Towards precipitation enhancement through cloud seeding in Kenya

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Abstract

The study investigated potential of enhancing precipitation through cloud seeding during October-November-December (OND) season. Rainfall, cloud top temperature (CTT), aerosol optical depth (AOD) and wind data were used. Short-Cut Bartlett correlation, composite wind and time series analysis, and HYSPLIT backward trajectory analysis were used to achieve the objectives of study. Precipitation showed decreasing patterns with peaks between pentad 65 and 68. Delineated dry years (18) exceeded wet years (9). Low level winds were predominantly north-easterly during dry years characterized by continental trajectory. AOD values increased in all stations during dry year with aerosol load being higher in areas characterized by depressed rainfall. Pollutants suspended 1000 above mean sea level (AMSL) originated from Arabian and India subcontinent and pollutants suspended below 1000 AMSL were predominantly south easterly during wet years originated from Western Indian Ocean and characterized by maritime trajectory. Mean CTT during dry/wet years were positve over coastal areas while central, Rift-valley and Lake Victoria basin showed negative values, indicating presence of seedable conditions and thus potential cloud seeding to enhance rainfall and alleviate existing water stress.

Introduction

Precipitation influences quality of human life through availability of fresh water.[1] In the tropics, it remains highly variable in space and time with many activities dependent on it.[2] Notably, Kenya is classified as water scarce country with renewable fresh water per-capita at 647 m^3 against minimum of 1000 m^3 recommended by United Nations.[3] Intensified competition for fresh water resources has exacerbated the existing water stress[4] has led to sharp increase in water stress on aquatic and wetland ecosystems.

The changes in tropical precipitation regimes and frequency of floods and droughts are observed to significantly influence climate.[4,5] Further, natural and anthropogenic changes in atmospheric aerosol are expected to influence precipitation process and thus hydrological cycle.[1] Aerosols serve as cloud condensation nuclei (CCN), modifying microphysical properties of cloud and thus thermodynamics of the atmosphere.[6] The response of clouds to changes in the ambient aerosol differs depending on the cloud type or aerosol regime.[7] Atmospheric aerosols have potential of suppressing/enhancing precipitation through changes in CCN concentration, cloud droplet size and droplet coalescence.[1]

Studies of both orographic and convective clouds have suggested that clouds whose tops are colder than -13°F (-25°C) have sufficiently large concentrations of natural ice crystals such that seeding will have no effect on precipitation.[8] There are also indications that there is a warm temperature limit to seeding effectiveness.[8,9] This is believed to be due to the low efficiency of ice crystal production by silver iodide (the most commonly used seeding material) at temperatures greater than 23°F (5°C), and to the slow rates of ice crystal vapor deposition growth at comparatively warm temperatures. Thus there appears to be a *temperature window* of about 23°F (-5°C) to -13°F (-25°C) where clouds respond favorably to silver iodide seeding (*i.e.* exhibit seedability). Dry ice (frozen carbon dioxide) seeding via aircraft can extend this temperature window to temperatures just below 32°F (0°C). Seeding by venting liquid propane may also present the potential to expand this window to approximately -2°C. Over EEA, weather modification studies to suppress hail dominated the period 1960s to 1980s. Dye and Breed[10] characterized clouds over Kericho tea estates and noted that cumulus clouds were continental in origin with the ice phase accounting for predominant precipitation formation mechanism. Another study[11] found that cumulus clouds and resultant hailstorms over Kericho were triggered when surface level westerly winds from Lake Victoria flows up the Mau escarpment and converged with Easterly winds over higher ground.

Therefore, the study investigated potential of enhancing rainfall through cloud seeding by considering likely presence of seedable conditions during the highly predictable OND season due to increased frequency of drought conditions and associated drop in water supply from major water towers such as Mt. Kenya and Mt. Elgon. Further, weather modification is amongst strategies included in the Kenya's long-term development (Vision-2030).[2]

Area of study: Kenya

Kenya, lies between latitudes 5° North and 5° south and between longitudes 34° and 42° east with an area of about 569,137 km^2. Annual rainfall follows bimodal seasonal pattern with long rains occurring in March-April-May (MAM) while short rains occur in OND. The climate is influenced by its equatorial location, topography, the Indian Ocean, the inter-tropical convergence zone (ITCZ) and the El Niño Southern Oscillation events.[12] The lakes occupy about 2% of total area while 18% is occupied by high agriculture potential areas while arid and semi-arid lands occupy about 80% of total land area. Figure 1 is a map showing selected synoptic stations used in the study.

