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A case study on cirrus clouds using PWV measurement

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ABSTRACT

Cirrus (Ci) clouds are high level clouds at an altitude above 6 Km. Ci clouds are composed of ice crystals and responsible for optical phenomenon such as mock suns and halos. Though Ci clouds are non-precipitating in nature, it has considerable role in case of weather forecasting. This paper explores a study of Ci clouds as indicators of fair weather and high altitude wind direction based on Precipitable Water Vapor (PWV) measurement. Brightness Temperature (TB) values from data obtained using satellite water vapor channel, along with pressure and temperature from Global Forecast System (GFS) are used in this study for PWV calculation. Data collected over a period of one year from 1st of January, 2014 to 31st of December, 2014 is considered here.

KEY WORDS: Cirrus, Mock suns, Halos, PWV, Brightness Temperature, GFS.

1. INTRODUCTION

Cirrus clouds are thin, cold clouds found at an altitude above 6Km. It is primarily composed of ice crystals rather than water droplets. Ci clouds plays major role in maintain the radiation in balanced state, hence the climate of our planet. Few decades ago the study of upper region of atmosphere is limited due to limited data availability. As the technology improved, more data is available from different platforms such as satellite, radar and lidar etc. Data from the geostationary satellite with high temporal resolution aid meteorologists in the weather forecasting. Since the cirrus cloud formation depends on the regions, it also helps to study the changes in that region.

Cirrus clouds are coming under high level cloud category, which have wispy appearance. Ice crystals in cirrus are formed from super cooled water droplets in the region of temperature below -20^{0}C to -30^{0}C. Researches show that the cirrus clouds have significant function in maintaining the energy budget of the planet and the climate changes. Cirrus cloud generally indicates fair weather. C_i fibratus, C_i uncinus, C_i spissatus, C_i radiatus and C_i vertebratus are common forms of cirrus clouds. The common optical phenomenon associated with cirrus clouds are mock suns and haloes. Halos, colored or white ring around Sun or Moon is the result of interaction of light with ice crystals in cirrus. An ice crystal causes the light to bend either 22^0 or 46^0. They are the commonly observed halos. Mock suns or sundogs are the outcome of refraction of sunlight by the plate figured ice crystals in cirrus cloud.

Jet streams are narrow currents of air in upper layer of troposphere moving with high velocity. It has significant role in aviation and weather forecasting. In aviation field, jet streams help to reduce the flight time and the fuel usage. C_i clouds are often found in the accelerating region in the jet streams. Hence the identification of the cirrus cloud pattern assists the identification of jet streams. PWV is the amount of liquid water that is obtained if water vapor in the atmosphere column is condensed and precipitated. PWV is calculated from Radiosonde data or infrared data obtained as a result of atmospheric transmission and emission. Upper tropospheric region contains only small amount of water vapor.

A study with the help of cloud photographs is conducted about cirrus clouds and related jet stream motion. Sky photographs taken over consecutive months are considered for this studies. Using the data from lidar and meteorological observation, a study is conducted about contrails, cirrus, and ice supersaturated region with high pressure. The study includes analysis of upper tropospheric humidity and ice particles to obtain the occurrence conditions of cirrus, contrails and ice supersaturated. Knowledge about the structure, composition and radiative properties of clouds is essential to understand its influence in climate and weather. A two dimensional numerical model, dependent on time is developed to understand the responsibility of processes in sustaining the cirrus clouds. Solar albedo effect and infrared greenhouse effects of cloud mainly depends on the optical properties. From the analysis of lidar data and Radiosonde, optical and geometrical properties of cirrus clouds can be determined.

