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Analysis of Natural Aerosols' Vertical Distribution in Sahelian Zone via the OPEN (Clouds Seeding Operation) Project in Chad

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Abstract

This paper consists in analyzing natural aerosols' vertical distribution in Sahelian zone via the project called Clouds Seeding Operation (OPEN) in Chad. It is devoted to the study of microphysical parameters, obtained by airborne measurements of aerosols concentrations, and carried out during two air flights: on June 18th, 2014, and November 5th, 2015. This allows studying the variability of their vertical distribution in number, surface and volume. Particles accumulations are studied in different levels according to flight altitude and considered constant at the level where principal physical processes responsible for the rise of the aerosols in the columns of the atmosphere are identified. At these altitudes, the concentrations of aerosols vary in space and time. Results are primarily concerning the granulometric distributions of aerosol particles on various levels and altitudes and the carried out analyses relate to the principal physical processes responsible for the vertical distribution of aerosol particles in the Sahel, and in particular in the areas of the flights of measurement in Chad.

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Keywords

aerosols, vertical distribution, Sahel, OPEN project, Chad.

Introduction

Aerosols are small solid and liquid particles suspended in the atmosphere. Mineral dust is produced by wind, arid and semi-arid surfaces erosion. Their production depends much more on weather conditions and physicochemical properties of the ground. These natural aerosols are qualified as the "desert ones ", because they are primarily composed of clays, silts, sands, plants detritus, pollens and various micro-organisms.

Thanks to their optical properties, atmospheric aerosols play a very significant role in the radiative budget absorbing and diffusing solar and telluric radiation (infra-red radiation coming from the ground). According to (Stephen and Meinrat, 1996), aerosols constitute today one of the sources of major uncertainties concerning the evolution of the climate, due to their complexity. They can indeed influence clouds formation and their cycle of life through indirect radiative effects. These mineral aerosols have harmful impacts on human health and on the environment, too.

The objective of this paper consists in analyzing natural aerosol particles vertical distribution in the Sahel. This study must be deepened thanks to the large data base available at the OPEN project. This project (OPEN) aims clouds seeding in order to increase precipitations in Chad

Sahelian zone. It is necessary to study the aerosols granulometric distributions in number, surface and volume, in the atmosphere before seeding.

Materials and Methods

The airborne data used within the framework of this paper come from the OPEN project. The objective of this project is the artificial modification of weather.

This modification was conducted in a discontinuous way from 2010 to 2015 under the authority of Chadian Air Force (Galmai *et al.,* 2018). Data were obtained from PCASP-100x (Passive Cavity Aerosol Spectrometer Probe) spectrometer. This optical counter is composed of a laser beam and an optical system.

Particle dimension is determined by measuring the light intensity that this one diffuses while crossing the laser beam. This material makes it possible to measure the size of aerosol particles in the range from 0.1 to 3 µm distributed in 30 channels. The width of the channels is ranges from 0.01 µm for the first channels, to 0.2 µm for the largest channels (last ten).

Two level flights were retained: flight of June 18th, 2014 and that of November 5th, 2015; The first took place during the wet period and the second during the dry period.

Using an Excel table sheet, we exploited AIMMS and PCASP counters during these two flights. The trajectories back and fro of the latter are represented on the map of Chad (figure 1). We inserted the dates of the flights in order to facilitate the reading of the various figures (table 1).

The approach adopted in this work consists in analyzing, the flights of June 18th, 2014 and November 5th, 2015:

Natural aerosols granulometric distributions in number surface and volume.

Vertical profiles of certain parameters (temperature, relative humidity and concentration in number of the aerosols);

Mesosynoptic situation at 925 hPa, 850 hPa and 500 hPa.

We studied mineral particles variations of concentrations at altitudes considered constant (level); those are summarized in the table below.

The granulometric distributions in number, surface and volume of aerosol particles are calculated at each level. The particles mean diameter D_p is calculated on a diameter interval of d_i to $d_{i+1}$by the formula:

$$\mathbf{D_p}=(\mathbf{d_i} * \mathbf{d_{i+1}})^{\frac{1}{2}} \quad \ldots(1)$$

The distribution in number is given by expression:

$$f(d) = \frac{dN}{d\ln d_p} = \frac{N}{\ln\delta_g\sqrt{2\pi}}\exp\left(-\frac{(\ln d_i - \ln\bar{d}_g)^2}{2(\ln\delta_g)^2}\right) \quad \ldots(2)$$

Where ***N*** is the total number of aerosol particles;
The average geometrical diameter is equal to the mean diameter in number:

$$\ln\bar{d}_g = \frac{\sum n_i \ln d_i}{\sum n_i} \quad \ldots(3)$$

And the geometrical standard deviation is:

$$\ln\delta^2{}_g = \frac{\sum n_i(\ln d_i - \ln\bar{d}_g)^2}{\sum n_i} \quad \ldots(4)$$

The distributions on surface and volume are deduced respectively from:

$$\frac{dS}{d\ln D_p} = \pi d^2 f(d) \quad \ldots(5)$$

And.

$$\frac{dV}{d\ln D_p} = \frac{\pi}{6} d^3 f(d) \quad \ldots(6)$$

Results and Discussion

The concentrations of mineral particles are studied at constant altitudes, where the plane makes a rotation of variable duration (table 1).

