This paper deals with the first of the cloud retrieval processes: the detection of clouds in the atmosphere. It is based on the discussion in Cloud and Precipitation Systems (ATSC 5210) class on cloud climatology and discusses various approaches taken to detect clouds. Various attempts at generating the global cloud climatology by using surface based observation and satellite measurements are discussed. A historical review of cloud climatology is given based on the works of Hughes (1984). The latter part deals with various operational environmental satellites and the approaches and algorithms of the satellite based instruments in detection of clouds.

Introduction
The sun is the primary source of energy on the earth. The energy received form the sun is directly or indirectly responsible for the processes taking place on the earth. This energy from the sun interacts with the earth-atmosphere system and maintains a radiation balance on the system. Of the various components of the earth-atmosphere system that interact on the radiation budget, clouds are, by far, the most important components. They are above the surface of the earth so they interact with the solar radiation before it reaches to the earth’s surface and interact with the long wave radiation from the earth and the atmosphere below it before it reaches the outer reaches of the atmosphere. Besides, clouds are highly variable in both time and space. Because of the roles of the clouds on radiation budget of the earth and their spatial and temporal variability, the global cloud climatology is necessary to better understand the global radiation budget and climate. It is because of this significance of clouds in radiation balance that climate models need accurate cloud data.

Clouds are suspended forms of condensed water in solid and/or liquid forms. They form when the relative humidity in the atmosphere starts to exceed 100% resulting in the condensation of the excess water vapor to form liquid/solid droplets. The relative humidity increases when the atmosphere cools down or when water vapor is added to the atmosphere. Evaporation from the surface, water bodies and evapo-transpiration from plants are the major sources of addition of water vapor in the atmosphere. Precipitation falling in dry atmosphere also gets evaporated adding water vapor to the atmosphere. Cooling process is done through lifting of a parcel of air or through radiative cooling. Lifting of a parcel of air is either through forced lifting over a physical barrier e.g. mountains or when warmer air passes over a wedge of cold air. In either case the lifted parcel gets cooler and hence increases its relative humidity.

Clouds are important in the energy and moisture balance in the earth system. They are part of the hydrological cycle and play an important role in the transportation of water and in scavenging of the atmosphere. Acid rain is an outcome of the role of clouds in the scavenging process and the chemical balance of the atmosphere. They also play important role in climate through their affect on the radiation balance of the earth. Clouds have higher reflectivity at visible and near infrared wavelengths of the solar radiation than the underlying earth surface so they reflect more incoming solar radiation. So presence of clouds tends to shield the surface from a large fraction of the solar radiation.
and causes negative forcing to the greenhouse effect. Clouds interact with the electromagnetic radiation by scattering and absorbing the radiation incident on them. The absorption and scattering properties of clouds depend on their physical and microphysical properties like the number of particles and their size distribution, shape and size of the clouds.

Early attempts on cloud climatology
Surface observation of clouds from land stations and from ships in ocean areas have been the major source of cloud cover data before the advent of airborne satellite measurements. Surface observations are taken on a regular basis over land but they are not uniform and very difficult to take during nighttime and over the oceans. Surface observations are taken on okta or tenths scale and overestimate the cloud amount as surface observers see the sides and the base of the clouds (Hughes, 1984). One of the early documented records of ocean cloud data is that of McDonald’s Atlas of Climatic charts of the Oceans, compiled from data spanning over 26 years. London (1957) used this data set for his cloud climatology. One of the early attempts at global cloud cover amounts was by Brooks who used surface observations from more than 1000 land stations. Various other authors and writers have attempted to give the cloud amounts on global and regional scale. The spatial scales used are from 5° to 10° latitudes and longitudes. Hughes (1984) Table 1 gives detail on the earlier cloud climatology attempts. After the satellite measurements were started in 1960 with the launch of Television Infrared Observation Satellite (TIROS) in April 1, 1960, cloud climatologies have been compiled by using both the conventional surface observations and satellite radiance data. Hughes (1984) gives a comparison between the satellite based cloud cover estimates and surface observation and their shortcomings. Early satellite based cloud climatologies were constructed by using satellite photographs and averaging and compositing visible brightness temperatures.

Environmental Satellites
Environment satellites are mainly of two types, namely the geo-synchronous and the polar orbiters. Geo-synchronous (geo-stationary) satellites are have a speed that matches the rotation of the earth so they are positioned above the same spot on the earth surface but due to their high elevation (~ 35800 km above the surface) they get a continuous full disc view of the earth. The polar orbiters provide a global coverage, and as the name applies, have orbits that span the poles. The Polar Operational Environmental Satellites (POES) orbit the earth about 14.1 times in a day.
In the detection of clouds, various airborne satellite instruments have been in operation. Most noteworthy is the Advanced Very High Resolution Radiometer (AVHRR) aboard TIROS. Data obtained from AVHRR has been instrumental in advancement of satellite-based measurements of the atmosphere.
Satellite estimate of cloud cover

