5. Multi-scale WV fluctuation characteristics over southern Africa

A small forcing can cause a small change or a huge one
- National Academy of Sciences (2002)

This Chapter presents results and discussion on the vertical WV model derived from SHADOZ network and HALOE satellites. Results depict spatial-dependent vertical differences in the WV model. Furthermore, the multi-scale organization is clearly evident in the spatial-temporal WV variability over the low- and mid-tropical Africa by use of NCAR/NCEP reanalysis and the in situ SHADOZ network data. In particular, the present chapter considers the use of WV derived from model simulations and in suit radiosonde data to assess the power law scaling behaviour of WV. Understanding of this complex behaviour contributes towards understanding the contribution of meteorological factors that influence geodetic tropospheric delay modelling.

5.1. Introduction

Analysis of WV variability in the low- and mid-tropical Africa is based on the *in situ* radiosonde observations of the SHADOZ station network comprising of Ascension, Irene (South Africa), Reunion (Reunion) and Nairobi (Kenya) and the numerical model simulations for the period from 1998 to 2006. The motivation for analysing WV fluctuations in the tropical Africa is driven by the desire to obtain an in depth understanding of the spatial-temporal WV fluctuations as well as study the mechanisms driving WV variability and its link to the climatic variables. Analysis of the climatic variables influenced by WV is essential for the accurate modelling of the influence of WV on the estimation of the geodetic tropospheric delay observable and of the regional hydrological cycle in Africa-South of the Equator. The analysis of WV fluctuations is based on the multiscale organisation paradigm as detailed in section 5.2, where a mean vertical profile of the troposphere WV is developed using the radiosonde measurements at Irene-South Africa and Malindi- Kenya. This research work has been published as journal articles; see Botai *et al*., (2010) and Sivakumar *et al*., (2010).

The principal effects of variations of WV in the troposphere are; (i) the effect on the radiative balance, and (ii) the effect on cloudiness (which indirectly influences the radiative field). Throughout the troposphere, WV exerts a strong influence over how Earth loses radiative energy to space and this sets a balance between the energy received and absorbed from the sun. The WV feedback (i.e., the feedback on global temperature caused by changes to WV resulting from increases in CO_2 and other gases) is now almost universally accepted to be positive and strong. Based on data from NASA's satellite borne atmosphere infrared sounder (AIRS) over the period 2003-2008, Dessler *et al*., (2008) assessed the tropospheric WV response to global-average surface temperature of the Earth and reported strong positive WV feedback with a magnitude of $\lambda_q \sim 2.04\ Wm^{-2}K^{-1}$. This finding corroborates results from climate model simulations.

Gettelman and Fu, (2008) used humidity and temperature data from AIRS to analyse how the upper troposphere responded to changes in the underlying surface temperature. These observations were compared with simulations of the NCAR community atmosphere model version 3 (CAM) described by Collins *et al*., (2006). The results from AIRS and CAM simulations found a positive WV feedback i.e., as the temperatures increase, the WV in the upper troposphere also increases to keep the relative humidity at nearly equilibrium.

The abundance of WV in the atmosphere has a significant consequence on the earth's climate. This is due to its large energy transfer associated with phase transition where short-term dynamics of the atmosphere is also affected. WV therefore plays a key role in both the radiative and dynamic processes of the climate system (Zveryaev *et al*., 2007). The sensitivity of precipitation, WV and temperature changes in large-scale atmospheric circulation makes identification of the regional trends in precipitation and their contribution to temperature and WV variability critical. This involves the formation of the Polar Stratospheric Clouds (PSC) which are the reservoirs of halogenated molecules involved in the spring ozone depletion. Acid rain in the form of H_2CO_3, HNO_3, H_2SO_4, etc., is formed by the reaction of CO_2, nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2) in their aqueous states.

Global distribution and variability of the atmospheric WV has been well documented (e.g., Dai, 2006). In addition, evidence of WV variability over regional scales has also been documented (see e.g. Trenberth *et al*., 2005). Further, WV is unique among atmospheric trace constituents due to the role it plays in creating saturation conditions prevalent in the atmosphere. This property is the most important factor governing the distribution of WV in the atmosphere, both in the troposphere and in the stratosphere.

In the troposphere WV varies by as much as four orders of magnitude in a vertical profile while in the stratosphere, variations are much smaller (~10% lower, as reported by Stenke and Grewe, 2005) but still significant. Furthermore, WV in the upper troposphere and low stratosphere plays a key role in atmospheric chemistry (Stenke and Grewe, 2005). For instance, the hydrogen oxides involved in catalytic reaction cycles which are responsible for the control of the production and destruction of ozone layer in the lower stratosphere are produced from the oxidation of WV and methane by excited oxygen atoms. In addition, the partitioning of the nitrogen and halogen family is influenced by the hydrogen oxides. Nitrogen and halogen elements are crucial for ozone removal in the stratosphere.