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Key words: water stress, cloud seeding, precipitation, rainfall.

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Materials and Methods

Daily rainfall, minimum and maximum temperature were sought from the Kenya Meteorological department and spanned a period between 1971 -2011. Gridded level 3 daily aerosol optical depth (AOD) and cloud top temperature (CTT) from MODIS sensor onboard Terra Satellite at a spatial resolution of 1°x1° from 2001 to 2012 was used. AOD indicated the amount of aerosol load while CTT was used to indicate temperatures for effective seeding, *i.e.* seedable conditions. These satellite data were sought from MODIS sensor on board the Terra satellite. The estimated uncertainty of the MODIS aerosol products have been reported to be 0.05 ±0.15 over land.[13,14]

Short-Cut Bartlett's was used to test the consistency and validity of meteorological parameters at 95% significant level given by equation 1:

$$S_k^2 = \frac{1}{n}\left[\sum x_i^2 - \frac{1}{n}\left(\sum x_i\right)^2\right] \qquad 1$$

where; k is the sub periods, S_k sample variance, X independent variables and n the sample size.

Rainfall anomaly index (RAI) was used to identify the dry and wet years based on OND seasonal rainfall in Kenya. RAI is given by equation 2 below.[15]

$$\gamma_t = \frac{1}{m}\sum_{j=1}^{m}\frac{100X_{tj}}{\bar{X}_j} \qquad 2$$

where; m is the number of stations used, $\bar{X}_j$ is the time dependent rainfall index as a percentage of the mean and averaged over all the stations, X_{tj} represents the time series of individual station for the OND seasonal rainfall and γ_t is the rainfall anomaly index. The wet years have large values (>125%), while the drought years have low values (<75%). The normal years are between 125% and 75%. The pentads (five day total) were calculated from the daily rainfall and aerosol products for the dry and wet years. Time series analysis and lagged correlation was then used to investigate relationships between meteorological parameters and aerosols products.

The trend of rainfall, aerosols and cloud top temperature were assessed using the equation for the slope of the regression line given in equation 3:

$$b = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sum(x-\bar{x})^2} \qquad 3$$

where x and y are the sample means average (known x's) and average (known y's).

Composites techniques, based on streamlines and isotach wind analysis were used to derive the composite wind pattern for the dry and wet year. The study utilized the 700 mb level (approximately 9500 feet MSL) as an index of important meteorological features regarding targeting of the seeding effects. At 700 mb level, wind is considered a good steering winds indicator as it an approximation of the direction along which storm elements will move. NCEP reanalysis data sets at 700 mb were used to generate wind roses that graphically display the average information for different potential seeding modes such as lower elevation, ground based generators; higher elevation remotely operated ground generators and airborne seeding. The wind roses were used to provide the frequency of wind direction and speeds by 22.5° wind sectors.

A plot of mean daily cloud top temperatures during dry and wet years were made aimed at deciding whether a specific storm period could be considered seedable. This is because seeding material such as silver iodide becomes an active ice nucleant at temperatures of about -4 to -5°C or colder in order for seeding to be effective.

Composite wind analysis of wet and dry years based on OND season was then used to investigate the space-time evolutions of the wind circulation in Kenya. Wind roses and HYSPLIT backward trajectory analysis provided information on sources and sinks of aerosols, wind speed and wind directions. HYSPLIT backward trajectory analysis was performed on archived meteorological data from the Global Data Assimilation System.[16]

Backward trajectory analysis was done using the HYSPLIT model. The model was run backward in time for five days to identify the sources of atmospheric aerosols over Dagoretti, Kakamega and Lodwar during the wet and dry OND season. The HYSPLIT model was initialized at 0000UTC on 15th November for both dry and wet OND season. The study assumed that this date represented the time when peak rainfall was expected. Three different altitudes for the stations considered were

