Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-195, 2016
Manuscript under review for journal Atmos. Meas. Tech.
Published: 27 July 2016

Atmospheric Measurement Techniques Discussions
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Validation of INSAT-3D sounder data with in-situ measurements and other similar satellite observations over Indian region

M. Venkat Ratnam*, A. Hemanth Kumar, and A. Jayaraman

National Atmospheric Research Laboratory, Gadanki, India

*vratnam@narl.gov.in ; Phone: +91-8585-272123; Fax: +91-8585-272018

Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-195, 2016
Manuscript under review for journal Atmos. Meas. Tech.
Published: 27 July 2016

Abstract

To date, several satellites measurements are available which can provide profiles of temperature and water vapor with reasonable accuracies. However, temporal resolution remained poor, particularly over topics, as most of them are polar orbiting. At this juncture, launch of INSAT-3D (Indian National Satellite) by the Indian Space Research Organization (ISRO) on 26 July 2013 carrying multi-spectral imager covering visible to long wave infrared region made it possible to obtain profiles of temperature and water vapor over Indian region with higher temporal and vertical resolutions and altitude coverage besides the other parameters. The initial validation of INSAT-3D data is made with the high temporal (3 h) resolution radiosonde observations launched over Gadanki (13.5°N, 79.2°E) during a special campaign and routine evening soundings obtained at 12 UTC. We also compared INSAT-3D data with the radiosonde observations obtained from 34 India Meteorological Department stations. Comparisons were also made over Indian region with data from other satellites like AIRS, MLS and SAPHIR and ERA-Interim and NCEP re-analysis datasets. INSAT-3D is able to show a better coverage over Indian region with high spatial and temporal resolutions as expected. Good correlation in temperature between INSAT-3D and in-situ measurements is noticed except in the upper troposphere and lower stratospheric region (positive bias of 2-3K). There exists mean dry bias of 10-25% in relative humidity. Similar biases are also noticed when compared to other satellites and re-analysis data sets. INSAT-3D shows large positive bias in temperature above 25^{o}N in the lower troposphere. Thus, caution is advised in using this data at those places for tropospheric studies. Finally it is concluded that temperature data from INSAT-3D is of high quality that can be directly assimilated for better forecast over Indian region.

Key words: Temperature, relative humidity, INSAT-3D, radiosonde, MLS, AIRS, reanalysis.

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1. Introduction

Temperature and water vapor play an important role in deciding the thermodynamic state of the atmosphere as they are considered as feedback parameters which alter the radiation and moist dynamics of the atmosphere. The stability of the Earth's atmosphere (troposphere and stratosphere) depends on the density of the air parcel at any particular altitude. The density of the air parcel depends on the amount of water vapor present in it and also its temperature. The water vapor is a highly varying parameter which is mainly responsible for precipitation and all other weather systems. It is the source of the latent heat which is released into the atmosphere during the cloud formation. It also dominates the structure of diabatic heating of the Earth's atmosphere (Trenberth et al., 2005; Trenberth and Stepaniak, 2003a; 2003b).These parameters vary in time and as well as in space (both vertically and horizontally) throughout the atmosphere.

Profiles of temperature (T) and relative humidity (RH) water vapor are traditionally obtained from the in-situ conventional radiosonde measurements which have high vertical resolutions and accuracies. However, they have limited spatial and temporal coverage. For this reason, the satellites are considered as the best source of information for obtaining these parameters which provide observations on a global scale and with improved temporal resolution based on the orbit in which the satellite is present. Among several satellites, Atmospheric Infrared Sounder (AIRS), Microwave Limb Sounder (MLS) and GPS Radio Occultation provide profiles of temperature and water vapor with reasonable accuracies. Recently Sounder for Atmospheric Profiling of Humidity in the Inter-tropical Regions (SAPHIR) onboard Megha Tropiques has been introduced which provides profiles of RH in the tropical latitudes (Venkat Ratnam et al., 2013). They have good spatial coverage but the temporal resolution of these satellites is poor. At this juncture launch of Indian National Satellite System (INSAT)-3D in July

2013 has gained lot of significance due to its geostationary transfer orbit which provides profiles of T and RH with high temporal resolutions, though restricted to Indian region only when compared to other satellites mentioned above. This data is expected to play important role in numerical weather prediction over Indian region. Before using this data for weather forecasting, it is essential to validate with in-situ, similar satellite and re-analysis data sets.

In this report, we discussed the features of T and RH obtained from INSAT-3D sounder. It adds a new dimension by providing continuous observations of T and RH over the Indian region and thereby useful in monitoring the Earth's weather systems continuously. In the first section we compared the broad features of T and RH obtained from INSAT-3D with the other satellite observations. It is followed by the validation of INSAT-3D data with high resolution radiosonde launched during a special campaign (Tropical Tropopause Dynamics Campaigns) (Venkat Ratnam et al., 2014) and routine evening soundings over Gadanki (13.5°N, 79.2°E), a tropical station in the southern peninsular India. We also compared this data with the India Meteorological Department (IMD) network of radiosonde consisting of 34 stations over Indian region. In this context it is worth to quote Mitra et al. (2015) where they compared INSAT-3D data obtained from January 2014 to May 2014 with 10 GPS stations of IMD. However, their work is restricted up to 100 hPa only and for initial 5 months. In the present work we extended comparisons for complete 2 years (2014 and 2015) and up to 10 hPa. Further, the comparisons are also made with other satellite observations like AIRS (Atmospheric Infrared Sounder), Microwave Limb Sounder (MLS), and SAPHIR (Sounder for Atmospheric Profiling of Humidity in the Inter-tropical Regions) and re-analysis data sets like ERA-Interim (European Center for Medium Range Weather Forecasts ECMWF), NCEP (National Center for Environmental Prediction).

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2. Database

2.1. INSAT-3D

The INSAT-3D which is considered to be the advanced version of all the other INSAT series satellites is the meteorological satellite of ISRO launched from Kourou, French Guiana as a passenger payload along with AlphaSat / InmarSatI-XL, ESA/ InmarSat by the European launch vehicle named Ariane-5 VA-214 on 26 July 2013. It was positioned at 82°E over the equator at an altitude of 35,786 km from the surface of Earth in the Geostationary Transfer Orbit (GTO) with the main objectives of monitoring the earth and ocean continuously thereby providing the data dissemination capabilities. It also provides an operational, environmental and storm warning system to protect the life and property. It carries four payloads namely the multi-spectral imager (optical radiometer) which provides the high resolution images of the mesoscale phenomena and local storms mainly in the visible band, apart from imaging the whole earth disk in the shortwave Infrared, middle Infrared, water vapor and low thermal Infrared channels. The atmospheric sounder which has 19 channels in shortwave infrared, middle infrared, long wave infrared (18) and visible (1) channel measures the irradiance and provides the profiles of T, RH and integrated ozone over the selected land mass of the Indian region every hour and whole Indian ocean every six hours as show in Table 1.

