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MOUNT RWENZORI (4750 M A.S.L., UGANDA): METEOROLOGICAL CHARACTERIZATION AND AIR-MASS TRANSPORT ANALYSIS

ABSTRACT: LENTINI G., CRISTOFANELLI P., DUCHI R., MARINONI A., VERZA G., VUILLERMOZ E., TOFFOLON R. & BONASONI P., *Mount Rwenzori (4750 m a.s.l., Uganda): meteorological characterization and Air-Mass transport analysis.* (IT ISSN 0391-9838, 2011).

The meteorological conditions at Mount Rwenzori (RWZ), in Western Uganda, are explored by analysing meteorological observations carried out during the years 2006-2009 by an Automatic Weather Station (AWS) installed at 4750 m a.s.l. in the eastern part of the Mount Stanley (0° 22' N and 29° 52' E), the most extensive RWZ glacial mass.

The AWS provides hourly measurements of the main meteorological variables: air temperature, rain precipitation, atmospheric pressure, relative humidity, wind speed and direction, and global short-wave irradiance. In this work we described the typical seasonal and diurnal variations of the meteorological parameters recorded during the period October 2006 – August 2007 and July 2008 - June 2009. Throughout these periods, a remarkable low variability of the main meteorological parameters is detected, as expected for an equatorial high-altitude site. Only for the rain precipitation amount a direct influence of the Inter Tropical Convergence Zone (ITCZ) can be detected. As deduced by the analysis of the typical seasonal diurnal variations, the local mountain weather regime is likely to dominate the variability of the meteorological parameters at RWZ. These measurements permitted to characterize for the first time the meteorological conditions of the Rwenzori Mountains. In addition, the Lagrangian model HYSPLIT has been used to calculate a 2-year climatology of three-dimensional air-mass back-trajectories in order to provide a description of the synoptic-scale atmospheric circulation affecting the measurement site, and verify the seasonal influence of the ITCZ on large-scale atmospheric circulation at RWZ.

KEY WORDS: Rwenzori, Meteorology, Air mass transport, ITCZ.

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INTRODUCTION

Meteorological observations at the Mt. Rwenzori (RWZ) are carried out in the framework of SHARE, Station at High Altitude for Research on the Environment, project, promoted and coordinated by Ev-K2-CNR with the support of Italian National Research Council (CNR). SHARE is an integrated and technological research program devoted to the environmental monitoring and climate studies in high mountain regions of Asia (Himalaya and Karakorum), Africa and Europe (Alps and Apennines). In this framework, continuous measurements of meteorological parameters and detailed analyses of atmospheric processes are supportive for a wide range of research activities carried out in different fields of study (atmospheric and climate science, glaciology, limnology, energy and water cycles, biodiversity and environmental medicine).

A permanent Automatic Weather Station (AWS) has been installed in Uganda at 4750 m a.s.l. in the eastern part of the Mt. Stanley, with the aim of filling the existing gap in meteorological observations in the area of equatorial Eastern Africa. The Rwenzori AWS therefore represents an important source of information for better understand climate variability and possible effects on tropical glaciers in the Eastern African highlands. Research activities on tropical alpine glaciers indicate that these ecosystems are highly sensitive indicators of tropical climate (Wagnon & *alii*, 1999; Francou & *alii*, 2003). In this region, glaciers have been shrinking over much of the 20th century (Hastenrath & Kruss, 1992; Kaser & Noggler, 1996; Kaser & Osmaston, 2002; Thompson & *alii*, 2002). As reported by Kaser & Osmaston (2002), over the Central Rwenzori Range, Mount Stanley could keep 35% of its glacier surface area of 1906, Mount Speke 25%, and Mount Baker only kept 8% until the early 1990s. These recession trends are common to the other glacierized massifs in the equatorial East Africa (Mt. Kenya and Kilimanjaro): as indicated by Kaser & *alii* (2004), the Kilimanjaro and Mt. Kenya glacier surface areas decreased by 85% and 75% respectively during the 20th century. According to Kaser (1992), Elena Glacier lost at least 60% of its surface from 1906 to 1990, while Taylor & *alii* (2006) reported that this glacier has retreated by 140 m ± 17 m from 1990 to 2005, thus confirming the overall recession trend. About the main cause responsible of these observed glacier recessions some authors suggest that the air temperature increase is the main driving force (Taylor & *alii*, 2006) whereas other authors suppose the increased incoming shortwave radiation related with a drier atmosphere in the East Africa (Mölg & *alii*, 2006) are the most important factors. The first survey of glaciers at RWZ was conducted in 1906, when the glacier cover over the entire range was estimated to be 6.5 km^2 (Kaser & Noggler, 1996) and the lowest altitude of glaciations was estimated to have reached 4400 m a.s.l. (Ostmaston, 1989). Scientific surveys carried out in the 1950s (Bergstrøm, 1955; Whittow & *alii*, 1963) and early 1990s (Kaser & Noggler, 1991, 1996; Talks, 1993) showed a continuing glacier recession trend, interrupted by a brief episode of terminal advance observed in the early 1960s (Whittow & *alii*, 1963; Temple, 1967), which coincided with a period of Lake Victoria rising by 2.5 m (Kite, 1981). Thus, permanent scientific meteorological observations in this mountain region can also provide useful hints for implementing investigations about hydrological variability in an area where the observed global climate change could seriously affect a large fraction of population.

The main goal of this paper was to determine the first characterization of the local meteorological conditions observed at RWZ during the period 2006-2009. Moreover, thanks to the continuous measurements of air temperature, rain precipitation, relative humidity, atmospheric pressure, wind regime and global short-wave radiation, we verified the seasonal influence of the Inter Tropical Convergence Zone (ITCZ) on weather conditions and atmospheric circulation at RWZ. With this purpose, by using a Lagrangian back-trajectory model, we also provide the analysis of the synoptic-scale atmospheric circulation which affects the measurement site for a representative 2-year period.