Advanced Very High Resolution Radiometer (AVHRR) data is utilized to calculate PWV over Hawaii using the split window technique. To scrutinize the accuracy, result obtained from the satellite data is compared with values obtained from Radiosonde and GPS. Tremblin (2011), describes that the atmospheric opacity at $200\mu m$ is observed over a period of three years to understand the requirement for the deployment of submillimetre range telescope at Dome C, Antarctica. A multilinear model is developed which is capable to predict the water vapor content in a region having similar conditions as Saudi Arabia. In this study, the PWV is calculated from vapor pressure and air temperature data from Radiosonde. The Ice Water Content (IWC) in the cirrus clouds helps to understand radiation budget and total water content in lower stratosphere and upper troposphere. The vertical distribution details of the IWC in lower stratosphere and upper troposphere is calculated from the LIDAR data collected by Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). Ice nucleation process in the cold cloud is complex compared with the warm clouds. Depending on the aerosol surface properties and environmental conditions different types of ice nucleation mechanism is found. Cirrus clouds are formed by the uniform freezing of cloud droplets and aerosol particle at very high relative humidity and very low temperature condition. Using Community Atmospheric Model Version 5 (CAM5) a study is conducted to determine the effects of dust aerosol on cirrus clouds in upper troposphere. Two ice nucleation parameterization which consider both homogeneous and heterogeneous cloud formation mechanism is used in the study.

Data:

Grid Sat: To overcome the limitations in data access from geostationary satellites, International Satellite Cloud Climatology Project (ISCCP) produced an archive named as ISCCP B1. The archive composed of data from international meteorological satellites. Grid Sat data is derived from ISCCP B1 data. It includes 6.7μm water vapor channel data and 11μm IR channel data. The data is stored in Network Common Data Format (NetCDF). GridSat data are provided in equirectangular projection which facilitates the mapping and subsetting of the data. Since the ISCCP B1 native resolution is approximately 8 km, the resolution of the equal area grid is 0.07° latitude (~8 km at the equator).

Grid Sat data contains data from Geostationary Operational Environmental Satellite (GOES) of United States, Geostationary Meteorological Satellite (GMS) and Multifunctional Transport Satellite (MTSAT) by Japan, Meteorological Satellite (Meteo Sat) by European Union and Feng Yun (FY) of China. Fig.1. shows a sample brightness temperature image and corresponding value indicator.

Radiometers are passive remote sensing instruments which measures the radiation emitted or reflected from the target. The imaging radiometers provide two dimensional picture of the target by electronic or mechanical scanning mechanism. GOES consists of a 5-channel imaging radiometer and a sounder, which is a 19-channel discrete filter radiometer. Sounders are capable to achieve more number of atmospheric profiles and cover more locations compared with Radiosondes. Radiometers measure the radiations in visible, short wave, medium wave and long wave range. It measures the parameters such as ozone distribution, surface and cloud top temperature. The GOES imager channel details are provided in Table.1.

Table.1.Goes imaging radiometer

GOES Imager					
Channel Wave Length (μm)	0.52 to 0.71	3.73 to 4.07	13.00 to 13.77	10.20 to 11.20	5.80 to 7.30
Purpose	Cloud cover	Night time cloud	Cloud cover & height	Sea surface temperature	Water vapor

Onboard sensors in Meteo Sat second generation satellites are Spinning Enhanced Visible and Infrared Imager (SEVIRI) and Geostationary Earth Radiation Budget (GERB). Among the twelve channels in SEVIRI, four are Visible and Near Infrared channels and remaining eight are Infrared channels. GERB is an optical instrument measures constituent of Radiation Budget of Earth.

The objectives of GMS mission are weather monitoring using visible & infrared spin scan radiometer (VISSR), meteorological data collection from data collection platform mounted on ships, buoys and weather stations. The aim of MTSAT mission is to obtain the weather images of Asia-Pacific region and aid air navigation. MTSAT imager includes one visible band (.55-.8μm) and four infrared channels (10.3-11.3μm, 11.5-12.5μm, 6.5-7.00μm and 3.5-4.00μm).

One of the payloads in the FY-2 geostationary satellite is the Visible and Infrared Spin Scan Radiometer (VISSR). Earth surface is scanned in a line by line format by the radiometer. For each pixel in the scan line, the radiometer measures the radiative energy in various spectral bands. These values are digitally coded and send to the ground station. Visible Channel (0.55-1.05μm) consists of four silicon detectors which converts the visible light into four channel analogue signal and it has a spatial resolution of 1.25 Km. Infrared Channel (10.5-12.5μm) and Water Vapor Channel (6.2-7.6μm) with resolution of 5Km measures the radiation from the Earth.