This atmospheric sounder gives profiles of T and RH at 40 pressure levels (1000, 950, 920, 850, 750, 700, 670, 620, 570, 500, 475, 430, 400, 350, 300, 250, 200, 150, 135, 115, 100, 85,70,60, 50, 30, 25, 20, 15, 10, 7, 5, 4, 3, 2, 1.5, 1, 0.5,0.2, 0.1 hPa) for every one hour at 10 km x 10 km in latitude and longitude resolutions covering 5-40°N and 60-100°E over India region. The INSAT-3D sounder provides T and RH profiles along with the total columnar ozone from the Infrared radiances obtained in different absorption bands during the clear sky conditions. The retrieval algorithm adopted for INSAT-3D sounder is same as that adopted for HIRS (High resolution Infrared radiation sounder) and GOES sounder which are mainly based on the retrieval algorithm of Hayden (1988), Ma et al. (1999) and Li et al. (2000).

2.2. Radiosonde observations

The processed and quality checked radiosonde data obtained from the Integrated Global Radiosonde Archive (Durre et al., 2006) over Indian region at different locations (0-40° N, 60-100° E) during the period 2014-2015 are obtained. The observed unexpected sharp spikes in the data are removed and the data values which are within the range ±2σ are only considered for comparison. Such stringent quality checked data obtained are utilized for comparing with the T and RH obtained from INSAT-3D. The 34 locations of the radiosonde stations over the Indian region (i.e., IMD stations) are shown in the Figure 1. The data from these IMD stations obtained at 00 UTC are only used for comparison as the 12 UTC data during this period is very sparse.

Further, high altitude resolution GPS radiosondes (Meisei RS-11 G, Japan) that were launched over Gadanki around 12 UTC are also used in the present study. Besides these routine evening radiosonde launches, the radiosondes that were launched as a part of special campaign between January 2014 and March 2014 over the same location are also utilized for comparison at sub-daily scales. The sensors used for measuring the T and RH are thermistors and carbon hygristors, respectively. The range of the T and RH measured by the sensors are -90 to +50 ° C and 1-100 % with an accuracy of 0.5 K and 5-7 %, respectively (Basha and Ratnam, 2009; Venkat Ratnam et al., 2014). During this campaign the radiosondes were launched for every 3 hours (11:30, 14:30, 17:30, 20:30, 23:30, 02:30, 05:30 and 08:30 IST) continuously for three consecutive days. The entire radiosonde datasets are interpolated to the pressure levels of INSAT-3D data.

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2.3. Other satellite observations

2.3.1. AIRS observations

AIRS is one of the payloads on the NASA Earth Observing System satellite called AQUA which is in a polar sun synchronous orbit revolving at an altitude of 705 km from the Earth's surface with an orbital period 98.99 minutes. It completes approximately 14.5 orbits per day and the separation between any two consecutive orbits near the equator is 2760 km. The partner payloads along with AIRS onboard AQUA satellite are microwave instruments AMSU and Humidity Sounder for Brazil. The satellite crosses the equator twice a day one being during the ascending node at ~13:30 UTC and the other one being during the descending node at ~01:30 UTC. It is a high spectral sounder with 2378 channels measuring the IR radiances at wavelengths in the range of 3.7–15.4 µm with a swath of 1,650 km and horizontal spatial resolution of 13.5 km at nadir (Aumann et al., 2003). We used the level 3 version 5 daily gridded data products (Susskind et al., 2006) that are obtained from the IR radiances of AIRS sounder during 2014 and 2015. The level 3 data products (AIRS V5 L3) are obtained from the level 2 swath data where the data of all the 15 orbits of the day are averaged together and the data has a latitudinal and longitudinal resolution of 1° X 1° at 24 pressure levels for T starting from 1000hPa to 1hPa and 12 levels for RH from 1000hPa to 100hPa. Note that RH data is reliable in the first 8 levels from the surface and up to 300 hPa (Waters et al., 2006).

2.3.2. MLS observations

MLS is one of the four payloads onboard NASA's EOS Aura satellite which is one among the six satellites (OCO-2, GCOM-W1, AQUA, CLOUDSAT, CALIPSO, AURA) that form the A-Train constellation. Similar to AIRS, MLS is also a polar orbiting sun synchronous satellite (AURA) which is at ~705 km, scanning its view from ground to ~90 km at 55 pressure levels with a global view covering from 82° S to 82° N by having ~15 orbits per day. It scans the Earth's atmosphere for every 25 seconds and provides 240 scans per orbit. The details regarding the MLS measurement technique, instrumentation are discussed by Waters et al. (2006). The MLS measures the thermal emission of the earth through its limb viewing geometry at microwave band centered near 118 GHz, 190 GHz, 240 GHz, 640 GHz and 2500 GHz whose retrieval algorithm can be found from Livesey et al. (2006). We made use of the Level 2 version 3 temperature and water vapor data during the period 2014 and 2015 that was downloaded from http://mirador.gsfc.nasa.gov. Note that water vapor from this instruments is more valid above 300 hPa only (Basha et al., 2013).

2.3.3. SAPHIR observations

SAPHIR is one of the four instruments onboard Megha Tropiques (MT) satellite which is moving in a circular low inclination orbit at 20° with 14 orbits per day. It provides a cross track scan of ±43° with a swath of 1705 km and resolution of 10 km at nadir. It is a passive remote sensing microwave sounder which operates at 6 channels close to 183.31 GHz (±11.0, ±6.60, ±4.30, ±2.8, ±1.2) retrieving integrated RH of the entire troposphere from brightness temperature at 1000-850 hPa, 850-700 hPa, 700-550 hPa, 550-400 hPa, 400-250 hPa and 250-100 hPa within ±30° latitudinal belt. The algorithms related to retrieval for the sounders of MT satellite are discussed by Gohil et al. (2012). This data has been validated against similar satellites and reanalysis data sets and found good except in level 1 (1000-850 hPa) (Venkat Ratnam et al., 2013). We made use of the SAPHIR data for comparison which was downloaded from www.mosdac.gov.in for the period 2014 and 2015.

2.4. Re-analysis datasets

2.4.1. ERA-Interim data

ERA-Interim is the advanced global atmospheric reanalysis which is produced by ECMWF. It provides gridded data products which include large surface parameters for every 3 hours and upper air parameters covering troposphere and stratosphere for every 6 hours starting from 1979 onwards. The data products are obtained from the model through sequential data assimilation method where the models are fed with the available observations to forecast the evolving state of the global atmosphere. The configuration and performance of the ERA-Interim reanalysis is explained clearly by Dee at al. (2011). It is even considered as the latest and most advanced global assimilation scheme which can predict the atmosphere at the nearest accuracy to what is theoretically possible (Simmons and Hollingsworth, 2002; Simmons et al., 2007). These data products are available over the entire globe at different latitude and longitude resolutions and for 37 pressure levels from 1000 hPa to 1 hPa. We have made use of 1°x1° data products of T and RH for the period 2014 and 2015.

