A satellite survey of cloud cover and water vapor in northwest Africa and southern Spain

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ABSTRACT

A survey of northwest Africa and southern Spain (including the Canary Islands) has been carried out using satellite data from the Meteosat Operational Service (in geostationary orbit at 0° longitude). The study was funded by European Southern Observatory (ESO) as part of the site survey effort for the Overwhelmingly Large Telescope (OWL), recently re-baselined as the European Extremely Large Telescope (E-ELT). Cloud cover and water vapor were surveyed over the area 20°N to 40°N and 20°W to 10°E using satellite data for the 7-year period January 1996 to December 2002. The study included a calibration of the Upper Tropospheric Humidity (UTH) for Meteosat-5, an aerial analysis of cloud cover and precipitable water vapor (PWV) and a verification of the satellite cloud cover using ground-based observations of sky conditions derived from extinction measurements made at the Observatorio del Roque de los Muchachos (ORM) on La Palma. In view of the importance of establishing the accuracy of the satellite method, a summary of results from earlier verification studies has been included in the relevant section.

Keywords: satellite, site survey, cloud cover, water vapor, northwest Africa, Canary Islands, southern Spain

1. INTRODUCTION

Two major initiatives to build next-generation extremely large telescopes (ELT) are currently underway in Europe1 and North America2. Since the performance of large telescopes at optical and infra-red wavelengths is critically dependent on atmospheric cloud cover and water vapor, it has been recognized that a quantitative survey of these conditions over areas of interest and at candidate telescope sites is and will continue to be an essential part of the site selection process for ELTs.

Different measurement methods may be used to quantify cloud cover and water vapor at telescope sites but basically there are two categories: ground-based observations and satellite observations. Ground-based observations provide ground-truth for a given site provided the method of observation is reliable. These sites are usually existing observatories where cloud cover is determined using some instrument or a human observer. However, comparable observations are usually not available at potential telescope sites or even many existing sites. In addition, where comparable ground-based data may be available (eg. all-sky cameras) they frequently cover different periods and/or a relatively short period. Further, making similar ground-based measurements at a large number of different sites over a suitably long period of time is logistically and financially prohibitive.

Meteorological satellites provide a consistent measurement of cloud cover and water vapor over a wide field of view. This allows for a quantitative aerial mapping of relevant cloud cover and water vapor parameters so that a reliable comparison of regions and sub-regions can be made. The spatial (< 10 km) and temporal (≤ 3 hours) resolution of the observations also ensures that measurements can be made of conditions at particular sites and that the diurnal cloud cover cycle is resolved. Further, most of the meteorological satellites observing different areas of the globe are equipped with similar instrumentation. This means that areas and sites observed by two or more different satellites can be reliably compared. Additionally, since satellite data archives now cover periods of 5 years or more for most locations, sites can be compared over a climatologically representative period.

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Satellite data from the Geostationary Operational Environmental Satellites (GOES-East and GOES-West) have been used to survey cloud cover and water vapor and to conduct comparisons of telescope sites in Northern Chile\(^3\), the southwestern USA and northern Mexico\(^2\) and Hawaii\(^1\). These studies have included comparisons between satellite and ground-based observations at selected sites within the viewing areas of these satellites. Agreement was found to be very good, with the clear fractions obtained using satellite and ground-based observations differing by only a few percent.

In a study for Max Planck Institute (MPI), Heidelberg, satellite data from the Meteosat Indian Ocean Data Coverage Service (in geostationary orbit at 63° east) were used to analyze and compare two sites in the Himalayan region with regard to cloud cover and water vapor\(^6\). While it was found that the Meteosat data were well documented and could be processed in a manner similar to GOES data, no comparisons with ground-based observations were carried out.

The area viewed by the Meteosat Operational Service (in geostationary orbit at 0° longitude) includes Africa and Europe (Figure 1). Developed observatory sites within the viewing area of this satellite include, among others, Observatorio del Roque de los Muchachos (ORM) on La Palma in the Canary Islands, Calar Alto in southern Spain, Sutherland in South Africa and the Gamsberg in Namibia. Since potential observatory sites of high quality may exist in areas near these a survey of cloud cover and water vapor was conducted for the area 20°N to 40°N and 20°W to 10°E covering northwest Africa and southern Spain (Figure 2). This area was identified as the logical starting point for identifying telescope sites in Africa since the Canary Islands, located just 300km off the northwest coast of Africa, have well established sites for optical astronomy. Several telescopes have operated at the ORM for a number of years and it is generally regarded as a very good site. For Europe and northern Africa, therefore, this site would be the logical benchmark against which other sites would be compared and measured. Additionally, since ground-based observations of cloud cover are available for this site, these can be used to verify the satellite measurements. In addition, the climate and topography of Morocco and its proximity to the Canary Islands are favorable indicators that potential telescope sites may be found in this area. Much of the area is dominated by subtropical high pressure and a desert climate. Several mountain peaks of suitably high altitude are found in this region.