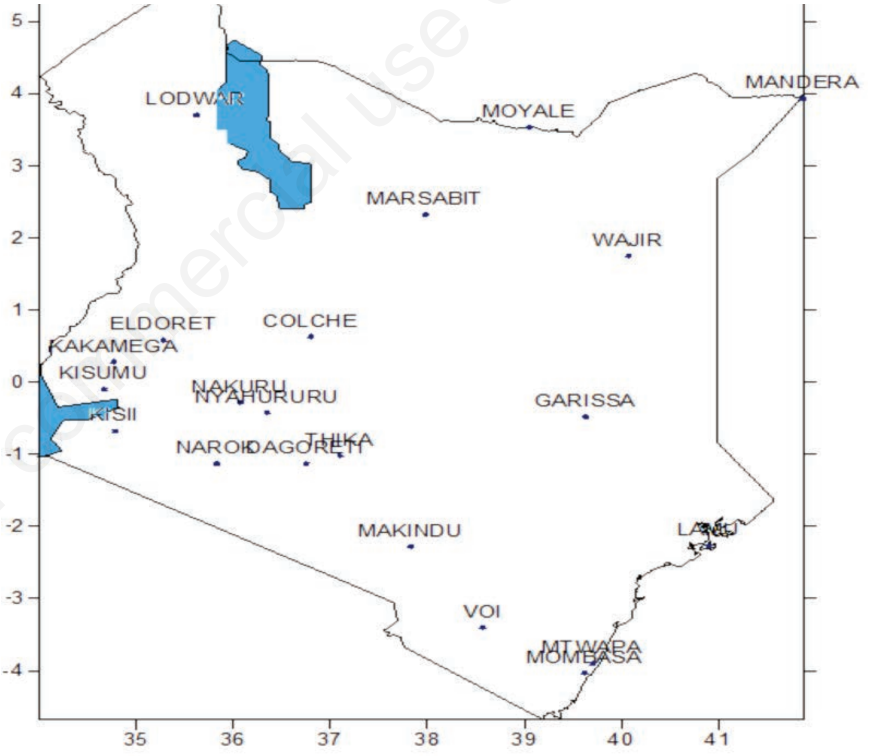

Figure 1. Map showing selected stations in the area of study.

Table 1. Classification of the dry, normal and wet rainfall anomaly scenarios.

Scenario type	Anomaly range (%)	Frequency (n=40)	Years
Dry	$\chi_t<75$	18	2005, 1974, 1998, 1975, 1987, 1980, 1985, 1996, 1976, 1973, 1981, 2010, 1993, 1983, 2007, 2003, 1979, 1971
Normal	$75\leq\chi_t\leq125$	14	2001, 1991, 1988, 2000, 2008, 1999, 1995, 1990, 1992, 1990, 2004, 1978, 1984, 1972
Wet	$\chi_t>125$	9	1997, 2006, 1977, 2011, 1982, 2002, 2009, 1994, 1989

used. These were at 500, 1000 and 1500 metres above the ground level.

Correlation anaysis was used to investigate the relationship between atmospheric aerosols and observed rainfall. The pearson correlation coefficients was tested for statistical significance at 95% confidence level using the student t test as described by equation 4:

$$t_{n-2} = r\sqrt{\frac{n-2}{1-r^2}} \tag{4}$$

where; *t*- is the value of the student-t-test, *n* - is sample size and *r* - the correlation coefficient being tested.

Results and Discussion

Results of homogeneity test based on Short -cut Bartlet test are presented Figure 2. At 95% significance level, Short-cut Bartlet test showed that the ration F computed (F value) between the highest sample variance and the smallest sample variance was less than the F tabulated (critical) for selected synoptic stations used in the study as shown in Figure 2. Therefore, the null hypothesis stated that all factor standard deviations (or equivalently variances) were equal was accepted against the alternative hypothesis.

Delineation of dry and wet years

Results of computed RAI are presented in Table 1 and Figure 3 with 18 years delineated as dry 9 years as wet and 14 years as normal. The wettest and driest year corresponded to 1997 and 2005 respectively. The 1997 wet year had anomalously high RAI of 328% compared to other wet years. Studies on the wet spell observed in 1997 OND rainfall season classified the event as unique and wettest period over the last 100 years in east Africa.[17] A detailed study[18] on the anomalous wet spell event of October 1997 attributed this unique event to the general mechanism that causes rainfall during the short rain season over the region which includes weakening or reversal of the east west (walker type) circulation over the Indian ocean; enhanced convergence between the northern and southern hemisphere trade winds and westward moving disturbances in the low level equatorial winds.