One way to investigate the variability of WV is to assess the variability of precipitable WV (*PWV*) which is derived from the Integrated WV (*IWV*) along the path of the balloon sounding, i.e.,

$$IWV = \int_{h_s}^{h_a} \rho_v \mathrm{dh}, \qquad (115)$$

Where ρ_v, and h_a are the density of WV and the top of the troposphere respectively. The IWV is then mapped into PWV using Equation (116),

$$PWV = \frac{IWV}{\rho_w}, \qquad (116)$$

where ρ_w is the density of liquid water. Using the gas state Equation, ρ_v can be obtained from

$$\rho_v = \frac{P_v}{R_v \times T}, \qquad (117)$$

where R_v= 461.495 $JK^{-1}Kg^{-1}$ is the specific gas constant for WV. The partial pressure, P_v of WV which is obtained from Relative Humidity (RH), as expressed in Equation (118)

$$P_v = RH \times e^{-\left[37.2465+0.213166\times T-2.56908\times 10^{-4}\times T^2\right]}. \qquad (118)$$

Here T is the absolute temperature in Kelvin. Since radiosonde observations are discrete data series of temperature and RH at different heights, the atmosphere layer could then be subdivided into discrete layers. This implies that, if the parameter field $\{\rho_v, T\}$ at each layer is assumed to be linear, then Equation (119) could be approximated as

$$PWV = \frac{1}{\rho_w} \sum_j \left(h_{j+1} - h_j\right) \times \frac{1}{2} \left(\rho_v^{j+1} + \rho_v^j\right). \qquad (119)$$

Radiosonde measurements have important applications in verifying WV computed from numerical weather prediction models: they are currently one of the main observation techniques to provide atmospheric water vapour profiles in an operational NWP system. Yang *et al*., (1999) stated that the horizontal scale of WV is, on average, larger than the existing model grid resolution of most the NWP systems. Therefore, even if WV fluctuations with short wavelengths exist, the fluctuations are not measured in most cases and ought to be ignored. This assumption would be acceptable in NWP system. However in space geodetic applications, such assumption could not be favourable at all. In such cases where geodetic stations are close to radiosonde stations, the data from radiosonde measurements is invaluable with regard to verifying WV derived from space geodetic techniques such as GPS, VLBI and WVR for tropospheric modelling of the geodetic delay observable.

Despite the emerging long records of satellite-based observations of atmospheric parameters that describe the structure and dynamics of the atmosphere, radiosonde measurements continue to prove useful in diagnosing the variations in the vertical temperature, humidity and wind speed and direction. As a result, the derived scale height of WV (this is based on the humidity information) distribution can be studied in order to determine the relations between the scale height vertical WV distribution and the rate of de-correlation of the integrated WV over horizontal separation. As reported by Ruf and Beus (1997), this relationship is as a result of the departure from the simple Kolmogorov behaviour of WV turbulence structure, since the horizontal separation approaches the scale height dimension.

Assessment of WV variability could be done using the WV mixing ratio (π) where the relation in Equation (120) and (121) is used to compute the precipitable WV.

$$PWV = \int_{h_s}^{h_a} \frac{\pi dp}{g}, \qquad (120)$$

Here, dp and g are the incremental pressure change with height in Pascal units and gravititational constant respectively, π is the mixing ratio of WV per gram of air.

In first section of this chapter, a mean vertical profile of WV in the South of the tropical Africa is modelled based on the data from selected radiosonde stations which are the part of SHADOZ network. The general approach in this chapter is to use SHADOZ *in situ* measurements and numerical weather model simulations to investigate the regional variability of WV. A description of the data sets and the methodology used in obtaining the reference profiles for different location is reported by Sivakumar *et al*., (2010). In the second part of the chapter, the multi-scale organisation of the regional WV variability noted by Botai *et al*., (2010) is reported.

5.2. Vertical profile of WV from SHADOZ data

The global time-mean distribution and large-scale variations of WV are fairly well characterised by satellite data sets, especially by HALOE satellites. In addition, *in situ* and ground-based data sets augment satellite information and present a picture consistent with satellite observations. *In situ* and ground-based data sets are also essential for revealing the behaviour of WV at smaller spatial scales, for long-term monitoring and for validation of satellite data sets. As one of the aims of the research work in this thesis a model (mean) profile for WV in Southern hemisphere latitude using about 10 years (1998-2007) of the SHADOZ balloon borne measurement from Nairobi-Kenya (1.29^0 S; 36.80^0 E; 1795 m), Malindi-Kenya (2.99^0 S; 40.19^0 E; -6 m), and Irene-South Africa (25.90^0 S; 28.22^0 E; 1524 m) was constructed and is reported in the ensuing sections.

The vertical profile of mean WV computed in this section is based on the data obtained from the SHADOZ measurements to obtain a height profile of WV in Southern region of Africa. Such profiles can be used as a reference for comparisons with other measurements such as satellite observations. The details about the data and quality of ozonesonde measurements can be found in several publications (e.g., Borchi *et al*., 2005; Sivakumar *et al*., 2007). At each radiosonde station, about 10 years of ozonesonde data gathered from 1998 to 2007 of Irene, from 1999 to 2006 of Malindi and from 1998 to 2007 of Nairobi stations was used. The measurement data for height region up to 30 km altitude are collected from SHADOZ data which are archived at http://croc.gstc.nasa.gov/shadoz/site2.html/. The SHADOZ measurement contains pressure, temperature, relative humidity and ozone. The mean value of WV mixing ratio in ppmv is found from the relative humidity data using the relation given by Equation (121);

$$\pi = 61121 \times RH \times \frac{e^{\frac{17502T(z)}{24097+T(z)}}}{P(z)}. \qquad (121)$$

Here, π is the mixing ratio, RH is relative humidity, T(z) is temperature in degree centigrade.

The height profile of WV is obtained for the regions of southern latitude hemisphere. The mean values of 10 years of SHADOZ *in-situ* measurement data are further used for making comparison. The mean WV profile calculated from the SHADOZ measurement for stations at Malindi and Irene is displayed in Figure 4.1 which indicates that the variability of WV increases with altitude and that there are notable high variations (this can been seen in terms if the spread or variances in the mixing rations) between 2 and 7 km. It can be observed that above 2 km, the relative variability of WV is greater than 20% in Malindi and 43% in Irene. Such difference indicates that the variation of WV concentration with latitude region. The variation of relative humidity with temperature also contributes to the WV variability in the stratospheric region. The questionable accuracy with altitude can affect the amplitudes of WV variability.