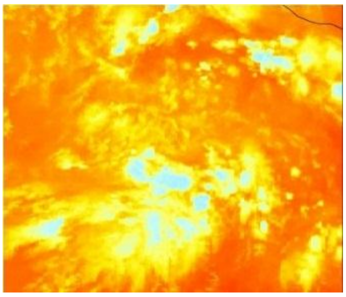

Fig.1.Sample brightness temperature data and indicator

Global Forecast System: The numerical weather prediction model Global Forecast System (GFS) developed by National Centers for Environmental Prediction (NCEP) runs four times per day to produce forecasts up to 16 days in advance. An atmospheric model, a sea ice model, an ocean model and a land model are combined to generate an accurate weather condition [13]. In horizontal direction the model divides the surface into square grids with dimension of 35 or 70 Km. In vertical direction the atmosphere is divided in to 64 layers and has temporal resolution of 3 hour for first 192 hours, while 12 hours after 192 hours. The model is updated in regular basis for improving the performance.

Students' Cloud Observation On-Line: Students' Cloud Observation On-Lin (S'COOL) is a project of National Aeronautics and Space Administration (NASA) collaborated with various educational institutions. The Ground observations by the students are used to validate the NASA's Clouds and the Earth's Radiant Energy System (CERES) instruments in various satellites. CERES is a high priority scientific satellite instrument to measure the solar radiation which is reflected and radiation emitted from top of the atmosphere to the surface for climate analysis. The satellite passing time is provided to the observers. Within a particular time of satellite passage, the cloud observed and other parameters such as temperature, pressure etc is noted. These observations are verified by comparing with data from satellite which pass through the location at that particular time. These observations are available in the website.

CERES instrument is a three channel radiometer, including short wave channel which measures the reflected sunlight, 8-12 μm long wave channel to measure the radiation emitted from the surface of Earth and a channel to measure all the radiations.

2. METHODOLOGY

In S'COOL data, the date, time, latitude, longitude, types of cloud observed are given. From these observations, locations with only cirrus clouds are selected and PWV is calculated for that locations. The Grid Sat and GFS data corresponding to these S'COOL observations are selected and PWV values are calculated. PWV is calculated from the upper tropospheric Humidity (UTH) and saturation mixing ratio values. For UTH calculation, brightness temperature (T_B) data of water vapor channel (6.7 μm) from Grid Sat is utilized. Temperature and pressure data for the saturation mixing ratio calculation is obtained from the GFS data. Since the cirrus clouds are non-precipitating clouds, water vapor content is low. The PWV values and other parameters are analyzed to understand the effects of cirrus cloud.

A. Upper Tropospheric Humidity Calculation: The water vapor channel calibration is tied to High Resolution Infrared Radiation Sounder (HIRS) super level water vapor channel. HIRS is a line-scan sensor in the NOAA polar orbiting satellite series with 20 spectral channels. The 20 channels include 12 long wave channels, one visible channel and seven short wave channels. Channel 12 is used to sense the upper tropospheric water vapor content. To use the data for climatic applications inter-satellite bias of data has to correct. Artificial Neural Network technique was used to derive the atmospheric water vapor and atmospheric profile and surface skin temperature from HIRS data. To create the training dataset, the profile is divided into 35 pressure levels varies from 1000 to 0.1 hPa. The profile having surface value less than 100 hPa is excluded. MODTRAN radiation transfer model is utilized to simulate the Brightness temperatures of each profile. A five layer back propagation neural network with one input layer, one output layer and three hidden layer is selected to derive the profiles.

The HIRS channel-12 climate data record (CDR) production includes the level 1B data reading, cloud removal, limb-correction and intersatellite calibration. The level 1B data contains the channel radiance, latitude, longitude, observation time, satellite altitude, scan line number and position in a scan line. The algorithm requires limb correction coefficient and inter satellite calibration coefficient. The limb correction coefficients are developed utilizing the linear multivariate regression algorithm from various HIRS channel. The intersatellite calibration coefficients are derived based on the zonal monthly average of overlapping satellites. The coefficient changes with respect to the observed brightness temperature. Limb correction and intersatellite calibration is applied to individual pixel. If the grid point value is missing then corresponding point is designated with 999.

In regression analysis one or more response values are predicted from a set of predictors. It estimates the linear relation between the predictor and the response. Let $m_1, m_2, m_3 ...., m_k$ be a set of k predictors related to the response Y. Then the regression model for the i^{th} sample is expressed as

$$Y_i = \alpha_0 + \alpha_1 m_{i1} + \alpha_2 m_{13} + ... + \alpha_k m_{ik} + \xi_i \qquad (1)$$

Where ξ is the random error, α_i, i=1,2,......,k is the unknown regression coefficients. α_0 is the intercept. Here assumptions are made like $E(\xi_i) = 0$, $Var(\xi_i) = \sigma^2$ and $COV(\xi_i, \xi_k) = 0 \ \forall \ i \neq i$. In case of n independent the model can expressed as

$$Y = M\alpha + \xi \qquad (2)$$

Y has dimension of $n \times 1$, M is $n \times (k+1)$, α is $(k+1) \times 1$ and ξ is $n \times 1$ in dimension. One method to estimate the α is to select the value of α such that it minimizes the sum of square of the residual $(Y - M\alpha)$. Let $\hat{\alpha}$ denotes the least square estimate of α which is given by

$$\hat{\alpha} = (M'M)^{-1}M'Y \qquad (3)$$

The predicted values are denoted by $\hat{Y}$ and is obtained as

$$\hat{Y} = M\hat{\alpha} \qquad (4)$$

Residuals are computed as follows

$$\hat{\xi} = Y - \hat{Y} = Y - M\hat{\alpha} \qquad (5)$$

Using the above algorithm the limb correction coefficients are calculated.

Upper tropospheric Humidity is one of the important parameter in the meteorology. UTH is the relative humidity averaged vertically over a region having pressure range between 200 mb and 500mb. Normally data from Radiosondes and satellite sensors are used to calculate the UTH. Radiosondes data have comparatively good vertical resolution while the horizontal coverage is low. The water vapor channel data (6.7µm) from GOES is used to evaluate the mesoscale model (MM5) UTH simulation. The combination of the UTH data with cloud imagery helps to understand the relation between moisture content and deep convection. As convection increases, the UTH over tropics also increases which accelerate the global warming. Soden and Bretherton derived an empirical relation between the brightness temperature (T_B) and UTH. The relation is given as,

$$\text{UTH}=\frac{\exp(\text{a}+\text{b}^*\text{T}_B)\cos\theta}{P_0} \qquad (6)$$

Where 'a' is the least squares fit intercept and b is the least squares fit slope of the regression line. The values are a=31.5 and b=-0.115K^{-1}. While θ is the satellite viewing zenith angle. The normalized pressure P_0 (hPa) is,

$$P_0 = \frac{p(\text{T}_{240k})}{p_1} \qquad (7)$$

$p(\text{T}_{240k})$ represents the pressure at a level where the temperature is 240 K and p_1 is 300 hPa. The value of P_0 is generally chosen as unity.

Saturation mixing ratio calculation: Saturation mixing ratio (w) is defined as the maximum amount of water vapor the air can carry at a particular temperature and pressure. Saturation mixing ratio increases with temperature. Saturation mixing ratio doubles for 10°C increment in the atmospheric temperature. The temperature and pressure data for the calculation is obtained from GFS data. The following formulas used to calculate saturation mixing ratio.

$$\text{w}=\frac{.622\times\text{e}}{p-\text{e}} \qquad (8)$$

$$\text{e}=6.11\times\exp\left(\frac{17.27\text{t}}{273.3+\text{t}}\right) \qquad (9)$$

Where w is the saturation mixing ratio at pressure p in hPa, e is the vapor pressure, and t is the temperature in degree Celsius. It is expressed in gm/Kg.

