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15.	**Abstract:** Investigation of cloud top temperature (CTT) and its diurnal variation is highly reliant on high spatial and temporal resolution satellite data, which is lacking over the Indian region. An algorithm has been developed for detection of clouds and retrieval of CTT from the geostationary satellite INSAT-3D. These retrievals are validated (inter-compared) with collocated in-situ (satellite) measurements with specific intent to generate climate-quality data. The cloud detection algorithm employs nine di_erent tests, in accordance with solar illumination, satellite angle and surface type conditions to generate pixel-resolution cloud mask. Validation of cloud mask with cloud-aerosol lidar with orthogonal polarization (CALIOP) shows that probability of detection (POD) of cloudy (clear) sky is 81% (85%), with 83% hit rate. The algorithm is also implemented on similar channels of moderate resolution imaging spectroradiometer (MODIS), which provides 88% (83%) POD of cloudy (clear) sky, with 86% hit rate. **Key Words:** Cloud cover, INSAT-3D, NICES, ECV			

List of Abbreviations

BT	-	Brightness temperature
BT_{MWR}	-	BT measurements from IR radiometer of MWR
BT_{TIR1}	-	BT at TIR1 channel of INSAT-3D
BTD	-	Brightness temperature difference
CALIPSO	-	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CC	-	Cloud Cover
ECV	-	Essential Climate Variable
GCOS	-	Global Climate Observing System
HLO	-	High Level Opaque clouds
INSAT-3D	-	Indian National geostationary Satellite – 3D
LLO	-	Low level opaque clouds
MAE	-	Mean Absolute Error
MBE	-	Mean Bias Error
NICES	-	National Information system for Climate and Environment Studies
NRSC	-	National Remote Sensing Centre
PC	-	Partial clouds
RMSE	-	Root Mean Squared Error
STC	-	Semi-transparent cirrus cloud

Cloud Top Temperature from INSAT-3D

1. Abstract

Investigation of cloud top temperature (CTT) and its diurnal variation is highly reliant on high spatial and temporal resolution satellite data, which is lacking over the Indian region. An algorithm has been developed for detection of clouds and retrieval of CTT from the geostationary satellite INSAT-3D. These retrievals are validated (inter-compared) with collocated in-situ (satellite) measurements with specific intent to generate climate-quality data. The cloud detection algorithm employs nine different tests, in accordance with solar illumination, satellite angle and surface type conditions to generate pixel-resolution cloud mask. Validation of cloud mask with cloud-aerosol lidar with orthogonal polarization (CALIOP) shows that probability of detection (POD) of cloudy (clear) sky is 81% (85%), with 83% hit rate. The algorithm is also implemented on similar channels of moderate resolution imaging spectroradiometer (MODIS), which provides 88% (83%) POD of cloudy (clear) sky, with 86% hit rate.

2. Introduction

Cloud cover (CC) is identified as an Essential Climate Variable (ECV) by Global Climate Observing System (GCOS). Accurate information of CC and its spatial and temporal variations is of paramount importance for climate studies. Indian national geostationary satellite, INSAT-3D, provides a unique opportunity to observe continuously over Indian subcontinent and surrounding regions at 4km spatial and 30mins temporal resolution. The datasets from INSAT satellite series are being widely used for studies on evolution and variation of clouds and their properties (*Gambheer AND Bhat, 2000; Roca and Ramanathan, 2000; Roca et al., 2005*). As part of National Information System for Climate and Environment Studies (NICES) program of ISRO, a new integrated algorithm was developed for retrieving CC at pixel level (i.e., 4km x 4km resolution) from the Imager on-board INSAT-3D with specific intent to generate climate quality data. Reliability of the retrieved CC was estimated through inter-comparisons with collocated observations from ground-based radiosonde and space based active sensor, Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard Cloud-Aerosol Lidar and Infrared Pathfinder satellite Observations (CALIPSO). The reported statistics are comparable with that of the same product from other satellites over different regions of the globe (*Hanna 2008; Hamann et al., 2014; Taylor et al., 2017; Huang et al., 2019*). Since the intention of retrieving the CC is to generate climate quality database, it is critical to assess reliability of the product in terms of GCOS standards (https://gcos.wmo.int). As per GCOS, CC product is recommended to be at 50km spatial and 3hourly temporal resolution with an uncertainty within 0.05%.