Space time distribution of meteorological parameters and atmospheric aerosols

Rainfall

Results of rainfall space time variability are presented in Table 2, Figures 4 and 5 for selected stations in Kenya. The slope of regression line showed negative values indicating decreasing rainfall over all stations except Garissa, Makindu and Voi stations during dry years. These stations are predominantly dry throughout the year. However, slopes of seasonal rainfall during wet years were either increasing or decreasing throughout the region and could be attributed to complex local and synoptic scale factors. The mean long term pentad rainfall showed depressed rainfall during the start and end of the season during both dry and wet years. Pentad 62 to 68 and pentad 65 to 69 recorded highest amounts of rainfall during dry and wet years respectively. Generally, the mean seasonal rainfall was high during dry years as compared to wet years over all stations.

Aerosol optical depth

Results of space time variability of aerosol optical depth over selected locations are presented in Table 3 and Figure 6. The slope of regression line (Table 3) showed that AOD values were increasing in all stations during dry year while wet year's showed slight increa-

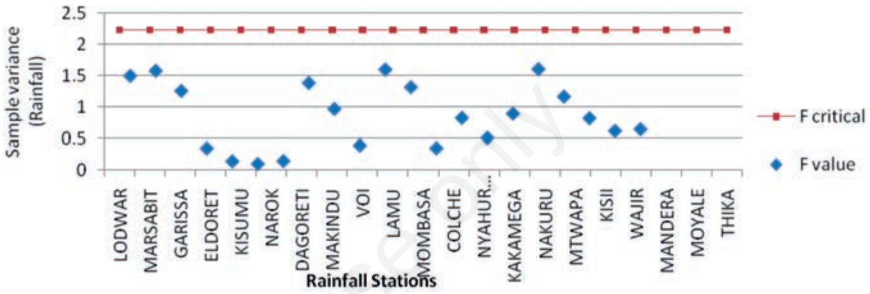

Figure 2. Analysis of variance over selected synoptic rainfall stations in Kenya.

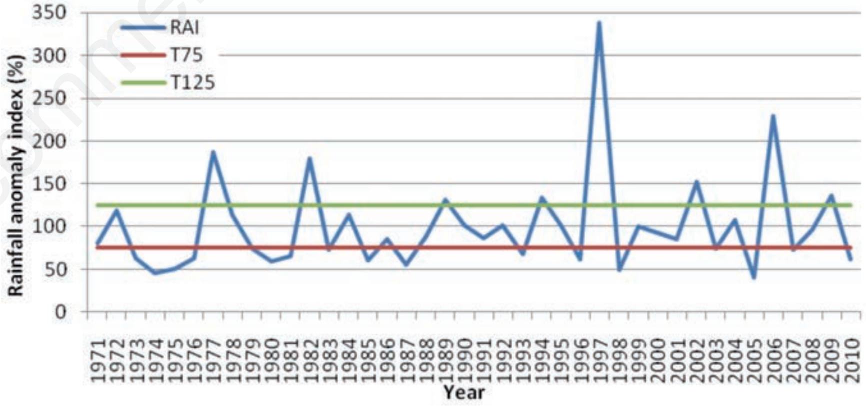

Figure 3. Time series of rainfall anomaly index.

Table 2. Slope of regression line of precipitation in Kenya.

Station	Dry	Wet	Station	Dry	Wet
Lodwar	-0.0339	0.13489	Lamu	-0.3549	-0.0478
Marsabit	-0.1395	-0.1392	Mombasa	-0.1692	-0.1816
Garissa	0.33792	-0.104	Kakamega	-0.5039	-0.0692
Kisumu	-0.0398	0.15443	Wajir	-0.0901	-0.0429
Dagoretti	-0.0232	0.141	Malindi	-0.6785	-0.1822
Makindu	0.21208	0.14784	Nyeri	-0.2216	-0.1479
Voi	0.33417	0.17007			

se/decrease patterns of AOD trend with values of less than 0.005. Furthermore, spatial analysis of aerosol load (Figure 6) showed higher AOD load in areas that received scanty rainfall throughout the year such as lodwar (4.2), Makindu (6.6), Meru (4.9) and Moyale (3.7).