An overview of the data used in this study is presented in section 2. The methodology used to derive cloud cover and PWV from the satellite data is described in section 3. Results from comparisons between the satellite measurements and ground-based measurements are discussed in section 4. A summary of previous verification studies and the verification performed for Meteosat using data from the ORM are presented. The aerial analysis of cloud cover and PWV for northwest Africa and southern Spain using 7 years of data (1996-2002) may be found in section 5.

2. THE DATA

2.1 Satellite data

Satellite data for the 7-year period January 1996 to December 2002 were obtained from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) by ESO. The data were prepared by EUMETSAT for the International Satellite Cloud Climatology Project (ISCCP). The data are the highest spatial resolution prepared by EUMETSAT for ISCCP (5 km x 5 km at the satellite sub-point) and are stored as rectified full earth disk images. 6.4μm (water vapor) and 11.5μm (IR window) channel data were analyzed to determine cloud cover and water vapor. Data for the study area were extracted from the full earth disk imagery. A sample image of the extracted sector is shown in Figure 3. For the data used in the ORM site analysis an additional extraction of the site pixel data was performed (see section 3).
2.2 Topography data

Terrain heights over the area of interest are needed in order to estimate surface temperature and pressure from the rawinsonde or gridded meteorological data used in the analysis (see section 2.3). This information is used to ensure that cold land surfaces are not mistakenly detected as cloud. Terrain height data in digital format were obtained from the Global 30 Arc-Second Elevation Data Set (GTOPO30)\(^7\) and data for the sector 20\(^\circ\)N to 40\(^\circ\)N and 20\(^\circ\)W to 10\(^\circ\)E were extracted. Since the topography data is higher resolution (~ 1 km) than the satellite data, the terrain height for any given satellite pixel location was deemed to be the highest point within the area (~ 5 km x 5 km) covered by the pixel.

2.3 Upper-air meteorological data

In order to determine the presence of cloud in the IR window channel imagery and to derive an absolute humidity from the satellite-derived relative humidity, a measurement of the temperature profile above the ground is required. For the ORM site analysis rawinsonde data from the Santa Cruz de Tenerife station were used. For the aerial mapping of cloud cover and PWV, the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR) reanalysis data were applied\(^8\). Rawinsonde data were also used to perform the UTH calibration for Meteosat.

3. METHODOLOGY

The satellite data used in this study are measurements of the monochromatic emittance of the earth and atmosphere at 11.5\(\mu\)m and at 6.4\(\mu\)m. In the IR window channel (11.5\(\mu\)m), emissions reach the satellite largely unattenuated by the atmosphere so that radiance values measured are due to emission from the surface. However when clouds are present they behave as absorbing and emitting "surfaces" so that, under these conditions, radiation reaching the satellite is from the cloud top. By using an independent temperature measurement the presence of cloud above the surface can be confirmed. Observations at 6.4\(\mu\)m (water vapor channel) are sensitive to the presence of water vapor in the layer between about 600mb (~ 4400 m) and 300mb (~ 9000 m). If this layer is dry, little of the emission from warm lower layers is absorbed resulting in the satellite observing high radiance values. As moisture levels increase in the layer, more of the outgoing radiation is absorbed and emitted to space. This occurs at colder temperatures, causing the satellite radiance to drop. If high altitude (cirrus) clouds exist above this layer even more of the outgoing radiation is absorbed and re-emitted to space at still colder temperatures. Under clear conditions radiance values can be calibrated in terms of the UTH from which the PWV can be derived. When cirrus clouds occur, their presence and thickness can be deduced.

The conversion from radiance counts (8-bit for ISCCP) to radiance and brightness temperature is accomplished as follows:

\[
R = \alpha (C_n - C_0) \quad [\text{Wm}^{-2}\text{sr}^{-1}] \tag{1}
\]

Where \(R\) = radiance, \(\alpha\) = calibration coefficient, \(C_n\) = 8-bit radiometer count and \(C_0\) = space count. The calibration coefficient (\(\alpha\)) is defined for various channels and provided by EUMETSAT. The relationship between radiance and brightness temperature is defined by the Planck function and may be written as:

\[
R = \exp [A + (B/T)] \quad [\text{Wm}^{-2}\text{sr}^{-1}] \tag{2}
\]

