CHAPTER 3

IMAGE-DATA ANALYSIS FOR SIGNATURES OF HYDROMETEORS
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3.0 INTRODUCTION

With the advances in visible (VIS) and infrared (IR) for observing of weather phenomena [1], the observations in the microwave (MW) portion of the electromagnetic spectrum (all using low earth orbiting satellites) have also developed [2]. Particularly because the microwave radiations can penetrate the clouds (especially cirrus) [118] and is differentially sensitive to a wide variety of geophysical parameters, like cloud liquid water [71], cloud ice water [72], rain drops [119], water vapour [82] etc., enables microwave sensors to provide an all-weather remote sounding capability, at any location, all the time (passes-dependent).

Remote sensing of different weather phenomena, using data from many microwave sensors, by visual inspection of the images, is extensively reported, e.g. [23] [30] [81] [78] [120] [119]. However, most of the earlier microwave sensors had coarse resolution. High spatial and temporal resolution, such as AMSU-B, is generally required to define the atmospheric meso-scale phenomena. Most importantly, the microwave frequencies can show direct precipitation signatures [119] [78], unlike the VIS and IR images. Precipitation is often shown more distinctly and with better spatial resolution by AMSU-B than the previous microwave instruments, especially if the area-extent of precipitation is small.
In this chapter, after indicating the study area in section 3.1, the sources for our data and procedures of selecting proper data for further analysis have been explained, in sections 3.2 and 3.3. Two methods, visual inspection and quantitative method, are used for analysis of data with respect to different types of hydrometeors viz.: (i) Heavy precipitation hydrometeors (Thunderstorms and heavy rain), (ii) Moderate and low precipitation hydrometeors (moderate and light rainfall as well as snowfall) and (iii) non-precipitation hydrometeors (moisture and cloud at different atmospheric levels, such as low level moisture, upper level moisture), along with clear sky and snow covered conditions.

In section 3.4 an attempt has been made to detect and produce accurate descriptions of these hydrometeors (different meso-scale weather systems) by visual inspection of the images. It is demonstrated by visual inspection of the images that data provided by AMSU-B sensors, when displayed pictorially, can aid the meteorologists to detect and find the exact location and extent (vertically and horizontally) of different types of hydrometeors.

The quantitative microwave brightness temperature signatures and the vertical structure for these hydrometeors have been investigated in section 3.5. The trend microwave signature, channel versus brightness temperature (graphically), is related to height variation of moisture and hydrometeors at any selected spot/station. Finally, for a selected area (of ~ 1000 km x ~ 200 km) over Iran region, where the meteorological conditions were unknown, the AMSU-B data, for a single day (08 December 2001) has been scanned. Using the graph of brightness temperature for a scan line, which passes through the convection area, the locations of the different hydrometeors, where present in this area, has been found.
3.1 STUDY AREA

In this study mostly data from Iran (23-45 N, 45-65 E) is used [120]. Iran is located in Middle East, bordering the Gulf of Oman, the Persian Gulf (south), and the Caspian Sea (north). Figure 3.1 gives the geographical location of Iran, along with some of the stations from which data collected.

As it is seen the stations are distributed over different location of Iran. The microwave data, in this study, from Advance Microwave Sounding Unit-B (AMSU-B), on the National Oceanic and Atmospheric Administration (NOAA15, 16 and 17) polar-orbiting environmental satellites, were used. Each satellite passes over Iran twice a day and time passes over Iran for each satellite is given in Table 3.1.
Table 3.1: Flyover time of NOAA satellites for Iran. The capital letters N and S indicates North and South.

### Table 3.1: Flyover time of NOAA satellites for Iran

<table>
<thead>
<tr>
<th>Satellites</th>
<th>NOAA16 N→S</th>
<th>NOAA15 N→S</th>
<th>NOAA17 N→S</th>
<th>NOAA16 S→N</th>
<th>NOAA15 S→N</th>
<th>NOAA17 S→N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time passes (IRT)</td>
<td>0 → 4</td>
<td>4 → 8</td>
<td>8 → 12</td>
<td>12 → 16</td>
<td>16 → 20</td>
<td>20 → 24</td>
</tr>
</tbody>
</table>

3.2 DATA SOURCES

This analysis employs two sets of data; Ground based data and satellite data.

(A) Ground data includes the hourly synoptic observations reported by Iran Meteorology Organization (IMO) [120] and the radiosonde data (dot circles in Figure 3.1) compiled by the University of Wyoming, Department of atmospheric sciences [51]. From this, ten different meteorological weather situations (including precipitating and non-precipitating hydrometeors), have been selected (Table 3.2) for analysis. Table 3.2 gives ten weather events (with short forms) and corresponding number of reporting events.

<table>
<thead>
<tr>
<th>Events</th>
<th>Stations</th>
<th>Events</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Clear Sky conditions (CS)</td>
<td>28</td>
<td>6. Heavy Rainfall (HR)</td>
<td>10</td>
</tr>
<tr>
<td>2. Snow Cover regions (SC)</td>
<td>20</td>
<td>7. Snowfall (SF)</td>
<td>15</td>
</tr>
<tr>
<td>3. Low level Moisture (LM)</td>
<td>15</td>
<td>8. Thunderstorms (TS)</td>
<td>10</td>
</tr>
<tr>
<td>4. Light rain (LR)</td>
<td>22</td>
<td>9. Upper level Moisture (UM)</td>
<td>20</td>
</tr>
<tr>
<td>5. Moderate Rainfall (MR)</td>
<td>23</td>
<td>10. Upper level Dry (UD)</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3.2: Meteorological weather events (with short forms) and corresponding number of reporting stations
The second data-sets, used, are the satellite data. The visible and infrared image data from IODC (Indian Oceanographic Data Centre), which is down linked via METEOSAT HRI [121] and the microwave level 1b data from AMSU-B onboard the NOAA polar-orbiting satellites, which are available from satellite active archive [84]. Level 1b data are radiometric calibrated brightness temperatures, and corresponding earth locations. Limitation for this data-set is due to the less time coverage of AMSU-B over the study area. It is less than 30 minutes per day (~ 5 minutes per passes). Our data mainly collected in years 2001 and 2002 where NOAA 17 was not launched (NOAA 17 launched on 24 June 2002).

### 3.3 DATA SELECTION PROCEDURES

For (1) clear sky and snow covered conditions, which are taken from cloud free atmosphere (VIS data), the AMSU-B observations are isolated with the help of collocated VIS/IR satellite observations (METEOSAT data). VIS and IR data shows clear (no-cloud) conditions, for snow covered and clear sky; (2) Moisture distribution at different altitudes (LM and UM) as well as UD the events are collected using radiosonde observations. Note that LM refers to where the relative humidity (RH) is more than 50%, up to 700 hPa (~3 km from sea level), for UM, relative humidity is more than 50% at higher level, at and above 500 hPa (~5 km) and for UD relative humidity is less than 20% at and above 500 hPa; (3) For the different intensities of rain including thunderstorms and snowfall the procedure, is to collocate the IMO reports with AMSU-B images, by finding the AMSU-B passes, which covers these reports. Then those IMO measurements that fit within the AMSU-B footprint (the event influence time for TS less than 10 minutes and for LR, MR, HR and SF ~ 30 minutes and for LM, UM, UD, SC and CS ~ 1 hours) are collected. In case of TS, although the time difference between IMO reports and AMSU-B passes was 10 minutes at maxi-
mum, the rapidly developing TS may have significantly changed their state within this
time frame. This may be the reason for the less number of data points (only 10 out of
183, see Table 3.2) and large data scatter for the TS (Figure 3.16).

The stations are distributed over different locations of Iran (Fig 3.1), and the
events are distributed over different days during May 2001 to February 2003. The
following limitations for the data selection have been observed: The IMO reports are
available only for a few stations (only 9 stations for the study area). Some types of the
events are naturally less, in the Iran region, especially HR, TS, and SF. For example,
for the SF only four stations (Tabriz, Tehran, Esfahan, and Mashhad) were available,
because the other stations (Ahwaz, Shiraz, Kerman, Zahedan, and Bandar Abbas)
are located in southern parts of Iran, which, rarely, receive snow. Note that all times
for AMSU-B data records, IMO reports, as well as radiosonde measurements are
given in GMT and as well as Iran standard Time (IRT); $IRT = GMT + 0430$ HR from
22 March to 22 September and $IRT = GMT + 0330$ HR for other times of the year.
About 150 passes of AMSU-B corresponding to the above 183 event-station reports
(Table 3.1) are used. The brightness temperature values, only at the locations (lati-
tudes-longitudes) of these 183 stations and close (in time) to IMO reports, are used.
Except for snow covered (SC), for all the other events, brightness temperature data of
five AMSU-B pixels (central pixel and 4 on 4 sides) have been considered. To study
properties of AMSU-B frequencies in SC regions, data from the Alborz Mountain, in
clear sky conditions, at winter season have been used. As there is no IMO report for
the Alborz, the clear sky condition is co-located by IR images and nearby station
(Tehran) reports. The Alborz Mountain, with about 5 km height [122], is located in
north of Tehran (Fig 3.1). During November to April, It is always covered by the
snow. Thus for SC, the average brightness temperature for six pixels ($2'3$) in the west-
east direction (because of physical shape of Alborz mountain, which extends in west
east directions) from region about 35 Km (2 pixels) north of Tehran, for 20 clear sky
conditions, have been calculated.