Cloud top temperature

Results of trend of cloud top temperature based on the slope of regression line of cloud top temperature and its spatial variability in Kenya are presented Table 4 and Figure 7. The slope of regression line (Table 4) was positive for most stations which showed that cloud top temperatures were increasing during both dry and wet year. Spatial analysis of cloud top temperature (Figure 7) showed that most stations in Northern and coastal stations indicated positive values while the central region and Lake Victoria basin stations indicated negative values of upto -20°C. Since studies have suggested that AgI participates in Bergeron-Findeisen and riming processes, areas with presence of super-cooled clouds (T<-5°C) with mixed phase would be suitable target for AgI seeding[19] in Kenya.

Wind analysis

Compostie wind analysis were based on surface winds at 700 hPa pressure levels for both dry and wet OND season. The Northesterly winds during the dry years (2005, 1974, 1998, 1975) and Southeasterly winds during the wet years (2006, 1977, 1982 and 2002) were used for composite wind analysis for the OND season as shown in Figure 7. It was observed that winds at 700 hPa were dominantly north easterlies during the dry OND season (Figure 8A) along latitude 4°N and relatively weak at 700hPa with less than 1.1 ms^{-1}. The Northeasterlies had maximum intensity of about 4.9 ms^{-1} along the equator at longitude 34.5°E. These North easterlies were noted to have its roots in the high pressure centre over arabia and India. Studies by Anyamba[20] established that these monsoonal air were mainly continental in origin with moderate sea trajectory and hence dry. The dominantly shallow and weak winds approaching the equator underwent rising motions in the vicinity of the equator. The convective activities resulted to observed precipitation over the region. Large scale systems occuring over these region would also have contributed to the precipitation received. In such situations, the normally dry northeast monsoon become very active weatherwise in eastern kenya.[21] It was observed that winds at 700 hPa were dominantly south easterlies during the wet OND rainfall season (Figure 8B) with increasing wind speeds above the surface along the equator with maximum wind intensity of of about 6 ms^{-1}. The cool and most southeast/southwest monsoon air flows from the Mascarene Anticyclone in the southern Indian Ocean. The

Table 3. Slope of regression line for aerosol optical depth in Kenya.

Station	Dry	Wet	Station	Dry	Wet	Station	Dry	Wet
Nyahururu	0.120	-0.005	Kisii	0.158	-0.001	Meru	0.160	0.000
Naivasha	0.221	-0.003	Kisumu	0.158	-0.001	Mombasa	0.205	0.001
Dagoretti	0.176	-0.007	Kitale	0.121	-0.002	Msabaha	0.188	0.005
Eldoret	0.122	-0.002	Lamu	0.236	0.003	Mtwapa	0.173	0.000
Embu	0.131	0.001	Lodwar	0.365	-0.002	Nakuru	0.120	-0.005
Garissa	0.224	-0.004	Makindu	0.173	-0.001	Nanyuki	0.160	0.000
Kabarak	0.120	-0.005	Malindi	0.188	0.005	Narok	0.140	-0.002
Kakamega	0.142	-0.001	Mandera	0.043	-0.003	Nyeri	0.131	0.001
Marsabit	0.274	-0.004	Moyale	0.095	-0.005	Voi	0.109	0.003

Table 4. Slope of regression line for cloud top temperature in Kenya.

Station	Dry	Wet	Station	Dry	Wet	Station	Dry	Wet
Nyahururu	0.32	0.33	Kakamega	0.78	0.75	Mandera	0.31	0.37
Naivasha	0.41	0.82	Kisii	1.18	0.67	Marsabit	0.16	0.68
Dagoretti	0.44	0.43	Kisumu	1.00	0.90	Meru	0.61	0.49
Eldoret	0.78	0.65	Kitale	0.32	0.47	Mombasa	0.39	-0.06
Embu	0.58	0.48	Lamu	0.65	0.52	Moyale	0.27	-0.12
Garissa	0.91	0.91	Lodwar	-0.09	0.28	Msabaha	0.36	0.36
JKIA	0.82	0.76	Makindu	-0.04	0.54	Mtwapa	0.81	0.91
Nanyuki	0.80	0.87	Voi	0.13	0.81	Malindi	0.38	0.88
Narok	0.82	0.63	Nyeri	0.51	0.80	Nakuru	0.89	0.36