3. Data and Methodology

3.1 Data

Imager onboard the Indian geostationary satellite, INSAT-3D provides observations over the Indian region at a temporal interval of 30 minutes (at HH:00 and HH:30) with visible (VIS), shortwave infrared (SWIR), mid-wave infrared (MIR), water vapor (WV) and thermal infrared (TIR1 & TIR2) channels (Katti et al., 2006). Specifications of these channels are given in Table 1. Present study uses level 1C, Asia sector product (ASIA_MER_L1C) from INSAT-3D Imager over India and surrounding regions bounded by 44.5°E-105.5°E and 10°S-45.5°N with spatial resolution of 4km, which is available through the SAC/ISRO web portal, MOSDAC (https://www.mosdac.gov.in). The present algorithm for retrieving CC makes use of VIS, MIR, WV, TIR1 and TIR2 channels. Spatial resolutions of VIS and WV channels are 1km and 8km respectively, whereas those of MIR and TIR channels are 4km. In order to maintain uniformity, measurements from VIS and WV channels are also provided at 4km spatial resolution to match with that of MIR and TIR channels.

Table 1. Specifications of INSAT-3D Imager channels.

Channels	Spectral Range (μm)	Central wavelength (μm)	Resolution (km)
Visible (VIS)	0.55-0.75	0.65	1.0
Short-wave Infrared (SWIR)	1.55-1.70	1.62	1.0
Mid-wave Infrared (MIR)	3.80-4.00	3.9	4.0
Water Vapour (WV)	6.50-7.10	6.8	8.0

Thermal Infrared I (TIR1)	10.3-11.3	10.8	4.0
Thermal Infrared II (TIR2)	11.5-12.5	12.0	4.0

3.2 Methodology

As a part of the NICES program of ISRO, an integrated algorithm is developed for identification of clouds from INSAT-3D Imager. Figure 1 depicts comprehensive flow chart of the developed algorithm.