3.4 VISUAL SIGNATURES OF HYDROMETEORS

In this section we are trying to indicate the microwave signatures of ten me­
teorological situations (events) of Table 3.2, over Iran (Figure 3.1), in more details,
using only visual inspection of the images. For this purpose, the AMSU-B brightness
temperature data (that are in bytes and derived by adding 100 to grey shade, which is
0 to 255) are converted in image form (see article 2.2). This gives the ranges of bright­
ness temperature to be 100 to 355 °K. But the actual data does not really extend in
this range (100 to 355 °K), therefore, the range of brightness temperatures is con­
densed between 189 to 321 °K (see Figure 3.2). Figure 3.2 gives the warmness and
coldness scale, which is used for all the images in this thesis. Of course, the brightness
temperature may rarely go out of this range (e.g. brightness temperature range in thun­
derstorms at all frequencies, or snow covered at 89 and 150 GHz (see article 3.5). An
attempt is made to consider the AMSU-B images at five frequencies and analyse
them, based on frequency variations for the specific event in the images, intensity-wise
and shape-wise.

![Figure 3.2: The warmness and coldness scale of brightness temperature (°C), which is
used for all AMSU-B images in this thesis.](image)

These images themselves can be a great direct help for knowing by visual
inspection, the exact locations, and extent as well as the rough altitude of hydrom­
eteor (i.e. frequency dependent weather conditions). Further, these shapes and align­
ments of corresponding hydrometeors will give idea of phenomena (like front or cyclone). The main limitation being the availability of the pass at the time and an advantage is some situations (events), like thunderstorm can be seen directly and easily on AMSU-B image with its exact location (within pixel size, 16 km) as well as its intensity (coldness), which is not directly observable in visible, infrared and water vapour images due to large surrounding cloud-cover. The visual signatures of these entire ten weather situation, are given below. Note clear sky (CS) is going to be reference image (Fig 3.3), for all other events, for differentiation.

3.4.1 Signature of Non-Precipitating Hydrometeors

A major difference when we think of precipitating hydrometeors (water droplets and falling snow) is heavier loss of earth radiation due to scattering (and reflecting losses enhancement due to emission from colder hydrometeors). However, in case of non-precipitating hydrometeors it can be (i) either only moisture (with no droplets) and hence not much of scattering loss and much of forward emission enhancement of radiation or (ii) it can be clouds with small droplets (with lower scattering losses than precipitating hydrometeors) along with forward emission particularly by the saturated moisture (which needs to be present in the cloud). In general, non-precipitating hydrometeors are consisting of an ensemble of suspended liquid or solid water particles. Water vapour and cloud droplets (non-precipitating hydrometeors) weakly absorb microwave radiation and that scattering of microwave radiation is negligible for non-precipitating drops. The differential transparency of non-raining clouds at microwave frequencies enables microwave sounders to be useful in cloudy regions unlike infrared sounders, for detection of water vapour. Absorption by water droplets increases with frequency [19]. Mugnai and Smith [12] [29], Mugnai et al., [22], and Adler et al., [23] have shown that cloud liquid water significantly affects microwave brightness
temperature. At frequencies similar to AMSU-B channels (89, 157, and 183 GHz) brightness temperature affects from cloud liquid water can be substantial [24] [25] [26] [27] [15].

Over the ocean, which provides a uniform cold background due to the low emittance of water, atmospheric water vapour and liquid water increase the brightness temperature measured by a satellite-borne radiometer (due to emission). But over the land, brightness temperature changes due to variable surface emissivity can equal those from atmospheric emission due to water vapour variations. Thus, the signature of water vapour, at lower levels of troposphere, is more difficult to discriminate at lower frequency such as 89 GHz. However, measurements at 150 GHz due to more sensitivity of this frequency to small water vapours droplets and ice crystals, may shows slightly improve capability of detection of water vapour. Non-precipitating hydrometeors, therefore, has some ambiguity in AMSU-B images. Signatures of non-precipitating hydrometeors at different altitudes along with the signatures of clear sky condition and snow covered regions, with details, are discussed below.

3.4.1.1 Clear Sky Conditions

Clear sky (CS) is obviously the best data for locating geographical ground feature, and the best frequency is 89 GHz, which is not affected by non-precipitating hydrometeors, and its weighting function peaks near the ground [24]. As an example, Figure 3.3 shows the AMSU-B images of 89 and 150 GHz on 09 October 2002 at (10.00 GMT) 14.30 IRT, along with visible satellite image from IODC (data downloaded via METEOSAT HRI), on 09 October at 10.00 GMT. This shows clear sky condition over Iran (Figure 3.3c). The Persian Gulf in south and the Caspian Sea in north of Iran, clearly can be seen in Figure 3.3c. In the Figure 3.3a and b, some of the
stations, from where data was collected are indicated by first three capital letters of the cities. These stations are: Tabriz (TAB), Tehran (TEH), Mashhad (MAS), Esfahan (ESF), Ahwaz (AHW), Shiraz (SHI), Kerman (KER), and Zahedan (ZAH).

A look at the 89 GHz image, in CS condition and in absence of low-level precipitating hydrometeors (but even with high level clouds), gives the landmarks (such as ground, sea and lake regions). The Persian Gulf (PG), Caspian Sea (CP), and Ormiel Lake (OL), are well-known landmarks and in Fig 3.3a can be seen clearly.
These landmarks are not much masked by moisture (are only slightly faint) and are seen in 150 GHz channel (Fig 3.3b) also. In fact, the 89 GHz is a window channel for water vapour and oxygen also, and one looks at the brightness temperature of the ground. The water surface emits less and has colder brightness temperature than the land, as their emissivities, at this frequency, are approximately 0.5 and 0.9, respectively [40].

Over the open water surfaces, the brightness temperature observed by the 89 and 150 GHz is very cold (e.g. up to 200K at 89 GHz and 240 K at 150 GHz, see Persian Gulf and Caspian sea in Figure 3.3a and b). Because the atmosphere is not significantly transparent at 150 GHz, which is on the tail of the water vapour absorption line. The measurements in this channel are thus particularly dependent on the distribution of water vapour in the lower troposphere (e.g. the east of Persian Gulf (Figure 3.6b) and south of Caspian Sea (Figure 3.5b) are the landmarks that are masked by low-level moisture.

The water vapour channel at 176, 180, and 182 GHz (image are not given here) do not see deep enough into the atmosphere to detect the land and cold water surfaces. Therefore, these landmarks never seen in water vapour frequencies (e.g. Fig 3.8 c, d). However, from 89 GHz, we can geo-locate the events visually immediately, and since all AMSU-B images are co-located, the geo-location (by visual inspection) can apply to all other channels as well.

The most notable are the differences between dry and wet surfaces, the effect of snow cover, as well as time of the day for the data recording. Dry surface tends to have the highest emissivities and high brightness temperature (related darker shade), while, the wet and snow covered surfaces tend to have the lower emissivity, and there-
fore, cools brightness temperatures compared to dry land. The observed variability for homogenous land surfaces is caused by variations in land surface temperatures and surface emissivities.

In clear sky condition, time of the day for data recorded is also an important variable that affects the brightness temperature, normally, in the lower channels of AMSU-B. This effect, for different passes, is shown in Fig. 3.4.

Figure 3.3: Brightness temperature variations for five AMSU-B frequencies (channels) in different passes over Iran region. The IRT denote to the Iran local time.

Channels 89 and 150 GHz are more affected by time of the day. This is due to strong surface (and near the earth) contributions of these channels. In afternoon, when the earth and its lower atmosphere become warm, the brightness temperatures for the lower channels (89 and 150 GHz) increase (pass 3 in Fig. 3.4). But, at night and early morning, when the earth has becomes cooler, the brightness temperature decreases
(Fig 3.4 pass 1 and 2). The channels 176-182 GHz are not much affecting by the time of the day because maximum contributions to brightness temperature for these channels comes from 700 hPa (~3 km and above) [27], which is not much dependent on the time of the day. These points will help us while discussing group-wise signatures below.

So, in short, the signature of CS is seen on 89 GHz (clearly and faintly on 150 GHz) as observation ability of all known landmarks.