Where \(T\) = brightness temperature [K] and A and B are regression coefficients. A and B are defined for each satellite observing channel and supplied by EUMETSAT. The UTH is a measure of the relative humidity of a layer extending approximately from 600 mb to 300 mb. For GOES data, Soden and Bretherton\(^9,10\) have derived a semi-empirical relationship between UTH and water vapor channel brightness temperature (\(T_{wv}\)) in clear areas. They used simplified radiative transfer theory to define the following logarithmic relationship between UTH and the brightness temperature:

\[
\text{UTH} = \frac{\exp(a + bT_{wv}) \cos \theta}{p_0} \tag{3}
\]
Where $\theta$ is the satellite viewing zenith angle, $a$ and $b$ are the least squares fit slope and intercept of the regression line as defined by the empirical relationship and $p_0$ is a normalized pressure variable. $p_0 = p(T=240K)/300$, where $p$ (in mb) is the pressure level where the temperature ($T$) is 240K. The factor $p_0$ accounts for the lifting (lowering) of the weighting function peak in warm (cold) airmasses. The values for $a$ and $b$ are seasonally dependent and determined for each month of the year. For the Meteosat-5 data used in this study a calibration for UTH was performed in a similar manner using rawinsonde data from 6 stations in the study area. In the calibration procedure $T_{\text{sw}}$ is obtained for the pixel location corresponding to the rawinsonde station using the satellite image which is closest in time to the rawinsonde sounding. Only clear days are used and observations are required to be within one hour of each other. When the UTH is derived temperature and dew point data are first interpolated to pressure surfaces at 25 mb increments. Then the mixing and saturation mixing ratio is obtained at each level and the relative humidity is computed using the method in Erasmus (2005). Finally the weighting function for the Meteosat-5 water vapor ($6.4 \mu$m) channel for a dry subtropical atmosphere is applied and the weighted UTH is determined. Further details on the calibration and the derived coefficients may be found in the full study report on which this paper is based.

The PWV is a quantity indicating the absolute humidity in the atmosphere above some predetermined altitude such as the surface or a constant pressure level. It is derived from the UTH. For pressure levels between 300mb and 600mb the relative humidity was set equal to the UTH. Then the corresponding mixing ratio ($x$) was computed using the equation $x = \text{UTH} \cdot x_s \cdot x_p$, the saturation mixing ratio, is a function of temperature and pressure and is computed using the temperature versus height (pressure) profile from the NCEP-NCAR reanalysis (area analysis) or rawinsonde (site analysis). Mixing ratio values for pressure levels below 300mb and above 600mb are obtained by scaling the mixing ratio values for 300mb and 600mb respectively to lower and higher pressure levels. In the area analysis this was done by linear extrapolation. For the ORM site analysis scaling was done using the moisture profile from the rawinsonde sounding for the closest station and time. Once the mixing ratio profile is obtained, then $\text{PWV} = \frac{\text{g}}{\text{g}} \frac{\text{dp}}{\text{dp}}$, where dp is the incremental pressure change with height in Pascals and g is the gravity acceleration constant. The units for PWV are then kg.m$^{-2}$ or mm of water.

Cloud is detected and classified using both the 6.4$\mu$m and 11.5$\mu$m imagery. First, the presence of cirrus clouds and their thickness is inferred from the 6.4$\mu$m imagery. The relationship between UTH and $T_{\text{sw}}$ (eqn. 3) is applicable under clear conditions. When UTH values rise to around 50%, cirrus cloud particles start forming by condensation and deposition. As the UTH rises further, the cloud particles grow in size and number and the cirrus cloud gets thicker. The relationship between UTH, cirrus cloud thickness and atmospheric extinction at optical wavelengths has been investigated by Erasmus and Sarazin and Erasmus et al. Atmospheric extinction measured by the Line Of Sight Sky Absorption Monitor (LOSSAM) at Paranal and La Silla Observatories was compared to UTH over extended periods. It was found that the UTH could be used to correctly discriminate between photometric and non-photometric conditions about 90% of the time. If UTH $\leq 30\%$, conditions are photometric 97.5% of the time. If 30% $<\text{UTH} \leq 50\%$, there is an 80% chance that conditions will be photometric. When the UTH is between 80% and 100% then the probability that conditions will be non-photometric is over 90%. For all cases with UTH greater than 100% (opaque clouds) no LOSSAM measurement could be made, thus indicating that conditions were unusable. If 50% $<\text{UTH} < 80\%$, observing conditions could be either photometric or non-photometric (with about equal probability). The last condition occurs only 6.4% of the time. In this study the following UTH threshold values were used to discriminate between photometric, non-photometric but usable and unusable conditions: Clear (photometric): UTH $\leq 30\%$, Transparent (spectroscopic): 30% $<\text{UTH} < 100\%$, Opaque (unusable): UTH $\geq 100\%$.

