Lightning is a very important and critical weather phenomenon, which affects people and the environment directly and indirectly. These can be in the form of inter-cloud, intra-cloud, cloud-to-air or cloud-to-ground flashes, the latter being the most dangerous to humans, vegetation (forests) and infrastructure. Every year, globally and in Swaziland, several deaths resulting from lightning are reported. Surface air, moisture and geographical features also play a role in thunderstorm evolution especially over heated high ground. Quantification and mapping of lightning has become a very important area of research throughout the world as a result of the effect of lightning on telecommunications, power utilities, aviation and the insurance industry, among other socioeconomic impacts.

The technology of remote sensing and their capabilities now enable many other parts of the world to detect nearly all lightning strikes in real-time with the ability to also locate the strike with high temporal and spatial accuracy. This is often complemented with ground-based detection networks, such as South Africa Weather Services’ new Vaisala system, to improve reliability and detection efficiency. This information has been successfully used in many areas to quantify the distribution of lightning through various spatio-temporal analysis techniques. This analysis can yield good results for applications such as assessing lightning risk for infrastructure such as transmission systems, modelling thunderstorm dynamics and estimating rain yields, and to quantify emissions of nitrogen oxides (NOx) which affect global atmospheric chemistry, more specifically the earth’s radiative transfer. In this analysis, data from the lightning imaging sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite was analysed to determine the spatial and temporal distribution of lightning over Swaziland, a country characterised by a complex terrain and climate.

In this article, nine years of lightning data (January 1998 to December 2006) from the lightning imaging sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite was analysed to determine the spatial and temporal distribution of lightning over Swaziland, a country characterised by a complex terrain and climate.

Study area

The Kingdom of Swaziland, located in southern Africa, is characterised by complex topography with elevation that decreases from an average of 1400 m on the west to below 100 m above sea level on the eastern part of the country giving rise to four major eco-climatic (commonly referred to as agro-ecological) regions, namely the near-temperate highveld, sub-tropical middleveld, the semi-arid lowveld and the Lubombo Plateau. The in-country climatic variations are largely controlled by the topography, the distance from the ocean and the prevailing winds resulting in four seasons every twelve months. The climatic seasons in Swaziland are the reverse of those of the northern hemisphere with December being mid-summer and June mid-winter.

Spring is during the months of August and October and summer is between November and January whilst autumn occurs between the months of February and April. Winter, the dry season, runs from May to July. Most of the rain falls during the summer months, often in the form of thunderstorms, which result in intense lightning activity. Topographic variations in the country result in climatic variations and atmospheric activity. Annual rainfall is highest on the highveld to the west of the country, between 1000 and 2000 mm depending on the year. On the east, the lowveld records between 500 to 900 mm per annum. Variations in temperature also follow the altitudinal gradients of the different regions with the highveld being temperate and, seldom hot while the lowveld may record temperatures of up to 40º in summer.

Methods

This analysis uses data from the satellite-based lightning imaging sensor (LIS) aboard the Tropical Rainfall Measuring Mission (TRMM) which was launched in November 1997 as a joint U.S. and Japanese mission aimed at understanding the global energy and water cycle by providing distributions of precipitation and the associated thermodynamics over the tropics [1]. The TRMM LIS measures total (intra-cloud, inter-cloud, cloud-to-air and

Fig. 1: Lightning flash distribution in Swaziland as observed by the TRMM LIS (1998-2006)
cloud-to-ground) lightning with high detection efficiency during both day and night at a sampling resolution of approximately 90 seconds over any given area during an overpass. The primary data source for this study is the quality controlled version 4.1 LIS flash observations in which there are improvements from the known limitations in the data processing algorithms of the preliminary (4.0) version.

The data for the period January 1998 to December 2006 was downloaded using the online search tool from NASA’s Global Hydrology Research Centre (GHRSC) website. This data consists of information on the date, time, location, number of events, number of groups and radiance. To compute diurnal cycles of lightning, the LIS lightning flash data were accumulated and averaged over 2-hour time bins for each individual hour of the day in order to mitigate sampling bias [2]. This data was imported and saved as a Microsoft Excel spreadsheet for input into a GIS (ArcGIS) for spatio-temporal analysis. The data was then stored as a geodatabase to allow easy integration of the data directly into GIS geoprocessing functions. The distribution of lightning flashes for the period under review is shown in Fig. 1.