3.4.1.2 Snow Cover

The two lower frequencies of AMSU-B are located on the weak water vapour absorption line (band) at 150 GHz and in the 89 GHz atmospheric window region. It yields significant information about land surface-variations (such as snow covered) because of the low atmospheric attenuation at these frequencies. The AMSU-B images of four frequencies (89-180 GHz), which are taken on 01 January 2003 at 0335 GMT (0705 IRL) along with IR image from IODC geostationary satellite at 0700 GMT (1030 IRT) are presented in figure 3.5. Although IR image show cloudy condition in south and south-east part of Iran however, it shows relatively clear condition around Tehran and Tabriz (Figure 3.5e). IMO reports for 30 and 31 December shows snowfall for most places in north part of Iran including Tehran (TEH) and Tabriz (TAB). It is seen that the snow covered regions, viz. Alborz Mountains at north of Tehran (TEH) and around Tabriz (TAB) in North West of Iran, appears with very cold spots in 89 (~198 °K) and 150 GHz (~200 °K), and also in 176 GHz (~240 °K for Alborz Mountains in north of Tehran and ~265 °K for around Tabriz) channels (Fig 3.5a-3.5c).

As mentioned, the 89 GHz channel is a window frequency for O$_3$ and H$_2$O
Figure 3.5: AMSU-B images (a-d) along with IR image from IODC geostationary satellite (e) for 01 January 2003 at 0335 GMT (0705 IRT). Tehran and Tabriz stations are represented by TEH and TAB on the images.
water vapour absorption lines, and looks at near the ground brightness-temperatures. The 150 GHz is also mainly for weak water absorption and is affected mostly by low-level atmospheric water vapours (below ~2 km) and under dry atmosphere is affected mostly by the ground surfaces. Under dry atmosphere, channel 176 GHz also sees down to 700 hPa levels (~3 km), which correspond approximately to the high-elevation geographical location, such as Alborz (~5 km from sea level). The clear sky and relatively dry conditions, therefore, allow the 150 and also 176 GHz to see down to ~3 km, which is within the range of Alborz height. Channel 182 GHz sees high-level moisture (about 300 hPa, i.e. ~9 km), and channel 180 GHz looks a little deeper (to about 500 hPa, i.e. ~5 near the range of Alborz Mountains) and therefore, snow covered in Alborz and under very dry conditions may slightly depress the brightness temperature in channel 180 GHz (e.g. see Figure 3.5d), but for Tabriz (TAB) signature of snow covered never seen in 180 GHz. Signatures of snow cover under any condition never seen in 182 GHz image (image is not given here).

**Conclusion**, the snow covered signature in AMSU-B images is appeared to be very cold at 89 and 150 GHz. Under dry atmosphere and for high elevation mountains region (such as Alborz), SC appears cold at 176 GHz and also slightly depress the brightness temperature in 180 GHz. Snow covered for Iran region under any condition never seen in 182 GHz.

### 3.4.1.3 Low Level Moisture

Figure 3.6, as an example, shows the images of four AMSU-B channel at 2257 GMT on 28 March 2002 (0327 IRT on 29 March 2002) and Table 3.3 also shows the variation of relative humidity over Shiraz station at 00 GMT (0430 IRT) on 29 March 2002. Although this radiosonde measurements (Table 3.3) exhibits very
humid condition at lower levels of the troposphere (e.g. RH=84% at surface), the signatures of this LM, is not easily visible in AMSU-B images, e.g. around Shiraz (SHI in Figure 3.6).

However, as mentioned in article 2.1.2, the 89 and 150 GHz channels of AMSU-B contain the lower-tropospheric water vapour information but are also affected by the earth’s surface. Therefore, understanding the emissivity properties of the earth’s surface at 89 and 150 GHz may be useful in order to discriminate between water vapour and the earth’s surface contributions to the measured brightness temperature at these frequencies (Table 2.4). The land surface emissivities are generally close to the unity and so there is poor contrast of water vapour emission against the radiometrically warm land background. In addition, over land brightness temperature

<table>
<thead>
<tr>
<th>PRES(hPa)</th>
<th>HGHT (m)</th>
<th>RELH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>849.0</td>
<td>1491</td>
<td>84</td>
</tr>
<tr>
<td>840.0</td>
<td>1580</td>
<td>54</td>
</tr>
<tr>
<td>720.0</td>
<td>2850</td>
<td>30</td>
</tr>
<tr>
<td>700.0</td>
<td>3078</td>
<td>52</td>
</tr>
<tr>
<td>630.0</td>
<td>3921</td>
<td>2</td>
</tr>
<tr>
<td>500.0</td>
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<td>7370</td>
<td>4</td>
</tr>
<tr>
<td>330.0</td>
<td>8730</td>
<td>7</td>
</tr>
<tr>
<td>300.0</td>
<td>9380</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 3.3: Pressure, Height and relative humidity for Shiraz station on 29 March 2002 at 00 GMT (04.30
changes due to variable surface emissivity can equal those from atmospheric emission due to water vapour variations. Thus, the signature of water vapour, at lower levels of troposphere, is more difficult to discriminate at 89 GHz. However, in 150 GHz, it slightly shows colder than radiometrically warm background due to more sensitivity of this frequency to small water vapour droplets and ice crystals, but visually it is difficult to distinguish (Figure 3.6b)

Detection of microwave signature of water vapour in lower troposphere is considerably better over water surfaces than over land. Water surface emissivities are
much less than unity (Table 2.4) and result in good contrast of water vapour emission against the radio-metrically cold water background (Figure 3.6). Over the open water, brightness temperature, observed by the 89 and 150 GHz, is 200 K at 89 GHz and 240 K at 150 GHz (article 3.4.1.1). But on 28 March 2002 at 2257 GMT (0327 IRT) west part of Persian Gulf is covered by low-level moisture and show warm brightness temperature (e.g. Abu Musa Island (ABM) in west part of Persian Gulf it is \(\sim 235\) and \(\sim 275\) at 89 and 150 GHz, respectively), which is signatures of emission by water vapour (Figure 3.6a, b).

The higher frequencies of AMSU-B (e.g. 176 and 180 GHz) have a weighting functions peak at mid and upper level of troposphere (\(\sim 3 - 8 \text{ km}\)) and does not see deep enough into the atmosphere to detect the signatures of this LM (Figure 3.6c and 3.6d). The 182 GHz (image is not given here) also weighting function peaks at upper level of troposphere (\(\sim 10 \text{ km}\)) and does not detect the signatures of LM.

So, in conclusion, the signature of low-level moisture over the land is not easily visible in AMSU-B images, but over water surface it can easily be seen.

3.4.1.4 Upper Level Moisture (Ice Clouds)

The AMSU-B frequencies in the vicinity of 183 GHz water vapour absorption line provide measurements of water vapour in mid and upper-level of troposphere. Figure 3.7, as an example, shows the images of all five AMSU-B channels on 04 May 2001 at 2326 GMT (0356 IRT) and Table 3.4 show the radiosonde report of relative humidity for Kerman and Tehran stations at 00 GMT (0430 IRT). As it can be seen from Table 3.4, the Tehran radiosonde measurements show very humid at upper level, above 500 hPa (RH > 70 %).
Figure 3.7: Images of five AMSU-B channels on 04 May 2001 at 2326 GMT (0356 IRT): a) 89 GHz, b) 150 GHz, c) 176 GHz, d) 180 GHz, and e) 182 GHz. The stations, which are indicated on images, are Tehran (TEH) and Kerman (KER).
The 89 GHz (i.e. window channel), relatively, cannot detect the signatures of moisture at an entire atmosphere (except large water vapour droplet at lower level can be detected). The 150 GHz is contained the lower-tropospheric water vapour information (~2 km). Therefore, this channel also cannot give any signature from moisture (ice clouds) above 700 hPa (~3 km). However, at frequencies in vicinity of 183 GHz (176, 180 and 182 GHz), where the extinction is very strong, the scattering from ice crystals is vividly noticeable. The ice clouds can trap the long wave radiation emitted from the earth surface, resulting in less radiation to space and low brightness temperature in comparison with clear sky condition.

The low brightness temperature area at 182 GHz (dark brown) in north west of Iran (including Tehran) in Figure 3.7e, and also east part of Iran (including Tehran) in Figure 3.9e, suggest to be signatures of upper level moisture (ice crystals), which is reported for Tehran station on 04 May 2001 (Table 3.4). The brightness temperature in these areas at frequencies of 182 GHz reaches to a value of ~ 230 °K (Figure 3.7e, and 3.9e). Although, 176 and 180 GHz frequencies are also slightly depressed due to the high moisture at upper level, the signature of that cannot easily seen in Figure 3.7c-d, and 3.9c-d. At this high frequency, the layer ice particles (ice cloud) act as scatters and scatter cold radiation, from above the cloud, back to the satellite (Ice particles can make significant contribution to the scattering of microwave radiations).

The appearance of water vapour, on these frequencies (176, 180, and 182 GHz), is similar to that on Geostationary Operational Environment Satellite (GOES) water vapour images at 6.7 and 7.3 micrometer (image is not given here), which also weight the mid-and upper troposphere.
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<tr>
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<td>RH (%)</td>
<td>PRES (hPa)</td>
<td>RH (%)</td>
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<tr>
<td>300</td>
<td>19</td>
<td>626</td>
<td>83</td>
</tr>
<tr>
<td>250</td>
<td>18</td>
<td>496</td>
<td>85</td>
</tr>
<tr>
<td>200</td>
<td>17</td>
<td>359</td>
<td>66</td>
</tr>
<tr>
<td>179</td>
<td>7</td>
<td>327</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 3.4: Pressure (in hecto-Pascal), Height (in meter) and relative humidity (RH %) for Kerman (04 May 2001 at 00 GMT) and Tehran (04 May 2001 and 07 January 2002 at 00 GMT) stations.

So, in conclusion, the signature of non-raining upper level moisture associated with cirrus cloud (or even without cirrus cloud) is appeared in water vapour frequencies 176, 180, and 182 GHz and it is absent in 89 and 150 GHz. The signature of UM, in these channels, often appear as low (cold) brightness temperature.
3.4.1.5 Upper Level Dry Regions (UD)

The signatures of upper level dry (UD) regions can also be seen in higher frequencies (water vapour channels) of AMSU-B. These regions (UD regions) often appear as high brightness temperature, in frequencies 176, 180 and 182 GHz. These three frequencies are very sensitive to water vapours or ice crystals and show the absorption from the wings of the 183.3 GHz absorption band, and their weighting function peaks in the mid and upper level of troposphere [27]. The warm brightness temperature regions, such as one indicated around Kerman (KER in Figure 3.7e), suggest to be the signature of dry conditions at upper level of troposphere, as it is observed by radiosonde for Kerman on 04 May 2001 (Table 3.4). This radiosonde shows a relatively dry condition at mid and upper level of troposphere, i.e. RH is less than 40% above 664 hPa (Table 3.4). Shapes of dry and moist regions, at upper troposphere, are often very large warm bands.

Because of less water vapour content, in these regions, allows the water vapour channels (176-182 GHz) to see lower, warmer portion of the troposphere. Thus, the greater contributions, from lower and warmer layers, increase brightness temperature for these channels. As the atmosphere is substantially opaque at these high frequencies, the Ocean/Land background does not affect the observed radiance in these frequencies. Therefore, these channels are useful for pointing out moist regions versus dry air at upper level of troposphere.

In conclusion, the signatures of dry region at upper level of troposphere are as warm brightness temperature (below their nominal values) in frequencies 176, 180 and 182 GHz and not so in 89 and 150 GHz channels.
3.1.5 Signatures of Precipitating Hydrometeors

At microwave wavelengths, the emissivity of the earth-atmosphere is normally less than unity [27], so there is significant reflection and a significant surface component to the radiance measured at the satellite. Water vapour, cloud water, and precipitation in the atmosphere are capable of increasing the optical thickness of the atmosphere [29], which in turn tends to increase observed brightness temperatures. At the AMSU-B frequencies, precipitating hydrometeors are only atmospheric constituent which is capable of producing optical thickness greatly exceeding unity [27].

Precipitating hydrometeors in the clouds and rain layers have microwave absorption, emission, and scattering properties [19] that can be used to derive information about rain, based on passive microwave measurements at frequencies above 90 GHz. In the absence of hydrometeors each AMSU-B frequency channel would penetrate a frequency-dependent water vapour and sound the average temperature in the corresponding atmospheric layer (Fig 2.4). For idealized wet adiabatic atmospheres saturated at all altitudes, this relation between the water vapour and temperature at any altitude is fixed, and since each 183 GHz channel penetrates a fixed water vapour, the idealized observed brightness temperature for each channel is also fixed for such saturated atmospheres. For saturated atmospheres (with wet-adiabatic lapse rate) in hypothetical absence of microwave-visible hydrometeors, the brightness temperature near 183 GHz would be largely independent of surface temperature and latitude, although small second order effects arise from the pressure-dependence of water vapour absorption [73].

The nominal brightness temperature sounded in saturated atmosphere, at 182 GHz, is ~235 K, corresponding to ice, whereas that for 176 GHz, it is ~260 K,
corresponding to both water and ice. Therefore, 176 GHz responds more strongly to
strait-form rain and low precipitation rates than does 182 GHz, which responds strongly
only when strong convection thrusts large ice particles substantially higher in the atmo-
sphere (otherwise mainly to cirrus clouds only).

Precipitating hydrometeors contribute both scattering and absorption to mi-
crowave; lowering brightness temperature below their frequency-dependent expected
nominal values for a saturated atmosphere. This cold precipitation signature is unique
because brightness temperatures below those corresponding to saturation generally
cannot be generated otherwise. As a matter of fact what is expected of rainy cloud is
colder part compared to surrounded non-raining (larger) area. Variable lapse rates or
relative humidity introduce small ambiguities (e.g. low altitude precipitation might oc-
cur under a dry air mass). Additional ambiguities appear because the relative contribu-
tions of hydrometeor scattering and absorption depend on the particle temperature
and the distributions of droplet size and shape [20].

The sensitivity of the frequencies similar to AMSU-B (such as SSM/T-2) to
precipitation hydrometeors have been studied by number of investigators, e. g. [81]
[78]. Aircraft observations and simulations show that the frequencies represented on
the AMSU-B can give detailed depictions of precipitation hydrometeors [27] [14]
[123][124][125]. Fortunately, the special resolution of AMSU-B is significantly good
to create useful images. In the further of this section, we are trying to indicate, the
signatures of different types of precipitating hydrometeors viz. light rain, moderate
rain, snow fall, heavy rain, and thunderstorms, by visually inspection of AMSU-B
images.
3.1.5.1 Light Rain and Drizzle

It is reported that for frequencies below 90 GHz, light rain or drizzle can not be easily detected because of smaller ice particles and low bulk volume density [81]. Measurements at 150 GHz show little progress in detecting light rain over land, due to sensitivity to sub-millimetres sized ice particles [78]. Figure 3.8 shows the brightness temperature images of four AMSU-B channels at 89, 150, 176 and 180 GHz on 02 April 2002 at 0835 GMT (1305 IRT). IMO, on 02 April 2002, for Shiraz (SHI) LR at 1320 and for Kerman (KER) overcast at 1320, has been reported. As it is seen in Figure 3.8, the signatures of light rain region can not easily distinguish in 89 and 150 GHz. Though light rain regions have similar brightness temperature at 89 and 150 GHz (in case of 02 April it is ~ 270 K), but they have slightly colder spots than only cloudy region, such as Kerman (with ~ 275 and 277 K at 89 and 150 GHz, respectively). Despite this difference, light rain, visually, cannot be easily distinguished from cloudy region at these frequencies (Figure 3.8a and 3.8b).

However, it seems that measurements at 176 GHz may show promise in detecting light rain regions over the land. This channel is very sensitive to smaller sized ice particles than 89 and 150 GHz due to its shorter wavelength (e.g. ~ 1.7 mm versus ~ 2 and ~ 3.4 mm). As it is seen, the signatures of light rain (SHI) can easily be discriminated from cloudy condition (KER) in 176 GHz image (Figure 3.8c). Because the signatures of clouds are not present at 176 GHz, while LR appears as light brown features in this frequency. The light rain regions are ~ 10 K colder than cloudy regions, in this frequency, e.g., in the case of 02 April 2002, the brightness temperature differences in light rain area (i.e. SHI in Figure 3.7) with cloudy area (i.e. KER in same Figure), $[T_B(176)_{Kerman} - T_B(176)_{Shiraz} \text{ or } T_B(176)_{CC} - T_B(176)_{LR}]$, is ~ 5, ~ 7 and ~ 9 K at 89, 150 and 176 GHz, respectively (i.e., e.g. $T_B(176)_{Kerman} - T_B(89)_{Shiraz} = \sim 5$). This is due to the
transparency of AMSU-B frequencies to non-precipitating clouds and also shows that high frequencies are more sensitive to small size precipitation hydrometeors. Signatures of light rain never seen in frequencies 180 GHz (Figure 3.8d) and 182 GHz (image is not given here). Therefore, signatures of light rain (LR) can be seen properly at 176 GHz.

![Figure 3.8: AMSU-B images on 02 April 2002 at 1305 IRT; a) 89 GHz, b) 150 GHz, c) 176, and d) 180 GHz. The capital letters, SHI and KER indicates Shiraz and Kerman stations, respectively.](image)

3.1.5.2 Moderate Rain (MR)

Figure 3.9 shows the four AMSU-B channel-images on 07 January 2002 at 1541 GMT (1911 IRT). The IMO, for Shiraz (SHI), Tehran (TEH), and Ahwaz (AHW)
stations, had reported rain, at 1920, 1925, and 1920 IRT, respectively. As it is seen in Figure 3.9, the signature of MR appears as cold spots at 89, 150 GHz and at 176 GHz. Note how only precipitating areas are highlighted at 176 GHz only. Brightness temperatures at these frequencies, in the raining area (for those stations that indicated in Figure 3.9), are ~255, ~254 °K, and ~275, respectively. Note that different precipitation systems have varying ice particle size (e.g. smaller particles in strait-form rain versus large ones in convective systems), and it may be change the observed brightness temperature in the raining area. In clear sky condition (and at this pass time), the brightness temperatures for 89, 150, and 176 GHz, are ~270, ~277, and ~298 °K, respectively. (Figure, 3.4). Thus, the signature of rain in AMSU-B images is appeared colder than the non-raining regions, especially at 150 and 176 GHz (~23 °K). When cloud liquid water are present in the atmosphere, the microwave instrument senses lower brightness temperatures because when amount of cloud liquid water increases, the microwaves originate primarily from the higher levels of the cloud and the brightness temperature decreases.

By comparing of the signatures of LR, in Figure 3.8, at Shiraz (SHI) with signatures of MR, in Figure 3.9, at Shiraz (SHI), Tehran (TEH), and Ahwaz (AHW) it can be seen that the signatures of LR and MR are not easily separable at 89, 150 GHz, except that MR slightly appears colder at 176 GHz.

However, at 180 and 182 GHz (image of 182 GHz is not given here), where the extinction is very strong, the scattering from ice above the rain clouds is vividly notice. Therefore, these high frequency measurements do not yield direct information about rain below the clouds (Figure 3.9d), and signatures of rain can not be seen in this frequencies. An important consideration, in sensing rain in the AMSU-B measurements, is that the satellite-borne passive microwave radiometers have a field of view
Figure 3.9: AMSU-B images on 07 January 2002 at 1541 GMT (1941 IRT). a) 89 GHz, b) 150 GHz, c) 176 GHz, and d) 180 GHz. The Tehran, Shiraz, and Ahwaz station on the images, are indicated with “TEH”, “SHI”, and “AHW”, respectively.
The signature of moderate rainfall is clearly seen in frequencies below 1.6 GHz (89, 150, and 1.76 GHz), but never seen at frequencies of 180 and 182 GHz. The signature is appears to be slightly colder at 150 GHz than that in 89 GHz, however, signatures of MR, visually, cannot easily separate from LR at either frequencies of AMSU-B.

3.1.5.3 Snowfall (SF)

IMO observation indicates snowfall for Mashhad (MAS), rain for Kerman (KER) and heavy rain for Bandar Abbas, on 12 January 2002 at 0720 IRT. The images of four AMSU-B channels, i.e. 89, 150, 176 and 180 GHz, at 0738 IRT (0408 GMT), are presented in Figure 3.10. As it is seen from Figure 3.10, the signature of snowfall appears as cold spots in 89 (253 K) and 176 GHz (268 K). It is colder at 150 GHz (245 K) than 89 and 176 GHz. The signature of snowfall condition, in AMSU-B lower frequencies, especially, at 150 and 176 GHz, is slightly colder than that for moderate rainfall (article 3.5.3). For example, snowfall ~ 12 and 6 K is colder than moderate rainfall (for the case of 07 January (rain) and 12 January (snowfall) at frequencies 150 and 176 GHz, respectively). The brightness temperature difference between 89 and 150 GHz \( (T_b(89) - T_b(150)) \), for snowfall is ~ 7 K (in case of 12 January), while, for rainfall, it is ~ 1 K (in case of 07 January. As mentioned above, at the same time as snowfall report (by IMO) for Mashhad (MAS) on 12 January 2002, for Kerman (KER) also rainfall has been reported. The brightness temperature differences \( (T_b(89) - T_b(150)) \), in this case, it is ~ 11 K. By comparison the areas around MAS and KER in Figure 3.10, visually also, it is seen that snowfall and rainfall have approximately similar appearances in AMSU-B images, and therefore are not easily separable, in case of 12 January. This may be due to the fact that different precipitation systems have varying ice particle size, and it may
be change the observed brightness temperature in the raining area.

Figure 3.10: AMSU-B images on 12 January 2002 at 0408 GMT (0738 IRT) snowfall IMO for Mashhad (MAS) at 0720 IRT snow fall, for Bandar Abbas (BAN) at 0730 heavy rain and for Kerman (KER) at 0720 rain has been reported.
Generally, depression of brightness temperature is largely cased by precipitation-sized ice particles [78]. Therefore, this difference, in snowfall region with respect to rainfall region, in case of 07 and 12 January, may be due to larger scattering by ice particles than that for raindrops as well as due to more intense of ice particles, which are larger in snowfall condition. On the other hand, absorption of rain drop is much larger than of ice particles. Thus, the thermal emission of the hydrometeors in rain regions may increase the brightness temperature in rainy area at frequencies of 150 and 176 GHz.

Despite the signatures of snowfall clearly can be seen at 150 and 176 GHz, but it is not separable from moderate rain fall (MR) in AMSU-B images. This may be due to large similarity between rainfall and snowfall in microwave regions.

3.1.5.4 Heavy Rain (HR)

The IMO reports indicate heavy rain for Shiraz (SHI) on 19 March 2002 at 0220 IRT and for Bandar Abbas (BAN) also on 12 January 2002 at 0720 IRT. The images for 12 January 2002 at 0738 have been presented in article 3.1.5.3 (Figure 3.10), and the images of four AMSU-B frequencies at 0236 in 19 March 2002 are presented in Figure 3.11. The cold areas (dark blue) on 150 GHz image, i.e. the north part of Bandar Abbas (BAN in Figure 3.10) and south west part of Shiraz (SHI in Figure 3.11), as well as south of Tehran (TEH in Figure 3.9), west part of Shiraz (SHI in Figure 3.8), in Tehran on 04 May 2001 (TEH in Figure 3.7) etc., are suggested to be showing the signatures of heavy rain. Note how only heavy precipitation areas are highlighted at 150 GHz only. These signatures clearly can be also seen as cold spots on 89 and 176 GHz images (Figures 3.11a and c, as well as Figures 3.10a and c). The
appearance of heavy rain, at 176 GHz, is somewhat similar to that on 89 GHz. It can be seen that signatures of heavy rain regions appears very cold at 150 GHz (e.g. ~200 K in case of 12 January and 196 in case of 19 March). While at 89 and 176 GHz, it is ~230 and ~235 K in case of 12 January and ~225 and ~238 in case of 19 March, respectively. The proper size of heavy rain regions may be determined at 150 GHz, which is much larger than the cold area on 89 and 176 GHz (Figure 3.10b and 3.11b). The small cell, which is appeared as very cold, at also in 89 and 176 GHz on east of Bandar Abbas in Figure 3.10, is suggested to be signature of light thunderstorm or heavy rain from Cumulonimbus.

As the 180 GHz weighting function peaks at 500 hPa (~5.5 km) and heavy rain, in mid-latitude and winter season mostly generated from the Nimbostratus (Ns) clouds, which are formed below 5 km. therefore, mostly heavy rain cannot be seen in 180 GHz (Figures 3.10d). Frequency 182 GHz that weighting function peaks at around 400 hPa (~9 km), also cannot detect the signatures of heavy rain regions. In brief, those heavy rain, which are generated from Ns clouds (e.g. in Bandar Abbas in case of 12 January), cannot be seen in 180 and 182 GHz at all, while those, which are generated from Cumulonimbus (Cs) clouds (e.g. in Shiraz in case of 19 March), may seen in 180 GHz but cannot be seen in 182 GHz. In case of 12 January 2002 that the signatures of heavy rain is not much cold in 176 GHz and not seen in 180 GHz also. It is suggested of rainfall mostly from clouds with relatively warm tops (Nimbostratus) and in which scattering by rain drops alone is masked by heavy cloud liquid water at higher level.

Heavy rain adds water on the land surface, results decreases the surface emissivity, increases the scattering, and therefore, gives more cool brightness tempera-
tures, in 89 as well as 150 GHz, when compared to the dry land. On the other hand, heavy rain comprises more intense of larger water droplets as well as ice particles in

Figure 3.11: The AMSL-B images for all five channels on 18 March 2002 at 2254 GMT (0236 IRT on 19 March 2002). The Shiraz station is indicated with "SHI" letters.
the lower and mid troposphere, where it is generated and falling. Therefore, causes more scattering of microwave frequency, which are weighted at mid troposphere such as 176 GHz, results cool brightness temperature for this frequency also.