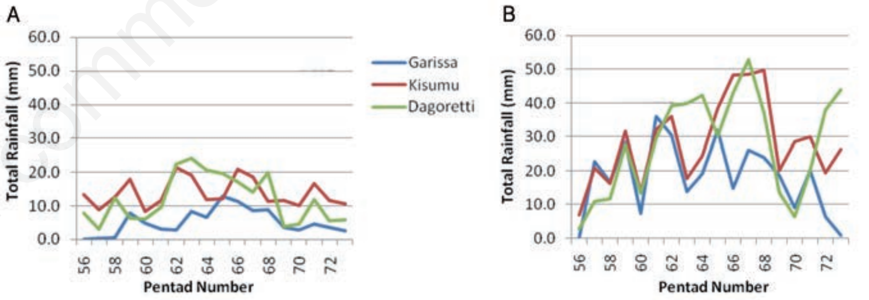

Figure 4. Long term mean pentad rainfall during A) dry and B) wet October-November-December seasons in Kenya.

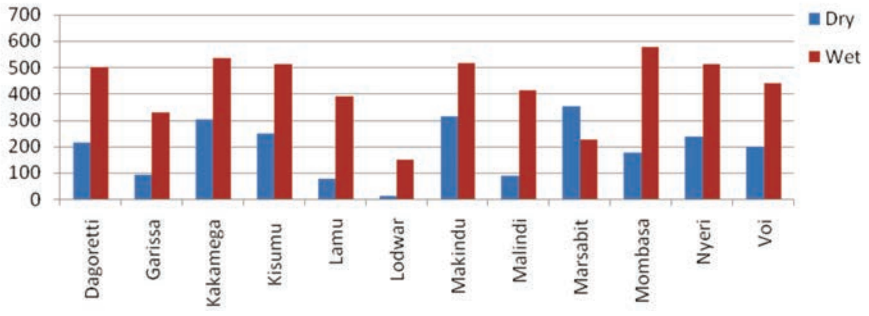

Figure 5. Long term mean seasonal rainfall during dry and wet years in Kenya.

considerate amount of rainfall during this period is attributed to interaction between the south east monsoon current, the congo airmass and the lake Victoria thermally induced meso-scale circulation.[22]

Hybrid-single particle Lagrangian integrated backward trajectory analysis

HYSPLIT trajectory analysis showed that during the dry season, aerosols were observed to have originated from the Arabian and India subcontinent especially at levels above 1000 m (Figure 9A). At levels below 1000 m, the local sources which could either be from natural or anthropogenic sources accounted for aerosols present in the atmosphere. During this typical dry period, aerosols were noted to be mainly continental in nature. During the wet seaon (Figure 9B) aerosols were mostly from the southwestern parts of the Indian Ocean especially below 1000 m above the ground. Above 1000 m, few aerosols trajectory were obeserved to originate from the continental arabian and indian sub continent region. During a typical wet OND season, aerosols were noted to be mainly maritime (oceanic) in nature. These trajectory analysis for the wet and dry OND season agreed well with other studies[23] have noted that pollutants reaching Kenya during the OND season mainly originated from the south western parts of the Indian Ocean and Arabian regions and were mainly characterised by their oceanic or continental nature of aerosols respectively.

The study also observed that at different levels above the ground, the atmospheric aerosol present in the atmsphere had different origns. It was assumed that these aerosols at from different origins underwent vertical mixing as they got advected inlands of the study region. Therefore, these mixed aerosols accounted for enhanced rainfall observed over the central kenya and western regions which had highly mixed type of aerosol composition.

