Cloud Cover Estimation over Selected Locations in East Africa Using Satellite Derived Reflectivity Data.

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ABSTRACT

The study aimed at improving the estimation of cloudiness over East Africa through establishment of the relationship between observed cloud cover and the satellite derived reflectivity. Two types of data were used, namely: remotely sensed data and the ground cloud observation for the stations over the selected area of East African region covering from 0.11^{o}N to 5.47^{o}S and 32.33^{o}E to 39.15^{o}E. The stations considered were Nairobi and Mombasa for Kenya, Dar-es-Salaam and Kilimanjaro for Tanzania, and Kampala, Makerere and Kasese for Uganda. The remotely sensed data were obtained from one channel of the Total Ozone Mapping Spectrum (TOMS) satellite. Correlation analysis indicated that there is a significant relationship between ground-based cloud cover and satellite-derived reflectivity. The relationship seemed to be influenced by the prevailing meso-scale features prevalent in the specific areas. Based on these correlation analysis results, it may be concluded that satellite-derived reflectivity can represent the observed cloud cover, and consequently models can be designed to estimate the in-situ cloud observations over areas lacking ground-based cloud observations.

1. INTRODUCTION

In-situ cloud observations have characteristic limitations including the insufficient number of observing stations especially in remote areas, the bias of the observer and even the topography. The advent of satellite systems such as Total Ozone Mapping Spectrum (TOMS), has among other things, enabled the generation of reflectivity data. Reflected radiation can come from two surfaces: the ground, and the tops of clouds. Reflectivity is determined from the measurements at 380 nm, or 360 nm in the case of Earth Probe.

These two wavelengths are known to have unique absorption characteristics for derivation of reflectivity (Torres et al., 1998). The albedo or reflectivity of the cloud is highly influenced by the radiative properties of aerosols. Cloud droplets form exclusively through condensation of water vapour on cloud condensation nuclei (CCN). This effect of both the absorbing aerosols and non–absorbing, determines the reflectivity of the cloud, where the high aerosol concentration tends to cause low-level clouds to have more very small droplets, which in turn increase the reflectivity of cloud, and thereby cause an indirect radiative forcing associated with these changes in cloud properties (Torres et al., 1998; Penner et al 2001; Twomey,1997; Khain et al., 2004; Miller et al., 1998).

On the other hand, an increase in albedo is associated with decreases in cloud droplet number which is a function of aerosols column concentration. Studies show that for optically thick clouds there is an expected increase in cloud albedo which is associated with the decrease in droplet size, where as for optically thinner clouds there is an unexpected decrease of cloud albedo with decreasing droplet size (Nakijima, et al., 2001). Clouds with the same vertical extent and the liquid water content are observed to have higher short wave albedo over continents than over oceans (Theodore et al., 2003). Thus water bodies are associated with suppressed cloud reflectivity, whereas in more polluted areas cloud reflectivity is enhanced.

The study seeks to investigate the relationship between ground based cloud cover observations and the TOMS satellite derived reflectivity and hence attempt to improve the estimation of cloudiness over East Africa using satellite data.

2. DATA AND METHODOLOGY

2.1 Data

In this study two types of data were used: remotely sensed data and ground based cloud observation for the stations over the selected area of East African region covering from 0.11°N to 5.47°S and 32.33°E to 39.15°E. The stations considered were Nairobi and Mombasa in Kenya, Dar-es-Salaam and Kilimanjaro in Tanzania, and Kampala, Makerere and Kasese in Uganda. This area borders the Indian Ocean to the East and is in the vicinity of Lake Victoria to the west. The weather and climate of the study area is influenced by the East African high lands and mountain features including Mt Kilimanjaro having a peak of about 5000 m from sea level.

The remotely sensed data were obtained from one channel of the TOMS satellite, nemely the Earth probe having data from July 1996 to June 2005 and were downloaded from the website http://jwocky.gsfc.nasa.gov. Table 1a, and 1b provide details of the station locations.

2.2 Methods

Daily ground-based data were also collected for the same period. These were then converted to dekadal values. Mass curve analysis was also used in data quality control. The data were discerned to be of good quality and hence subjected to analysis. The techniques used in this study in order to achieve the goal were statistically oriented and included graphical, zero lagged correlation, and regression analyses as well as relative percentage error analysis methods for validating satellite-derived data (Muthama, 2003).

The techniques applicable here, for validation of cloud cover estimates from satellite data, require that the stations used are identified for each homogeneous climatic zone of the country. Each selected for validation must be remained in the same position over a period of 30 years which includes the validation period 1996 to 2005. There must be no gap in the data for any given station during the validation period, 1996 - 2005. (Muthama, 2003). Such techniques include:

(i). Estimation of Bias

$$B = \frac{1}{N}\sum_{i=1}^{n}\left(E_e - O_i\right)$$

Where

E_e - satellite reflectivity estimate

O_e - Reference ground based data

A positive bias indicates that the estimate ex-

Table 1a The stations for the aerosols and reflectivity data with their coverage Using Earth Probe data for the period 1996-2005.

Country	**Station**	**latitude**	**longitude**
Kenya	Nairobi	1°6’S	35° 47’E
Uganda	Kampala	0.11N	32.20E
Tanzania	Dar es Salaam	5°28’S	39° 09’E
	Kilimanjaro	3°04’S	37° 20’E

Table 1b Rainfall and cloud cover Stations and their time coverage

Country	Stations	coverage
Kenya	Nairobi and Mombasa	2003-2004
Uganda	Makerere University and Kasese	2004-2005
Tanzania	Dar es Salaam and Kilimanjaro	2004-2005

Table 2 Correlation coefficients between cloud cover and satellite derived reflectivity for various stations. *The coefficient is not significant.

No	**station**	**Time of observation (GMT)**	**No of data points**	**Correlation coefficient**	**Computed t-value**	**Tabulated t-statistic at 0.05 significance level**
1	Dar es Salam	600	25	0.058	0.280	*0.381
		1200	25	0.829	3.576	0.381
2	Kilimanjaro	600	25	0.822	3.568	0.381
		1200	25	0.612	2.859	0.381
3	Nairobi	600	72	0.603	6.318	0.243
		1200	72	0.588		0.243
4	Mombassa	600	72	0.110	0.924	0.243
5	Makerere	600	25	0.598	3.576	0.381
6	Kasese	600	22	0.137	0.621	0.433

(ii) Error separation method

Error separation method is based on error variance which may also be described in terms of root mean square (RMS) error.

$$Var(Rs - Rg) = var(Rs - Ra) - Var(Ra - R_T)$$

Where Rs is the satellite based reflectivity estimate.

Ra is the areal average for a given homogeneous climatological zone.

R_T is the ground based cloud cover value.

The Root Mean Square (RMS) is expressed as:

$$RMS = \left\{ \frac{1}{N^2} \sum_{i=1}^{N} \left(R_s - R_g\right)^2 \right\}^{1/2}$$

A target of 5% and a threshold of 10% are adopted. The RMS error gives an indication of the accuracy of the satellite-based estimates.

(iii) Relative percentage error method

The analysis of deviation was performed using the relative percentage error method (RE) is given by:

$$RE = \frac{C_o - C_s}{C_o} \times 100\%$$

Where C_o is the Observed ground based cloud cover, and C_s is the satellite based cloud reflectivity.

A target of 2% and a threshold of 5% are adopted. The RE error gives an indication of the accuracy of the satellite-based estimates with respect to ground based observations.

The RE was adopted for this study.

3. RESULTS AND DISCUSSION

Single mass curve analysis for the satellite derived reflectivity and the ground-observed cloud cover showed homogeneity of data for all the stations which investigated. The plots of time series analysis between reflectivity and cloud cover for all the stations are as given in Figures 1 (a), (b) and (c).

Figures 1(a)-(c) show the relationship between satellite-derived reflectivity and ground based cloud data at different stations (a)Dar es Salaam, (b)Kilimanjaro, (c) and (d)Nairobi and (e)

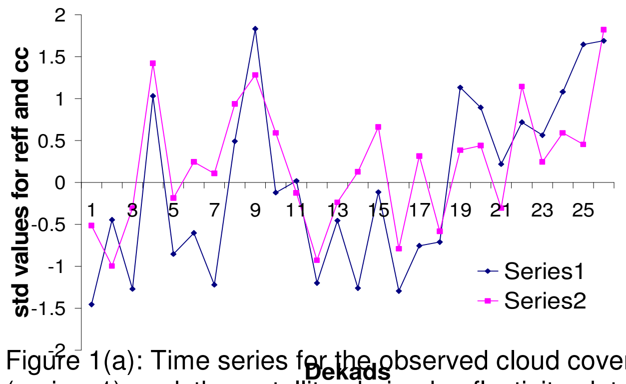


Figure 1(a): Time series for the observed cloud cover (series 1) and the satellite derived reflectivity data (series 2) over Dar from Sept 2004-Jun 2005.

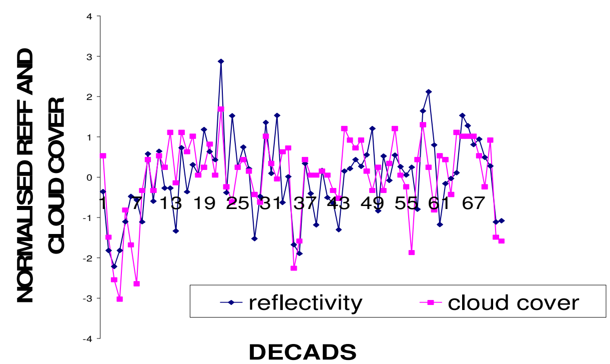


Figure1 (b): Time series for the reflectivity and cloud cover at 0600hrs *(GMT) for Nairobi from Jan 2003-Dec2004.*

Generally all plots show that there is a positive correlation between the satellite-derived data and the observed cloud in all the analyzed stations. In some cases, like Kilimanjaro, where the two curves cross each other, this can be explained by possible bias of the ground based cloud observation, in terms of cloud amount as well as type and height, data as well as the missing satellite in some days.

3.1 Relative Percentage Error method

Relative percentage error analysis was performed to assess the agreement between the satellite estimations for reflectivity and the in situ cloud observed data. Figure 2(a) and 2(b) are the relative percentage error analysis for stations including Kilimanjaro and Dar es Salaam, and which provides percentage error between 0% -7% but less than 10% with an average error ranging from 2.95% - 4.7% but less

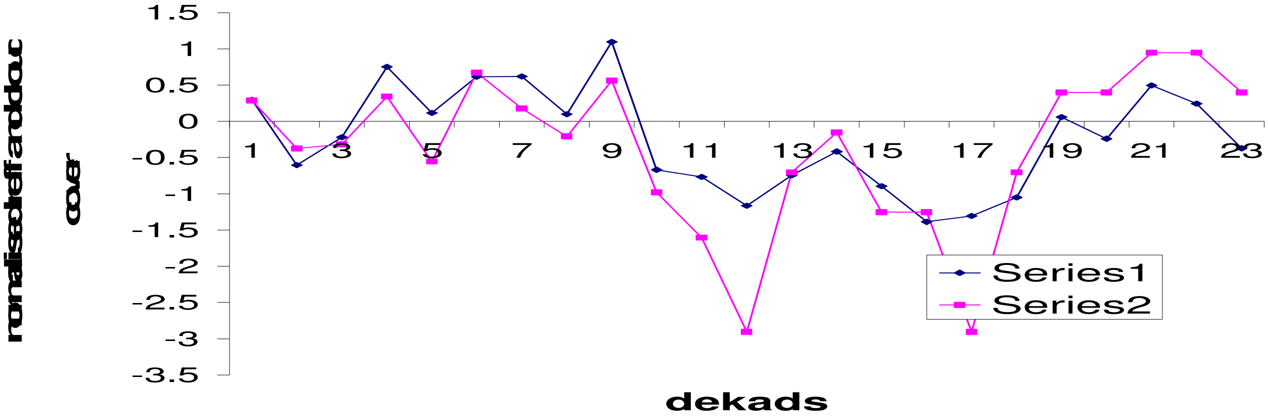
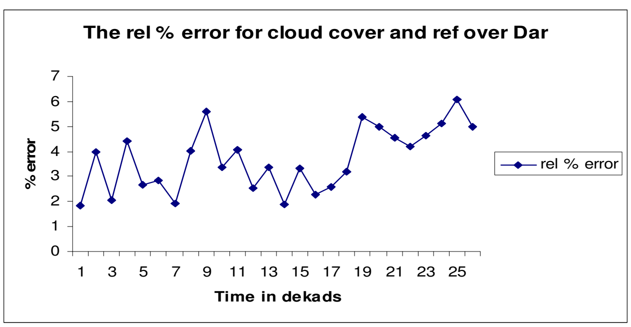
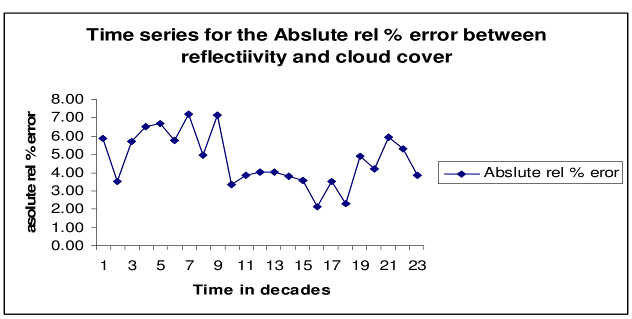


Figure 1(c): Time series for the reflectivity (Series 1) and cloud cover (Series 2) over Kilimanjaro from Sept 2004-

This indicates that the differences between the satellite-derived estimations and the in-situ observations are not big, hence this verifies that satellite estimations are good and may be to be used for analysis and other purposes such as representation the stations having no ground-based cloud observations, over the study area. Also it gives a good potential for designing a model which can be used to estimate the cloud observations using the satellite derived reflectivity data. Graphical analyses depicts the existence of a relationship between the satellites derived data and the surface observed cloud data.



2(a) Dar es Salaam



2(b) Kilimanjaro

Figure 2: Time series for the relative % error for cloud cover and reflectivity over (a)Dar es Salaam and (b)Kilimanjaro from Sept 2004-Jun 2005.

3.2 Correlation analysis

Results of correlation analysis reveal that correlation coefficients for cloud cover and reflectivity over Dar es Salaam, Mombasa and Kasese at 0600hrs (GMT) are very small with that of Dar es Salaam being the smallest (0.058429) and not significant. This can be explained by the influence of water bodies on albedo around these stations. The Indian ocean, neighboring Mombasa and Dar es Salaam, and lake Victoria, neighboring Kasese, have very low albedo. Kilimanjaro and Nairobi having high correlation coefficients between cloud cover and reflectivity at all the observational times (0600hrs and 1200hrs (GMT)). This can be practically explained by the influence of high altitude for Nairobi and Kilimanjaro but more significantly the snow cover over the top of mountain Kilimanjaro (snow have high reflectivity) may be responsible.

Another interesting case is that of Dar es Salaam having low correlation at 0600hrs (GMT) and high correlation at 1200hrs (GMT) this can be explained by the effect of low insolation at 0600hrs and high insolation at 1200hrs which is the period of maximum temperature and high convective activity depending upon the moisture content present in the atmosphere at that specific time or day.