The flight of June 18th, 2014 comprises 7 levels (figure 3) and flew over the provinces of the Lake, Mao, Bahr-el-Ghazal, Hadjer-Lamis and Chari-Baguirmi (figure 1), while the flight of November 5th, 2015 carried out measures in an airstream (Figure 1 and 3) above Massakory in the province of Hadjer-Lamis.

Aerosols vertical profile

The total concentration of mineral particles varies according to altitude. For the flight of June 18th, 2014 (figure 4), the concentration of mineral particles decreases going from the level of the ground (772.88 cm^{-3}) to an altitude of 1000 m (282.68 cm^{-3}). It increases between 1000 and 1502 m up to the maximum value of 835.16 cm^{-3}. It appears then that the concentration of aerosols ranges between 170 $cm^{-3}$and 316 cm^{-3}at 2000 m till the maximum altitude.

On the other hand, for the flight of November 5th, 2015 (figure 4), the concentration of aerosols particles lies overall between 198.33 cm^{-3} and 310.99 cm^{-3} from ground level to 2500 m of altitude; it presents just a light increase (543.53 cm^{-3} at 820 m), then a reduction (146.99 cm^{-3} at 2331 m). It reaches the value 10116.34 cm^{-3} at maximum altitude.

Vertical distributions of the aerosols

The granulometric distributions of aerosols concentration in the atmosphere vary according to the size of the mineral particles and to the level of each altitude. In the two studied cases, the distribution in number concerns more the fine particles than the large particles.

For June 18th, 2014, it seemed higher for the particles of diameter ranging between 0.11 and 0.16µm at altitude 6514m and one observes a minimal peak of distribution in number of mineral particles at altitude 4886m (figure 5). While for the flight of November 5th, 2015, it was also noticed that this one is maximum at altitude 4844m and low at the level of 2908m (figure 5).

The distributions on surface and volume (figure 5) show that concentrations of fine particles are dominant and in parallel, a weak concentration of large particles in the zone. These distributions are strongly centered on the particles of diameters ranging between 0.14 and 1.2 µm. The majority of the concentrations of mineral particles measured during these two flights are mainly made up by fine particles, in mode of accumulation, in detriment of the large particles (coarse mode).

Physical phenomena responsible for the vertical distribution of the mineral aerosols during two flights

The vertical distribution of mineral particles concentrations in the areas of study, presents a large variation according to altitude. These various values of concentrations in the zone are due to atmospheric dynamics and thermal conditions.

Chad is dominated by the circulation of the Harmattan and monsoon winds. The convergence of these two air masses generates the convective movements which send a great quantity of mineral aerosols in the columns of the atmosphere.

Influence of atmospheric circulation on the aerosols vertical distribution

The variation of mineral particles concentration according to altitude is due to the winds convergence at the level of the Intertropical Front (the FIT). In the experiment undertaken during the flight of June 18th, 2014, the distribution in total number of mineral particles concentration increased (13167.70 cm^{-3} being the value of maximum concentration) between altitudes of 966 m to 2612 m, a level from which it decreased until maximum altitude. The weather situation of the day (figure 6) was characterized by the convergence of monsoon and Harmattan flows which involves a strong ascent of the air masses, creating thus the cumulonimbus groups which caused the rise of particles concentration in the zone. This ascent generates a significant concentration of aerosols particles in the average troposphere up to the level of 500 hPa to which the maximum concentration 257.37 cm^{-3} of fine particles at altitude of 6849 m appeared. The movements, at this altitude, are supported by a vertical transport; they are responsible for the increase in concentrations of mineral aerosols. The distributions on surface and volume at this level, show that the concentration of fine particles is dominant and concentration of large particles is very weak.

In the same way, at the level 850hPa (figure 6), say approximately 1480 m, a cyclonic circulation took place in the zone, involving an atmospheric turbulence which eliminated the aerosol particles from the atmosphere. At this level, this disturbance generating a significant quantity of specific moisture induced the thermal instability which caused the convective movements. This phenomenon contributed to the increase in concentration of mineral particles at this altitude. In addition it is observed a significant reduction in the maximum concentration, amounting to 13167.70 cm^{-3} of mineral particles at the altitude of 2612 m, then 2906.37 cm^{-3} at the altitude of 4886 m, and then reaching 316.59 cm^{-3} at 6514 m, and finally 257.37 cm^{-3} at 6849 m. This reduction is due to the turbulence of the atmosphere and the fact that certain particles are trapped like in a core of condensation during the formation of clouds; however, when these clouds precipitate, the particles trapped in the water droplets disappear from the atmosphere.

The distribution on surface and volume during the flight of November 5th 2015 at various studied altitudes, present a significant domination of concentration of fine particles, diameters ranging between 0.1 and 0.8 µm, and a very weak agglomeration of particles of diameter higher than 0.8 µm. The weather at 925hPa (figure 6) consists of the convergence of two masses of air to the centre whose strong wind streams intensity coming from the circulation of the anticyclone of Libya, with its band located towards 31° N, involves a significant ascent of the mineral particles in the troposphere (500 hPa) (Drobinski *et al.*, 2009) and a maritime mass of air coming from the Middle-East. The maximum of the mineral particles transport is localized in the band of latitude ranging between 10° N and 25° N (Leon *et al.*, 2009); (Marticorena *et al.*, 2010); (Adams *et al.*, 2012); (Senghor *et al.*, 2017). The maximum value 198606.43 cm^{-3} of the distribution in number to maximal altitude represented the convective transport of the atmospheric particles. The maximum concentration (7620.4 cm^{-3}) at altitude of 971 m decreases to 4983.82 cm^{-3} at altitude of 1941 m; indeed, the particles are transported by the convective movements of the zone at a significant specific moisture: certain mineral particles are then washed by precipitation or atmospheric turbulence. The distribution in number of the aerosols is decreasing from first level (altitude of 971 m) to the fourth level (altitude 3875 m) from which it increases again until reaching its maximum concentration. This variation is more influenced by the atmospheric dynamics; thus, between 850hPa and 500 hPa (figure 6), a Saharan cyclonic circulation, includes a significant quantity of mineral particles. These emitted particles are transported vertically until maximum altitude by thermal and dynamic effects. This displacement being horizontal, contribute to reach maximum concentration (198606.43 cm^{-3}) of aerosols particles at the altitude of 4844 m in this zone.

At sun rising, the heat flow increases and heats the surface of the ground, which induces the heating effects between surface and the winds, thus creating the jets. This phenomenon involves the increase of wind speed on the surface which can produce a significant quantity of mineral particles. According to Bou Karam *et al.*, (2008), the night jets appear all the year on the area of Bodélé and according to Peter (1995) and Davis (2000) works, they extend to several tens and several hundreds of kilometers. These jets contributed in an active way to the vertical distribution of aerosol particles concentrations at various altitudes considered.

Table.1 Ranges of measurement time for concentrations of mineral particles at various levels during June 18, 2014, and November 05 2015.

Variation of time (beginning-end)	Duration	Constant altitude (m)
Flight of the 18/06/2014		
24896,84375-25344,75	447,90625	4886
25835,625-26449,46875	613,84375	966
27319,26563-28316,04688	996,78125	6849
29010,89063-29465,75	454,85937	967
30243,5625-31255,34375	1011,78125	6514
31873,17188-32399,125	525,95312	972
32650-33874,70313	1224,70313	2612
Flight of the 05/11/2015		
36757,82813-37430,67188	672,84375	971
37714,59375-38073,54688	358,95313	1941
38336,4375-38684,4375	348	2908
38993,28125-39453,17188	459,89063	3875
39613,1875-40077,01563	463,82813	4844

Fig.1 Locations of measurements of June 18th, 2014 flights (red) and of November 5th, 2015 (blue)

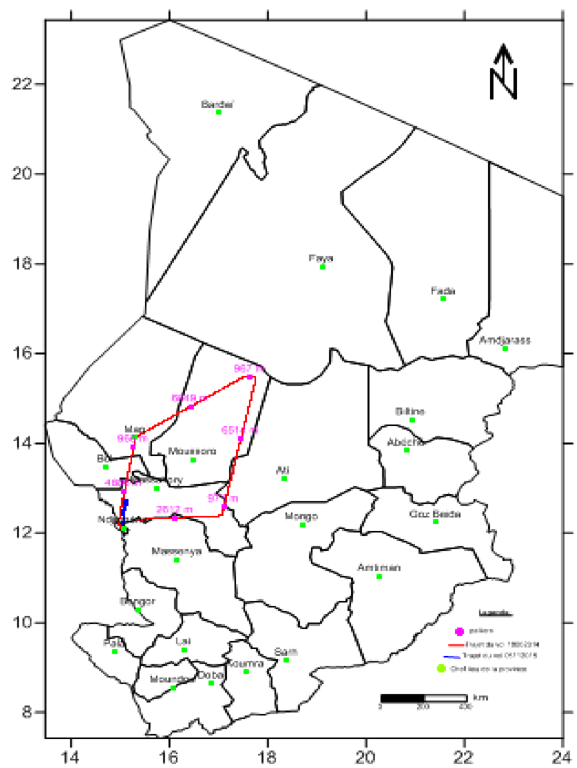


Fig.2 Profiles and trajectory of the flights of June 18th, 2014 and November 5th, 2015 in two dimensions (red) and three dimensions (blue).

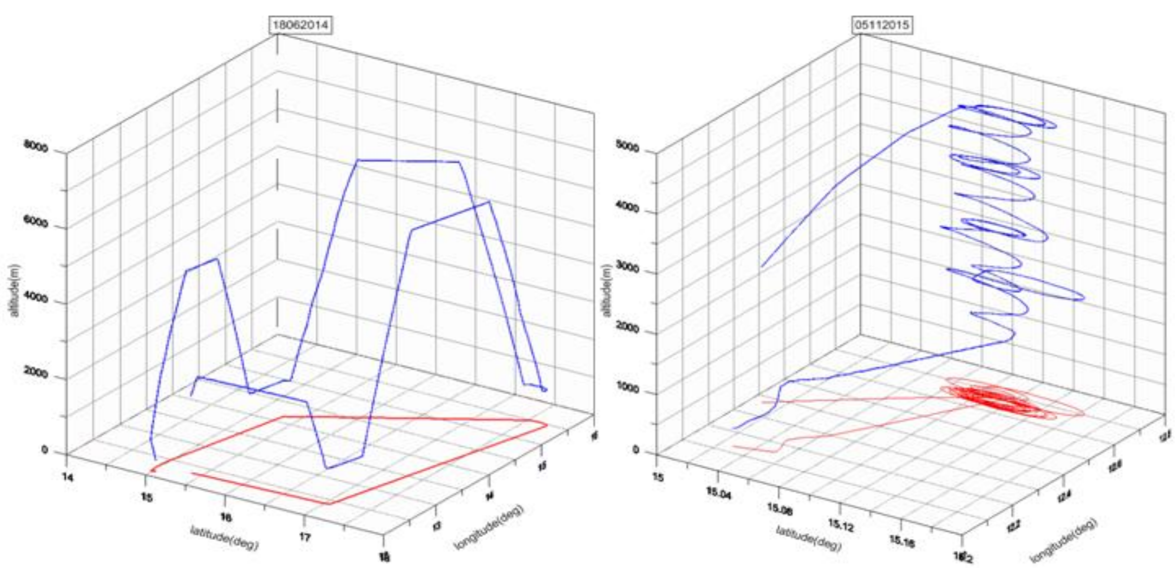


Fig.3 Temporal curves of air temperature, relative humidity and levels profile of the two studied flights.

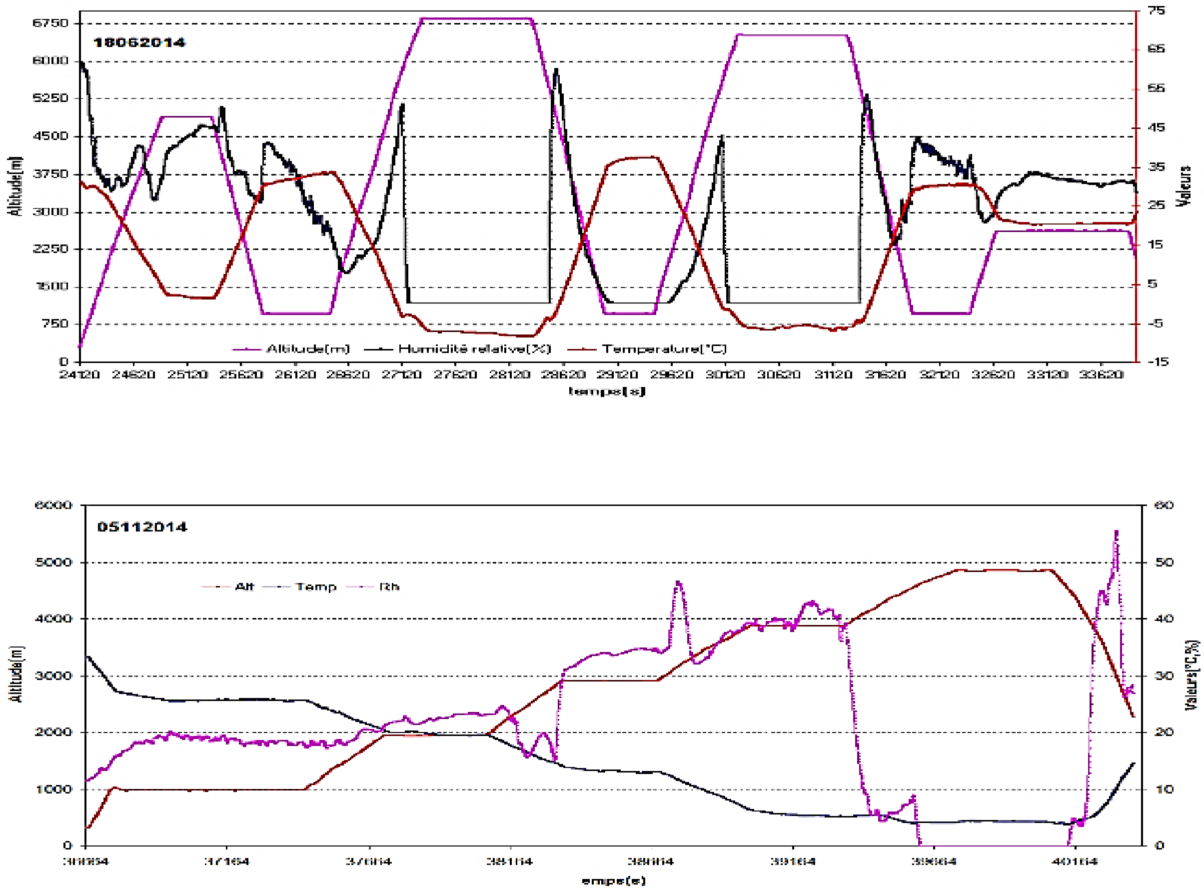


Fig.4 Vertical profiles of the total concentration of aerosols particles for the two studied flights

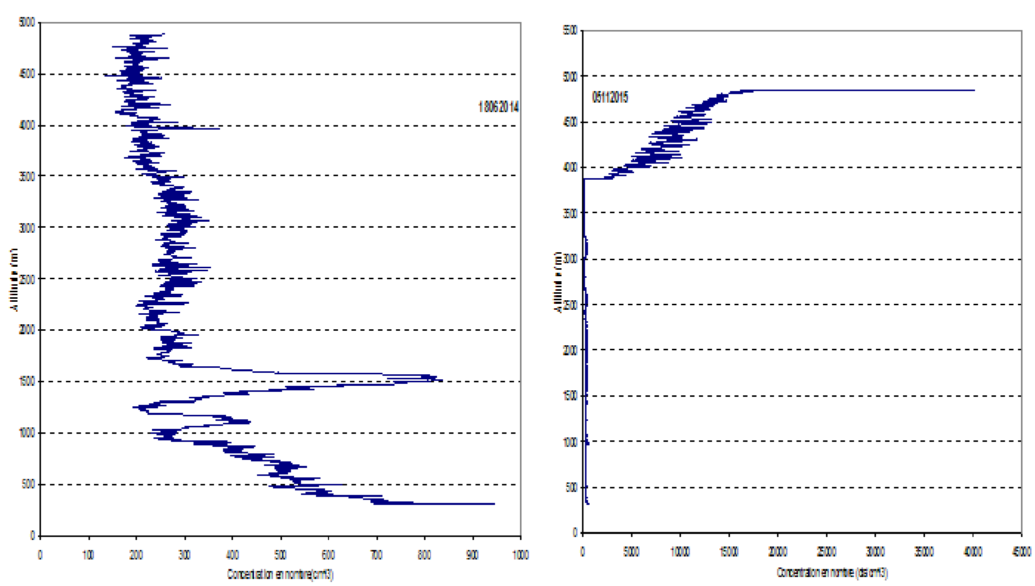


Fig.5 Graphs presenting the distributions in number, surface and volume of the populations of aerosols recorded at constant altitudes of the flights of June 18th, 2014 (left column) and of November 5th, 2015 (right column)

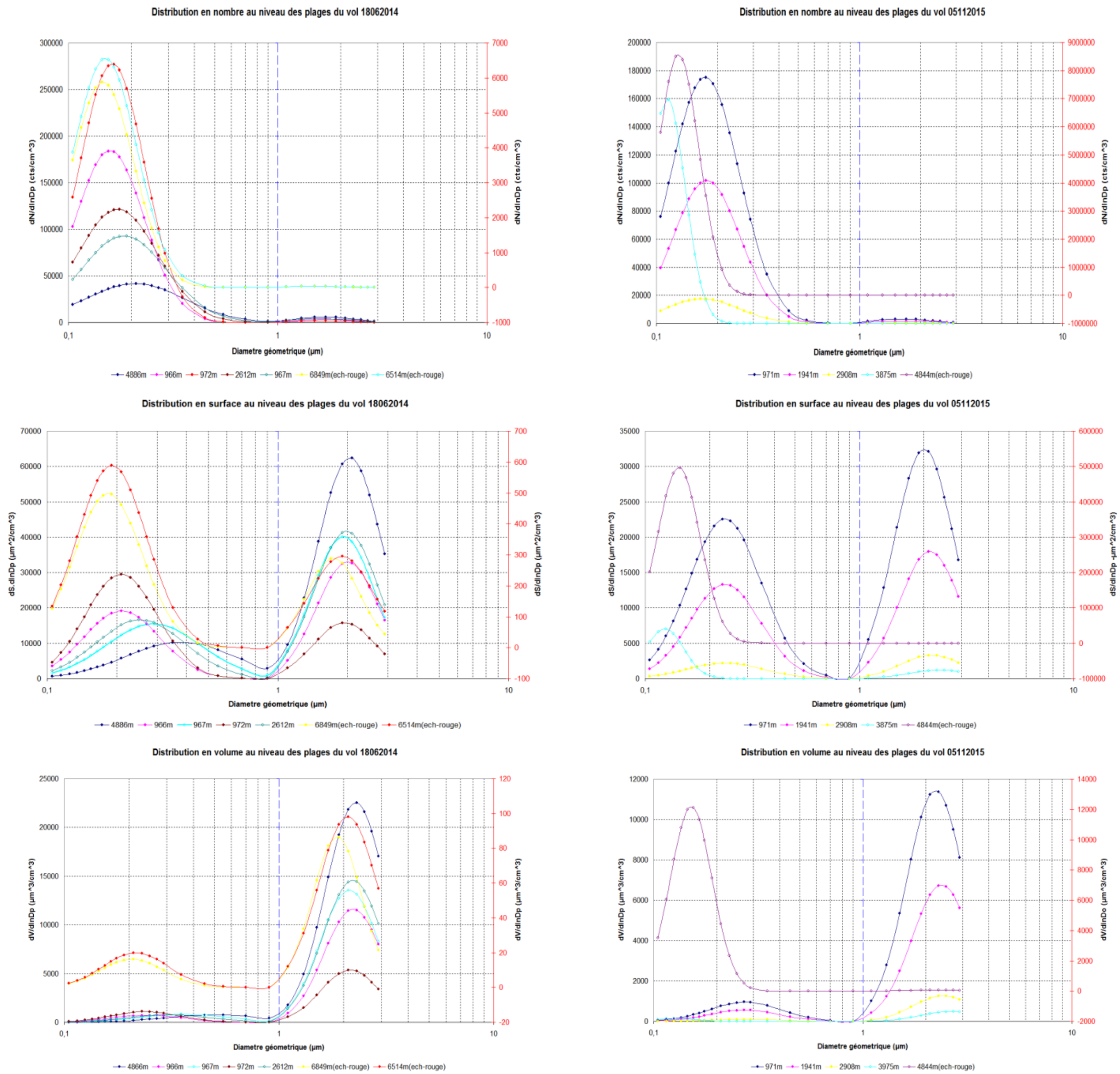


Fig.6 Winds and specific moistures at the levels 925, 850 and 500 hPa during the two flights of June 18, 2014 (left column) and of November 05, 2015 (right column)