2.4.2. NCEP/NCAR data

This data set is a joint product of National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR). Similar to ERA-Interim data this is also provides gridded data which is available from 1948 onwards. NCEP data represents the state of Earth's atmosphere by incorporating the global historical observations and the output of global numerical weather prediction (NWP) model (Kalnay et al., 1996). These data products are available all over the globe at 2.5^{o} x 2.5^{o} latitude –longitude resolution at 17 pressure levels starting from 1000 hPa to 10 hPa for temperature and 8 pressure levels for RH from 1000 hPa to 300 hPa. We made use of this data for T and RH during the period of 2014 and 2015.

3. Results and discussion

3.1. Spatial variation of T and RH over Indian region

In this section, the observations of the advanced ISRO geostationary INSAT-3D satellite sounder which provides continuous observations over land and ocean of Indian region are discussed as they are very important in weather forecasting. The continuous observations of the sounder are very much important as these observations can be introduced and combined with model output for a better forecast of the Earth's atmosphere. Before it is used for any scientific purpose, it is essential to compare / validate with other similar data sets. Figure 1 shows the spatial variation of T and RH over Indian region at 850 hPa pressure level obtained from INSAT-3D satellite on 2 May 2015 (averaged over a day). White patches show the non-availability of the data due to topography (Himalayan Mountains). Higher temperatures of about 5-6 K over the main land mass than surrounding sea can be noticed. On the contrary, very low values of RH over the land mass than surrounding ocean can be noticed.

The simultaneous observations from MLS and AIRS over the Indian region obtained around 13:30 IST (i.e., ascending node for AIRS and MLS) on the same day is considered for comparison. Spatial variation of T and RH over Indian region observed at 500 hPa pressure level from INSAT-3D, MLS and AIRS satellites on 2 May 2015 around 13:30 IST is shown in Figure 2. Spatial variation of T and RH over Indian region obtained from ERA-Interim and NCEP at the same pressure level at 06 UTC (11:30 IST) is also shown. In general, though major features in the spatial variation of T resembles among different satellites and re-analysis data sets, however, large difference in the RH is noticed. Particularly AIRS show large RH variations over Bay of Bengal (BoB) and Himalayan region when compared to other two satellites. Similar high variation in RH is also seen by ERA-Interim (Figure 2i). Very low RH values in the central India

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and toward west in all the satellite observations can be noticed. The quantitative difference between INSAT-3D and other satellite measurements and re-analysis data sets will be discussed in later sections.

3.2. Comparison between INSAT-3D and radiosonde observations at sub-daily scales

INSAT-3D sounder provides the profiles of T and RH over Indian region for almost every hour. It is desirable to compare these profiles at different timings of the day which is difficult to do with existing polar satellites. Thus, we compared the INSAT-3D profiles of T and RH with radiosonde observations obtained over Gadanki and also using IMD network of radiosondes. It is well known that the most common and widespread in-situ instruments for providing accurate profiles of T and RH are radiosondes. However, accurate measurements of RH are found to be a challenging task with the help of radiosondes in the upper troposphere and lower stratosphere where the concentration of water vapor is very low. In addition to this there exists radiation error in temperature measurements as explained by Luers and Eskridge, (1998) and Wang et al. (2003). We have used high accuracy and vertical resolution radiosonde over Gadanki that were launched for every 3 hours continuously for three consecutive days, during a special campaign called Tropical Tropopause Dynamics campaign (TTD) (Venkat Ratnam et al., 2014) conducted over Gadanki between January 2014 and March 2014. This data is used to validate the INSAT-3D measurements at sub-daily scales.

The radiosonde data obtained during the TTD campaigns are interpolated to the pressure levels of INSAT-3D for the similar hours whenever observations are available. Typical temporal variation of T and RH obtained from radiosonde launched over Gadanki during one of the TTD campaigns conducted from 27 January 2014 to 30 January 2014 is shown in Figure 3. Data obtained from INSAT-3D for similar timings are also shown in the bottom panels. White patches

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show the non-availability of the data. In general, similar diurnal variation in the T and RH between radiosonde and INSAT-3D can be noticed though the magnitude differs. Very cold temperatures (~190 K) present near the tropopause region (100 hPa) are captured well by INSAT-3D. The existence of high humidity layer at 300 hPa, persisting for more than a day, is also captured well by the INSAT-3D. The T and RH over Gadanki obtained from INSAT-3D and radiosonde are averaged over 3 days and the mean and standard deviation are shown in Figure 3(e) and 3(f), respectively. From these profiles, no significant difference in the T can be noticed but there exists underestimation in RH by INSAT-3D (assuming radiosonde as standard technique). INSAT-3D shows a dry bias of 20-35% in RH when compared to radiosonde observations. No significant day-night differences are noticed between INSAT-3D and radiosonde observations.

3.2. Comparison between INSAT-3D and radiosonde (IMD and Gadanki) observations

We also compared INSAT-3D measurements obtained during 2014 and 2015 with the radiosonde observations over the 34 IMD stations which are spread throughout the Indian region whose locations are shown in the form of filled circles in Figure 1. Besides these, the routine evening radiosonde observations launched around 12 UTC over Gadanki during 2014 and 2015 were also utilized for day-to-day comparisons. The radiosonde data of all the IMD stations are interpolated to the pressure levels of INSAT-3D for uniformity. The correlation co-efficient values obtained for T and RH between INSAT-3D and Gadanki radiosonde launched around 12 UTC and IMD radiosonde launched around 00 UTC over Indian region are obtained separately for each day during the period 2014 and 2015. The correlation values are obtained for all the levels in T whereas only up to 300 hPa in RH and is shown in Figure 4. A very high correlation (>0.8) in T between INSAT-3D and IMD /Gadanki radiosonde is observed in the lower troposphere (Figure 4a). However, correlation decreases above 700 hPa (850 hPa) between INSAT-3D and Gadanki (IMD) radiosonde. There exists consistent correlation of more than 0.6 throughout all levels with Gadanki radiosonde but drastically decreases above 250 hpa in case of IMD radiosondes. It is interesting to notice higher (lower) correlation below (above) 850 hPa between Gadanki radiosonde and INSAT-3D. However, it is quite opposite in case of IMD radiosonde for which reasons are not known. The correlation values of RH obtained between INSAT-3D and Gadanki radiosonde is always higher (greater than 0.65) throughout the profile than the correlation obtained between INSAT-3D and IMD radiosonde observations (less than 0.5) shown Figure 4b. Mitra et al. (2015) has reported similar correlations using 10 IMD stations using 5 months (January 2014- May 2014) of the data. However, their work is restricted up to 100 hPa due to frequent balloon burst of IMD radiosondes at that altitude. In the present study we report up to 10 hPa and also using complete two years of the data for Gadanki location. The observed good correlation (0.6-0.7) between INSAT-3D RH and Gadanki radiosonde RH may be attributed to the improved RH sensor used in Meisei radiosondes that were used over Gadanki.