3.3 Linear Regression modeling

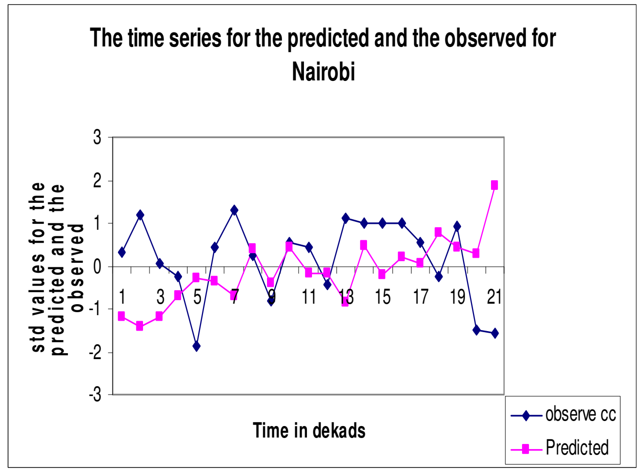
Table(3) summarizes the linear regression models which can be used to estimate cloud cover using reflectivity. Using the Fisher statistic ratio (goodness of fit ratio - F), the regression model in Table 3 have highest F value over Kilimanjaro and lowest over Makerere where as the P value is highest over Nairobi and lowest over Dar- es Salam, this implies that all the models except for Makerere will provide good results with that of Nairobi and Kilimanjaro being the best models.

When the models were tested for the estimation of the cloud cover using the satellite observations, they provided good results for various stations, examples of which are given by Figure 3 (a) and 3(b).

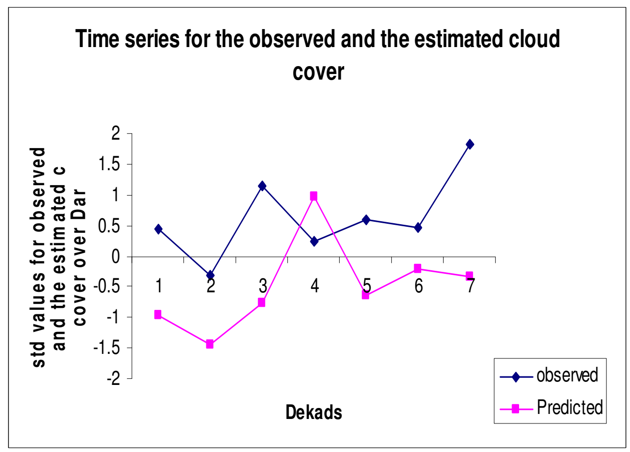
Figures 3(a)and 3(b) are the time series plots for the model estimations and the observed cloud cover for different stations including (a) Nairobi and (b) Dar es Salaam, respectively. Generally the figures show that the models have some notable operational potential. The figures illustrate that both curves follow, to some extent, approximately the same pattern except for some few points. This suggests that, to some extent, the satellite data can be used to estimate cloud cover over the study area. More data would however, help verify this suggestion.

4. CONCLUSION

There exists significant correlation between ground based cloud cover and satellite derived reflectivity at Kilimanjaro and Nairobi, with low values at Dar es Salaam, Mombasa and Kasese at 0600h (GMT). Based on these significant correlation coefficients the study found that the satellite derived reflectivity can be used, to some extent, to represent the cloud cover for stations or areas having no cloud observations. Considering the strong linear relation between the cloud cover and the satellite derived reflectivity for most of the stations under investigation, it may be concluded that cloud cover can be estimated using the satellite derived reflectivity.



(a)Nairobi



(b) Dar

Figure 3(a)-(b)):Time series for observed and the estimated cloud cover over (a) Nairobi (b) Dar es

Table 3. Summary of the regression models and their statistical values for cloud cover and reflectivity over vari-

		The table shows the regression model analysis					
Station	**equation**	**P value**	**F value**	**sign F**	**t-statistic**	**std error**	**Multiple R**
Nairobi	Y=0.651x+ 0.010	0.929	35.566	0.000	0.09	0.784	0.649
Dar es Salaam	Y=0.1x-0.455	0.007	21.661	0.000	-3.099	0.637	0.749
Kilimanjaro	Y=1.29x-0.426	0.014	36.775	0.000	-2.967	0.497	0.887
Makerere	Y=-0.094x-0.518	0.097	0.079	0.784	-1.813	1.025	0.084

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