The interest for this preliminary study was to find out if lightning is a random activity or if there are space-time trends or clusters (i.e. if certain areas are more prone to lightning) within the country. The geoprocessing functions in ArcGIS were used to calculate statistical values used to quantify pattern and to identify the locations of statistically significant lightning clusters. Calculations were based on the Euclidean (straight line) distance between two points and the spatial conceptualisation was an Inverse Distance Weighting method, which assured that no local lightning flashes were excluded from the analysis.

Two indices were calculated as a measure of spatial distribution of lightning in the country weighted by time (month) of lightning activity. These were the Nearest Neighbour Index (NNI) and the Anselin’s Local Moran Index. The null hypothesis for these pattern analysis approaches states that there is no pattern, i.e. the expected pattern is one of hypothetical random chance. The Z score, which is a measure of standard deviation and a test of statistical significance that helps decide whether or not to reject the null hypothesis, was calculated for both analyses.

The Nearest Neighbour Index is expressed as the ratio of the observed distance to the expected distance (hypothetical random distribution) [3, 4].

\[ \text{NNI} = \frac{A_d}{E_d} \]  
where:

\[ A_d = \frac{\sum d}{n} \]  
and:

\[ E_d = \frac{1}{2} \sqrt{\frac{d}{n}} \]

\[ n \] is the number of points and \( A \) is the map area.

Values less than 1 generally indicate a clustering pattern while values greater than 1 indicate dispersion. The Z score test of statistical significance for the NNI is calculated as follows:

\[ Z_d = \frac{A_d - E_d}{\sigma_{A_d}} \]

where \( \sigma_{A_d} \) is the standard deviation of \( A_d \):

\[ \sigma_{A_d} = \sqrt{\frac{0.0683}{n}} \]

The NNI is a simple measure of spatial arrangement and it is therefore subject to several limitations. Apart from inaccuracies in the interpretation of results it also suffers from requiring the use of artificial boundaries to compute the map area. This can introduce bias into data that are on or near the edge of the study boundary. Because the NNI considers only the distance to the nearest neighbouring point, it is somewhat insensitive to complex patterns and may not consider the overall spatial arrangement of points in the distribution. To evaluate points for overall pattern, it is necessary to employ a more advanced analytical technique such as spatial autocorrelation indices, hence the Anselin’s Local Moran Index was also computed.

The Anselin’s Local Moran Index is used as a local indicator of spatial association, which is calculated for individual zones around each observation within a defined neighbourhood to identify clusters and outliers [3, 4]. It is calculated as follows:

\[ I = \frac{n}{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (x_i - \bar{x})^2} \]

where \( n \) is the number of points, \( W_{ij} \) denotes the spatial weight matrix, and \( x \) denotes the frequency of the lightning.

Because the distribution of the statistic is not known, high positive or high negative standardised scores are taken as indicators of similarity or dissimilarity respectively. If Moran’s I index value for any lightning flash point is positive, then the lightning has values similar to neighbouring features’ values. If the value is negative, then that point is quite different from neighbouring values. The occurrence of lightning due to spatial location and timing (month) were clustered to reveal clustering patterns. The Z score, described earlier, was also calculated in this regard.

Results and discussion

The Nearest Neighbour index values are as shown in Table 1. The NNI

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>NNI</td>
<td>0.95</td>
</tr>
<tr>
<td>Z score</td>
<td>-10.1 (standard deviations)</td>
</tr>
<tr>
<td>Significance level</td>
<td>0.01</td>
</tr>
<tr>
<td>Critical value</td>
<td>-2.58</td>
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</tbody>
</table>

Table 1: Nearest Neighbour analysis results
is 0.95, which is indicative of a clustering pattern. The results show that there is less than 1% likelihood that this clustered pattern of lightning distribution could be the result of random chance. To test the significance, the value of Z is compared with a normal distribution. The NNI and standard normal deviates (Z score) of the lightning dataset (Table 1) indicates that the lightning flashes exhibit some degree of clustering.