For cases where the 6.4$\mu$m analysis indicates a clear or transparent signature the infra-red window (11.5$\mu$m) channel data were used, additionally, to determine the presence of cloud in the middle and lower troposphere. In principle the procedure for cloud detection is straightforward. Pixel temperatures ($T_p$) computed from the 11.5$\mu$m satellite data were referenced against an independent temperature measurement. Typically temperature drops with height in the atmosphere, so if $T_p$ is colder (by some margin) than the surface temperature (for example) at a given pixel location, the presence of cloud above the surface is indicated. In practice, however, there are some obstacles to the task of unambiguous cloud detection. As a first step towards determining the cloud detection temperature threshold ($T_c$) with which $T_p$ must be compared, the surface pressure ($P_s$) and corresponding surface temperature ($T_s$) for a given location was estimated using the NCEP-NCAR reanalysis data (or rawinsonde sounding) and the terrain height. However, the actual surface temperature may be warmer or colder than $T_s$ since there is usually additional cooling (night) or warming (day) of the air near the ground. If the estimated surface temperature is cooler than the actual surface temperature
(daytime) cloud detection is not compromised. If cloud is present (even a thin layer near the surface) during the daytime, the cloud top temperature ($T_d$) will be colder than the estimated surface temperature. So if $T_d > T_i$, cloud is correctly determined to be present. However, if the actual temperature is colder than $T_s$ and $T_d < T_i = T_c$, then two conditions are possible - cloud may be present or the ground is cold and is incorrectly being interpreted as cloud. In order to avoid this problem an exclusion zone is defined in which cloud can not be detected (Figure 4). $T_r$ is revised so that it is based on a pressure altitude higher than the surface ($P_s - P_{sc}$). At the same time the thickness of the exclusion zone must be minimized so that cloud near the ground does not go undetected. For the aerial analysis a generally applicable method for defining the depth of the exclusion zone is needed. In a previous study, a method was developed that parameterises the depth of the exclusion layer in terms of night length and time elapsed between sunset and the satellite observation time (the length of time the ground has cooled). This method required site-specific parameterization and is therefore better suited to analyzing particular sites. In this study the depth of the exclusion zone was determined empirically for each of the daily satellite image scan times. Details on the methodology are provided in Erasmus and van Rooyen. The maximum depth of the exclusion layer was found to be about 2000m. For high terrain locations (where $P_s - P_{sc} > 750mb$), $T_r = T(750mb)$. Over lower terrain (where $P_s - P_{sc} > 750mb$), $T_r = T(750mb)$. If cloud is detected in the 11.5µm imagery then the pixel location was re-classified as opaque. If not, then pixel locations classified respectively as clear or transparent remain clear or transparent.

Rather than using just one pixel to represent the “sky” above a particular location, a cluster of pixels was used. As shown schematically in Figure 5, a 9-pixel area may be used to represent the astronomical sky. At the level of the Tropopause (about 12 km) for an observer on the ground viewing the sky, this 9-pixel area would correspond to the sky within approximately 45° of zenith for the Meteosat ISCCP data used in this study. Individual pixels were classified as clear, transparent or opaque and then the counts for each category were used to classify the observing conditions for the astronomical sky. The following scheme was used in the area analysis performed for this study: Clear (Photometric) = All 9 pixels are clear, Transitional (Spectroscopic) = 6-8 pixels are clear (1-3 pixels are transparent or opaque), Opaque (Unsuitable for astronomy) = 5 or fewer pixels are clear.

In the aerial analysis, this 9-pixel template is applied to each pixel location in the mapping domain. A solar clock algorithm is used to compute true local sunrise and sunset time at each pixel location and a composite of “night-time” and “daytime” conditions is constructed using applicable images. Further divisions into Day1, Day2, Night1 and Night2 were made by dividing the relevant period exactly in half. Satellite images are available every 3 hours at 00UT, 03UT, 06UT, 09UT, 12UT, 15UT, 18UT and 21UT while the NCEP-NCAR reanalysis and rawinsonde data are available twice daily at 00UT and 12UT. Of these observations in relation to the diurnal cycle of temperature, when synchronizing the satellite and NCEP data, the 00UT NCEP data are used for satellite images between sunset + 2 hours and sunrise + 2 hours and the 12UT NCEP data for images between sunrise + 2 hours and sunset +2 hours.

The methodology described in this section was developed as an independent, stand-alone way to process the satellite data. Ground-based observations were not used to tweak or “calibrate” the method. It therefore provides an unbiased measure of cloud cover and PWV that is generally applicable for all existing and potential telescope sites. These facts should be borne in mind when considering the results from verification studies presented in the following section.
4. VERIFICATION OF SATELLITE CLOUD COVER AND PWV

Satellite-derived cloud cover and PWV measurements have been verified in a number of previous studies using ground-based observations. Selected results from these studies are reviewed in this section. Additionally, as part of this study, satellite observations of cloud cover were compared to ground-based observations made at the ORM on La Palma. Comparisons of satellite and ground-based measurements of cloud cover and/or PWV have been carried out for Paranal\textsuperscript{13,16}, Chajnantor\textsuperscript{17}, San Pedro Martir\textsuperscript{4}, Cerro Tololo\textsuperscript{5} and Mt Hopkins\textsuperscript{19,20}. In some cases only statistics for the same period were compared but for others measurements were also compared on a monthly, nightly or hourly basis.