Although, the time differences between the AMSU-B measurements and IMO reports are only 16 and 18 minutes in case of 19 March and 12 January, respectively, rapidly developing heavy rain may have significantly changed their state within this time frame. For example, in Bandar Abbas itself, on 12 January may be signatures of rain can be seen, which is reported at 0820 (Figure 3.10). The AMSU-B image of channel 150 GHz, on 12 January 2002, also show that the heavy rain area is extended to Sirjan city (SIR), about 300 km North-east of Bandar Abbas, see Figure 3.10, where the local reports show heavy rain at 07.00 to 08.00 IRT.

Signatures of heavy rain is appear to be very cold at frequencies below 180 GHz, in some cases may be seen at 180 GHz also, but never seen in 182 GHz images. Frequency of 150 GHz may show proper size of heavy rain regions.

3.1.5.4 Thunderstorms

Signature of thunderstorms (TS) is drastically different from the other meteorological situations of Table 3.1, i.e. is present in all AMSU-B channels. For example, the IMO reports on 08 December 2001 at 0220 IRT and on 04 May 2002 at 0320 IRT show thunderstorm for Ahwaz and Tehran stations, respectively. The AMSU-B images (for all five channels) for 08 December 2001 at 0221 IRT and for 04 May 2002 at 0336 IRT are presented in Figures 3.12 and 3.13, respectively. The Tehran and Ahwaz stations are indicated with "TEH" and "AHW" on the images, respectively (Figures 3.12 and 3.13). As it is seen from these Figures, the signature of thunderstorm is present at all five AMSU-B channels and appears to be very cold at 150 and
176 GHz. The nominal brightness temperature sounded for 182, 180, and 176 GHz, in saturated atmosphere, are ~ 235, ~ 240 K (corresponding to ice), and 260 K.

Figure 3.12: AMSU-B images on 08 December 2001 at 0221 UTC, a) 89 GHz, b) 150 GHz, c) 176 GHz, d) 180 GHz, and e) 182 GHz. The Alwaz station that thunderstorm reported at 0220 UTC is indicated with “AHW” on the images.
corresponding to both water and ice [24]. Therefore, the 180 and 182 GHz responds strongly only when strong convection thrusts large ice particles substantially higher in

**Figure 3.13:** AMSU-B images on 04 May 2002 at 0336 IRT, a) 89 GHz, b) 150 GHz, c) 176 GHz, d) 180 GHz, and e) 182 GHz. The Tehran station that thunderstorm reported at 0320 IRT is indicated with "TEH" on the images.
the atmosphere. All cases discussed previously could not appear at these high frequencies. This sensitivity to convective thunderstorm strength is suggested in Figure 3.12 and 3.13, where thunderstorms in Tehran (TEH) and Ahwaz (AHW) are imaged by all AMSU-B channels. Note how only the strongest thunderstorms cells are highlighted at 182 as well as 180 GHz (Figure 3.12d-e and 3.13d-e). The sharp edges bounding likely precipitation zones isolated smaller cold convective cells most evident at 150 and 176 GHz (Figure 3.12b-c and 3.13b-c).

Therefore, at frequencies above 176 GHz, the vertical extent of thunderstorm gives altitude distribution of cloud mass, and the horizontal extent gives the thunderstorm-precipitation area. The coldness may roughly indicate the rain intensity. For example, the appearance of thunderstorm area on Fig 3.12 at 150 and 176 GHz shows that most heavy rainfall should have occurred in the south and south-eastern of Ahwaz, around Shadegan (SHA on Fig 3.12). Indeed it did happen, because on December 08, 2001, 14.6 and 37 mm rain falls are reported for Ahwaz and Shadegan stations, respectively.

Therefore, the AMSU-B images are useful tool for detecting heavy precipitation areas at the meso-scale, which may permit monitoring the location and also the rain boundaries that it may further allow for tracking of thunderstorms. Here the AMSU-B surely has an edge over other satellite imagery.
3.5 QUANTITATIVE SIGNATURES OF HYDROMETEOR

Though the visual inspection (section 3.4) is quick for operational forecasting, it will always be better to give a quantitative measure of the fussy statements about coldness and warmness brightness temperature. This section will give the quantitative microwave signatures of the hydrometeors with more details as observed in AMSU-B data.

3.5.1 The Measurements

For the purpose of quantitative signatures first, the average brightness temperatures are calculated for 5 pixel at a station (see Table 3.1) each AMSU-B frequency at selected longitude, latitude station position in images, separately for each of 183 events of Table 3.2. Then, for each specific event an averaged overall stations is calculated and presented in Table 3.2 (along with corresponding standard deviations). For example, 274±2 is the average of 28 5 pixels (see table 3.2) for clear sky (CS); 28 events from all stations on 89 GHz channel with rms deviations σ = 2.

For better visualization, the variations of brightness temperature with frequency-channels, for all these ten situations (of Table 3.2), are plotted in Figure 3.16. From Fig 3.16 it can be seen that the graph is sufficiently different, for each of these situations. Therefore, these graphs can be considered as multi-spectral microwave sig-

<table>
<thead>
<tr>
<th>Freq. (GHz)</th>
<th>CS</th>
<th>SC</th>
<th>UD</th>
<th>UM</th>
<th>LM</th>
<th>LR</th>
<th>MR</th>
<th>SF</th>
<th>HR</th>
<th>TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>89</td>
<td>274±10</td>
<td>225±10</td>
<td>267±6</td>
<td>266±8</td>
<td>259±7</td>
<td>256±6</td>
<td>253±6</td>
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<td>239±7</td>
<td>202±25</td>
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<tr>
<td>150</td>
<td>278±9</td>
<td>232±9</td>
<td>272±6</td>
<td>269±8</td>
<td>262±8</td>
<td>255±8</td>
<td>248±10</td>
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<td>240±4</td>
<td>240±3</td>
<td>234±3</td>
<td>202±24</td>
</tr>
</tbody>
</table>

Table 3.4: Average $T_B$ (K), over all stations, for the ten weather situations.
natures for the different types of hydrometeors, i.e., weather situation (Table 3.2) along with clear sky condition, beyond Is. Hence, they are separable. However, there are some "not clearly separable" cases as well (all this is discussed below in details).

3.5.2 Classification of Hydrometeors and Signatures Indications

The signature of each of weather situations (hydrometeors), which are presented in Table 3.2, is different from others as stated above (Fig. 3.14). To find out still better discrimination of these hydrometeors, Figures 3.15-3.19 summarizes the averages of brightness temperatures for each of these ten meteorological situations for each frequency-channel separately. Data-scatter (bars around the mean) for TS is larger than the other events (at all frequencies). The ranges of BT, for TS, is large: 81 K (145-226 K) at 89 GHz and 71 K (151-222 K) at 182 GHz, while this range, for LM, is only 16 K (249-265 K) at 89 GHz and 30 K (237-267 K) at 182 GHz (Figure 3.15 and 3.19). The figures indicate that although some classes, e.g. HR with brightness temperature between 200 and 220 K at frequency 150 GHz, (Fig 3.16),

![Fig 3.14: The T, variations for five AMSU-B frequencies channels in different passes on Iran region. The IRT denote to the Iran local time. (SIRT)](image-url)
are relatively well separated only at some frequencies. It is obvious that discrimination (between these meteorological situations can not be accomplished from brightness temperature at any one of five AMSU-B frequencies only. But by combination of two (or more than two) frequencies these classes may be distinguishable. For example, SC can be distinguished from other situations by combination of channels 89 and 176 GHz. Because, SC is very cold at 89 GHz (brightness temperature less than 225 K) and it is warm at 176 GHz; (brightness temperature more than 255 K) (Figures 3.15 and 3.17 & also Fig. 3.10). Note that this is not so for any of the other nine events.

However, from these Figures it can be seen that all of these ten weather situations (simultaneously together) are not earlier distinguishable at any one of the five AMSU-B channels data only. By considering the brightness temperature values at 89 GHz (along with 150 GHz) in Figure 3.14, these ten weather situations can be conveniently classified into three major classes viz. (I) Heavy precipitation and snow cover class (TS, HR and SC), (II) Moderate precipitation class (LR, MR, and SF) and (III) Non-precipitation class (LM, UM, UD, and CS).

The distinguishing points are: (a) $T_B$ at 89 and 150 GHz as well as 176 GHz, (b) slopes of average $T_B$ between 89 and 150 GHz and (c) cross over of average $T_B$ curves between the frequencies, such as 89 and 150 GHz, and also between the lower
Figure 3.16: Range of brightness temperature (K) for different types of hydrometeors (weather events) at frequency of 150 GHz (channel 17 of AMSU-B).