Precipitable Water Vapor Calculation: PWV changes according to the changes in the atmospheric temperature, wind direction and time of the day. The calculation of PWV is as follow

$$\text{PWV}=\frac{1}{g}\int q_v \cdot dp = \frac{1}{g}\int \text{UTH}\cdot\text{w.dp} \qquad (10)$$

Where g is the acceleration due to gravity and its value is 9.8m/s^2 and q_v is the water vapor mixing ratio, which represents the mass of water vapor per mass of dry air. The incremental pressure change is given by dp. PWV can be expressed in Kg/m2 or mm of water.

3. RESULTS AND DISCUSSION

The PWV is calculated only for the sites having cirrus clouds. Some anomalies are observed from the calculated PWV values. Even though C_i cloud formation depends on amount and distribution of water vapor, these clouds are non-precipitating in nature. However cirrus clouds with precipitation observations are obtained from the S'COOL data. More factors are considered to analyze this exception. Based on these factors, data is divided and explored further. Cloud thickness is one of the properties to identify the clouds. The total available data is divided into three category based on the cloud opacity. Opacity indicates the optical thickness of the clouds. This study considers opaque, transparent and translucent conditions. Opaque clouds are thicker clouds which do not allow the light to pass through it. These clouds have gray color. Clouds with medium thickness come under the translucent class. Transparent clouds are thin clouds.

PWV values are computed and tabulated separately for three opacity condition. PWV values under transparent opacity condition are given in Table.2. From the data, the maximum and minimum values of PWV for every month are included in the table.

Table.2.PWV values for transparent opacity

No	Lat	Long	Date	Rain (Y/N)	T_B (K)	Temperature (K)	PWV (Kg/m^2)
1	46.42	-84.35	28/01/2014	Y	227.9	248	1.67
2	46.42	-84.35	28/01/2014	Y	226.8	247.4	1.62
3	42.58	-71.8	10/02/2014	N	236	270	5.87
4	40.23	-80.21	23/02/2014	N	234	272.6	10.13
5	36.2	-115.12	25/02/2014	N	246.3	282.2	2.95
6	40.23	-80.21	4/05/2014	N	236.8	275.6	7.39
7	40.23	-80.21	6/05/2014	N	238.3	278.4	6.69
8	-26.83	-65.2	29/05/2014	N	257.1	289	2.26
9	-26.83	-65.2	4/06/2014	N	253	293	2.07
10	40.23	-80.21	10/06/2014	N	240.6	282.9	10.25
11	40.23	-80.21	25/07/2014	N	241.2	282.2	5.56
12	40.23	-80.21	7/08/2014	N	243.1	284	6.03
13	40.23	-80.21	19/08/2014	N	246.8	286.8	3.61
14	-34.69	-58.5	12/09/2014	N	244.6	281.2	3.53
15	-34.69	-58.5	27/09/2014	N	237.7	278.3	8.73
16	40.23	-80.21	4/10/2014	N	245.5	281.4	2.33
17	40.23	-80.21	27/10/2014	N	236.3	284.4	13.99
18	40.23	-80.21	10/11/2014	N	235.3	279.3	13.13
19	40.23	-80.21	14/11/2014	N	241.3	259.2	0.998
20	40.23	-80.21	26/12/2014	N	238.5	275	7.65
21	40.23	-80.21	27/12/2014	N	241.8	276.6	2.54

Cirrus clouds are non-precipitating clouds. Though, from the observation, two exception cases are noticed in transparent opacity case. Along with PWV values, T_B and atmospheric temperature data is also considered. From S'COOL data, it is found that precipitation is observed on January 28. A gap of around 3 hour is in between the two observations. In case of non-precipitating observations, T_B is in the range of 230 and 255 K. While with precipitation, T_B value is below 230 K.