Cloud cover at Paranal determined by a human observer every two hours at night over the period January-August 1998 was compared to satellite-derived cloud cover measured every 3 hours. The clear fractions were found to be 80.9\% and 82.9\% respectively. The satellite cloud cover fraction was obtained using an early version of the methodology described in section 3 which necessitated using an IR window channel detection threshold based on a high altitude pressure altitude (Tr = T(400 mb)). Based on a subsequent assessment of low cloud occurrence at Paranal the satellite clear fraction that would be obtained using the updated methodology would be 1.3\% lower, thus bringing the satellite and ground-based observer into even better agreement.

The PWV at Paranal was also compared for the above mentioned period and the medians for the satellite and a ground-based radiometer (dark sky emissivity meter) were found to be 3.73 mm and 3.66 mm respectively. For an earlier period in 1993 using 413 contemporaneous data points the root mean square, mean absolute and mean difference between the radiometer and the satellite were found to be 0.99 mm, 0.72 mm and -0.08 mm respectively. Using the Antofagasta rawinsonde sounding, it was shown that a mean error of 5\% (more or less the accuracy of the sensor) in the relative humidity over the layer between 700 mb and 100 mb (corresponding essentially to the atmosphere above the site) results in an error in the PWV of about 1 mm. This shows that the satellite and radiometer PWV are in remarkably good agreement.

A verification of satellite PWV measurements was also made for Chajnantor, the site of the Atacama Large Millimeter Array (ALMA), using data collected in the period October 1998 – December 1999. Satellite PWV was compared to that derived from 183 GHz ground-based radiometer data by Delgado \textit{et al.} (1999) who converted the 183 GHz radiometer measurement to PWV using a simple atmospheric model and surface meteorological data. PWV was also computed using data from a series of rawinsonde campaigns conducted at or near the site. For the satellite-rawinsonde comparison, 52 pairs of observations were obtained, for the radiometer-rawinsonde comparison, 31 pairs and for the satellite-radiometer comparison, 26 pairs. Observations compared were within one hour of each other. Figure 6 shows that the three methods of measurement are highly correlated with the Pearson correlation coefficients (r) greater than 0.9. Statistical tests (z and t) show that r values this large are significant at the 1\% level (less than a 1\% probability the correlation is due to a chance deviation in the sample).

![Figure 6. Scatter plots, least squares fit lines and correlation coefficients for combinations of PWV measurement methods for Chajnantor.](http://proceedings.spiedigitallibrary.org/ on 06/26/2013 Terms of Use: http://spiedl.org/terms)
A comparison was made between satellite-determined sky cover and records of observing conditions at San Pedro Martir (SPM) Observatory for a one year period (June 1997 to May 1998). Since 1982 a record of observing conditions has been kept for SPM\textsuperscript{18}. Using periods of “half-nights”, conditions were classified as Photometric (less than 15% cloud cover or no more than 30 minutes of cloud cover in a 5 hour period) or Spectroscopic (more than 15% but less than 65% cloud cover). These definitions are fairly similar to the categories defined in section 3 for the satellite data analysis. Figure 7 is a plot of the monthly values. In some months, for the ground-based observations, less than half of the nights were sampled. For the satellite, observations are made every night, typically three times per night. The annual figures for both photometric and spectroscopic fractions are shown in Table 1. It is clear from this comparison that there is good agreement between satellite-based and ground-based measurements of observing conditions for SPM. Differences in the fractions obtained for each observing method are consistent with differences in the definitions of what constitutes photometric or spectroscopic conditions.

Table 1. Photometric and spectroscopic fractions (%) for San Pedro Martir for the period June 1997 to May 1998 as determined from satellite and ground-based observations.

<table>
<thead>
<tr>
<th></th>
<th>Photometric</th>
<th>Spectroscopic</th>
<th>Usable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>69.8</td>
<td>11.8</td>
<td>81.6</td>
</tr>
<tr>
<td>Ground</td>
<td>67.5</td>
<td>15.6</td>
<td>83.1</td>
</tr>
</tbody>
</table>

For the 23-month period June 1997 to April 1999, satellite and ground-based observations of cloud cover were compared at Co. Tololo on a nightly, weekly and monthly basis. The ground-based measurement of cloud cover is an estimate made by a human observer of the fraction of the sky covered by cloud at night in eighths. Four observations are made per night at 3-4 hour intervals. A spatio-temporal average of the clear fraction for each night is computed by averaging the four observations. Additionally, the individual observations were classified using the following sky cover categories (matched as closely as possible to the satellite categories): Photometric: Zero cloud cover, Spectroscopic: 1 - 3 eighths cloud cover and Unusable: 4 eighths or more cloud cover. These were then used to compute the weekly and monthly average clear fractions. For the satellite measurement, to ensure that the night is adequately sampled, at least three images are required to compute a valid nightly average clear fraction. The average was computed by counting the number of clear pixels and dividing by the total number of pixels. This method is computationally similar to that used to determine the nightly average clear fraction for the ground data.