Further, to quantity the differences between INSAT-3D and Gadanki radiosonde, we discuss the fractional difference at all levels between routine radiosondes launched around 12 UTC over Gadanki and INSAT-3D T over the same site during the period 2014 and 2015. The fractional difference of T for each day is calculated separately and then averaged over 2014 and 2015. The balloon bursting altitude of the radiosonde is also estimated for those which are utilized in estimating the fractional difference. The fractional difference of T and RH and balloon bursting altitude are shown in Figure 5. It is clear from the figure that the difference is very less in the troposphere (~0.5 K). The mean fractional difference in the troposphere is less than 0.5 K, and it is about 1 K in the upper troposphere and lower stratosphere. However, positive bias

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(INSAT-3D showing higher temperatures) of 2-3 K is noticed (shown as standard deviations) in day-to-day differences in INSAT-3D. When we segregated season wise fractional differences, higher fractional difference during monsoon season is noticed (figure not shown) mainly due to less number of matches between INSAT-3D and radiosonde due to over sky. Most striking feature to be noticed is the consistent positive bias of 1% (~2 K) in T in the upper troposphere and lower stratosphere. The mean fractional difference in RH shown in Figure 5b reveals 20-30% dry bias in INSAT-3D when compared to radiosonde. Standard deviations show dry bias of 40-60% in day-to-day comparison of RH between INSAT-3D and radiosonde. Thus, from figure 5, it is clear that INSAT-3D is able to provided T measurements with high accuracies but huge dry bias is observed in RH. Thus, caution is advised while using RH data from INSAT-3D.

3.2. Comparison between INSAT-3D and other satellite and re-analysis data

The T and RH measured from the radiances of 19 channels of INSAT-3D sounder are compared with that are obtained from other satellites like AIRS, MLS and SAPHIR (only RH) during the period 2014 and 2015. Besides the satellite observations, re-analysis datasets like ERA-Interim and NCEP are also utilized for comparing the data obtained from INSAT-3D. The T measurements obtained from AIRS, MLS, ERA-Interim are converted to a spatial resolution of 1° X 1° in latitude and longitude. The 1° X 1° gridded AIRS and MLS T measurements are interpolated to 40 pressure levels of INSAT-3D. Whereas, the INSAT-3D data is converted to a spatial resolution of 2.5° X 2.5° to compare with the T obtained from NCEP. The difference in T between INSAT-3D and AIRS and MLS are estimated for each day, whereas it is estimated for every six hours between INSAT-3D and ERA-Interim and NCEP. The zonal mean latitudinal difference of T between different satellites and re-analysis datasets is obtained for each day and then averaged for 2014 and 2015 which is shown in Figure 6. Note that the differences that are

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greater than 1K are only shown in this figure. In general, the difference in T between INSAT-3D and other satellite and reanalysis data sets lies within ± 1 K and extends to 2 K in the UTLS region. Above 25°N, INSAT-3D shows positive bias of more than 4 K up to 300 hPa compared to AIRS but up to 700 hPa with rest of the data sets. Consistent positive bias of 2-3 K in the UTLS region can be noticed in INSAT-3D particularly compared with other satellite measurements. Above 4 hPa, consistent negative bias of more than 3 K is noticed in INSAT-3D when compared to other data sets. In general, less difference between INSAT-3D and NCEP is noticed than ERA-Interim. Thus, the difference in T between INSAT-3D and other datasets is least in the lower and mid troposphere below 25°N, whereas it increases in the lower troposphere above 25°N.

The RH data obtained from AIRS, MLS, ERA-Interim are converted to a spatial resolution of 1° X 1° in latitude and longitude and then interpolated to the first 21 pressure levels of INSAT-3D. To compare the INSAT-3D RH data with NCEP RH data, the RH data obtained from INSAT-3D is converted to the actual resolution of NCEP, i.e., 2.5°X2.5° latitude and longitude grids. Note that information on RH data obtained from NCEP is present only up to 300 hPa, MLS from 300 hPa and above, whereas RH from AIRS and ERA-Interim is considered up to 100 hPa beyond which the concentration of water vapor is very low. But, the RH obtained from SAPHIR in the troposphere is measured as integrated relative humidity at certain levels as mentioned in the section 2. In order to compare the INSAT-3D RH data with SAPHIR RH, the former is converted to the pressure levels of SAPHIR. The zonal mean latitudinal difference between INSAT-3D and all other datasets is obtained as mentioned in the previous section and is presented in Figure 7. In general, INSAT-3D shows a dry bias of 5-10% in the lower and mid troposphere below 25°N when compared with AIRS (Figure 7a), ERA-Interim (Figure 7c) and

NCEP (Figure 7d) re-analysis datasets. However, it shows a dry bias of more than 10% when compared with MLS RH (Figure 7b). Note that INSAT-3D also shows a wet bias around 700 hPa with all the datasets. A high dry bias in the lower troposphere above 25˚N is observed between INSAT-3D and AIRS, ERA-Interim and NCEP, whereas the bias in the same region is less with MLS. The wet bias (~20%) between INSAT-3D and AIRS above 300 hPa is mainly due to low accuracies of AIRS at those altitudes (Waters et al., 2006). There exists a dry bias of 20% between INSAT-3D and SAPHIR in first two layers but reduced to less than 10% above (Figure 7e). In this context it is worth to quote findings of Venkat Ratnam et al. (2013) who have reported that the first layer (1000-850 hPa) of SAPHIR has large difference when compared to similar satellites. Thus, the present result of large difference between INSAT-3D and SAPHIR in the lower most layers is expected. Note that no data is there in SAPHIR above 27^{o} due to its low inclination.

4. Consistency check in T measurements of INSAT-3D in the UTLS region

From the previous section, it is clear that INSAT-3D overestimates T by 1% in the UTLS region. However, in order to check whether this positive bias is consistent or not, we compared the tropopause temperature obtained from radiosonde. The cold point tropopause temperature (CPT) which is the minimum in the temperature profile below 20 km is obtained from radiosonde and INSAT-3D for each day during 2014 and 2015 and is shown in Figure 8. Consistent positive bias of 2-3 K is seen in CPT between INSAT-3D and radiosonde as expected, however, general trends match well between the two. The CPT obtained from INSAT-3D matches well with the radiosonde observations and shows a clear annual variability with higher values during the summer monsoon months (JJA) and lower values observed in winter months (DJF). This seasonal variability of the CPT over the Indian Monsoon region during different

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seasons is consistent with that reported by Mehta et al. (2010). These results are also consistent with that reported earlier over other tropical latitudes (Newell et al., 1969; Reed and Vlcek, 1969; Reid and Gage, 1996; Seidel et al., 2000) who attributed it to the annual modulation of Hadley cell. Thus, INSAT-3D data can be effectively utilized to investigate the tropopause characteristics, however, with a known caution of overestimation of T by 2-3 K. As the data from INSAT-3D is available for almost every hour this data is very much useful to investigate Stratosphere Troposphere Exchange (STE) process occurring at sub-daily scales.

5. Summary and Conclusions

The quality of the new data product mainly the temperature and relative humidity obtained from the sounder payload onboard INSAT-3D is discussed. A detailed comparison of the data (temperature and relative humidity) obtained from INSAT-3D with the existing in-situ radiosonde measurements over the entire Indian region, other similar satellite (AIRS, MLS and SAPHIR) observations and re-analysis (ERA-Interim and NCEP) datasets has been carried out in the present study. Following are the main conclusions drawn from the study.

1. INSAT-3D provides measurements with very good spatial and temporal coverage over the Indian region when compared to any other satellites as expected.
2. INSAT-3D is able to measure the general features of temperature and relative humidity similar to the radiosonde observations even at sub-daily scales. However, magnitudes differs (underestimates) in relative humidity measured by INSAT-3D. There is no day-night difference in the temperature measurements of INSAT-3D.
3. The mean difference between INSAT-3D and radiosonde temperature in the troposphere is less than 0.5K with standard deviations of 1K. However, mean difference in RH is as high as 20-30% with standard deviations of 40-60%.

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4. The RH obtained from INSAT-3D shows high correlation values (0.6-0.7) with the Gadanki radiosonde RH than the IMD radiosonde (less than 0.5) due to improved sensor.
5. There exists consistent positive bias (~ 2-3 K) in temperature in the upper troposphere and lower stratosphere in INSAT-3D.
6. A dry bias of 10-25% in the INSAT-3D measured RH when compared to similar satellites and reanalysis data sets are noticed.
7. In general, temperature from INSAT-3D agrees well with all the other satellite measurements and reanalysis data sets below 25^{o}N, whereas a difference of ~4K in temperature above 25^{o}N is noticed. INSAT-3D shows less temperature difference around tropopause region with AIRS and ERA-Interim datasets.

It is found that there exists large difference between INSAT-3D and other datasets both in temperature and relative humidity above 25°N latitude. Thus, caution is advised in using INSAT-3D data over those locations. It is important to note that INSAT-3D shows good agreement with the conventional in-situ radiosonde observations of both Gadanki and IMD locations over the Indian region giving a sign of good reliability to use the former datasets for measuring the temperature and relative humidity spatially and temporally. Very low difference in temperature between INSAT-3D and radiosonde observations provides the scope of using the INSAT-3D data into the numerical weather models for better forecasts. However, caution is again advised while using the RH where most of the time a mean dry bias of 20-30% is noticed. Though consistent positive bias of ~2-3 K is observed in the cold point tropopause temperatures, the variability in tropopause obtained from INSAT-3D shows excellent match with the in-situ radiosonde observations during 2014 and 2015. Thus, INSAT-3D data can also be used to study the tropopause characteristics at sub-daily scales which are not possible with any existing satellites and hence Stratosphere-Troposphere Exchange processes.

Acknowledgements: The INSAT-3D data used in the present study obtianed from MOSDAC is greatly acknowldged. We thank AIRS, MLS, ERA-Interim and NCEP teams for providing data used in the present study through their ftp sites.

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Figure captions:

Figure 1. Spatial variation of (a) temperature and (b) relative humidity over Indian region at 850 hPa pressure level obtained from INSAT-3D satellite on 2 May 2015 (averaged over a day). The filled circles (magenta) in both the panels show the locations of IMD radiosonde stations selected within 0-40˚N latitude and 60-100˚E longitude (Indian region) for comparing INSAT-3D observations. White patches show the non-availability of the data.

Figure 2. Spatial variation of temperature over Indian region at 500 hPa pressure level obtained from (a) INSAT-3D, (b) MLS, (c) AIRS, (d) ERA-Interim and (e) NCEP on 2 May 2015 around 1330 IST. (f) – (j) same as (a) to (e) but for relative humidity. White patches show the non-availability of the data.

Figure 3: Temporal variation of (a) temperature and (b) relative humidity obtained from radiosonde launched over Gadanki during the TTD Campaign conducted from 27 Jan. 2014 to 30 Jan. 2014. White patches show the non-availability of the data. (c) and (d) same as (a) and (b) but observed by INSAT-3D. The mean profiles of (e) temperature and (f) relative humidity obtained from radiosonde (red) and INSAT-3D (blue). Horizontal lines indicate standard deviations.

Figure 4: Correlation coefficients obtained in (a) temperature and (b) relative humidity at different pressure levels between INSAT-3D and 12 UTC Gadanki radiosondes (red line) and 00 UTC IMD radiosondes (black line). Horizontal bars show the deviations in correlation coefficients obtained from 34 stations. Note that correlation coefficient up to 300 hPa is only obtained for relative humidity.

Figure 5: Mean difference (thick line) and standard deviation (dotted lines) observed in the temperature between INSAT-3D and radiosonde launched at around 12UTC over Gadanki

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during 2014 and 2015. The blue line in (a) represents the number of radiosondes reaching at different altitudes with top-right axis.

Figure 6: Zonal mean latitudinal difference between the INSAT-3D temperature and (a) AIRS, (b) MLS, (c) ERA-Interim and (d) NCEP temperatures observed during 2014 and 2015. The contours whose differences are within 1K are omitted.

Figure 7: Zonal mean latitudinal difference between the INSAT-3D RH and (a) AIRS RH, (b) MLS RH, (c) ERA-Interim RH, (d) NCEP RH and (e) SAPHIR RH observed during 2014 and 2015. White patches show the non-availability of the data. The dotted (thick) line contours show the negative (positive) differences between INSAT-3D and respective data sets.

Figure 8: Time series of cold point tropopause temperatures (CPT) observed over Gadanki during 2014 and 2015 by INSAT-3D (blue line) and radiosonde (red line) at 12 UTC. These are the 5-point running average of CPT.

Table caption:

Table 1: The principal absorbing gases of the Infrared radiation in the atmosphere at different channels in INSAT-3D with their central wavelengths and their purpose of retrieval.

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Table 1: The principal absorbing gases of the Infrared radiation in the atmosphere at different channels in INSAT-3D with their central wavelengths and their purpose of retrieval.