MEASUREMENT SITE AND EXPERIMENTAL

The meteorological observations analysed in this work were collected within the Rwenzori Mountains National Park (RMNP) at the borderline between Uganda and Congo (fig. 1). The RMNP covers most of the central and eastern half of the homonymous range (also named «Mountains of the Moon») and is characterized by the presence of tropical alpine glaciers, which have been recently recognized as highly sensitive indicators of tropical climate (IPCC, 2007; Wagnon & *alii*, 1999, Francou & *alii*, 2003). Lying slightly North of the Equator, RWZ is a mountain range extending for 95 km along the western East African rift valley, and can be subdivided by six ice-capped mountains and several lower peaks periodically snow covered (Whittow & *alii*, 1962). The RMNP encompasses Africa's third, fourth and fifth highest peaks (Mt. Stanley, 5109 m a.s.l., Mt. Speke, 4889 m a.s.l. and Mt. Baker, 4842 m a.s.l) in an alpine highland of glaciers, snowfields and lakes (e.g. Victoria Lake, George Lake, among others) which play an important role as water sources in the region. Although not as high as Mt. Kilimanjaro, and slightly lower than Mt. Kenya, 70% of the RMNP area is above 2500 m a.s.l. (Butynski, 1993). RWZ is characterised by the presence of passes and deep valleys, leading to a very complex topography that can significantly affect air-mass circulation and meteorological conditions. In fact, most of the soils encompassed by RWZ are characterised by a well-marked altitudinal zonation caused by combination of age, climate and erosion history (WHC-AS, 2004).

The climate in equatorial East Africa is dominated by the seasonal displacement of the ITCZ (see, e.g. Waliser, 2003; Slingo & *alii*, 2005), which determines four seasons: a short «winter», throughout January and February, is followed by the «long rains» from March to June. The summer (July and August) is followed by the «short rains» season, from September to December. However, this dry-wet season modulation is more evident in the coastal East Africa (Slingo & *alii*, 2005), while it is not so clearly defined in the inner areas of the continent, where RWZ is located. In fact, synoptic-scale investigations of typical meteorological regimes, showed that this region is characterised by an higher intra-annual stability (Nicholson, 2009; Suzuki, 2010).

The AWS for meteorological observations at RWZ were installed on June 2006 on the SE slopes of the Mt. Stanley at 50 m from the terminus of the Elena glaciers (fig. 2). The measurement site (0° 22' 34. N; 29° 52' E; 4750 m a.s.l.) is open to the East along the Bujuku valley (fig. 1), while higher mountain peaks are present within a range of about 2.5 km toward North-West (Margherita peak, 5019 m a.s.l.), North-East (Vittorio Emanuale peak, 4894 m a.s..l.), and South-East (Eduard peak, 4843 m a.s.l.). The experimental set-up is composed by a Lastem-LSI AWS which provides measurements of the seven standard meteorological variables (see table 1 for details about sensors). Specific humidity, a well-known tracer for atmospheric boundary layer (ABL) air-masses (e.g. Henne & *alii*, 2008A) has been calculated by applying the Clausius-Clapeyron equation. This station is similar to the other Ev-K2-CNR AWSs already installed in the high altitude regions of Himalaya and Karakorum: the sensors are mounted on a 2-m and a 5-m mast and are alimented by solar panels. Data, with a 1-hour temporal resolution, are stored in a data-logger and downloaded on a memory stick during maintenance campaigns leaded by Ev-K2-CNR or during almost-regular inspections by Uganda Meteorological Department (UMD) personnel. During these interventions the AWS functionality was also carefully evaluated and possible problems on the meteorological sensors as well as technical interventions have been noted for valida-

FIG. 1 - Map of RWZ region (curtsey by http://www.skimountaineer.com) with AWS location (black square, 0° 22' 34. N; 29° 52' E; 4750 m a.s.l.). The insert indicates the location of RWZ in Africa. The average positions of the ITCZ are indicated for January (blue) and August (red) according to Nicholson (2009).

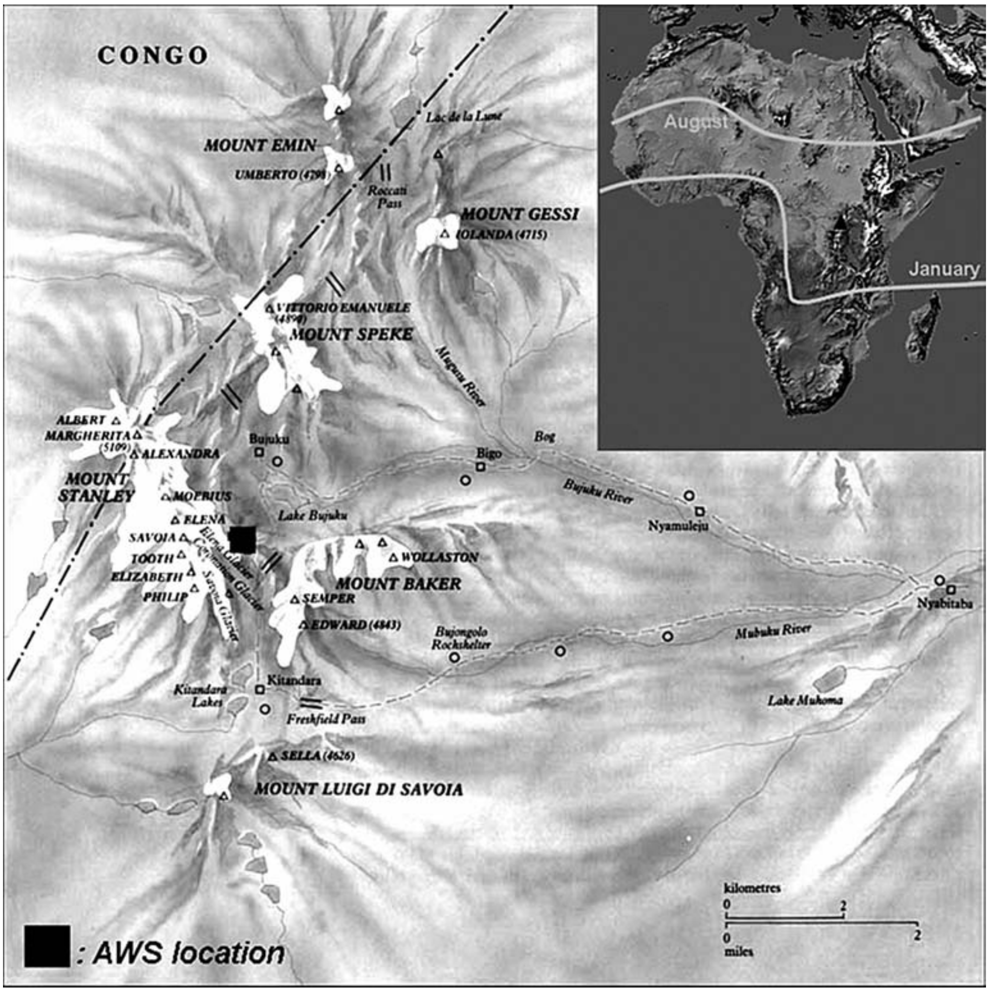


TABLE 1 - Meteorological sensors installed on Rwenzori AWS (Manufacturer: LSI-Lastem, Italy)