Relationship between atmospheric aerosols and rainfall

Results of relationship between atmospheric aerosols and rainfall in Kenya was investigated by correlation analysis and results pre-

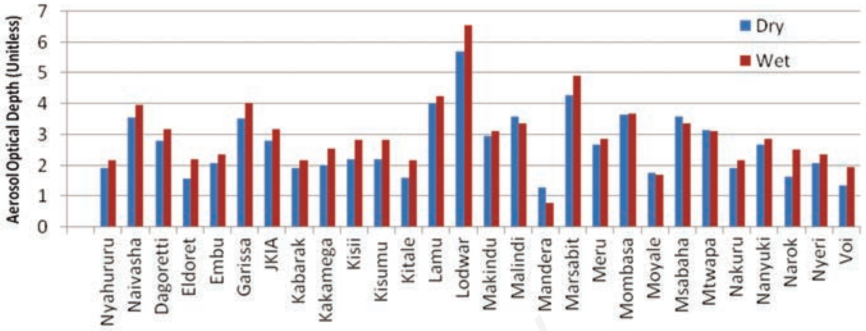

Figure 6. Spatial variability of aerosol optical depth during dry and wet years in Kenya.

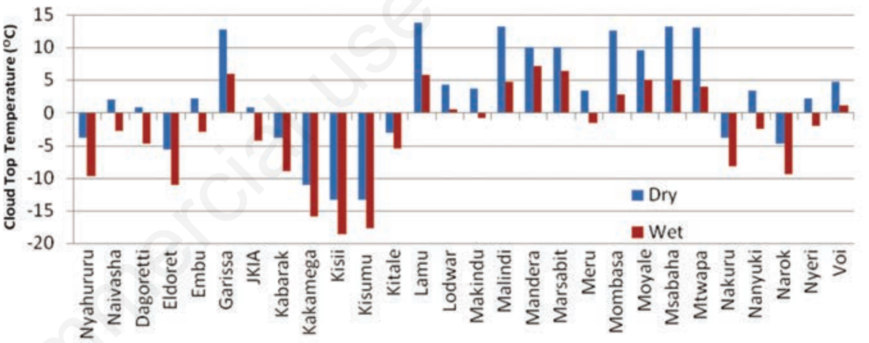

Figure 7. Spatial variability of cloud top temperature during dry and wet years in Kenya.

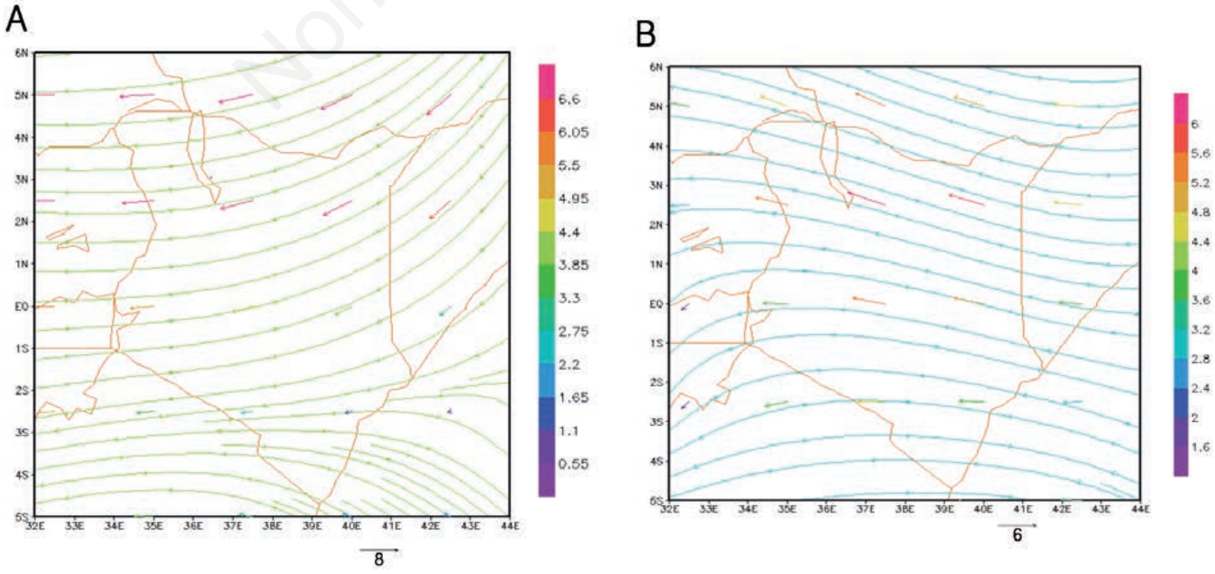

Figure 8. Wind patterns at 700 hPa during A) dry and B) wet years during October-November-December season.

sented in Table 5. Based on correlation analysis, most stations recorded highest values of correlation coefficient during both dry and wet years. During dry years, the stations Lodwar (0.66), Mombasa (-0.64), Lamu (-0.56), Nyeri and Malindi (-0.47) while Kakamega (0.71), Voi (0.50) and Malindi (-0.47). Negative relationship observed over coastal stations were attributed presence of higher amounts aerosols acting as cloud condensation nucleus such as sea salt that competed for available moisture and thus inhibited cloud formation by forming many tiny droplets. This made it impossible for the cloud droplets to precipitate. The positive values of *r* over most continental areas indicated that atmospheric aerosols had a positive contribution to rainfall formation process. The student *t* test indicated that significant relationship between atmospheric aerosols were noted over Lamu, Lodwar, Malindi, and Mombasa locations during dry years and over Kakamega, Lodwar and Malindi during wet years.

Conclusions

Long term pentad rainfall showed depressed rainfall at the start and end of the season during dry and wet years and thus necessitates a means of enhancing rainfall such as cloud seeding. Depressed rainfall over lodwar, Makindu, Meru and Moyale areas were attributed to higher AOD load while mixed aerosols composition over the central kenya and western regions accounted for enhanced rainfall. Seasonal weather variation controlled transport of pollutants with low level winds being predominantly north easterlies/easterlies during the dry/wet OND season. The mean cloud top temperature during dry and wet years were positve over stations located in the coastal areas while negative values indicating presence of seedable conditions over the central, rift and Lake Victoria basin region. This would alleviate expected water stress especially in key sectors that rely entirely on rainfall as a source of fresh water. Further, research to characterise composition and properties of aerosols in region is necessary.

Table 5. Relationship between aerosol optical depth and precipitation in Kenya.

AOD/precipitation	Dry year			Wet year		
	r	t computed	t tabulated	*r*	t computed	t tabulated
Dagoretti	0.09	0.37	2.12	-0.38	-1.63	2.12
Garissa	0.27	1.10	2.12	-0.24	-0.98	2.12
Kakamega	0.38	1.65	2.12	0.71	4.08	2.12
Kisumu	0.08	0.32	2.12	0.24	0.99	2.12
Lamu	-0.56	-2.67	2.12	0.08	0.34	2.12
Lodwar	0.66	3.47	2.12	0.45	2.02	2.12
Makindu	-0.12	-0.50	2.12	0.34	1.43	2.12
Malindi	-0.47	-2.13	2.12	-0.47	-2.13	2.12
Marsabit	0.40	1.75	2.12	0.36	1.53	2.12
Mombasa	-0.64	-3.31	2.12	-0.17	-0.69	2.12
Nyeri	0.49	2.25	2.12	-0.30	-1.26	2.12
Voi	-0.05	-0.20	2.12	0.50	2.34	2.12

AOD, aerosol optical depth.

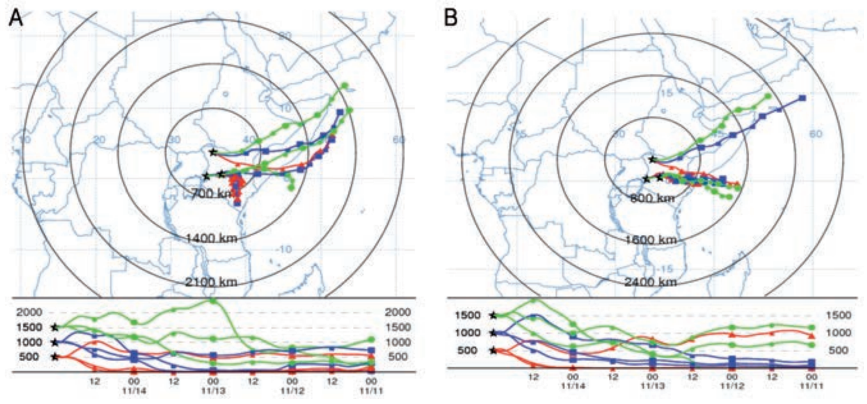

Figure 9. Trajectory analysis for selected locations during A) dry 2005 and B) wet 2006 years.

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