While considering the atmospheric temperature, similar variations can be found. In normal case, temperature range is 259-293 K. However, in exception cases, atmospheric temperature of around 248K and a low PWV value around 1.6Kg/m^2 is observed. Lower value of saturation mixing ratio is also obtained in the above cases. Normally the saturation mixing ratio for condensation process is low. The lowest value for PWV obtained during November is 0.998 Kg/m^2. Atmospheric temperature corresponds to observation is 259.2 K which is low compared with other days. The maximum value of PWV obtained during October is around 13 Kg/m^2. The related atmospheric temperature was above 278 K. Considering the T_B, the transparent clouds have higher values compared with the opaque clouds. Most of the observations give T_B values above 240K.

Table.3.shows the PWV values for translucent opacity conditions. Based on the ground observation, precipitation is found in translucent cloud opacity type, on October 19. Here the corresponding PWV value is 21.86 Kg/m^2 and a low T_B value is obtained. Brightness temperature for normal case shows a range of 234-247 K, while for exception case, T_B is 229 K. Except the exception case, the maximum PWV obtained is 11.54 Kg/m^2 with atmospheric temperature 288.1 K and T_B of 241.9 K. The atmospheric temperature measured is higher in this case. And, a medium value for T_B is also obtained. The minimum value measured for PWV is 4.43 Kg/m^2 with 282.8 K of atmospheric temperature and 245 K of T_B shows medium values.

Table.3.PWV values for translucent opacity

No	Lat	Long	Date	Rain (Y/N)	T_B (K)	Temperature (K)	PWV (Kg/m^2)
1	45.29	4.24	23/02/2014	N	234.8	274.8	6.83
2	-26.83	-65.2	27/05/2014	N	246.8	283.4	5.27
3	-29.42	-66.85	8/06/2014	N	240	282	7.33
4	-29.42	-66.85	16/06/2014	N	245	282.8	4.43
5	-34.69	-58.5	2/07/2014	N	240.6	278	7.18
6	45.29	4.24	19/09/2014	Y	229.3	282	21.86
7	45.29	4.24	26/09/2014	N	235	281.9	8.99
8	-29.42	-66.85	25/10/2014	N	234.5	293	10.25
9	-22.8	-43.1	2/11/2014	N	243	288.5	4.78
10	45.29	4.24	20/11/2014	N	235.7	282.2	8.31
11	-29.42	-66.85	7/12/2014	N	241.9	288.1	11.54

Thick clouds do not allow the sunlight to pass through it. These clouds are rarely observed during the data collection. Table.4 shows the PWV value for the opaque condition. Few opaque clouds are observed, when compared to transparent clouds and translucent clouds. In this case, a higher PWV value of 14.21 Kg/m^2 is obtained. Atmospheric temperature measured is 289.7 K and T_B is 241.7 K. The lowest value of PWV measured is 1.22 Kg/m^2 with 282.2 K atmospheric temperature and 238.8 K brightness temperature.

Table.4.PWV values for opaque condition

No	Lat	Long	Date	Rain (Y/N)	T_B (K)	Temperature (K)	PWV (Kg/m^2)
1	-34.69	-58.5	6/06/2014	N	238.5	275.5	6.32
2	38.33	-75.15	20/11/2014	N	238.8	282.2	1.22
3	-29.42	-66.58	28/11/2014	N	241.7	289.7	14.21

4. CONCLUSION

This paper presents a detailed study of the properties of non-precipitating cirrus clouds that found at heights greater than 20,000 ft (6,000 m). The study of clouds gives details about the atmospheric changes. The study is conducted based on Precipitable Water Vapor (PWV) measurement. Even though, cirrus clouds are mainly composed of ice crystal, the PWV value with parameters such as Brightness Temperature (TB) and atmospheric temperature helps to study the properties of cirrus clouds. PWV values ranging from 0.99 kg/m2 to 14.00 kg/m2 are obtained in the analysis for normal cases. Since the cirrus clouds are associated with jet streams, this study can be extended to identify the Jet streams. On combining this information with more weather data, the direction and speed of jet streams can be calculated which can be used for aviation applications.

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