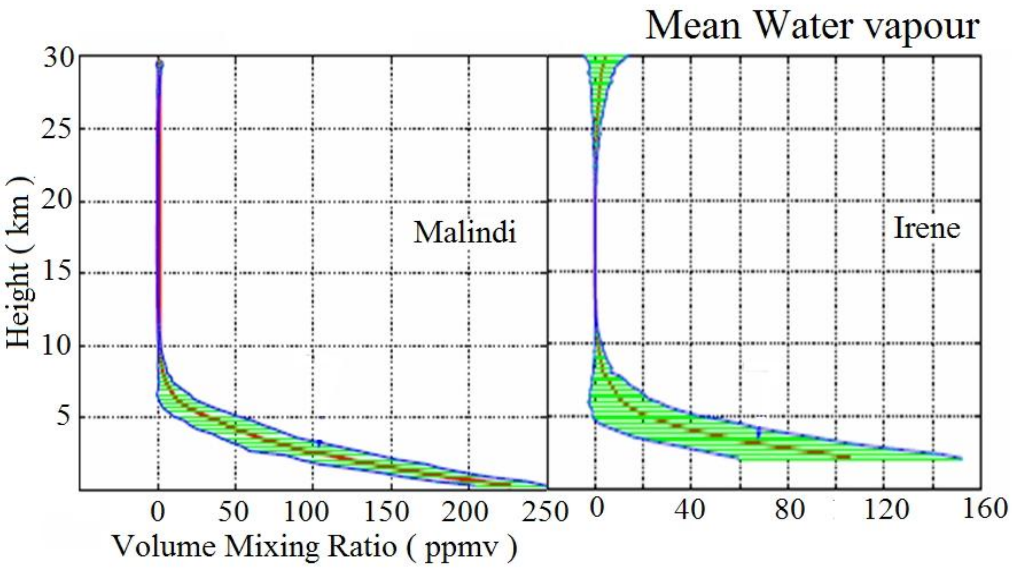

Figure 5.1. Height profile of mean water vapour obtained from SHADOZ datasets.

The mean WV profile of about 10 years of SHADOZ network stations (in this case Malindi and Irene) was derived and has been used to verify WV profiles retrieved from other satellite measurements, such as; GPS and HALOE (see for instance, Sivakumar *et al.*, (2009a)). Additionally, these results would be useful for initializing numerical models and improving parameterizations of radiative and cloud processes. In general, the vertical structure of WV can be used to investigate the occurrence of turbulent events in the atmosphere which could be associated with local weather conditions and passage of fronts. Refractivity profiles computed from radiosonde data could also be used to describe the turbulent fluctuations through the analysis of the structure constant. These measurements have vital applications in assessing the occurrence of ducting conditions which could have adverse effects in geodetic observations (especially microwave measurements) as well as radio communication.

5.3. Multiscale organisation of WV in mid- and low-tropical Africa

A number of ground based and space borne remote sensors are available to provide the vertical and horizontal profiles of WV, for e.g. radiosondes, Light Detection And Ranging (LiDAR-Raman), GPS, VLBI, WVR(Raschke, 2002). Furthermore, considering the high temporal and spatial variability of WV, depicting how the WV fluctuations are organised into diurnal, synoptic, seasonal and climatic categories, could provide useful information in meteorology (numerical weather prediction and climatology) and space geodetic studies. The variability of WV is associated with spatial structure and unique modes of variability inherent in the rotated Principal Component Analysis (PCA) of the WV energy spectra. The PCA rotating component of WV captures the dominant modes of the WV in temporal scales with similar spatial organisation (Petr, 2005). This linear transformation of PCA allows easy interpretation of the strongest spatial relationships of WV features that drive atmospheric weather systems over a particular region. Saco and Kumar (2000) used similar methodology to capture the spatial patterns of the coherence in the temporal scales of variability of stream flow response. On the other hand, Schubert *et al.*, (1998) separated different temporal scales (by choosing the scales independently) of precipitation using a pre-designed filter.

Multiscale spatial-temporal structures of WV describe the movement of water within and between the Earth's atmosphere, oceans and continents (Trenberth *et al*., 2005; Zveryaev and Allan, 2005). Soden and Fu (1995) assessed the temporal structure of WV using satellite-derived upper-tropospheric relative humidity over the tropical region (30^0 S - 30^0 N) and concluded that a positive relationship between relative humidity and deep convective processes exists. Though, the global spatial distribution and trends in WV are dominated by large-scale dynamics, such as., El Nino- Southern Oscillation (ENSO) rather than the thermodynamics, (See., Zveryaev and Allan, 2005), the linkage between WV anomalies and atmospheric circulation processes is difficult to establish due to the complexity of the spatial-temporal structures of WV. The spatial and temporal variability of WV in the mid- and low-tropical Africa ranges from a few kilometres to thousands of kilometres and from a few minutes to several days, similar to the meso- /synoptic scale processes, respectively (Husak, 2005). Therefore, the analysis of the correlations of WV between the spatial grids is of great practical importance for studying the conditions that lead to the development of hazardous weather systems.

In order to understand the feedback processes operating within the mid- and low-tropical Africa, a robust methodology of examining the spatial-temporal structure is required. In this study, the spatial and temporal organisation of WV is analysed simultaneously using orthogonal wavelet transformation which allows for calculating the total energy of WV by summing up their individual scales either in spatial or temporal regimes. The spatial-temporal fluctuations of WV are investigated which further helps to understand the regional weather patterns in the East, Central and Southern Africa. Results obtained from this study would also form the basis for future comprehensive analysis of the relation between WV variability and the associated atmospheric weather systems as well as any other forcing mechanisms observed in the low- and mid-tropical Africa. In addition, the goal of this study is to understand the mechanisms driving WV variability and its link to the climatic variables which are essential for accurate modelling of the regional hydrological cycle.