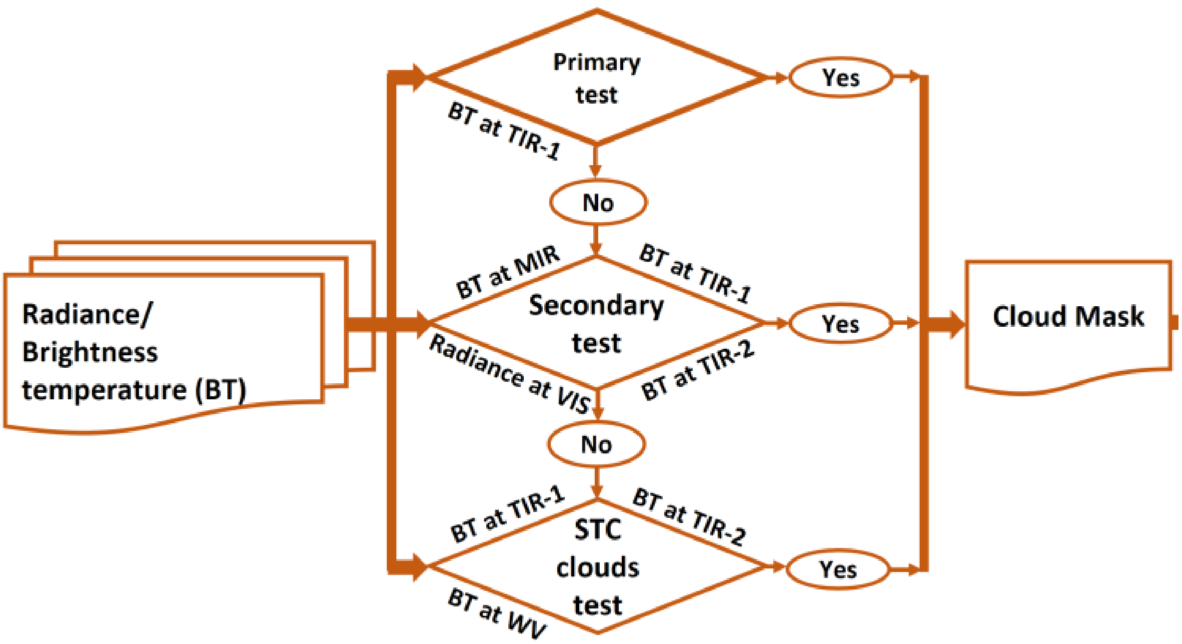
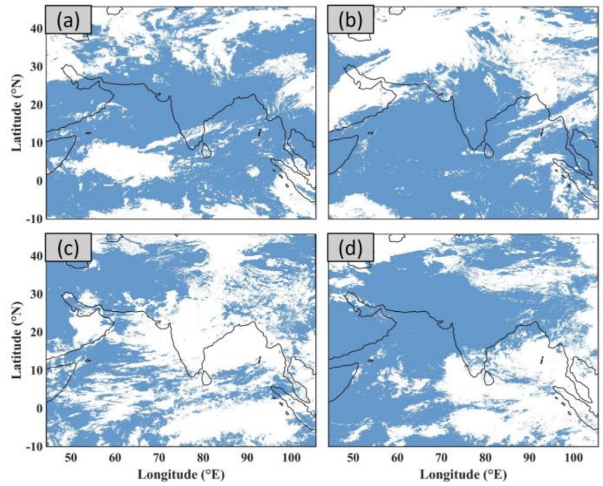


Figure 1: Flow chart depicting the algorithm for retrieving cloud top temperature from INSAT-3D Imager (Detailed flow charts and descriptions of methodology are available in *Lima et al., Remote Sensing, 11, 2811, doi: 10.3390/rs11232811, 2019*).

3.3 Retrieval of Cloud Cover (CC)

CC is retrieved from INSAT-3D Imager at 4km (CC4km) spatial resolutions. Detailed information on CC4km retrieval is available in Lima et al., 2019 and Lima et al., 2020; however, it is briefly described here (as shown in Figure 1). The detection scheme contains a series of hierarchical decision tree tests, which exploit differences in spectral signatures of clouds and underlying surfaces. Each pixel undergoes a subroutine that provides information of surface type (ocean and land) and solar illumination conditions (day, night, twilight and sunglint). Solar elevation angle (δ_Sun) is used to describe solar illumination conditions; where it is considered as day time when δ _Sun > 10, night when δ _Sun = 0 and twilight when 0 < δ _Sun < 10. This classification is critical in defining proper thresholds for cloud detection, especially over the Indian region where surface characteristics are highly heterogeneous in nature with di_erent geo-spatial features. The cloud detection algorithm involves three set of tests: a primary test (for all types of surfaces and solar illumination conditions), a combination of four (three) secondary tests during day/twilight (night) and a combination of two tests for identifying STC clouds. Successful performance of this cloud detection algorithm relies on the selection of proper thresholds for various spectral tests. The threshold values, which better suit to local atmospheric and surface conditions, used in this study are either generated or adopted from previous studies. The primary test uses different criteria for the thresholds over land and ocean and is, in general, capable of identifying most of the cloud pixels with very high confidence. Secondary tests are applied only on those pixels, which are not identified as cloudy by the primary test. In the secondary test, a pixel is considered as cloudy if it satisfies at least three (two) out of four (three) tests during day time/twilight (night time) conditions. Though primary and secondary tests are sufficient enough to identify most of the clouds, these tests are observed to fall short in detecting STC clouds due to high transparency at visible and IR wavelengths. Hence, the present algorithm uses additional two tests for detecting STC clouds from the remaining pixels.Cloud pixels, identified through the cloud detection scheme, are categorized into four classes; high level opaque clouds (HLO), low level opaque clouds (LLO), semi-transparent cirrus clouds (STC) and partial clouds (PC) and are then subjected to CTT retrieval accordingly. Further details can be found in published papers *Lima et al., 2019* and *Lima et al., 2020*. Figure 2 depicts cloud mask retrieved from the INSAT-3D Imager, by employing the present algorithm.