For the nightly analysis and comparison there were 395 nights with adequate contemporaneous data coverage for the satellite and ground observer. Individual nights were then classified as follows: Photometric = nightly average cloud cover ≤ 0.125 (This value corresponds to the lowest cloud detection threshold used by the ground observer (1/8) which is marginally larger than the lowest detection threshold of the satellite (1/9)), Spectroscopic = 0.125 < nightly average cloud cover < 0.5 and Unusable = nightly average cloud cover ≥ 0.5. The results of the comparison are shown in Table 2. The hit rate is 74.9% with only 5.3% being misses (differ by two categories). 19.7% of the cases differ by one category. Table 3 shows the percentage of photometric, spectroscopic and unusable nights over the comparison period for each method. A plot of the monthly usable fraction is shown in Figure 8. The curves track each other very well over the comparison period. Once again the comparison shows good agreement between the satellite and ground-based methods.

Table 2. Counts of photometric, spectroscopic and unusable nights as determined by the satellite and a ground observer for Co. Tololo over the period June 1997 to April 1999.

<table>
<thead>
<tr>
<th>Ground/Satellite</th>
<th>Photometric</th>
<th>Spectroscopic</th>
<th>Unusable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photometric</td>
<td>197</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>Spectroscopic</td>
<td>21</td>
<td>15</td>
<td>29</td>
</tr>
<tr>
<td>Unusable</td>
<td>6</td>
<td>10</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 3. Percentage of photometric, spectroscopic and usable nights as determined by the satellite and a ground observer for Co. Tololo over the period June 1997 to April 1999.

<table>
<thead>
<tr>
<th></th>
<th>Photometric</th>
<th>Spectroscopic</th>
<th>Usable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground observer</td>
<td>58.2</td>
<td>16.2</td>
<td>74.7</td>
</tr>
<tr>
<td>Satellite</td>
<td>56.7</td>
<td>10.9</td>
<td>67.6</td>
</tr>
</tbody>
</table>
A significant disagreement between satellite cloud cover and ground-based observations has been observed at only one astronomical site – Mt Hopkins. Satellite data were compared to ground-based measurements made by the 2 Micron All Sky Survey (2MASS) over the period 1997/06/07 to 1999/09/30 during which the satellite and 2MASS data overlap. An in-depth analysis of the discrepancy between the two data sets has been carried out and the findings are discussed in another paper being presented at this conference\(^{19}\) and in a detailed report\(^{20}\). The main conclusion from this investigation was that non-weather related factors such as poor seeing, high backgrounds and telescope focus problems caused conditions to be considered non-photometric by 2MASS on a large number of nights (96 out of 621) which were mostly free of cloud. The number of clear hours during these nights accounts for the discrepancy.

An additional verification of the satellite cloud cover measurement was carried out as part of the study discussed in this paper using data for the ORM on La Palma. Ground-based observations used to determine sky cover conditions were made by the Carlsberg Meridian Telescope (CMT). The CMT uses about 50 photometric standards per night to determine atmospheric extinction. From these measurements the number of hours of photometric data and non-photometric data were determined\(^{21}\). Using this information, the *nightly photometric fraction* was determined for each night by dividing the number of photometric hours by the total number of hours observed. In processing the CMT data it was found that, on a number of nights, the sum of the photometric and non-photometric hours is significantly less than the night length. Unfortunately it was not possible to determine if these hours were “lost” due to technical problems, weather-related events or simply because observations were not made through the whole night. Therefore, when comparing the CMT data to the satellite it was decided to limit the comparison to nights where the total number of CMT hours observed was at least 80% of the night length.

The same fraction was computed using the satellite data. Using satellite images for the observing night (sun more than 9° below the horizon), the nightly clear fraction was computed by counting the total number of clear pixels in each image using the 9-pixel site designation and dividing by the total number of pixels. At least 3 images per night were required otherwise the night was excluded from the comparison. The satellite nightly clear (photometric) fraction is a spatio-temporal average and so partly clear sky coverage is included (e.g. in a given satellite image only some of the 9 pixels may be clear). This actually corresponds well to what is considered to be a “photometric” sky in the CMT measurements since for these only a limited part of the sky is required to be photometric\(^{22}\). In both cases, since partly clear skies are allowed, the clear or photometric fraction is, in effect, the usable (photometric plus spectroscopic) fraction.