The main data source used in this particular study is about 8 years of upper air radiosonde/ozonesonde data archived at the SHADOZ station network consisting of Ascension, Irene, Reunion and Nairobi). The publication by Thompson *et al.*, (2003) provides further details about the SHADOZ network. The geographical positions of the SHADOZ stations and the details about data considered for the present study are tabulated in Table 5.1.

Table 5.1 SHADOZ network stations used in the current study.

Station	Longitude	Latitude	Elevation	# of Launch	Time Period
Nairobi	36.80 E	1.27 S	1795.00	370	Jan 1998 to Aug 2007
Reunion	55.48 E	21.06 S	24.00	293	Jan 1998 to Oct 2006
Irene	28.22 E	25.90 S	15.24	232	Nov 1998 to Dec 2006
Ascension	14.42 W	7.98 S	91.00	397	Jan 1998 to Dec 2006

The SHADOZ stations were configured to obtain mean information of WV over four grids, and designated WV_g time series. In addition, a time series of integrated WV (hereafter, WV_{ncep}) was constructed from the average over four grid points of each SHADOZ station

(See, Figure 5.2), using the NCEP/NCAR reanalysis (Kalnay *et al*., 1996) data whose zonal and meridional spatial resolution is 2.5^0.

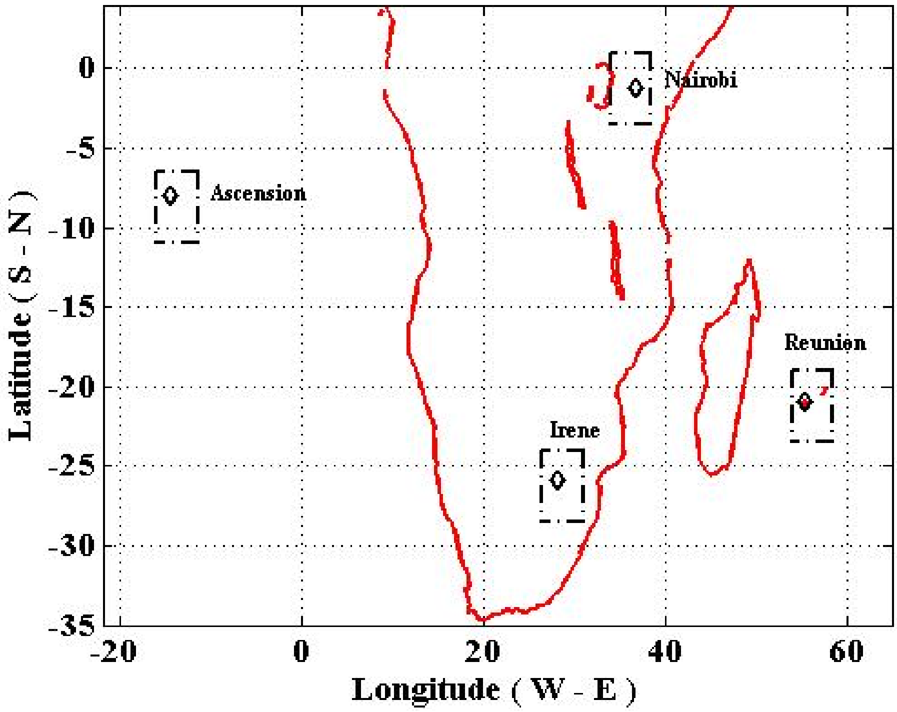

Figure 5.2. The SHADOZ stations with the corresponding grid boxes formed by the closest four grid points of reanalysis data from the National Centres for Environmental Prediction and Atmospheric Research.

For each NCEP/NCAR grid point, the temporal series of WV_g is tested manually for inherent normal distribution and then transformed by Box-Cox transformation (Box and Cox, 1964) which ensures a normal distribution. Prior to the Box-Cox transformation, the WV data sets are detrended. Further, in order to account for latitudinal distortions, each point of WV_g anomalies are weighted by the square root of the cosine of latitude (North *et al*., 1982). The resulting time series has been linearly detrended and subjected to non-decimal Haar wavelet transformation (Lindsay *et al*., 1996) to capture localised temporal fluctuations.

In contrast to the Fast Fourier Transform (FFT), the wavelet power spectrum (absolute value squared of the wavelet transform) provides the total energy of the WV_g time series at a given scale while FFT gives information about what frequencies are present in the signal, but lacks the ability to correlate the frequencies with the time of their presence. In general, the difference between Fourier and wavelet coefficients is that the former is influenced by a function on its entire domain (global measure), while the latter is influenced by local features. The wavelet power spectrum is therefore chosen in this study as a better measure of variance attributed to localised events. The wavelet coefficients at each time scale were used to compute the energy spectrum per spatial scale to form a temporal scale series (S) over the grid points (G) to form a matrix D with dimensions S × G.