(i)

Figure 2: INSAT-3D retrieved (i) cloud mask at 07:30 UTC on (a) Jan 1 (winter season), (b) April 1 (pre-monsoon season), (c) Aug 1 (monsoon season) and (d) Nov 1(post-monsoon) of the year 2016. The blue and white colored areas in the figure (i) represent clear-sky and cloudy regions respectively (Figures are from Lima et al., Remote Sensing, 11, 2811, doi: 10.3390/rs11232811, 2019).

4. Validation of products

In order to provide weather and climate researchers more confidence on the products, quality of retrieved cloud cover (CC) is assessed through validation and inter-comparison using in-situ and other satellite measurements.

4.1 Validation of INSAT-3D retrieved CC with CALIPSO and MODIS:

In order to ensure accurate evaluation of generated cloud mask by implementing the present algorithm on INSAT-3D, collocated reference datasets are carefully prepared from CALIOP and MODIS. From CALIPSO 5 km cloud layer dataset, clear and cloud pixels for inter-comparison are identified by using feature classification flags at different atmospheric layers and their quality assessment. Accuracy of clear and cloud features from CALIOP is ensured by considering only those pixels with quality assessment (QA) value high (high value of QA is same as the CAD score > 70). Due to the multiple averaging resolution scheme adopted in the CALIOP product retrieval algorithm, the 5 km layer product includes layers with fundamental horizontal averaging distance of 5 km, an intermediate distance of 20 km and a maximum of 80 km. This leads to an overlap of features in vertical dimensions in the CALIOP data and such overlapping is avoided by considering only pixels with horizontal averaging of 5 km. After segregating highly confident clear and cloud pixels at each layer from CALIOP, a binary cloud mask is generated in which cloud pixels are those with at least one layer of confident cloud feature and clear pixels are those with all layers of clear feature. From the level 2 MODIS cloud product, only those pixels, which are classified as either confident clear or cloudy are considered for comparison in the present study. However, in order to perform inter-comparisons, collocated pixels are identified among INSAT-3D, MODIS and CALIOP by using the nearest neighbour approach with a maximum distance of 500 m separation between centers of the pixels, within -30 min temporal difference.

4.2 Implementation of INSAT-3D Algorithm on MODIS Channels

The developed cloud detection algorithm for INSAT-3D is applied on the radiance/reflectance data from comparable channels of MODIS. MODIS channels considered here are having central wavelengths at 0.645 µm, 3.9 µm, 6.715 µm, 11.03 µm and 12.02 µm, which are close to the VIS, MIR, WV, TIR1 and TIR2 channels of INSAT-3D respectively. Basically, MODIS provides reflectance at visible and radiance at remaining channels. In order to implement the present cloud detection algorithm on MODIS channels, radiances of all channels except 0.645 µm channel are converted to BT using Planck's equation. Other datasets used in the cloud detection algorithm, such as SST climatology and GTOPO30, are re-gridded to the spatial resolution of MODIS data. Finally, all tests in the present cloud detection algorithm are applied to MODIS channels, as they are implemented on INSAT-3D channels. The cloud mask thus generated, by implementing the algorithm on MODIS channels, is validated using reference dataset from CALIOP and MODIS.