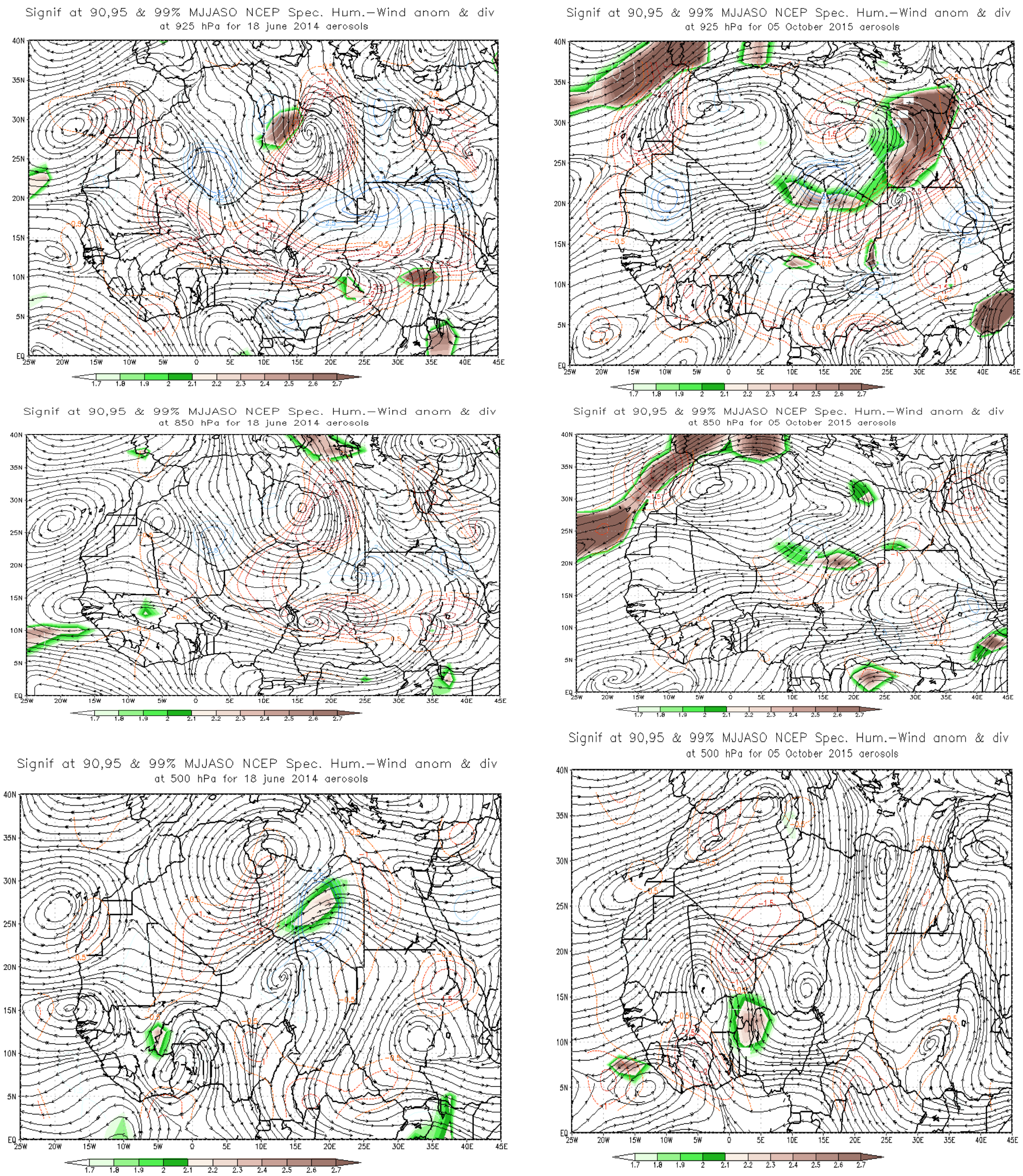
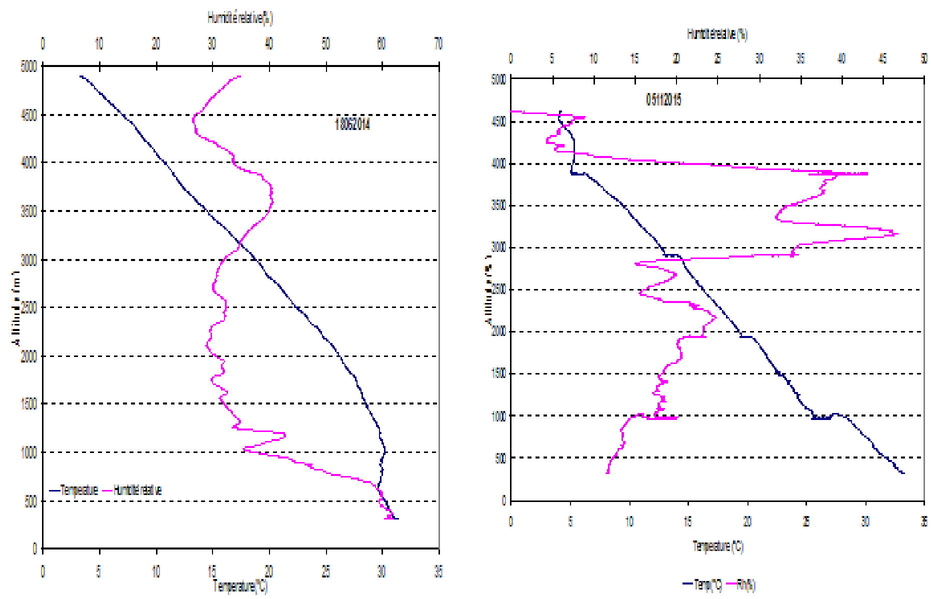


Fig.7 Curves of temperatures and the relative humidity for the two flights



Temperature influence on aerosols concentration

In the case of June 18th, 2014 flight, an inversion of temperature between altitudes of 500 and 1000 m is observed. It is associated with the mass of hot air generated by the convergence of the air masses (hot and cold) at the level 925hPa, which created thermal instability responsible for the upswings.

This phenomenon increased the maximum concentration (835.15 cm^{-3}) of mineral particles on the level at 1502 m. According to Goudie and Middleton, (2001) works, Schepanski *et al.*, (2007); Bou Karam *et al.*, (2008); Peter and Martin, (2010); Adams *et al.*, (2012), the convergence of two flows (South-western monsoon and North-eastern Harmattan) vertically causes the risings supported by a transport which increases the concentrations of the aerosols in troposphere. In the same topics, Pierre *et al.*, (2014), showed that aerosols can also be transported in convective clouds till higher troposphere (> 16 km) at a rate of six particles per cubic centimeter.