The calculated WV_g values from radiosonde measurements at the SHADOZ stations and from the NCEP/NCAR reanalysis data are plotted in Figure 5.3 (gridded NCEP/NCAR reanalysis data is plotted in the left panel and while the four SHADOZ stations; (a) Nairobi (b) Ascension (c) Irene and (d) Reunion are plotted in the right panel. It is clear from the figure that the NCEP/NCAR reanalysis data exhibit a cyclic trend over the period of observations, whereas such cycles are not evident in the SHADOZ observations. The difference might be due to the coarse latitude and longitude resolution of NCEP/NCAR data that were averaged over the station grid box, while each SHADOZ station corresponds to a particular location. In addition, sensitivity of the balloon measurements may have contributed to the differences in WV_g from the two measurements. Further to this, NCEP/NCAR reanalysis data are based upon simulation with possible inherent biases. The differences between the NCEP/NCAR reanalysis data and SHADOZ station data were calculated for each station. Results concluded that the Irene and Reunion stations have higher mean deviations (~ 40 mm) while the Nairobi and Ascension stations have a mean WV_g deviation of ~ 30 mm (this is depicted in Figure 5.4).

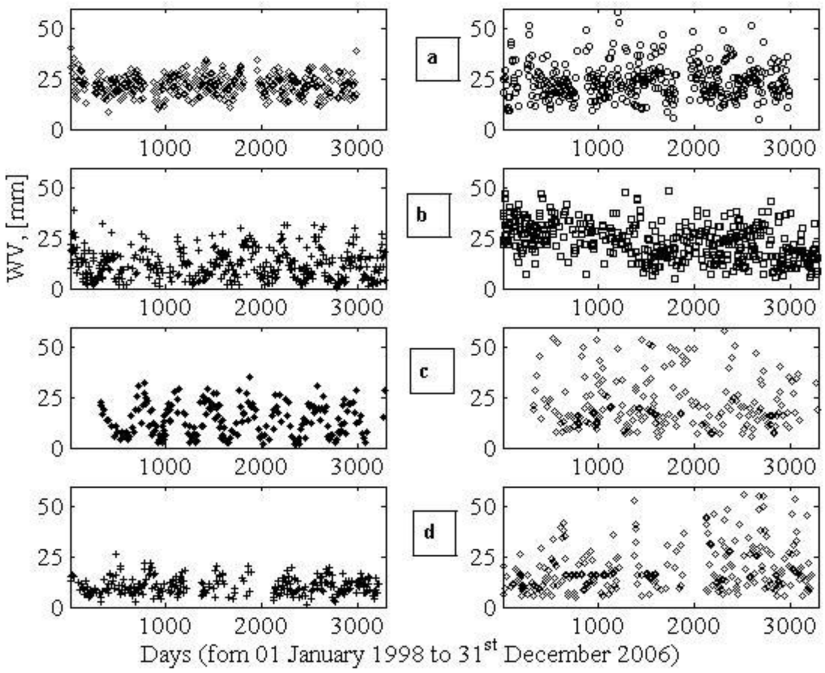

Figure 5.3. Daily integrated spatially averaged Water Vapour, WV_g [mm] for (a) Nairobi (b) Ascension (c) Irene and (d) Reunion.

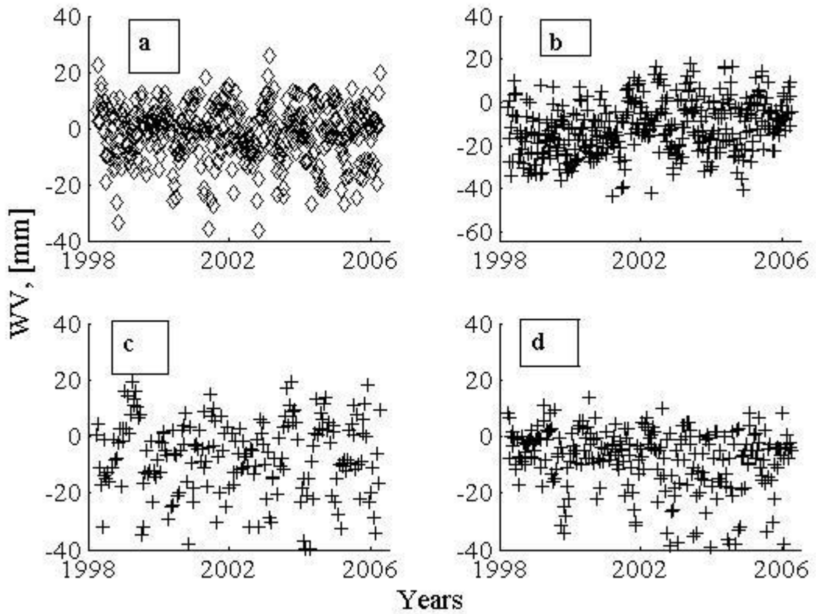

Figure 5.4. Differences of Water Vapour in mm, calculated from four SHADOZ stations (a: Nairobi, b: Ascension, c: Irene and d: Reunion) and the gridded NCEP/NCAR reanalysis.

It is understandable from Figure 5.4 that the variability pattern in WV is difficult to discern from the time series. The excursions from the mean signify the presence of exogenous processes that play a significant role in WV_g fluctuations. These stochastic processes are manifestations of local weather system processes (eg., convection, precipitation). To better understand these fluctuations, the nature of distribution of WV needs to be known. The standard probability distributions of WV_g are used and are compared to the normal Guassian distribution. The normal Guassian distribution has been generated by selecting random data sets.

To assess the normal (Gaussian) distributions of WV_g, the QQ-plots were drawn between the Guassian generated and WV_g probability distribution. A linear variation in the QQ plot could signify a normally distributed time series. This distribution has been tested, individually for each station as shown in Figure 5.5. The obtained regression coefficients illustrate that the SHADOZ station; Ascension has high linearity in comparison to that of Nairobi, Irene and Reunion. A maximum non-linear fluctuation component of ~10% was obtained for Reunion. On the other hand, Irene, Nairobi and Ascension have values of ~8%, 5% and 1%, respectively. The results reported here imply that WV over Ascension follow a normal distribution and appear not to be affected by non-linear local weather conditions.