The next stage of the analysis was to perform cluster analyses in an attempt to identify the individual clusters of pits with similar values that the descriptive statistical tests seem to indicate exist. The results of the Anselin’s Local Moran Index appear to confirm the results of the NNI test, namely that a degree of clustering appears to be evident in the lightning flashes. The zones having higher absolute Local Moran Index were selected and using a confidence level of 95% for the Z-score, the clusters were identified and are shown in Fig. 2.

When performing the lightning pattern analysis, it yielded either very high or very low Z scores, indicating that it is very unlikely that there is no observed pattern as represented by the null hypothesis. These zones of clustered lightning activity reveal a spatial pattern that runs parallel to the altitudinal variations with a relatively significant level of activity located in the elevated areas. Theoretically, it is stated that higher altitudes are more sensitive to solar heating, thus giving rise to an unstable thin atmosphere, which results in thunderstorms (and lightning) [5, 6]. The topography in these areas provides conditions favourable for convective activity thus the formation of thunderstorms. In-depth analysis is required to determine the local conditions, which give rise to these clusters.

During the cool and dry winter the level of lightning is low. During the transition periods of spring and autumn, there is still evidence of thunderstorm activity. The monthly periodicity over the nine-year period is evident from Fig. 3, with peaks during the summer and troughs during the winter months. The seasonal analysis results indicate that the mainly summertime lightning activity over much of the country is modulated by the diurnal cycle of solar insolation. Convective instability caused by afternoon solar heating is most likely the cause of the sharp afternoon peaks (Fig. 4). Lightning occurs less frequently during winter as a result of low instability and moisture in the atmosphere as opposed to summer.

The LIS flash time in the data, which was converted to local solar time, analysed for diurnal variability revealed a distinct pattern. The diurnal variation in lightning activity is shown in Fig. 4 in 2-hour bins and indicates a bimodal pattern of lightning during the late afternoon (between 14h00 and 20h00 local time) and a second peak during the late evening hours (22h00-00h00). Convective instability arising from the afternoon solar heating causes the afternoon peaks. The local secondary maximum in lightning activity is evident during the early morning hours for the summer season. This could be influenced by the formation of a nocturnal low-level jet that aids in the transport of low level moisture or stratiform precipitation [7]. This diurnal cycle is also consistent with observation of the development of storms over the southern Africa region in the late afternoon and early/late evening [8].

Conclusion
In the absence of a ground-based system in Swaziland, the country can benefit from the use of satellite information, which can be used to quantify lightning parameters. The use of geographic information systems (GIS) combined with modern advanced and remote sensing techniques can be used to solve a wide range of complex issues such as those stated earlier in this paper. The combination of GIS and remote sensing with appropriate meteorological data sets produces exciting synergies for improved decision-making in the future. GIS now offers much more than just the display of meteorological data, it also provides the capability of combining quality-controlled data with other geo-referenced information to perform advanced spatial analysis capable of calculating meaningful value-added results.
The lightning activity in Swaziland shows a clear seasonal variation. The monthly comparison indicates maximum activity during summer, where the most vigorous period occurs in the late afternoon to the early evening. A reasonable level of activity is also observed during spring and autumn months. Peak activity is found in certain areas of high elevation in mountainous areas. This suggests the presence of convective development and stratiform precipitation according to the local and mesoscale circulation weather systems affecting the country.

The combined coordinates of lightning flashes used in the creation of spatial representation of lightning density gives insight into the pattern of lightning distribution in Swaziland. In addition to the traditional visual display of the location of lightning activity on a map, the GIS can also provide an opportunity for precise calculations of the proximity of lightning activity relative to critical infrastructure and other lightning sensitive areas. The derived spatial representation, in conjunction with ground-based systems, could help researchers conduct in-depth analyses of the patterns and trends of lightning and to define the lightning climatology of the country.

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