPW, the ARH is able to give the intensity of rainfall. These observations reflect that LI alone is not sufficient to indicate occurrence of rainfall, the other two parameters, i.e. TPW and ARH should also be considered simultaneously.

The scatter plots of rain rate with LI (calculated by taking initial parcel properties at 950 hPa), LI (calculated by taking initial parcel properties at 1000 hPa), TPW, ARH and RI for the entire period of May-August 2007 are shown in Figs (5-9), respectively. From Fig. 5, it is observed that the maximum rain occurred (during the above mentioned period) when LI is negative. Also, the probability of occurrence of high rain increases with decrease in the LI values in most of the cases. Some rain spikes were also observed at positive values of LI. Since, the period of study is the Indian summer monsoon, LI is also calculated for a parcel lifting from 1000 hPa. For this, only those RO profiles are used which reached at 1000 hPa. The scatter plot of calculated LI with rain is shown in Fig. 6. From the figure, it is clear that trend of occurrence of rainfall with LI is similar as shown in Fig. 5. Here, also the maximum rainfall is observed when LI is negative.

The occurrence of rainfall increases with the high value of TPW as shown in Fig. 7. The maximum rain observed when TPW lies between 40 to 60 mm. In most of the cases, the intensity of rain rate shows the positive correlation with the TPW, i.e. the intensity of rain rate increases with the increase in the value of TPW. Here, also some rainfall is observed at low value of TPW but these rainfalls are of very low intensity as observed from the figure. The corresponding trend of rain rate with average relative humidity is shown in Fig. 8. It is clearly seen from the figure that the occurrences of rain increase with the increase of ARH value. The maximum intensity of rain occurred when ARH value is greater than 75%. The peak of rainfall, i.e. the rain intensity can be directly correlated with the average relative humidity in atmosphere.
Figure 3 — Time series of rain rate (mm hr\(^{-1}\)), precipitable water, average relative humidity and lifted index averaged over the region (30°E-110°E and 10°S-35°N). Rainfall is taken at only those locations where collocated COSMIC 1-d var temperature and humidity profile is available.

Figure 4 — Tangent point locations of the RO profiles used during 3-7 May 2007.

Figure 9 shows the trend between the rain rate estimates and the average value of refractivity (RI) between 950 hPa and water vapour point. From the scatter plot, it is observed that RO average refractivity is also showing the good agreement with intensity and occurrence of rainfall. The high value of average refractivity is the signature of rainfall occurrence and its intensity. During this period, the maximum rain occurred when average refractivity is greater than 175. The intensity of the rain rate also increases with the increase of average refractivity. The main reason
for this is that the water vapour height is at a higher level in a humid troposphere as compared to relatively dry troposphere. Thus, higher average refractivity is indicative of more moisture in lower troposphere; and refractivity, being a function of pressure, temperature and water vapour pressure, is indicative of atmospheric instability. The background atmospheric temperatures over tropical region like India being stable and less variable compared to water vapour is a potential reason behind the fact that increase in average refractivity above a certain threshold indicates increase in atmospheric instability.

The above mentioned moisture and stability indices are also calculated from GPS radio sonde profiles in order to verify the results obtained from RO derived indices. For this, Vaisala GPS radio sonde profiles recorded have been used during the second phase of Arabian Sea Monsoon Experiment (ARMEX-II) for the period March-June 2003. Here, all the mentioned indices are calculated by taking surface pressure at 950 hPa to the water vapour point height. Table 1 shows the daily rain fall recorded during June 2003 and the calculated indices. From the table, it is clear that whenever there is a rainfall recorded during this period, the LI values are negative; relative humidity value is greater than 65%; total precipitable water greater than 50 mm with the high values of RI.
The maximum rain fall recorded on 15 June 2003. On that day, the calculated ARH, TPW and RI value are maxima with negative value of LI. Similarly, on other days the behaviour of moisture and stability indices with rainfall occurrence and intensity are same as it has observed with RO observation.

From the above results obtained from RO observations and GPS radio sonde observations, it is found that RO refractivity and derived indices are efficient to pick up the occurrence as well as the intensity of rain rate events. The combination and condition statistics when applied to the calculated parameters will reveal more details about the occurrence and intensity of rain fall.

Table 2 reflects the percentage probability of occurrence and intensity of rainfall found by applying different conditions on the derived indices. When LI is negative and is less than -2 with other two parameters (TPW and ARH) varying freely, the total probability of rainfall during May - August 2007 has been found to be 45.6 and 40%, respectively. It is also observed that the probability of occurrence of rainfall greater than 2 mm hr\(^{-1}\) is very less as compared to the probability of rainfall occurrence less than 2 mm hr\(^{-1}\).

When two parameters, i.e. LI and TPW, are considered with some conditions, the probability is found to improve further as indicated in Table 1. For instance, 53% of profiles with LI less than -2 and TPW greater than 50 mm are associated with some rainfall. As well as probability of occurrence of high intensity of rain fall also increases. When all the three parameters are considered with a condition that LI less than -2, TPW greater than 40 mm and ARH greater than 90%, rainfall probability improves drastically to about 90% with probability of rain rate exceeding 2 mm hr\(^{-1}\) becoming 10%.

![Fig. 9 — Scatter plot of average refractivity during May-August 2007 with collocated daily rain rate from TRMM](image)
Table 3 reflects the percentage probability of occurrence and intensity of rainfall when LI is replaced with RI. It clearly indicates that results are almost similar as obtained from LI, TPW and ARH as shown in Table 2. When both the tables are considered and the conditions are applied to either one (LI/RI) or two (LI/RI and TPW) parameters, the better probability of rainfall occurrence is observed in case RI is used in place of LI (Table 3). The probability of rainfall greater than 2 mm hr\(^{-1}\) also shows some improvement when RI is used along with moisture parameters. Here, also the maximum probability of rainfall occurrence is found 90% when RI greater than 180, TPW greater than 40 and ARH greater than 90% (Table 3).

These results reflect the efficiency of RO data in weather analysis. The present study indicates that along with LI, TPW and ARH, RI can also be a potential parameter to measure occurrence and intensity of rainfall. In other words, results emphasize that RO average refractivity (above a certain threshold) is a measure of instability of the atmosphere and can be used as stability index instead of LI. The threshold used for the stability and moisture indices are somewhat arbitrary particular to this period and the region of study. The detailed study is required to investigate if they are region dependent.

### 4 Conclusions

The variation of rain rate with the LI, TPW, ARH and RI calculated from RO refractivity and 1-d var retrieval P, T, and e is explained during May-August 2007. The study reflects that without any additional data set, RO measurements are sensitive enough to give the signature of intensity and occurrence of rainfall. By applying some condition on the calculated parameters, the RO data gives about 90% probability of rainfall occurrence. During the study, the RI came up as a potential stability index of the atmosphere and can replace lifted index. Thus instead of LI, RI can also be used along with moisture indices to judge the atmospheric instability. Future studies should address the forecasting and nowcasting of occurrence and intensity of rainfall by using other ground and space based measurements with RO data as well as by assimilating numerical weather prediction models over the Indian region.

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