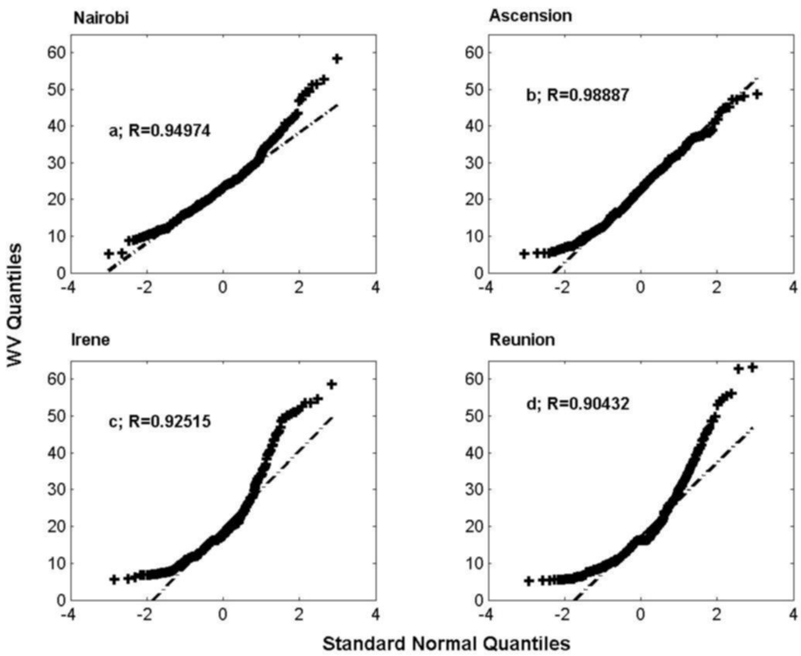

Figure 5.5. Quartile-quartile (QQ) plot of a Gaussian distribution, and the probability distribution of WV_g at the four SHADOZ stations under consideration.

To study the local temporal fluctuations of WV, the Haar wavelet transform of maximum overlap discrete technique has been applied. The wavelet coefficients derived from the WT of WV are used to assess, capture and discriminate between the different modes of local fluctuations in time series in the frequency-time space. Each SHADOZ stations' mean WV data were grouped into years and months. The corresponding monthly mean over the 8-year period of data is subjected to WT after performing de-trending. Figure 5.6 depicts the obtained wavelet coefficient (amplitude) at different temporal scales of 3, 8, 12 and 36 months (from bottom to top) or the time period of oscillation of WV_g at a given location.

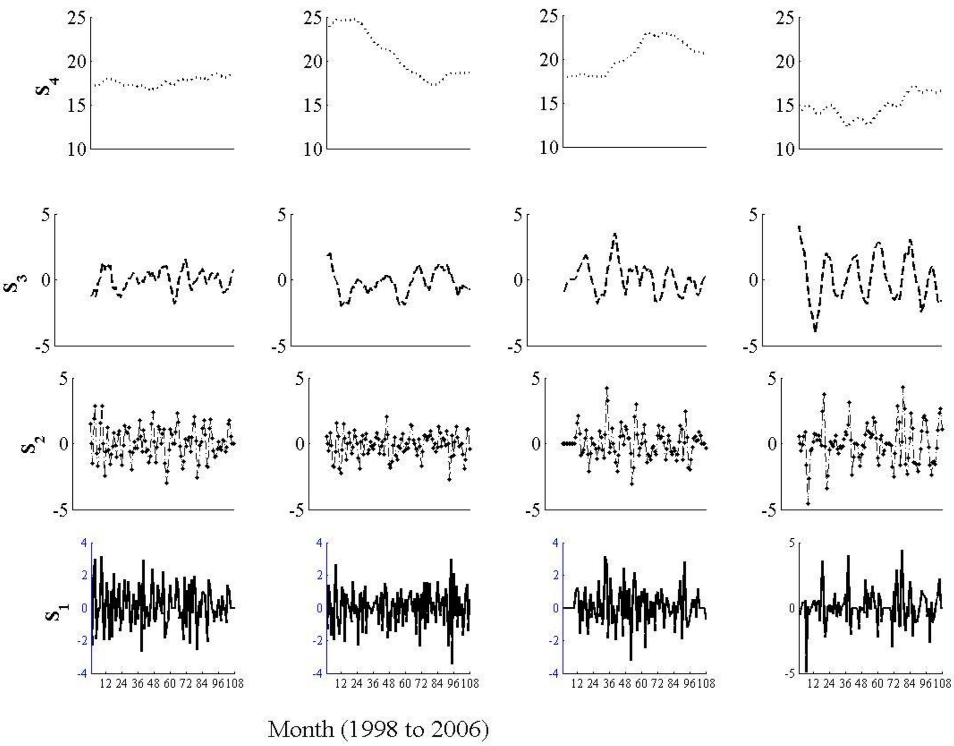

Figure 5.6. Haar wavelet spectra at different scales and at different station locations (Ascension, Reunion, Irene and Nairobi) - from left to right, respectively.