Figure 3.17: Range of brightness temperature (K) for different types of hydrometeors (weather events) at frequency of 176 GHz (channel 20 of AMSU-B).
Figure 3.18: Range of brightness temperature (K) for different types of hydrometeors (weather events) at frequency of 180 GHz (channel 19 of AMSU-B).

Figure 3.19: Range of brightness temperature (K) for different types of hydrometeors (weather events) at frequency of 182 GHz (channel 18 of AMSU-B).
frequencies (89, 150 GHz) with respect to upper frequencies (180, 182 GHz).

3.5.2.1 Heavy Precipitation

The class I (group), which is considered as heavy precipitation hydrometeors, includes TS, HR, and SC with normally the lowest brightness temperature surely at 89 GHz. For example, the $T_b$ (89 GHz) value, for this group which is related to HR, is highest about 243 K (related to HR) and the lowest one is about 145 K (related to TS, Figure 3.14 & 3.15). At 150 GHz the highest value of $T_b$ for this class, is about 240 K (for SC), and the lowest one is around 125 K (related to TS). While TS and HR are still separable at 150 GHz, the SC mixed up with the second class (Figure 3.16). However, at frequencies 176 GHz and above HR and SC are converged to similar values as class 2 and 3. Note however that TS is clearly separable at all five AMSU-B frequencies, from all other events (The signatures are discussed, in more details in next article and Fig. 3.20).

3.5.2.2 Moderate Precipitation Hydrometeors

The class II, which is mentioned above and composed of moderate to low precipitation hydrometeors (SF, MR, and LR), have moderate $T_b$ values at all frequencies. The other specification of this class is that they have negligible slopes of average $T_b$ from 89 to 150 GHz (Figure 3.14). A maximum difference in $T_b$ from 89 to 150 GHz is -5K (for MR) and minimum of that is only -1 K (for LR). All events of this class have similar ranges variation of brightness temperature at all frequencies. For example, the highest $T_b$ value (at 89 GHz), for this class, is about 266 K and the lowest one is about 235 K (at 150 GHz they have slightly colder range of brightness temperatures than 150 GHz, e.g. the highest $T_b$ (150) value, for this class, is about 262 K, and the lowest one is around 232 K and average $T_b$ of this class is limited
between 255 and 280 K at 176 GHz (Figure 3.15-3.17). At Frequency of 176 GHz except LR, which slightly mixed up with LM in class III, class II are separable from class III.

3.5.2.3 Non-precipitation Hydrometeors

The class III contains non-precipitable hydrometeors (LM, UM. UD. and CS) from which no precipitation is expected. The average brightness temperature, for class III, are lowest and with a wide range between 255 and 295 K at 89 GHz (than for class III). The non-precipitating hydrometeors show slight rise from 89 to 150 GHz, but otherwise, for the other frequencies, it is same as lower / medium precipitating hydrometeors in class II.

As it is seen, the non-precipitating hydrometeors, all are having similar trend for channel-wise $T_b$ variation i.e. slight rise from 89 to 150 GHz, then a major rise up to 176 GHz, followed by a continuous fall up to 182 GHz.

3.5.3 Signature Discussions

The signatures of above mentioned three classes, in AMSU-B data, are described in more details and discussed, in the following articles. For convenience of discussion and better visualization of similarities and dissimilarities between these classes, the differences in average brightness temperature values between two successive frequency channels $\nu_1$ and $\nu_2$, which may be more useful, are defined as:

$$\Delta T_h(\nu_1, \nu_2) = T_h(\nu_1) - T_h(\nu_2)$$

Table 3.5 shows the calculated values between $\Delta T_h(\nu_1, \nu_2)$ for all events in Table 3.4.

The calculated differences (slopes) in Table 3.5 clearly show that:

a) The $\Delta T_h(150, 89)$ for all precipitating hydrometeors are negative, while
for non-precipitating hydrometeors it is positive.

b) The $\Delta T_h(150, 89)$ increases with increase of intensity and concentrations of hydrometeors (LR ~1, MR ~5, HR ~23, adn TS ~29). i.e. the channel 150 GHz more responsive to water droplet (due to scattering) and becomes colder and colder from LR to TS.

c) The $\Delta T_h(176, 150)$ for all situations is positive and is approximately similar for all situations, except TS which shows the least change (12K) (Table 3.5). Thus the channel 176 GHz can not see the rain, due to its high altitudes weighting functions except under convection thunderstorms, which is extended up those altitudes. On the other hand, channel 150 GHz become cold due to more scattering due to water droplets and ice crystal. At ~2 to 3 km, itself scattering becomes more important as rainfall intensity increases, so that the $\Delta T_h(176, 150)$ also increases positively (not only as for $\Delta T_h(150, 89)$) with increasing rain intensity (except TS) up to some maximum value for HR.

d) Looking at $\Delta T_h(180, 176)$ and $\Delta T_h(182, 180)$, it is seen that the responses of all three water vapour channels to cloud (UD, LM), rain (LR, MR), ice crystals (UM), snowfall (SF), are all negative (except HR & TS) and that there is decrease magnitude of $\Delta T_h(182, 180)$ or

<table>
<thead>
<tr>
<th>Class</th>
<th>Non precipitation Hydrometeors</th>
<th>Precipitation Hydrometeors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_h(v_1, v_2)$</td>
<td>CS</td>
<td>SC</td>
</tr>
<tr>
<td>$\Delta T_h(150, 89)$</td>
<td>+4</td>
<td>+7</td>
</tr>
<tr>
<td>$\Delta T_h(176, 150)$</td>
<td>+22</td>
<td>+37</td>
</tr>
<tr>
<td>$\Delta T_h(180, 176)$</td>
<td>-27</td>
<td>-10</td>
</tr>
<tr>
<td>$\Delta T_h(182, 180)$</td>
<td>-21</td>
<td>-16</td>
</tr>
</tbody>
</table>

Table-3.5: Calculated values average differential brightness temperature, between two successive frequency channels of $v_1$ and $v_2$, for all meteorological situations of Table 3.1.
The response of water vapour channels to heavy precipitating hydrometeors like HR and TS give positive values of $\Delta T_n(180,176)$, while the $\Delta T_n(182,180)$ have a negative value for HR and positive values for TS.

3.5.3.1 Class I: Signature Differences in TS, HR and SC

Out of the events of this class, except SC which is non-precipitating hydrometeor, other two (HR and TS) are having heavy precipitating hydrometeors. Their multi-frequency signatures are more clearly presented in Fig 3.20. At 89 GHz, the $T_b$ values are showing that TS is the coldest, next is HR and SC is warmest. For frequencies above 150 GHz, HR and SC are following similar variations of Brightness Temperature except that HR is shifted to the colder values by $\sim 10K$. Between 89 and 150 GHz HR and SC have a cross over: $T_b(89) > T_b(150)$ for HR, and $T_b(89) < T_b(150)$ for SC. From graphs of average $T_b$ (Fig. 3.20) it can be seen that signature differences, for the events of this class, are very clear at 176 GHz as shift in brightness temperature and convex / (Figure 3.20). At upper frequencies TS has opposite trend with respect to SC. TS is continually increasing at all frequencies above 150 GHz, while for SC from 89 to 176 GHz there is an increase and then from 176-182 a decrease. HR has similar trend as SC except that for HR from 176 to 180 GHz there is slight increase (instead of decrease for SC). At 182 GHz, HR and SC are converged to the similar values. As can be seen, the maximum fall appears between frequencies 150-176 GHz. On the other hand, $T_b$ variations for TS show fall from 89 to 150 GHz, and then smooth increase up to 182 GHz. Although the 150 GHz is good frequency for discriminating the TS from HR and SC, but it is not useful for discriminating of HR from
However, at frequencies 176 and as well as 180 GHz, these three events are clearly separated.

The 150 GHz frequency shows very cold brightness temperature for TS and HR, because thunderstorms and heavy rain mostly comprise of large water vapour droplets and as well as ice particles at mid-level of troposphere, which scatter microwave at low frequencies also. It is more so for TS than HR.

![Figure 3.20: The average values of brightness temperatures as a function of frequency-channel for three events of group I; SC, HR, and TS.](image)

### 3.5.3.2 Class II: Signature Differences in SF, MR and LR

The SF, MR, and LR, which comprise the medium intensity precipitating hydrometeors, belong to class II. All are having the average ground $T_{bg}$ (at 89 and 150 GHz) of medium level i.e. below $T_{bg}$ of LM (Fig 3.14) but more than Class I. Their
Multi-frequency mean variations i.e. signature curves (along with LM for the reference) are presented in expanded form in Fig 3.21.