The temperature during the flight of November 5th, 2015 is decreasing from ground surface until 3900 m height altitude from which an inversion of temperature is organized. The relative humidity proved very weak this day at the surface of the ground until 2800 m height, and reached its maximum at the altitudes ranging between 3000 and 3900 m. The weather of this day indicated, at level 850 with 500 hPa, a Saharan cyclonic circulation, associated with temperature inversion between altitudes of 3900 and 4400 m which heat the mass of air at this level. These horizontal movements related to the strong intensities of the flow of Harmattan, involving the increase in concentration of mineral particles on the maximum height level, are confirmed by Masaru and Natalie (2005) works, which reveal that, aerosols are transferred onto the vertical by dry convection at the level of the thermal depressions or the level of the topographic depressions.

Local influence on the vertical distribution of the mineral aerosols

Let us recall here that the North of Chad is delimited mainly by two mountainous solid masses which are: the solid mass of Tibesti, located at the North-West and culminating to 3400 m and the solid mass of Ennedi, located at the North-East and having an altitude of 1400m. These two blocks of mountains are separated by jef-jef plateau whose average altitude rises to 500 m; he connects the desert of Libya and the central depression of Chad which channels Saharan cyclonic circulation coming from Libya penetrating Chad. According to Remini (2018) this corridor plays the role of Mega-Venturi. Cyclonic circulation coming from Libya circumvents the solid mass of Tibesti and the solid mass of Ennedi and divides winds (NW-SW) transporting mineral particles coming from Sudan; while penetrating in the corridor, the fluid nets are tightened, which increases the speed of the wind. This one is then increased right after having crossed the corridor between Tibesti and Ennedi.

This particularly high speed causes the depression of Bodélé, which is the origin of 20% of mineral dust in the world (Martin, 2005). This wind, charged with mineral particles, comes to run up against the obstacles in hollow of Lake Chad which is opposed to these currents, dividing this flow of wind into two branches on both sides. Indeed, this, endoeric water surface of 1350 km^2 is exposed to a very high temperature in dry season and a strong insulation during all the year what leads a consequent evaporation throughout the year. This phenomenon generates moisture above the Lake which lowers the temperature of the humid air. According to Remini, (2001) the variation in the temperature caused by the contact of the dry wind current (of high temperature) with the mass of fresh air above the Lake involves a variation of density and, consequently, the formation of a current density which will be deviated by this fictitious obstacle. This division of the transporting wind current of dust makes increases the speed of the wind on the level of the collars and makes it possible for the wind to even further raise mineral dust in the atmosphere until reaching the Atlantic Ocean. These phenomena are favorable to the increase in concentration of mineral particles to various altitudes which we studied.

This work concerned the analysis of the vertical natural aerosols distribution in Sahelian zone at the dates of June 18th, 2014 and November 5th, 2015. The result shows that the concentrations of aerosols particles vary in time and space. Concerning the flight of June 18th, 2014, the total concentration of mineral particles amounts to 254871.1598 cm^{-3} at 966 m; it reaches the maximum values from 517692.7408 cm^{-3} at 2612 m and minimal 29569.03576 cm^{-3} at 6849 m. This variation is due to atmospheric circulation and the thermal conditions which are at the origin of the vertical distribution of mineral particles, like the weather wind situation at the level of 925hPa which supported the rise of concentration of mineral particles at altitude 2612 m and until maximum latitude. Beyond this altitude, it decreases under the effect of atmospheric turbulences or the effect of scrubbing. On the other hand, for the flight of November 5th, 2015, the total concentration of aerosols particles decreases at the ground until the altitude of 3875 m and increases starting from this altitude until the latter, at the level of which it is 70 times higher than that raised at 971 m. The provided contributions of Saharan flow coming from Libya with a mean velocity of six meters a second, causing the temperature inversion, associated the hot mass starting from the altitude of 3880 m, thus create the increase in concentration of mineral particles to maximum altitude.

We also notice that the total concentration of particles of aerosols measured the 18th at altitude of 971 m is higher than the raised total concentration of aerosols particles the 5th at the same altitude. That of the 5th, at altitude of 4844 m, is more significant than the concentration of measured aerosol particles of the 18th at the same level. This variation of total concentration of particles is due to the local influence combined with atmospheric dynamics and thermal effects.

The distribution in number of aerosols particles for the two flights at the levels of altitudes considered is almost identical to all the levels; it is centered on the particles of diameters ranging between 0.1 and 0.6 µm, and low in coarse mode. The distributions on surface and volume are strongly centered on the particles of diameters ranging between 0.14 and 1.2 µm. The majority of the concentrations of mineral particles measured during these two flights are largely dominated by fine particles, in mode of accumulation, in detriment of large particles or coarse mode.

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