The relation between the period of oscillation of WV_g fluctuations and the wavelet scale index is obtained from the equation $s=2^{j-1}$, where the j^{th} index denotes the period. The method of deducing the wavelet co-efficient is reported by Percival and Walden (2000). Although, scale-1 (~3 month) does not offer any clear information on the fluctuations, other higher order scales show a significant oscillation at all the stations. Notably, the annual oscillation (scale-3) is clearly distinguishable at all the stations. In comparison to all the stations, Nairobi exhibits a clear cyclic variation. For almost all the stations, the scale-4 (3-year) component does not complete one period of a cycle, inferring that the periodicity is more than 12-years. It is noted here that the maximum possible number of scales obtained depends on the length of data period used. The log-log plot of the wavelet energy which is depicted in Figure 5.7 reveals an approximate power law scaling at lower time scales, which break down at high time scales. These results are consistent with the results reported by Lay (1997) and Cho *et al*., (2000). At high time scales, the break down in the linear relationship is associated with response of WV_g fluctuations to tele-connection patterns such as the influence of ENSO in the low and mid- tropical Africa; see for example Trenberth *et al.*, (2005).

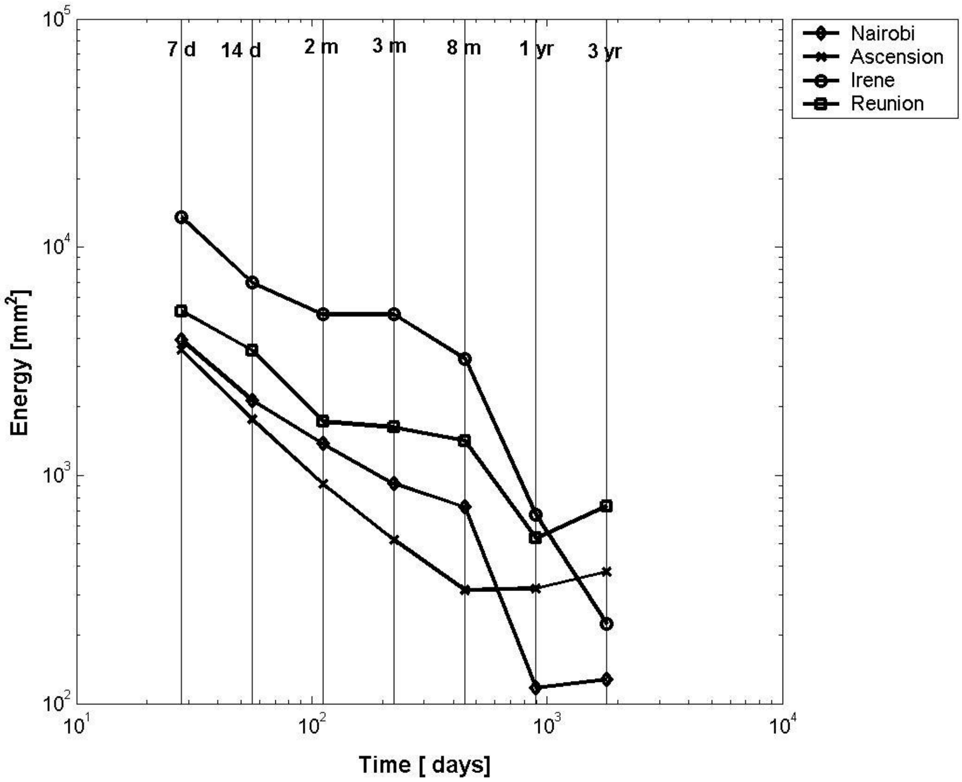

Figure 5.7. Approximate power law scaling of the WV derived wavelet energy.

PCA has been determined for the wavelet coefficients of all the four stations, and the calculated variance is presented in Figure 5.8. The first three variance components account for 98% of the WV_g variations. The first component represents high frequency temporal fluctuations (monthly time scales) and accounts for 67% of the variability. Component two represent the variance associated with annual fluctuations, and accounts for about 27% of the WV_g fluctuations. About 4% of WV_g variability is associated with low frequency fluctuations (1< timescales < 9-year).

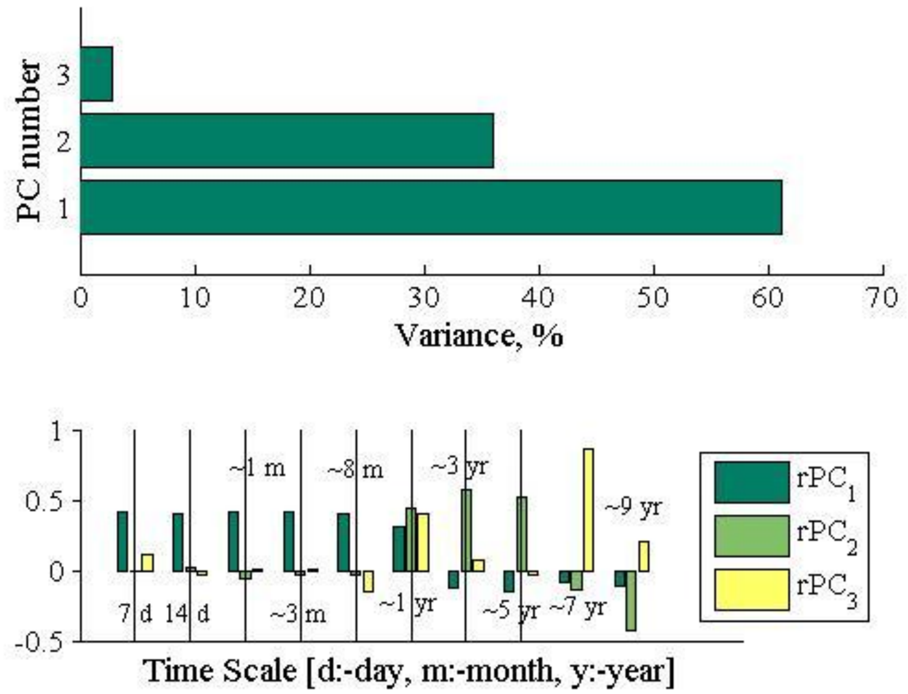

Figure 5.8. Co-variance of the Principle Component Analysis (PCA) components obtained from the four stations under consideration.