Measured variables	Sensor Type	Model	Accuracy
Atmospheric pressure	Slice of Silica	CX115P	±1 hPa (–20°C ÷ +45°C)
Air temperature	Thermoresistance	DMA572	±0,1°C (at 0°C)
Relative humidity	Capacitive Plate	DMA572	1.5% (5÷95%, at 23°C) 2% (<5>95%, at 23°C)
Wind speed	3-cup anemometer	DNA022	0.1 m/s +1%
Wind direction	Potentiometer	DNA022	1% Full scale
Total precipitation	Tipping Bucket	DQA030	1-10 mm/min: 1%
Global short-wave radiation	Thermopile	DPA153	<5% (Total achievable daily uncertainity)

tion data purposes. The data used in this analysis were validated by applying the necessary quality check procedures, following the guidelines defined within the CEOP (Coordinated Energy and Water Observation Project) experiment (http://www.ceop-he.org/cms/). Thus, data were flagged as «bad», «dubious» or «good». Within this analysis only data flagged as «good» were considered. During the investigation period starting from the AWS installation (on June 2006), «good» data availability covered the 62% for all variables at daily resolution, with the lowest data coverage (54%) as being observed for relative humidity observations during the «short rains». This relatively low data availability was primarily due to a long-lasting data gap occurred from 5 September 2007 to 29 June 2008, due to the objective difficulties of managing an AWS at a high altitude equatorial site often characterized by water vapour saturation which can promote early degradation of the AWS sensors as well as of data acquisition and storage systems. For these reasons, this data-set can provide representative information (data coverage better than 92%) about meteorology at RWZ which occurred in the periods from October 2006 to August 2007 and from July 2008 to June 2009.

With the purpose of investigating the properties of the synoptic-scale atmospheric circulation affecting the RWZ region, we analysed 6-day-long back-trajectories calculated every 4 h (at 00, 06, 12 and 18 UTC) with the Hybrid Single-Particle Lagrangian integrated Trajectory model (HYSPLIT, Draxler & Hess, 1998). Trajectory calculations are based on the GDAS (Global Data Assimilation System) 3-hourly operational system produced by the US

FIG. 2 - AWS location at the terminus of Elena Glacier at RWZ.

National Weather Service's National Centers for Environmental Prediction (NCEP). NCEP post-processing of the GDAS converts the data from spectral form to a 1-degree latitude-longitude grid and from sigma levels to WMO mandatory pressure levels. Two separate runs were performed respectively for the years 2008 and 2009, with the purpose of retaining a representative climatology of synoptic-scale air-mass advection to RWZ.

HYSPLIT back-trajectories, providing the geographic location and altitude of air parcels with 1-hour resolution along each path, have been calculated for a receptor point at the AWS coordinates and at 3600 m a.g.l. (above ground level), corresponding to the actual AWS altitude. Since RWZ represents the highest mountain relief in the area, we are confident that the interaction with the model topography (which does not match exactly with the real topography) can be minimized by this approach and that calculated wind fields can be reasonably representative of the large scale circulation near the RWZ summits.

RESULTS

Average and seasonal values of meteorological parameters

With the aim of calculating the typical annual and seasonal values of the meteorological parameters, 1-hour data observations were aggregated on daily averages (tab. 2). Even if, as showed by Henne & *alii* (2008B), the equatorial East Africa is influenced by two distinct wind regimes (north-easterly winds in boreal Winter; south-easterly winds during boreal Summer) and two rainy seasons (when the ITCZ crosses the equator), the meteorological parameters were characterised by a small intra-seasonal variability at RWZ, as shown by the analysis of mean values or standard deviations (tab. 2). In fact, the analysis of the so-called «stability parameter» (i.e. the ratio between the standard deviation and the average value) showed very low absolute values (lesser than 2) for all the analysed quantities (tab. 2), suggesting that RWZ observations were well representative for the typical «stable» equatorial climate (Nicholson, 2009; Suzuki, 2010). This also indicates that an in-situ definition of a drier and wetter season dipole related to the inter-seasonal displacement of the ITCZ, is quite complex: remarkable stability is in fact also evident for atmospheric pressure, relative humidity and daily precipitation amount, which are the obvious meteorological variables embodying a monsoon-like cycle.

Considering mean seasonal precipitation and relative humidity, higher values were found during the two rainy seasons, while the driest season was the Winter when, due to the southern displacement of the ITCZ, northerly drier air-flows are likely to affect the measurement site region (see Section 3.3). In particular, in good agreement with Osmaston (2006), total rain precipitation higher than 500 mm were found for the «long rain» and «short rain» seasons (with a maximum value of 540 mm during the «short rain» 2007), whereas values lower than 215 mm characterised the winter and the summer seasons (with an absolute minimum of 62 mm during winter 2007).

The atmospheric pressure (yearly average: 581 hPa) was characterised by almost constant values along the year.

TABLE 2 - Basic statistical properties of the Rwenzori AWS meteorological variables, evaluated at daily resolution in the October 3rd 2006 - June 30th 2009 time interval. The table includes mean (median for WDIR) and standard deviation, stability parameter, and percentage of missing days for all the considered period and for each single season. TEMP is the air temperature, PREC the total precipitation, PRES the atmospheric pressure, RH the relative humidity, WSPD the wind speed, WDIR the wind direction, RAD the global short-wave radiation

Period	Statistical Parameter	TEMP °C	PREC mm day^{-1}	PRES hPa	RH %	WSPD m s^{-1}	WDIR °N	RAD W/m²
All data	Mean	-0.35	4.0	581.4	90.4	3.58	130.2	121.7
	Standard Deviation	0.78	4.7	0.7	8.7	2.32	21.8	49.3
	Stability	-2.21	1.18	0.00	0.65	0.10	0.17	0.40
	Missing Data (%)	37.8	37.8	37.8	42.6	37.8	37.8	37.8
Winter (JF)	Mean	-0.41	3.0	571.6	86.9	4.02	123.6	117.8
	Standard Deviation	1.05	4.3	75.4	11.8	2.58	18.1	54.3
	Stability	-2.55	1.42	0.13	0.14	0.64	0.15	0.46
	Missing Data (%)	33.7	33.7	33.7	45.5	33.7	34.3	34.8
Long Rains (MAMJ)	Mean	-0.19	4.1	581.7	91.1	3.84	126.4	127.5
	Standard Deviation	0.73	4.9	0.6	7.3	2.03	19.7	53.3
	Stability	-3.82	1.19	0.00	0.08	0.53	0.16	0.42
	Missing Data (%)	38.6	38.6	38.6	38.6	38.6	38.9	38.6
Summer (JA)	Mean	-0.40	3.7	581.3	91.9	2.59	141.9	121.5
	Standard Deviation	0.65	4.1	0.6	7.4	1.60	25.6	46.8
	Stability	-1.64	1.10	0.00	0.08	0.62	0.18	0.39
	Missing Data (%)	42.4	42.4	42.4	42.4	42.4	42.4	42.4
Short Rains (SOND)	Mean	-0.49	4.6	581.2	90.1	3.79	128.6	115.6
	Standard Deviation	0.69	5.0	0.7	8.5	2.78	21.3	42.7
	Stability	-1.42	1.08	0.00	0.09	0.73	0.17	0.37
	Missing Data (%)	34.1	34.1	34.1	46.4	34.1	34.1	34.1

This reflects the very low variations of seasonal geopotential height over continental equatorial Africa (Suzuki & *alii*, 2010).

Despite its elevation, the measurement site does not appear to be an extremely windy location, probably thanks to the sheltering effect of the near mountain ridges (see fig. 1 and fig. 2). At RWZ, slightly higher wind speed (yearly average: 3.6 m/s) was observed during Winter (average: 4.0 m/s), while the less windy season appeared to be the Summer (average: 2.5 m/s). This could indicate that during Winter the measurement site was more affected by the stronger large-scale circulations than during Summer (see Section 3.3), when light breeze circulation within the local ABL could also play a major influence on the local wind regime. As will be shown in the Section 3.3, large-scale circulation was prevalently easterly over RWZ. This, together with the constraint of the local topography, leaded a East/South-East wind direction to dominate throughout the different seasons (tab. 2).

No obvious inter-seasonal variability was found for air-temperature (yearly average: –0.35°C) and short-wave solar radiation (yearly average: 121.7 W/m^2) which are characterised by the same (small) seasonal cycle. In fact, both the quantities were characterised by the lowest average values during the short-rains (–0.49°C and 115.6 W/m^2, respectively) and by the highest during the long-rains (–0.19°C and 127.6 W/m^2, respectively). Even if caution should be adopted in commenting these small seasonal variations, nevertheless this could indicate that large-scale meteorology and local mountain conditions strongly interact in determining the specific meso-climate of RWZ. For the purpose of better investigating this point, in the following Section we carefully describe the typical seasonal diurnal variations of the observed meteorological parameters.

Diurnal cycle of meteorological parameters

Being situated on the South-Eastern slope of the Mt. Stanley Plateau, the AWS location can be influenced by the development of thermally induced wind systems. In fact, as being the site not far from the equator, the large solar irradiance at the surface can represent a driving force able to strongly influence the local meteorological conditions and wind regimes. At the AWS site, the temperature (fig. 3a) shows a daily temperature cycle of about 5-6°C quite similar during all the seasons and probably reflecting the equatorial meteorological stability. After an increase (ranging from +1.8°C to +2.4°C, depending on the season) in the morning hours following the sunrise, the typical temperature diurnal cycles showed relatively constant values during the central part of the day (fig. 3a). This small daily variation can be related to the frequent occurrence of in-cloud conditions at the measurement site. This is in agreement with the analysis of the relative humidity diurnal cycle (fig. 3b), characterised by very high values (greater than 85%) and by the absence of any significant diurnal variation (caution should be deserved in analysing relative humidity behaviours, due to the rather high percentages of missing data). This limited the radiative day-time warming and the night-time cooling, also leading to almost constant air-temperature values during the night with only a moderate decrease until sunrise. The cloudy conditions occurring over the measurement site also prevent large amount of global short-wave radiation to reach the surface. In fact, the average values of the global short-wave radiation did not exceed 450 W/m^2 during the central part of day (fig. 3c). This is significantly lower than the values (ranging at the local noon from about 1000 W/m^2 to 1200 W/m^2) that should be observed at similar altitudes in the equatorial areas, as deduced by the application of the model described by Bird & Hulstrom (1981). For the most part of the year, similar low values of global short-wave radiation were also observed over the «cloudy» Mt. Kenya (–0.062 °N, 37.297 °E, 3678 m) by Henne & *alii* (2008A). Even if further activity should be deserved in verify possible shielding by the near mountain peaks or possible drifts in the pyranometer measurements, the appearance of a well-shaped «Gaussian» diurnal cycle, sug-

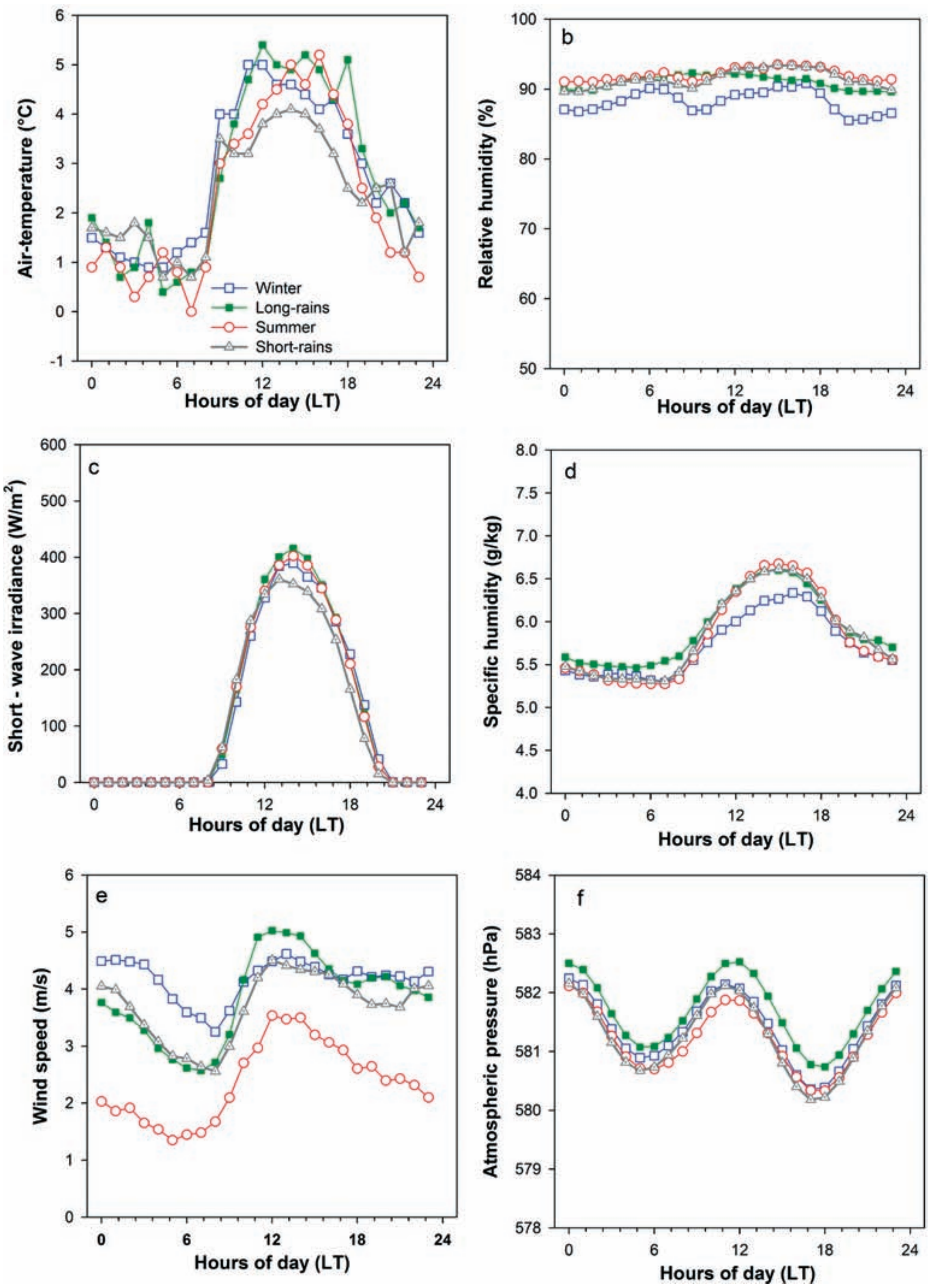


FIG. 3 - Typical (average) diurnal seasonal cycles for air-temperature (a), relative humidity (b), global short-wave radiation (c), specific humidity (d), wind speed (e) and atmospheric pressure (f) at RWZ.

gested that clouds were continuously present in the region, where the mountains trap the humid air from the Congo basin leading to persisting cloud cover above 2500 m a.s.l. (Osmaston, 2006). Only during the short-rains, the early decrease of short-wave global radiation after 12:00 LT (fig. 3c), could indicate a small diurnal cycle in the cloud formation. At RWZ, larger values of specific humidity were observed during the afternoon-evening in respect than during night-early morning (fig. 3d). As indicated by Henne & *alii* (2008A) and Bonasoni & *alii* (2010), this could indicate air-mass transport from the lower troposphere by thermal valley/up-slope circulations. With the aim of better elucidating this point, we calculated the average wind speed during the four seasons (fig. 3e). On average, for each season, the highest wind speed values were observed in the afternoon (ranging from 3.5 m/s in summer to 5.0 m/s during the long-rains), with a minimum in the early morning: around 5:00 LT during Summer (average values: 1.3 m/s) and around 8:00 LT for short-rains/long-rains (average values: 2.5 m/s) and Winter (average value: 3.2

m/s). The wind speed variability is fairly similar to the observations by Bonasoni & *alii* (2010) at the Nepal Climate Observatory - Pyramid (NCO-P, 5079 m a.s.l., in the high Khumbu valley, Nepal) during the South Asia summer monsoon: at the RWZ thermal up-valley/up-slope winds triggered by daylight ground heating on the lower valleys can affect the site during the central part of the day. During the afternoon-evening the «pumping effect» of the latent heat release relating to water vapour condensation on cumulous clouds (e.g. Bollasina & *alii*, 2002) can provide further energy to feed up-ward air-mass transport until the night, when the AWS observations are more representative of the large-scale synoptic-scale circulation. The weakening of wind speed in the first hours of the morning is likely to indicate the transition between the «synoptic-scale» and the ABL-influenced wind regime. This picture is supported by the analysis of the local wind direction (here not shown), showing maximum wind occurrence from South-East (55-65% of occurrences) as well as flows from South and East (20%). Only at 12:00 LT an increase of East wind direction (from 20% to 32%) was observed. This, probably, indicated the increased influence of up-slope thermal winds during the central part of day. This preliminary analysis, also suggest that the AWS location is only marginally influenced by westerly/north-westerly downward «katabatic» flow emerging from the not-far Elena glacier (accounting only for the 5% of night-time observations).

The local mountain circulation strongly influence the diurnal precipitation cycles at RWZ. In fact, the average amount of rain precipitation as well as the fraction of hours for which rain was observed, were characterised by clear diurnal cycles during all the seasons with higher values during day-time (fig. 4). This indicates that diurnal convection, can trigger the occurrence of in-situ precipitation during day-time. According with the different seasons, changes in the shape of diurnal precipitation are observed, possibly indicating a link between large-scale seasonal transitions and local weather regimes. However, it should be noted, that the AWS is insensitive to the snow precipitation which can be detected only after melting. Thus, it is possible that actual total precipitation during night-time, when the typical air-temperature is not far from the freezing point, could be underestimated.

The daily behaviour of atmospheric pressure (fig. 3f) shows a systematic semidiurnal variation characterised by an amplitude of about 2 hPa, with diurnal maxima at 12:00-00:00 LT and diurnal minima at 06:00-18:00 NST. This semidiurnal pressure cycle, already been observed in Himalayas (Ueno & Pokherel, 2002; Bonasoni & *alii*, 2010) and in other high altitude sites (e.g. Petenko & Argentini, 2002), can be explained considering the atmospheric tidal related to the warming of upper atmospheric layers due to the interaction between ozone and solar radiation (Chapman & Lindzen, 1970).

Synoptic-scale atmospheric circulation analysis

With the aim of investigating the influence of synoptic-scale transport patterns at RWZ, the HYSPLIT back-

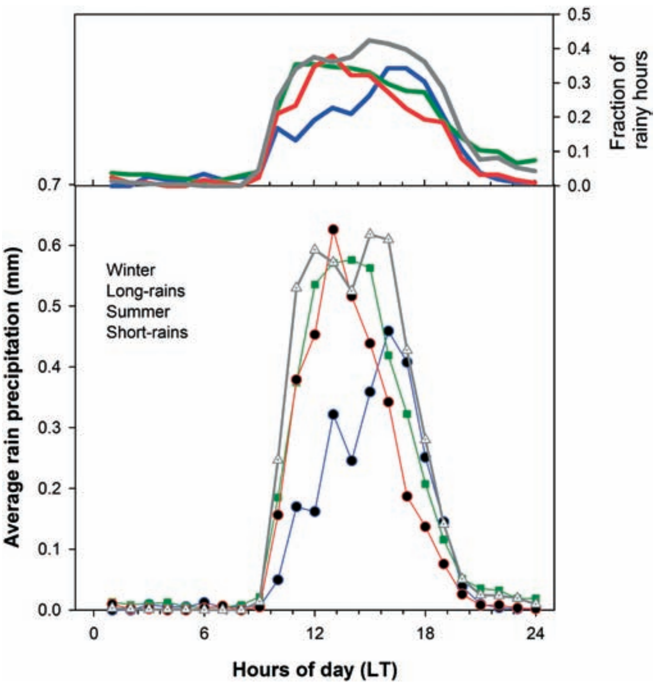


FIG. 4 - Seasonal cycles for the fraction of hours with rain (upper plate) and typical (average) diurnal cycle for rain precipitation (bottom plate) at RWZ.

trajectories were studied using a non-hierarchical cluster analysis (see Dorling & *alii*, 1992). A cluster methodology available in the HYSPLIT-tool package have been applied: at each step of the agglomeration process, the appropriate number of clusters was determined by analyzing the variations of a specific statistical parameter, i.e. the total spatial variance (e.g. Dorling & *alii*, 1992). As clustering variables we used each 6-hourly trajectory position (for a total of 24 points along each single back-trajectory). A total of 5171 back-trajectories have been analyzed for years 2008-2009 and the identified clusters were considered representative for the synoptic-scale circulation affecting the measurement site during the 6 hours centred around the back-trajectories arrival time.

This analysis leaded to the identification of 7 main synoptic circulation pathways at RWZ. As will be shown in the following, the synoptic-scale circulation here deduced, is strongly dominated by easterly flow. This appears to be in good agreement with in-situ wind direction observations (see Sections 3.1 and 3.2.), suggesting that despite the rough topography characterizing the measurement site regions, AWS observations are likely to be reasonably representative for the large scale atmospheric conditions. With the aim of providing an overview of each air-mass cluster, the concentration field of back-trajectory points (expressed as logarithm of total numbers per domain grid) are reported in figure 5a while in figure 5b, the vertical cross-sections of the calculated back-trajectory clusters have been summarized. The logarithmic

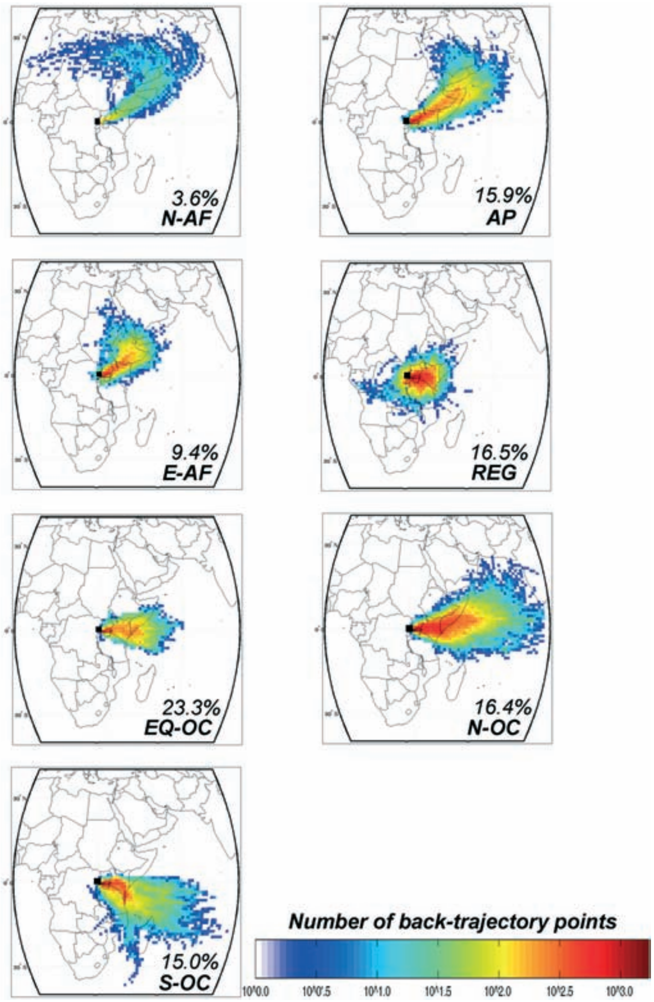


FIG. 5a - Field concentration (expressed as the logarithm of the number of back-trajectory points passing over a 1°×1° grid) of HYSPLIT 3-D back-trajectory clusters at RWZ for the period January 2008 - December 2009.

scale has been adopted to emphasize the transport paths also on «peripheral» regions far away from the measurement site.

North-Africa (N-AF): this air-mass cluster contributed to the 3.6% of synoptic-circulation observed at RWZ. It is characterised by downward motion from the upper troposphere with 6-day old air-masses originating in the region of the sub-tropical jet stream (fig. 5b), suggesting occurrence of stratosphere-to-troposphere transport during this synoptic-scale circulation.

Arabian Peninsula (AP): for this synoptic circulation class, which were detected during the 15.9% of time, air-masses mainly originated over Arabian Peninsula, following an anticyclonic patterns towards the measurement site. This air-mass cluster, principally observed during the summer period, was dominated by downward motions from the free troposphere, even if not-negligible uplift areas can be observed around 50°E (fig. 5b).

East Africa (E-AF): the 9.4% of air-masses arriving at RWZ have been encompassed by this cluster. Back-trajectories originated over the Africa Horn region and, similarly to the AP cluster, were characterised by north-easterly downward flow from the free troposphere. For this cluster, synoptic-scale upward motions from the surface are likely to occur from 40°E to 50°E and within the measurement site region (fig. 5b). In particular, during the short-rains and the winter seasons, this can favour the transport to RWZ of biomass burning products emitted from West Ethiopia, South Sudan and Angola (Roberts & *alii*, 2009).

Regional (REG): the 16.5% of airflows toward RWZ were represented by this synoptic circulation which also represents the only cluster with westerly air-mass advection. This air-mass cluster describes situations with relatively slow air-mass advection with air-masses originating within 1000 km from the measurement site and possibly experiencing ascending motions from lower troposphere up to mountain summit (fig. 5b).

Indian Ocean (EQ-OC): this cluster contributed for the 23.3% of air-masses at RWZ and was characterised by a quasi-zonal flow along the Equator, with synoptic-scale uplift over the East African coast-lines (fig. 5b).

Northern Indian Ocean (N-OC): this air-mass cluster, which contributed for the 16.4% of air-masses arriving to the measurement site, was characterised by long-range advection from the Indian Sea and the southern Pakistan/western Indian coastlines. As deduced by the cluster vertical cross-section (fig. 5b), a significant upward motion originate in the area from 40°E to 60°E, i.e. from Africa Horn and Western North Indian Ocean.

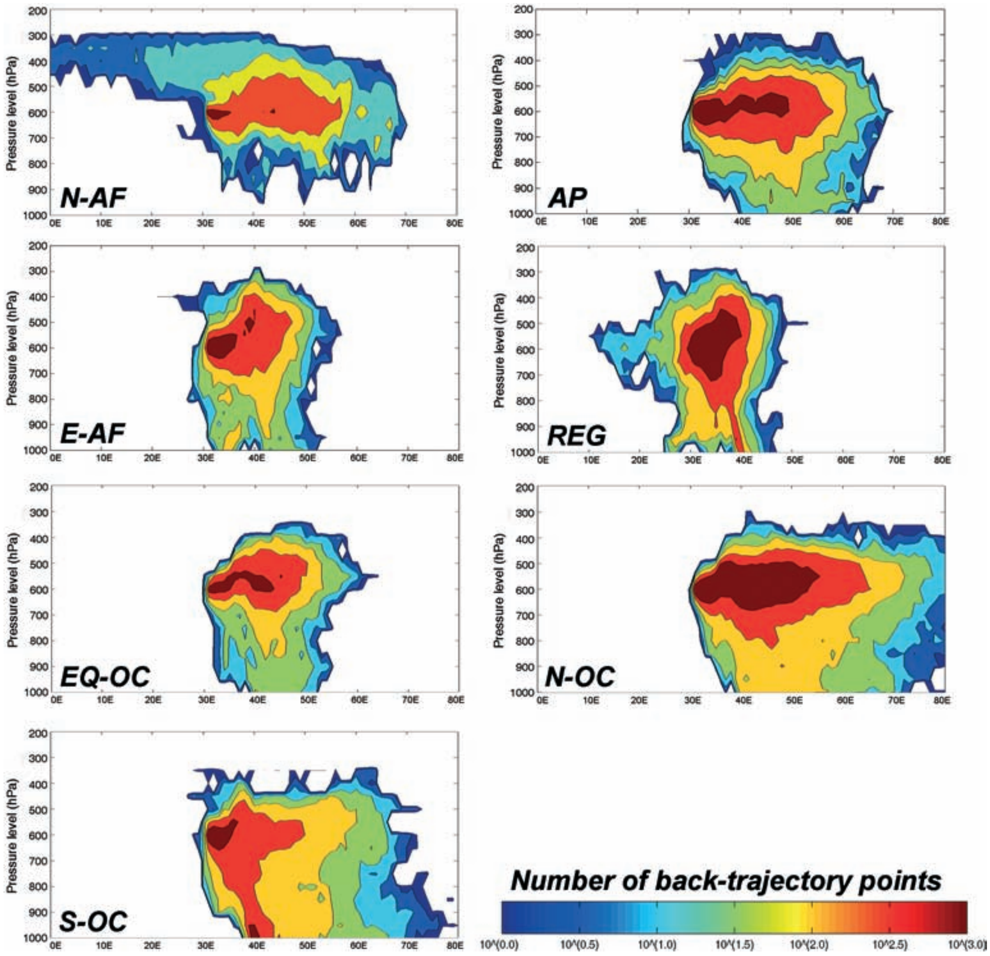
Southern Indian Ocean (S-OC): the 15.0% of back-trajectories arriving at RWZ traced transport pathways from the South Indian Ocean. Within this cluster, also air-masses originating over Madagascar can be found. As being generally characterised by prevalent ascending motions from the surface, this synoptic-scale circulation can be associated to the advection of air-masses representative for the oceanic ABL (fig. 5b).