The nightly clear (photometric) fractions were compared using the nights for which both CMT and satellite data were sufficient. 629 nights in the period 1999-2002 were used. Nights were compared by defining three sky cover categories for the night as follows:

- **Photometric:** Clear/Photometric fraction greater than 90%
- **Spectroscopic:** Clear/Photometric fraction between 50% and 90%
- **Unusable:** Clear/Photometric fraction less than 50%

Table 4 shows the counts for each combination of categories as determined by the satellite and the CMT measurements respectively. Defining a “Hit” as complete agreement, “Neutral” as disagreement by one category and a “Miss” as complete disagreement the following rates are determined from the data in Table 4: Hit = 66.1%, Neutral = 28.0% and Miss = 5.9%.
Table 4. Counts of nights in different observing categories as determined from satellite and ground-based observations at ORM.

<table>
<thead>
<tr>
<th>Ground</th>
<th>Satellite</th>
<th>Photometric</th>
<th>Spectroscopic</th>
<th>Unusable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photometric</td>
<td>330</td>
<td>81</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Spectroscopic</td>
<td>63</td>
<td>52</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Unusable</td>
<td>16</td>
<td>17</td>
<td>34</td>
<td></td>
</tr>
</tbody>
</table>

In terms of the difference between the satellite and ground-based measurements, there is no bias towards either method. The satellite overestimates the clear fraction by one category on 80 nights relative to the ground measurement and the ground measurement overestimates the clear fraction by one category on 96 nights relative to the satellite measurement. The corresponding number of nights for overestimation by two categories is 16 and 21 respectively. Taking night length into account, the clear/photometric hours were computed for the 629 nights and divided by the possible hours. The fraction of photometric time, including time when only part of the sky was photometric, was found to be 83.7% and 85.3% for the satellite and ground-based observations respectively. The percentage of photometric nights was 65.0% and 68.7% respectively. Given the differences in the measurement methods, the timing of observations and the constraints applied in the comparison (as described above), the satellite and ground-based measurements were found to be in remarkably good agreement.

5. AERIAL ANALYSIS OF CLOUD COVER AND PWV

For the study area covering northwest Africa and southern Spain (including the Canary Islands) (20°N to 40°N and 20°W to 10°E) satellite data for the period 1996 to 2002 were processed and aerial maps showing the distribution of clear skies were constructed using GrADS. The frequency of occurrence of each sky cover category was counted for each pixel location, expressed as a percentage frequency and then isokephs (lines joining places with equal frequency of occurrence. fr. G. isos, equal, and kephalaion, sum) were drawn. Clear fraction maps were compiled for the 7-year period overall, by season and for different times of the day. Due to space limitations not all maps could be presented in this paper. It is important to note that the clear fractions are derived using individual images 3 hours apart. Thus, for a given pixel location the clear fraction is the count of clear signatures divided by the total number of images processed. The fraction of clear or photometric nights will be lower. For example, if 6 or more hours of clear skies are required for a night to be considered clear, then a sequence of 3 or more images per night would need to be clear.

The map showing the distribution of clear skies for night-time hours over the 7-year period 1996-2002 is shown in Figure 9. The map indicates that the latitudinal maximum for the clear fraction occurs at about 28°N. At this latitude there is only a slight west to east gradient with the clear fraction dropping about 5% over the land areas compared to the ocean. The clear fraction drops to the north and south of this latitude. In addition, increases in cloud cover of about 15% are observed over the highland areas of the Atlas Mountains and the Ahaggar Plateau (southern Algeria) compared to locations at a similar latitude further west over the ocean. This increase occurs because mountains are preferred areas for cloud development by convection, particularly in the summer months.

Figure 9. Fraction of time that skies are clear (%) at night over the period 1996 to 2002.
In addition, at other times of the year, cloud cover is enhanced by orographic lifting of the air stream over these highland areas. The map also shows that the clearest locations in the Atlas mountains are those located furthest south and west, i.e. in the Anti-Atlas range.

The seasonal maps (not shown) reveal the same general pattern as observed in the overall map and show that the latitude belt with the clearest skies migrates northwards in summer and southwards in winter. This is consistent with the seasonal movement of the subtropical high pressure region. Over the Atlas Mountains and the Canary Islands, cloudiness is greatest in winter. This is due to the more southerly path and greater strength of cyclones and fronts at this time of the year. The enhancement of cloud cover over the highland areas due to the development of convective storms in the summer is confirmed.

Maps showing the distribution of the clear fraction for the four day-night periods defined in section 3 (not shown) indicate that the diurnal variations in cloud cover are small over the ocean and coastal areas and larger over inland areas. This is consistent with the fact that the oceans moderate the daily cycle of temperature, an important control for diurnal cloud cover variations. Daily variations in cloud cover are particularly noticeable over the high terrain areas which have a significant increase in cloud cover in the second half of the day. This is caused by convective cloud (thunderstorm) development in the afternoon hours which dissipates at night. The convective cycle of cloud cover is particularly noticeable in the south-western part of the Atlas mountains. In the north-eastern Atlas the daily cycle of cloud cover is less marked showing that orographic effects on cloud cover are more important than convection in this region.

Maps constructed to show the distribution of PWV over the study area consist of isokeph plots of the percentage frequency of occurrence of PWV values below selected thresholds, namely, 1 mm, 2 mm and 3 mm respectively. The PWV map for the 2mm threshold is shown in Figure 10. The plots are for PWV in the atmosphere above the 750 mb pressure level (~ 2500 m). Where the terrain is higher than this pressure level, PWV is for the atmosphere above the surface.

The isokephs on the PWV maps exhibit linear ramp-like characteristics in certain areas. These artifacts are most noticeable in areas where moisture levels are low and where the upper-air meteorological data used to derive the PWV from the satellite measurement is sparse. As noted in section 2, the NCEP-NCAR upper-air data used in the analysis has a resolution of 2.5° x 2.5° in the horizontal. In addition, the coverage of upper-air meteorological data used as input for the NCEP-NCAR reanalysis in this area is relatively poor, being worst over the inland areas of northwest Africa. Consequently, horizontal temperature variations in this area would be poorly resolved in the NCEP-NCAR data. Since latitudinal temperature variation is generally significantly larger than longitudinal variation in the atmosphere, the latter is particularly poorly resolved in the area in question. This temperature resolution problem spills over into the computation and hence plotting of PWV. The tropics are an exception. Even though upper-air data quality is equally poor in this area, the moisture signal (from the satellite) is strong and spatial variations in water vapor are significant. Because this is the case, variability in the satellite-derived PWV field can be detected and resolved even though the upper-air temperature field is poorly resolved.

Figure 10. Percentage frequency of occurrence of PWV values below 2 mm over the period 1996 – 2002.
As is the case with cloud cover, the water vapor minimum is found at about 28°N latitude. This is consistent with drying of the air as it subsides in the subtropical high pressure region. There is little variation from west to east across this latitude belt. Moisture levels increase to the north and south of the subtropics. This is the case since these areas experience more disturbed weather events which inject moisture found near the surface into the middle and upper troposphere. The spatial pattern observed in Figure 10 is consistent for all three of the PWV thresholds used. Diurnal and seasonal variations in PWV are very small which is consistent with the findings from other studies of PWV at existing and potential telescope sites using satellite and rawinsonde data.3,17,24.

The altitude dependence of PWV does not show up clearly in Figure 10 because the terrain areas above the 750mb pressure level (~2500 m) are small, because smoothed digital elevation model terrain heights are used in the area analysis and, additionally, because the isokephs have been smoothed. Within the general pattern of PWV shown in Figure 10, the lowest PWV values would be found at the sites with the highest altitude.

6. CONCLUSIONS

Cloud cover and water vapor (PWV) were surveyed over the area 20°N to 40°N and 20°W to 10°E using satellite data from the Meteosat Operational Service (in geostationary orbit at 0° longitude) for the 7-year period January 1996 to December 2002. The area surveyed covers northwest Africa and southern Spain (including the Canary Islands). Several developed observatory sites exist within the area surveyed. The Observatorio del Roque de los Muchachos (ORM) on La Palma in the Canary Islands was used as a reference site, a benchmark against which other potential sites could be compared and measured. Ground-based observations of cloud cover for this site were used to verify the satellite measurements.

Verification studies conducted at a number of existing telescope sites around the globe have shown that the satellite measurement of cloud cover and PWV agrees well with ground-based measurements of these quantities. A comparison of satellite and ground-based measurements of cloud cover made at the ORM using data for 629 nights in the period 1999-2001 have confirmed the reliability of the satellite method. The clear (photometric) and usable (photometric plus spectroscopic) fractions obtained for ORM using the two methods differ by about 2-3% (the satellite clear fractions being lower than those from the ground-based data set).

An aerial mapping of cloud cover reveals that the cloud cover minimum for the study area occurs at about 28°N latitude. At this latitude there is only a slight west to east gradient with the clear fraction dropping about 5% over the land areas compared to the ocean. In terms of potential telescope sites over the continent with a sufficiently high altitude, the clearest locations are found in the far southwest of the Atlas mountains (i.e. in the Anti-Atlas range). The region of lowest PWV coincides with the clearest latitude belt. Within this region, because of the altitude dependence of PWV, the highest peaks would have the very lowest PWV.

REFERENCES


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