Detector	Ch. No.	Wavelength(µm)	Principal absorbing gas	Purpose
Long wave	1	14.67	CO_2	Stratosphere temperature
	2	14.31	CO_2	Tropopause temperature
	3	14.03	CO_2	Upper-level temperature
	4	13.64	CO_2	Mid-level temperature
	5	13.33	CO_2	Low level temperature
	6	12.59	Water vapor	Total precipitable water
Mid wave	7	11.98	Water vapor	Surface temperature, moisture
	8	10.99	Window	Surface temperature
	9	9.69	Ozone	Total ozone
	10	7.43	Water vapor	Low level moisture
	11	7.04	Water vapor	Mid-level moisture
	12	6.52	Water vapor	Upper level moisture
Short wave	13	4.61	N_2O	Low level temperature
	14	4.54	N_2O	Mid-level temperature
	15	4.48	CO_2	Upper level temperature
	16	4.15	CO_2	Boundary level temperature
	17	4.01	Window	Surface temperature
	18	3.79	Window	Surface temperature, moisture

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536 **Figures**

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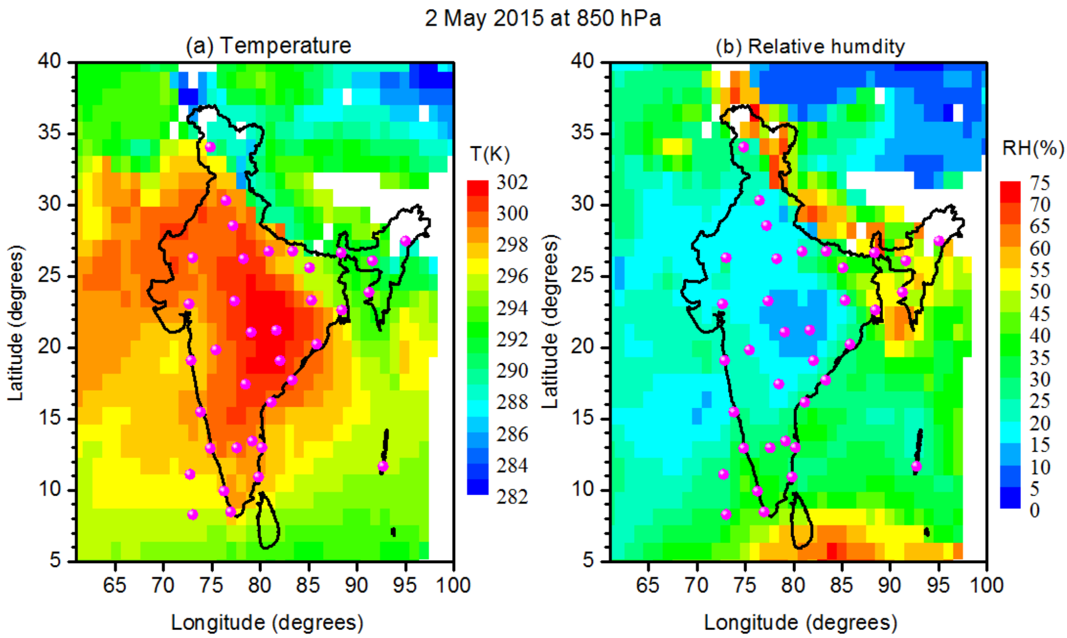

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539 **Figure 1.** Spatial variation of (a) temperature and (b) relative humidity over Indian region at 850

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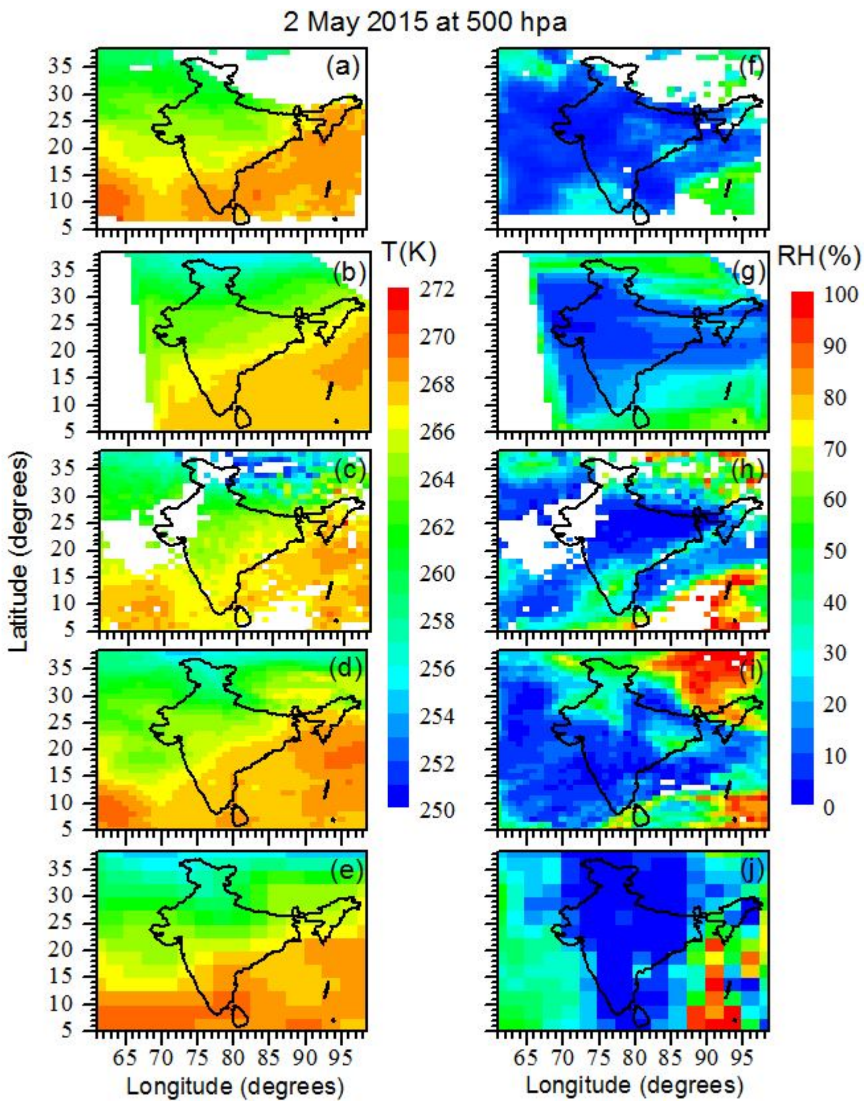

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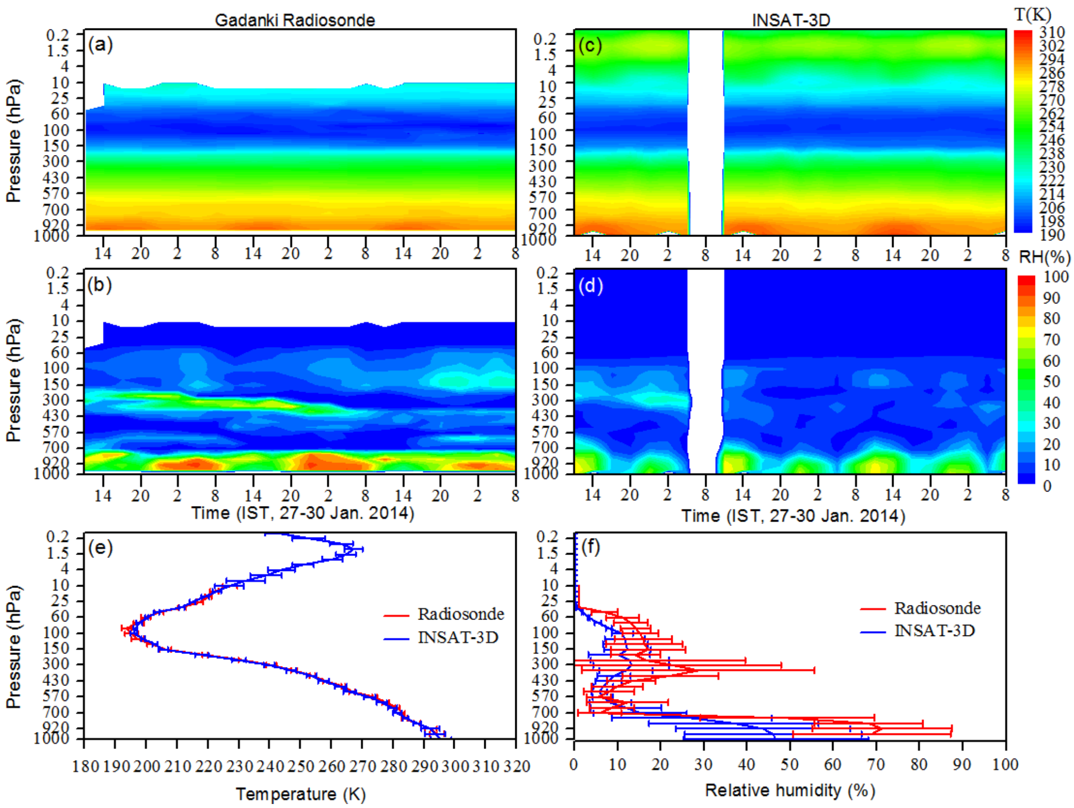