(i)

Satellite/ Sensor	Hit Rate (%)	Cloudy Regions		Clear Regions	
		POD (%)	FAR (%)	POD (%)	FAR (%)
CALIPSO	83.12	81.42	18.21	84.57	15.76
MODIS	79.40	72.84	09.28	91.61	28.35

(ii)

Satellite/ Sensor	Hit Rate (%)	Cloudy Regions		Clear Regions	
		POD (%)	FAR (%)	POD (%)	FAR (%)
CALIPSO	85.99	87.67	10.40	83.24	19.62
MODIS	84.34	75.74	5.99	94.37	23.08

Table 2. (i) Algorithm implemented on INSAT-3D channels. (ii) Algorithm implemented on MODIS channels

5. Comparison of Cloud detection scheme

Comparison of INSAT-3D retrieved cloud mask using the current algorithm is carried out with collocated measurements from CALIOP and MODIS. Moreover, the developed cloud detection algorithm for INSAT-3D is applied on the radiance from comparable channels of MODIS and compared the output against the CALIOP data. Quantitative outcomes of the above analysis are presented in the form of statistical scores, namely; hit rate, probability of detection (POD) and false alarm rate (FAR). Hit rate is fraction of the correctly detected (in comparison with reference data) cloud and clear pixels out of the total number of pixels considered, whereas POD is fraction of the cloud/clear pixels detected with respect to the reference (CALIOP or MODIS) cloud/clear pixels and FAR is fraction of the falsely identified cloud/clear pixels out of the total number of detected cloud/clear pixels. Detailed information on cloud identification is available in *Lima et al., 2020*.

5.1 Comparison of INSAT-3D Retrieved Cloud Mask with CALIPSO Cloud Data

INSAT-3D detected cloudy and clear-sky regions agree with the CALIOP retrievals over India and surrounding regions for 83% of the time. As indicated by the POD values, 81% of cloud and 85% of clear-sky pixels in CALIOP products are detected as cloudy and clear-sky respectively by INSAT-3D with the present algorithm. Compared to CALIOP retrievals, 18% (16%) of clear-sky (cloud) pixels are identified falsely as cloudy (clear-sky) by the present algorithm, as indicated by the FAR values. The differences observed are mainly attributed to differences in sensor characteristics and sampling foot prints. CALIOP has a small footprint of 70 m diameter along its sub-satellite track, where it provides measurements at every 333 m, whereas INSAT-3D data used in the study are at a spatial resolution of 4 km x4 km. When an INSAT-3D pixel is partially clouded and CALIPSO passed through its cloud free portion, the former detects the pixel as partially cloudy and the latter does as clear, hence leading to an uncertainty in comparison. In order to examine performance of the current algorithm further, these results are compared with the reported comparison results of similar passive sensors with CALIOP retrievals.

Table 3: Inter-comparison of cloud mask algorithm applied to INSAT-3D imager data with clouds from the CALIOP sensor for one year from March, 2016 to February, 2017.

Hit Rate (%)	Cloudy Regions		Clear Regions	
	POD (%)	FAR (%)	POD (%)	FAR (%)
83.12	81.42	18.21	84.57	15.76

6. Conclusion

Satellite-based datasets of geophysical variables are crucial for climate research as they represent state of the Earth's climate system. These datasets are useful to examine climate and its variability as well as to fine tune atmospheric model developments. Climate quality data of CC are being generated from INSAT-3D satellite observations. Comparison of CC at pixel level (4km x 4km resolution) with MODIS and CALIPSO shows mean hit rate of 83%. The CC product currently generated is referred to as Version 2.0 and is disseminated through NICES web-portal of ISRO.

7. Description of Data

File Name (Daily) : XXX3D_L3_PP_4km_VVV02_DDDMMMYYYY
(X-Satellite, L-Level3, P-Product name, V-version, Y-Year, M-Month, D-Date)

Parameters	: CC
	:
Geographic Coverage	: 44.5°E-105.5°E and 10°S-45.5°N
Unit	: -
Spatial Resolution	: 0.04°×0.04°
Temporal Resolution	: Half-hourly
File Format (Data)	: NetCDF
File Format (Image)	: TIFF

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