The seasonal variation of cluster occurrences (tab. 3) is affected by the seasonal displacement of the ITCZ (fig. 1). In fact, during boreal winter, ITCZ is situated South to the equatorial Africa favouring a synoptic-scale north-easter-

TABLE 3 - Seasonal cluster frequencies at RWZ for the period January 2008-December 2009: AP (Arabian Peninsula), N-AF (North Africa), E-AF (East Africa), REG (Regional), EQ-OC (Equatorial Indian Ocean), N-OC (North Indian Ocean), S-OC (South Indian Ocean)

Cluster	Winter	Long rains	Summer	Short rains
AP	12.6%	21.6%	23.5%	8.0%
N-AF	1.4%	7.8%	1.3%	1.6%
E-AF	10.7%	8.4%	15.0%	6.9%
REG	7.8%	12.2%	35.2%	15.4%
EQ-OC	27.0%	20.1%	10.7%	31.0%
N-OC	35.6%	17.2%	7.4%	10.6%
S-OC	4.8%	12.6%	6.9%	26.5%

FIG. 5b - Vertical cross sections (expressed as the logarithm of the number of back-trajectory points) of 3-D back-trajectory clusters at RWZ for the period January 2008-December 2009.



ly/easterly circulation over the RWZ region. This is reflected by the strong prevalence of the N-OC (36%) and EQ-OC (27%) clusters. In particular, as the vertical air-mass displacement along the N-OC back-trajectories was usually characterised by upward motions, it is likely that these air-masses could be characterised by not-negligible levels of anthropogenic pollution emitted from South Asia (Phandis & *alii*, 2002). During the long-rains season the ITCZ started to move northward crossing Uganda and RWZ region. On the synoptic-scale circulation, the movement of the ITCZ across Uganda is reflected by the lack of a prevalent air-mass cluster, even if northerly circulations (N-OC, EQ-OC, AP) still dominate. During this season, we also observed the greatest contribution of the N-AF circulation (8%), which was almost absent in the rest of the year. During boreal summer, the ITCZ is situated at about 20°N over North-East Africa, southern Arabian coastlines and Himalayan arc in South Asia (fig. 1). However, for this period of the year, RWZ was affected by the highest REG contribution (35%). This is in agreement with the findings by Suzuki & *alii* (2010) and Nicholson (2009), showing a flat geopotential gradient over Equatorial Africa during summer associated with weak wind fields, which likely favour air-mass recirculation at regional scale. From March to August, significant AP contributions have been pointed out by HYSPLIT simulations. Considering that Arabian peninsula represent an important source region for mineral dust (Liu & *alii*, 2008), it is not reliable that dust transport to RWZ can be favoured by this synoptic-scale circulation. When the ITCZ crosses moved again toward the equatorial Africa, from September to December, S-OC (26%) and EQ-OC (31%) contributions were maximized at RWZ, indicating that advection of oceanic wet south-eastern air-masses was favoured.

CONCLUSIONS

In this work, we analysed the seasonal and diurnal behaviours of meteorological parameters observed at Mt. Rwenzori (4750 m a.s.l., West Uganda) in the framework of the experimental activity carried out within the SHARE project. Despite the adverse environmental and logistic conditions which characterise this high-altitude equatorial measurement site, the analysis of the continuous measurements carried out by an Automated Weather Station allowed to provide important information about air-temperature (TEMP), relative humidity (RH), atmospheric pressure (PRES), rain precipitation (PREC), wind speed (WSPD), wind direction (WDIR) and global short-wave radiation (RAD). Moreover, simulations performed by using the HYSPLIT model, permitted to characterise the synoptic-scale atmospheric circulation for a 2-year period (January 2008-December 2009).

For all the considered parameters, the seasonal variations observed during the periods October 2006-August 2007 and July 2008-June 2009, have been characterised by a small variability across the year. This is in agreement with Nicholson (2009) and Suzuki & *alii* (2010), showing that the continental equatorial Africa is characterised by a higher intra-annual stability of the meteorological regime. In particular, the observed mean values were: (–0.35 ± 0.78) °C for TEMP, (90.4 ± 8.7) % for RH, (581.4 ± 0.7) hPa for PRESS, (4.0 ± 4.7) mm/day for PREC, (121.7 ± 49.3) W/m^2 for RAD, (3.6 ± 2.3) m/s for WSPD. Only for the total seasonal precipitation amount in the wet seasons a rather clear influence of the ITCZ can be observed. Over Equatorial Africa, the days influenced by the presence of the ITCZ are usually identified by daily precipitation larger than 3 mm (Suzuki, 2010). At RWZ, similar precipitation rates were observed for lesser than 34% of days during winter and summer months, while 47% of days during the short-rains and the long-rains showed daily precipitation greater than 3 mm. This indicated that the ITCZ influence on the occurrence of the wet seasons is rather evident at RWZ, even if the classical definition of an ITCZ-led wetter-drier season dipole at RWZ is less applicable than in other areas of East Africa (Nicholson, 2009).

Due to the combined interaction of the large-scale atmospheric circulation and the local topography, the dominant WDIR was from E-SE at the measurement site. Only for WSPD a seasonal behaviour can be detected, with lowest values during summer than in other seasons, probably related to the weak wind fields characterizing equatorial Africa during this season. As suggested by the low RAD and the high RH, the measurement site is often characterised by «in-cloud» conditions (49% of hourly observations were characterised by RH exceeding 95%). Slightly lower average RH and PREC values were observed during the «dry» winter season in respect to the other seasons.

As deduced by the analysis of the seasonal diurnal variations of specific humidity (a tracer for low-tropospheric air-masses) and wind speed, the measurement site is likely to be influenced by thermally-induced wind circulation characterised by the up-ward transport of wetter ABL air-masses during afternoon-evening. Probably, during the night, the measurement site is more representative of «free tropospheric» conditions with a stronger influence of the synoptic-scale atmospheric circulation. As deduced by these observations, this local mountain weather regime is likely to significantly influence the variability of the meteorological parameters at RWZ: the typical diurnal variations were characterised by clear 24-hour cycles during all the analysed seasons.

When focusing on large-scale atmospheric circulation, a prevalent easterly regime was deduced. As shown by the back-trajectories calculated by means of the HYSPLIT model, 7 main circulation clusters affected RWZ for the years 2008-2009: AP (Arabian Peninsula), N-AF (North Africa), E-AF (East Africa), REG (Regional), EQ-OC (Equatorial Indian Ocean), N-OC (North Indian Ocean), SOC (South Indian Ocean). On annual basis, the most frequent contribution was related to the EQ-OC circulation (23.3% of occurrence) even if not-negligible roles have been played by AP (15.9%), REG (16.9%), N-OC (16.4%) and S-OC (15.0%). Depending on the different synoptic-scale circulation, specific atmospheric processes (i.e. stratospheric air-mass intrusions, transport of biomass burning emission or mineral dust) are likely to influence the atmospheric properties over RWZ.

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