Decadal fluctuations cannot be inferred convincingly due to the short time-span of the data (8-years from 1998 to 2006). These results indicate that there is a distinct spatial structure for each short term temporal WV_g variation in the low and mid-tropical Africa region that could be attributed to synoptic/seasonal-scale weather systems, which is consistent with findings from Husak (2005) who reported that seasonal weather systems, topography, the Inter-Tropical Convergence Zone (ITCZ) and monsoon winds affect WV distribution and fluctuation. Jin *et al*. (2008) also reported that the variability of WV in China is dominated by seasonal variations. In addition, the spatial distribution of WV dependence on the thermodynamic relationship between WV and temperature has been reported in Zveryaev and Allan, (2005).

The marked differences between WV fluctuations at longer timescales could be attributed to the WV response to tele-connection patterns such as ENSO in the low and mid-tropical Africa; this is in line with the findings of Trenberth *et al*., (2005) who had indicated that the variability of WV is dominated by the evolution of ENSO. This link shows a strong relationship over the oceans between WV and Sea Surface Temperatures (SSTs). Further, the African low and mid- latitude WV has a strong link to rainfall due to its close association with the mean wind flow, and convergence of moisture by trade winds as well as their links to SSTs. In addition, the correlation analyses performed between surface temperature and WV show that a link exists between WV anomalies and regional air temperature variations with marked seasonal dependence (the results are not presented here) over all four SHADOZ stations.

5.4. Concluding remarks

In an effort to analyse regional spatial and temporal features of WV variability over low and mid-tropical Africa, NCEP/NCAR reanalysis data around the SHADOZ network of four stations were used to calculate spatially averaged WV (VW_g) over the period from 1998 to 2006. The WV_g was calculated as the spatial average of the four closest NCEP/NCAR grid points around the SHADOZ stations to form grid cells. Based on these grid cells, data from NCEP/NCAR reanalysis data were also used to calculate the vertically integrated column of WV over the same time epoch for comparison. For the first time, the WV_g variability in the low and mid-tropical Africa was analysed using *in-situ* data from the SHADOZ network. The results show that WV exhibits high frequency fluctuations in the wavelet space. Common to the entire SHADOZ network considered in this study is the pattern of temporal WV_g fluctuations with monthly time scales dominating. This dominant variance appears to be associated with locally driven WV variations such as the local weather systems. Our results show that WV also exhibits the power law scaling in the wavelet energy. The approximate log-log linear relationship at smaller temporal scales that breaks down at synoptic scales suggests that the energy-times spectra of WV on different temporal scales are correlated. Furthermore, based on PCA, three dominant modes emerge. These modes explain ~ 98% of the total spatial variance of the normalized energy in WV fluctuations. To validate the current findings, future studies will involve the use of observations such as HALOE (Russell *et al*., 1993) and regional numerical simulation model data sets to determine the temporal and spatial organisation of PWV data at finer spatial and temporal scales.

In general, from the current analysis, results indicate that WV exhibits high frequency fluctuations in the time-frequency space. For the entire SHADOZ network considered in this study, monthly time-scales dominate the pattern of temporal WV fluctuations. This dominant variance appears to be associated with locally driven WV variations such as the local weather systems. Our results show that WV also exhibits the power law scaling in the wavelet energy. The approximate log-log linear relationship at smaller temporal scales breaks down at synoptic scales. This behaviour suggests that the energy-times-frequency spectra of WV on different temporal scales could be correlated.

Mechanisms that influence the global WV distribution can also be assessed in the context of their role in regional tropospheric WV fluctuations. Tropospheric regional WV is influenced by the dynamics and the seasonal changes in temperature. The ability of the atmospheric dynamics influencing water follows from the steep slope of the Clausius-Clapeyron equation: this relates to the rapid increase in water holding capacity of the atmosphere. The environmental lapse-rate then rapidly decreases the WV with altitude (at a scale height of ~2 km).

Our understanding of factors controlling long-term changes in tropospheric WV is inadequate to explain the observed variations or to provide good projections in the near future. In the lower stratosphere, the observed changes in WV could be linked to changes in other greenhouse gases, such as, ozone and methane. It is fairly clear that atmospheric processes (e.g., transport, convection, and clouds) are involved in determining the distribution of tropospheric WV, but their influences are very difficult to quantify. Since it is also difficult to predict how these might change in response to natural and human-induced climate change, future changes in the distribution and variability of tropospheric WV still remain unknown.

It is generally accepted that there is a cancellation effect between increasing humidity and decreasing temperature with height. Furthermore, the uncertainty over the precise WV concentration in the troposphere, and even greater uncertainty over trends in upper tropospheric humidity and temperatures, makes it impossible to carry out a firm quantitative estimate of the tropospheric radiative consequences of long-term changes in tropospheric WV. However, present knowledge indicates that the radiative response to long-term changes in upper tropospheric WV will almost certainly be significant. Due to this, the following recommendations are proposed. Firstly, upper tropospheric WV should be monitored with a view to determine long-term variations. More observations of the tropical tropopause region (15-20 km), by both *in situ* and remote sensing methods, are needed to improve our understanding of stratosphere-troposphere exchange. Furthermore, in order to assess robust estimates of WV variability, complementary observations and techniques are recommended.

Second, in order to have a balanced view of all the mechanisms that drive WV variability in the troposphere, combined measurements of WV, cloud microphysical properties, and chemical species are recommended.