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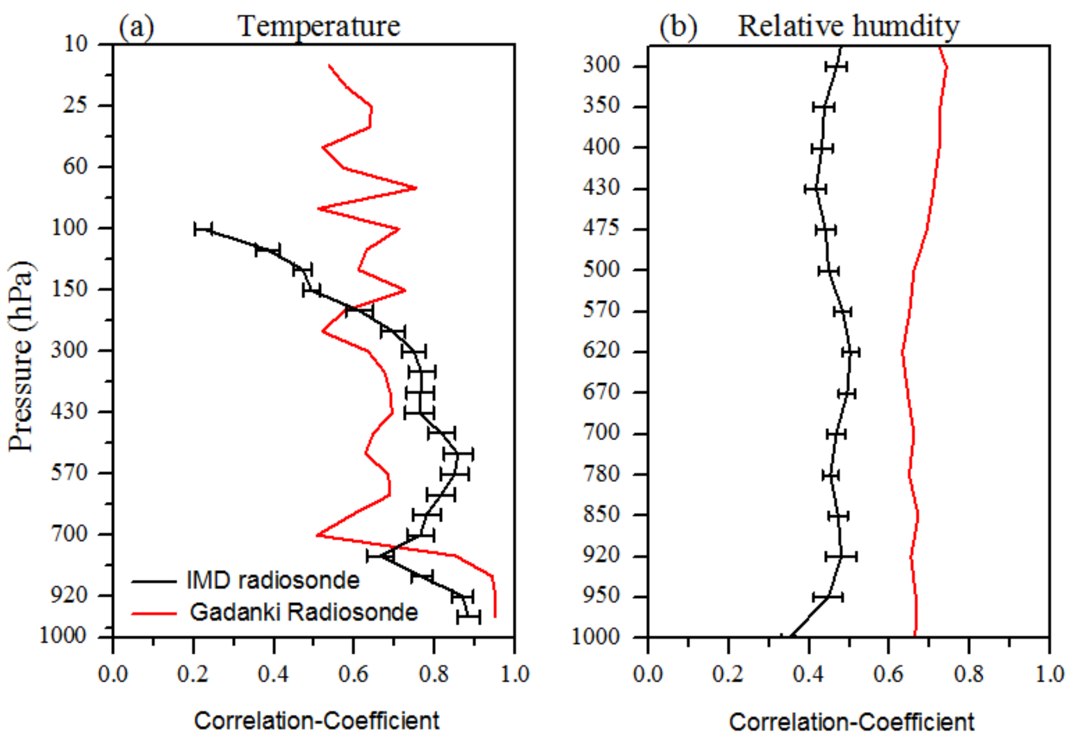

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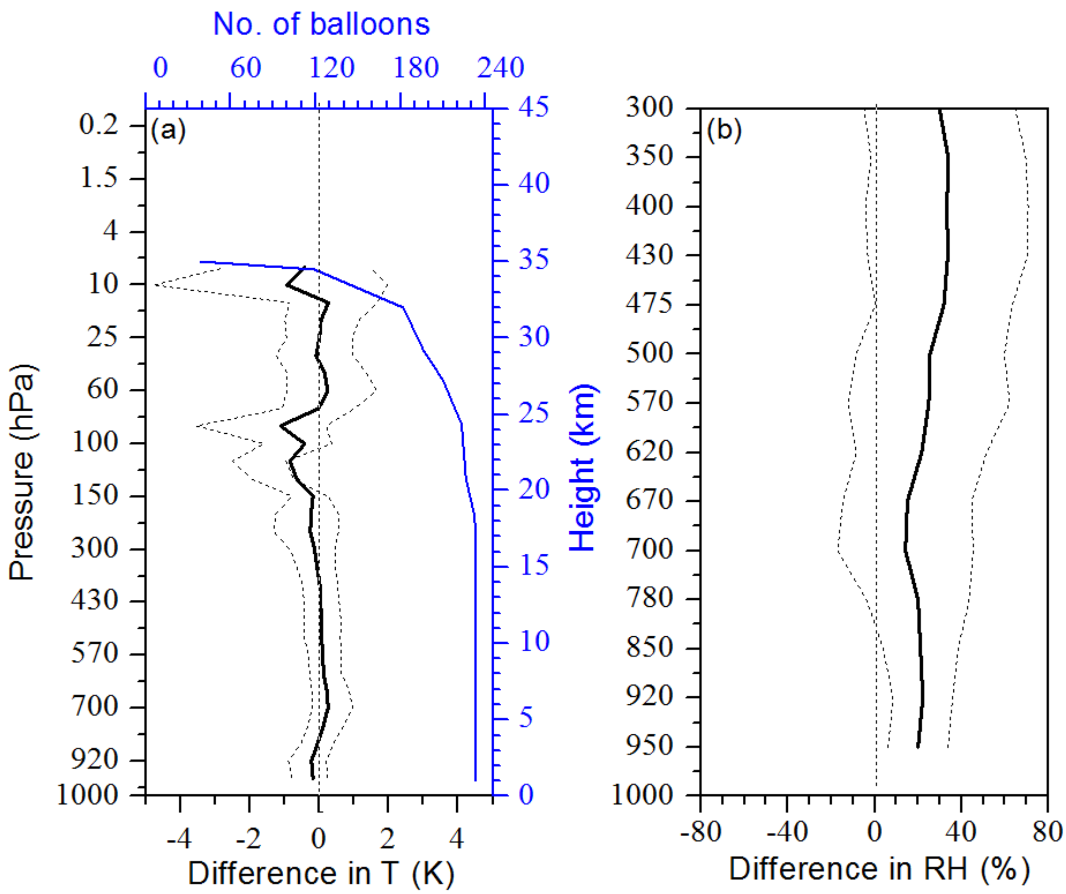

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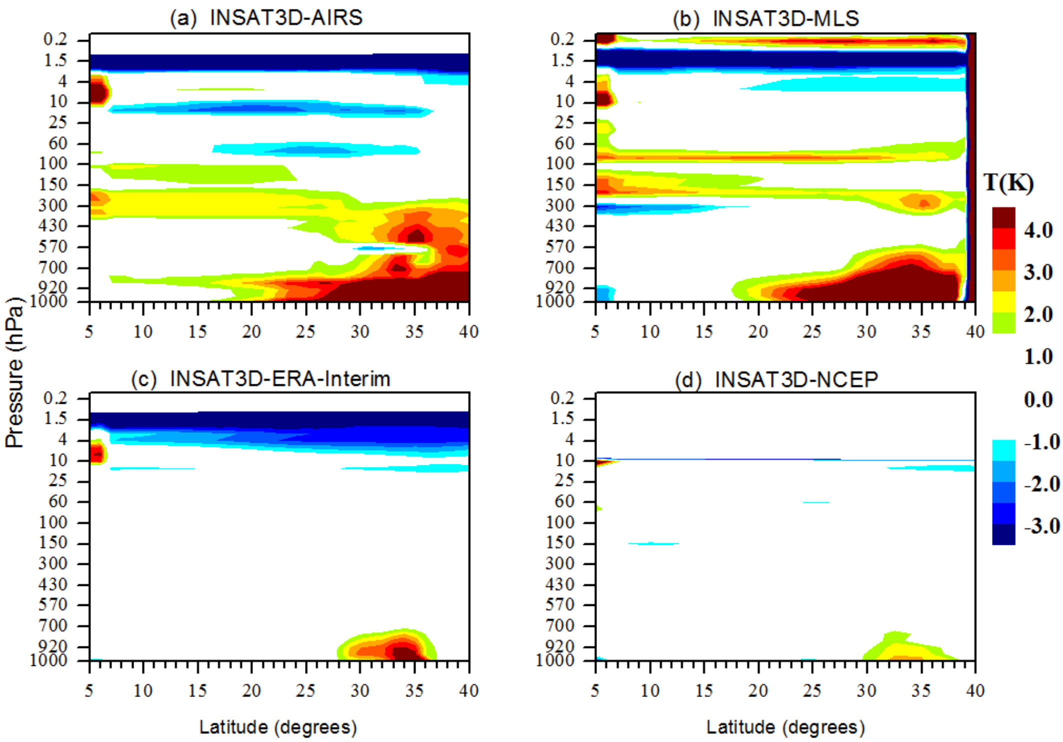

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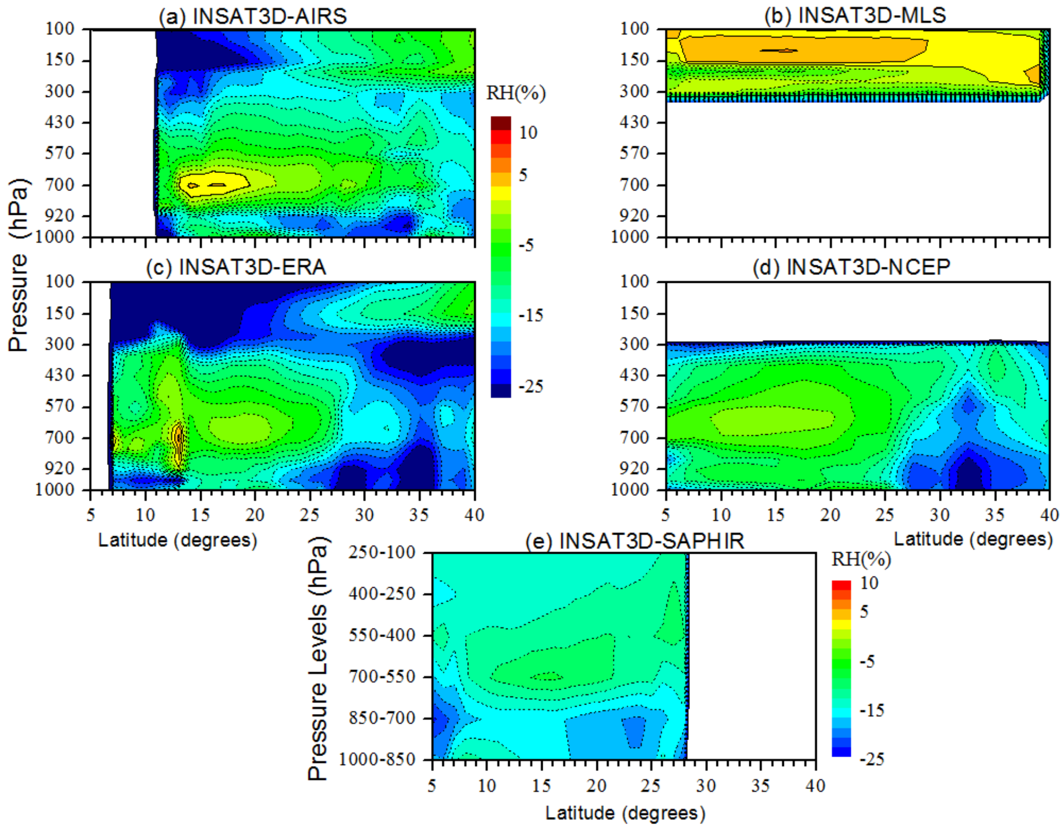

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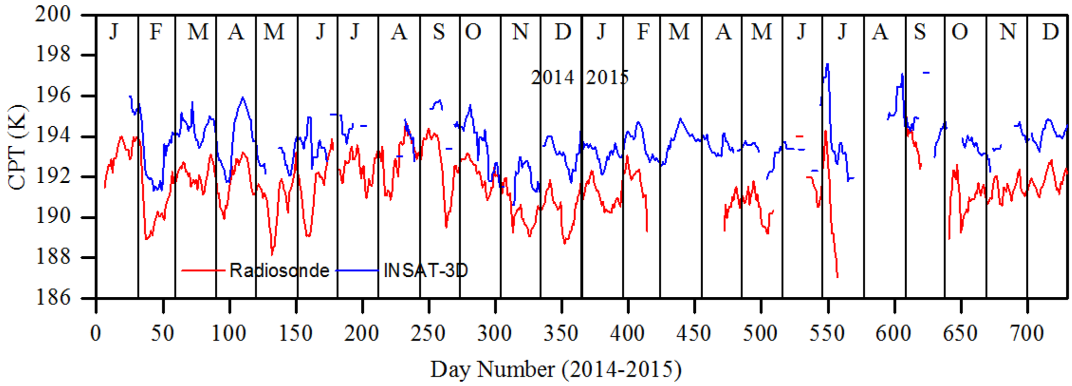

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