Cloud retrieval from satellite data involves two steps. The first of the cloud retrieval processes is the determination of presence or absence of clouds. It involves separation of cloudy and clear pixels. In cloud retrieval process, satellites measure the upwelling radiance or reflected radiance from the earth and the atmosphere and use the radiance counts to estimate the cloud cover and cloud properties. One of the advantages of satellite measurement over conventional surface observations is its continuous coverage (Bean and Somerville, 1981) but satellite estimates are indirect data and inferred from radiance values measured by the satellite-based instruments. Satellites contain instruments that detect reflected solar radiation (visible and infrared) and emitted radiation from the surface and the atmosphere (infrared). This detected radiation is then used to infer the presence or absence of clouds. The detection algorithm uses the different property of earth’s surface and cloud tops to distinguish between the two. However, because of the high uncertainty in the measured value of radiation, it is not easy to detect whether the radiation detected is from the clouds or from the earth’s surface. Here an attempt is made to describe some of the cloud detection algorithms.

Bean and Somerville (1981) used the TIROS data to develop a worldwide cloud cover model. The algorithm uses both infrared and solar radiation. The detection of clouds is based on their high albedo. Albedo (A) is estimated from the incoming and outgoing solar radiation. The values of the albedo are calculated by using the formula

\[ A = \frac{(I_{in} - I_{ab})}{I_{in}} \]

The value of A was calculated each day of the season for each grid point and the minimum value was noted. The minimum value of A (A\(_{min}\)) is taken as that from the surface and so the fraction of cloud cover x is given by

\[ A = x r + (1 - x) A_{min} \]

where r is the reflectance from the clouds. The value of r is estimated from brightness temperatures measured from the satellite and the surface temperature using Gray (1978), given by

\[ r = -0.000265 z^2 + 0.0295 z + 0.10 \]

where z is the height of the cloud estimated by taking the difference between the surface temperature and the brightness temperature. The daily cloud cover is then calculated for each pixel for four three-month periods. The mean distribution of clouds for each three-month period was then fit into beta probability distribution function and models were created for each season.

The most common cloud detection algorithms are the threshold method, the statistical method, the spatial coherence method and the radiative transfer method. Threshold method requires the knowledge of surface brightness temperature in case of infrared radiation and surface radiance in case of visible or near infrared measurements. This method distinguishes between a cloudy pixel and a clear pixel by comparing the measured radiance relative to a predetermined threshold level. The threshold values are determined from previous observations or from theoretical simulation. In the single channel threshold test, the threshold is taken as a certain fraction increment in visible reflectance or in IR brightness temperature from the clear sky values. A pixel is labeled cloudy if the visible reflectance is greater than the sum of clear sky reflectance and the threshold value or in the case of IR, if the brightness temperature is less than the brightness temperature difference between the clear sky case and the threshold value. Because the radiative properties of surfaces are different and dependent on factors like...
vegetation, surface type etc. the threshold methods are not global. Threshold method uses both single channel and multiple channels.

The statistical cloud retrieval method is used for large group of pixels having similar surface types. Radiance values are expressed in histogram and isolated clusters are identified.

The spatial coherence technique is based on the assumption that clouds are situated in layers and they possess temperature according to its altitude and all the clouds in a layer emit radiation that is characteristics of that layer. In this method is best suitable for homogenous underlying surface. Local standard deviations are plotted against the mean radiance or the brightness temperatures (in case of infrared channels) and the scatter plot gives two distinct clusters of low standard deviation points corresponding to clear field of view and cloudy field of view separated by higher standard deviation values. The differences in the radiance (brightness temperatures) of the cloudy and clear clusters can be used to estimate the cloud height. The cloud cover ($A_c$) for a single layer cloud is given by

$$A_c = \frac{(I - I_s)}{(I_c - I_s)},$$

where $I$ is the mean radiance given by $I = (1 - A_c)I_s + A_c I_c$, $I_c$ and $I_s$ are cloudy and clear sky radiances respectively. Coakley (1983) extended the spatial coherence method to multilayer clouds as well.

Radiative transfer method is the most sophisticated methods among these methods. In this method, the cloud retrieval is determined by fitting the atmospheric radiative transfer models to observed radiances. Increasing the channels in the models can be used to infer multilayer clouds. For better accuracy, it uses a host of ancillary input data. Goodman and Henderson-Sellers (1988) give a detail description of these methods.

**International Satellite Cloud Climatology Project (ISCCP)**

ISCCP has developed its own algorithm for cloud detection. One of the important features of ISCCP is that it uses a host of operational environmental satellites and uses both geo-stationary and polar orbiters. The ISCCP algorithm uses the data from narrow spectral bands, visible 0.65±15 $\mu$m and IR window 11±1 $\mu$m.