It can be seen from these three graphs of group II that they are not as clearly differentiable as for class I. Some reasons for similarities and differences may be pointed out. In SF, $T_B$ is depressed due to scattering loss by ice particles which reaches an average value of approximately 248 and 244 at 89 and 150 GHz, respectively. Increase of average of $T_B$ at 89 GHz for LR (256 K) and MR (253 K), may be due to emission from water vapour at low level of the troposphere. Similarly, the slight decrease of $T_B$ from LR to MR may be due to scattering loss by larger water droplets in the MR rain. The similar response of water vapour channels (176-182 GHz) to rain and snow shows the “cold” rain (the layer of above rain are composed ice crystals), which is always happening in Iran region. These points may be informative about this class and useful in discussion below.

(a) The average $T_H$ for SF, MR, LR, and LM, at 89 and 150 GHz, are successively increasing from cold to warm. (b) The main signature of this class II is fall in $T_B$ from 89 to 150 GHz [with respect to class III]. This is followed by rise up to 176 and again a linear fall to 182 GHz (through 180 GHz). (c) Although Figures 3.15-3.19 show that the events of this class are not separable from each other at all five AMSU-B frequencies but Figure 3.21 as well as Figure 3.14 shows that the LR may be separated from SF and MR at frequency 176 GHz by their cross over in addition to shifts at $T_H$ at 89 GHz. (d) Signatures of SF and MR have maximum ambiguity with only one plus point, that these two curves cross-over at lower and higher altitudes, i.e. $T_B(150)_{SF} < T_B(150)_{MR}$ but $T_B(176)_{SF} > T_B(176)_{MR}$, whereas $T_B(182)_{SF}$ and $T_B(182)_{MR}$ are converged to similar values.
The AMSU-B signatures do not distinguish between cloud ice (MR) and precipitating snow particles (SF). Small cloud ice particles, such as are found in ordinary non-precipitating cirrus, are not invisible to the AMSU-B lowest frequency (89 GHz), while the large, dense ice particles found in cumulonimbus anvils affects the 150 as well as 176 GHz of AMSU-B channels.

In this class II all have negative slope between 89 and 150 GHz (T_B(150 GHz) < T_B(89 GHz)), because of low level hydrometeors at ~ 3 Km, (unlike class III, no ice particles or droplets at that level the non precipitating class).

3.5.3.2 Class III: Signature Differences in LM, UM, UD and CS

The events of this group, which comprise LM, UM, UD and CS, are all non-precipitating hydrometeors, and have ground T_g above that of LM (on 89 GHz). From Figure 3.17 it can be seen that the events of this class (except LM, which is
mixed up with I.R from class II), can clearly separate from class II as all these (class III) curves are having higher $T_i$ at all frequencies. The $T_i$ at 176 is less than 275 K ($T_i(176)_{\text{II}} < 275$ K) for class II, while for class III it is higher than 280 K ($T_i(176)_{\text{III}} > 280$ K (see Fig. 3.17). Multi-frequency signatures of four events, in this class, are presented in expanded form in Fig 3.22. From this Figure it can be seen that in general the curves are not clearly separate (same as for class II) beyond error bars. But some points may be noted for average value.

(a) At 89 and 150 GHz, LM, UM, UD, and CS have successively increasing mean $T_i$, from 259, 266, 267, 274 K (Table 3.2), though not clearly (error bar long, large about 7 to 10 K).

(b) As indicated above, general $T_i$ variation, for the events of this group, is slight rise, from 89 to 150 GHz (as against class II when it is oppo

Figure 3.22: The average values of brightness temperature as a function of channel-frequency for three events of group II-2: CS, UD, and UM, along with LM for the reference.
site, a fall) and then a major rise, from 150 to 176 GHz, and then a major fall, from 176 to 182 GHz (Table 3.5).

(c) As in case of SF and MR, the LM-UM and UD-SC curves give ambiguous signature. Because, at 176 GHz, they have less than $\sigma$ differences (Fig. 3.17 and Fig. 3.22).

(d) Despite the nearly same $T_B$ at frequencies 89 and 150 GHz, for UD and UM, the $T_B$ signatures are remarkably (beyond $\sigma$) different at frequencies near 183 GHz. Because of scattering by ice particles. UM case yields a near linear decrease in $T_B$ to only 263 and 243 K at 180 and 182 GHz, respectively. While this decrease, for UD, is 278 and 261 at the same frequencies. The slope of this decrease turns out to be strongly dependent on the size and concentrations of ice particles.

However, that itself becomes the signatures to distinguish UM and UD because the curves show cross over $[T_B(89 and 150)]_{LM} < T_B(89 and 150)]_{UM}$ as well as $(T_B(89 and 150))_{UD} < T_B(89 and 150)]_{CS}$, whereas $T_B(180 and 182)]_{LM} > T_B(180 and 182)]_{CS}$, and $T_B(180 and 182)]_{UM} > T_B(180 and 182)]_{CS}$.

3.5.4 A Case Study (of a Thunderstorm, Heavy Rain, Light Rain and Clear Sky etc.)

Finally, we have selected one day on which thunderstorms and rain have been reported and we have calculated $T_B$ for a scan line which crossed through thunderstorm at Ahwaz. Figure 3.23 shows the AMSU-B $T_B$ measurements at different frequencies along a scan line, from A (30.82 N, 46.67 E) to B (29.67 N, 55 E) shown in Figure 3.24, that crosses through the center of the thunderstorm, which is reported in
Ahwaz at 0230 IRT. Note that Ahwaz is slightly above not of Persian Gulf (Fig. 3.1) and this scan is not through Gulf. This is not very clear in Fig. 3.24 (89 GHz) image. Note also how Ahwaz gives detailed weather situation (shape, size and surrounding), than the ground based station report (this storm is on chain of storms).

Figure 3.23 shows that brightness temperature minima was at present in all frequent channels (Fig. 3.23 gives Radar-like vertical profile). However, the maximum $T_d$ depression occurred at 150 GHz, which reached to a value of less than 115 K. The minimum temperature depression occurred at 89 GHz, which was less than 63 K, as compared with more than 115 K and 104 K at 150 and 176 GHz, respectively. These values indicate the presence of a large number of frozen hydrometeors. The 150 GHz channel is more sensitive to ice particles and has large scattering parameters in comparison with 89 GHz.

![Figure 3.23: Brightness temperature of Five AMSU-B channels across of thunderstorm, which is reported for Ahwaz (31.28 N, 48.72 E) on 08 December 2001 at 0230 IRT.](image-url)
For better visualization, the $T_b$ variations for window and weak water vapour absorption (89 and 150 GHz) are separately presented in Figure 3.25 and those for water vapour channels are given in Figure 3.26. As is seen from Figures 3.25 and 3.26, the location of the maximum of depression (49.3° E) does not correspond to the Ahwaz station (48.72° E). However, large ice particles must have been present near the center of thunderstorm and must have produced a large amount of rainfall, over much wider area of ~.

In this case study, the area around 46.6° E to 47.8° E shows the clear sky condition, which is indicated by $T_b$ about 265 and 273 at 89 and 150 GHz (Figure 3.23). It corresponds to that one indicated in Figure 3.3 for midnight passes in clear sky conditions (Figure 3.3).

At 52.3° E these appear to be one more rainy area (not reporting station), because the $T_b$ for both channel 89 and 150 GHz, had decreased to a value of about 244-245 K. $T_b$ of 89 GHz is very slightly colder than 150 GHz (Fig. 3.25). As $T_b$ at 176 and as well as 180 GHz slightly depressed than surrounding (e.g. to a value of 264 and 253 K, respectively), while channel 182 GHz is not effected (Fig. 3.26), by
Figure 3.25: Brightness temperature of 89 and 150 GHz channels across of thunderstorm, which is reported for Ahwaz (31.28 N, 48.72 E) on 08 December 2001 at 0230 IRT.

Figure 3.26: Brightness temperature of three water vapour channels (176, 180 and 182 GHz) across of thunderstorm, which is reported for Ahwaz (31.28 N, 48.72 E) on 08 December 2001 at 0230 IRT.

Comparing this condition with Fig. 3.20, one can see that it is the signatures of cold heavy rain regions, which is extended up to about 7 - 8 km altitudes.
The area around 53.3 E to 53.9 E which shows the depression at lower channels (89 and 150 GHz) show the signatures of warm rain or light (warm rain refers to a rain without ice layer above that), because of that the water vapour channels, which are weighted above 700 hPa, can not detect the warm rain regions (Figure 3.25 and 3.26). Not that this analysis is done sitting in India (and could have been done in few minutes of the “weather” (pass-dependent), if we had a NOAA receiver, which Iran local people won’t have known in such a detail (without satellite data). Probably only Radar may have done it. Surely we can tell many more facts about this weather events, looking at Fig.3.24 (This won’t have been that vivid using visual inspection of last article 3.4). This point is very important for air-route diversion / plannin.