ISCCP was established in 1982 as a part of World Climate Research Programme (WCRP) to produce more accurate cloud climatology. ISCCP uses visible and infrared radiance data from various operational satellites e.g. Meteosat, GMS, GOES and NOAA satellites, to infer the cloud cover. Its algorithm is based on threshold test and statistical tests. It consists of five steps in identifying the clouds. The steps are as follows:

1. Space contrast test
2. Time contrast test
3. Cumulation of space/time statistics
4. Construction of clear-sky composites
5. Radiance threshold test

Space contrast test is uses threshold technique to distinguish between ground and clouds. The maximum IR brightness temperature, $T_{max}$, or minimum visible radiance, $R_{min}$, in a small region is compared to the neighboring pixels and if the IR brightness temperature or visible radiance of the pixel is less than $T_{max}$ – a threshold value for IR, or greater than $R_{min}$ + a threshold value, then the pixel is determined as cloudy. In time contrast test, a radiance value of a location is compared to the values of a day earlier and a day after for
the same time of the day. The test is carried separately with the value of day before and
day after. If the magnitude of the difference is greater than a predetermined threshold
value, it is taken as cloudy and if the difference is smaller than some other predetermined
smaller value then it is taken as clear. Rossow and Garder (1993) give detail description
of these methods. Logic test is then applied by combining the time contrast tests and
space contrast tests. In this step the ‘cloudy state’ obtained by using the two time tests,
i.e. cloudy state obtained from time contrast test with that of a day earlier and from time
contrast test with that of a day later. This is then compared with the space contrast test to
infer cloudy condition.
The third step employs statistical method over the infrared and visible radiances for
various time and space scales to account for variation of clear radiance values with time
and space. The forth step involves the formation of clear sky composites for infrared and
visible wavelengths and the last step involves comparison of each observed value with
the clear sky composite value.
Rossow et al. (1993) have compared the ISCCP cloud amounts with estimations using
other algorithms and other datasets. The ISCCP climatology has global cloud climatology
at 3-hour interval having spatial resolution of 280 km, monthly averages and monthly
averages at 3-hour interval. The comparison is done among cloud climatology obtained
from ISCCP, surface observation data, Meteor satellite data and Nimbus 7 data.
Comparison between ISCCP cloud cover and the surface observations collected by
NOAA National Meteorological Center for the periods January 1984, July 1985 and
October 1986 show that the ISCCP amounts are 11% lower with a standard deviation of
almost 40%. The bias in the ISCCP with respect to surface observation has a seasonal
dependence. Rossow et al. (1993) estimate the wintertime negative bias of ISCCP is 8%
more than in summer time.
Global, regional and seasonal comparison of ISCCP cloud cover with the other methods
give global annual of more than 60%. Nimbus 7 estimates almost 9% less than the other
methods. The daytime estimation is in better agreement between the surface observation
and ISCCP. The root-mean-squared (RMS) difference for the daytime and nighttime are
respectively 1.7 and 5.8 %. Rossow et al. (1993) show that the seasonal variation of cloud
cover is not that significant. Seasonal variation in the ISCCP, surface observation and
meteor satellite data is less than 0.7% and 1.7% for Nimbus data.
Global cloud climatology shows that the northern hemisphere has about 5% less cloud
cover than the southern counterpart that has larger area covered with ocean. Ocean
surface has higher mean annual cloudiness than the land surface. All the four methods
give land-ocean cloudiness difference of more than 10% with ISCCP showing the highest
difference of 23.1% and Nimbus 7 showing the lowest value difference of 11%.
Regional variation of cloud cover is also significant. ISCCP and Meteor data show
highest cloud cover in the mid latitudes while surface observation and Nimbus 7 show
highest cloud cover in the polar region. There is a good agreement between the four sets
of data over land except in the polar region. The RMS difference shows values of 3.7%
for land surface and 13.8% for polar land surface.
Stratospheric Aerosol and Gas Experiment (SAGE)
SAGE employs a completely different approach to detection of high clouds. It was designed for measuring aerosol and trace gases by using solar occultation data but it can detect optically thin cirrus clouds that are difficult to detect by other vertical viewing satellites. Unlike the other satellites, SAGE satellite looks horizontally at the earth’s surface and looks at the attenuation of solar radiation when it is viewing horizontally. It views sunrise and sunset (and moon rise and set) events horizontally and measures the attenuation caused by the optically thin or sub-visible cirrus. When the sun/moon is high up and above the atmosphere, the radiation reaching the satellite is free of attenuation and during the setting and rising events the radiation traverses the atmosphere so it can detect the magnitude of attenuation caused by the atmosphere. This makes it capable of self-calibration.

Remarks
Conventional surface observations and satellite-based measurements have been used to construct global and regional climatology of cloud cover. They have their own strengths and weaknesses and can compliment each other. Both the surface observation and the satellite observation have errors associated with their respective estimation of cloud cover. The errors in the satellite estimate arise due to sub-pixel cloud variation. Increasing the spatial resolution can reduce this error. Satellite estimation also has detection errors, especially in detecting low clouds at nighttime. Broken cloudiness also adds to the error. The surface observations are, to a large extent, dependent on the individual observer and the height of the clouds from the point of observation.
Studies done by using satellite measurements and surface based observations show that the global cloud cover is around 60% with large variation in fractional cloud cover between land and ocean and little seasonal variation.

References: