International Journal of Physical Sciences

Volume 13 Number 2 30 January , 2018
ISSN 1992-1950

Academic Journals

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DOI: 10.5897/IJPS2017.4703
Article Number: 81CDF5D55935
ISSN 1992 - 1950

http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

High-latitude thermospheric zonal winds during low solar activity period

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Received 2 December, 2017; Accepted 18 January, 2018

Changes resulting from the cyclical nature of the sun's energy output result to variations in thermosphere-ionosphere system parameters. The prolonged low solar activity period of solar cycle 23 provides an opportunity to study the thermosphere-ionosphere system parameters when the sun was at its ground state. The CHAMP satellite has provided wind data that can be used for investigation of neutral thermospheric parameters such as zonal winds and density. Using zonal wind data from 2006 to 2008 generated from CHAMP accelerometer readings using an iterative algorithm, the diurnal variation of averaged zonal thermospheric winds in the high latitudes (70 - 80°N) has been investigated. In the analysis we grouped the data into four seasons; the March and September equinoxes, and the June and December solstices. The wind data is binned into local time bins and averaged to find the hourly mean speeds. The results reveal maximum eastward and westward wind speeds going above 150 m/s for each of the seasons considered. Of particular interest is the observation that despite the expected complex behavior resulting from the expected magnetospheric inputs, the diurnal patterns are similar to those obtained in the mid-latitudes in an earlier study with data from this algorithm. Due to likely errors arising from the longitudinal effects of mixing composite solar times, there is need for simultaneous measurements in the high latitudes.

Key words: CHAMP satellite, high latitude, solar activity, thermosphere.

INTRODUCTION

The thermosphere is the first layer of the earth's atmosphere that receives the sun's ultraviolet (UV) and extreme ultraviolet (EUV) radiations. These radiations ionize the neutral molecules that make up the thermosphere forming an embedded ionized region; the ionosphere. The thermosphere is coupled to the ionosphere by the interactions between the ionized and neutral species. A thorough understanding of thermospheric variability is important in establishing the state of the earth's upper atmosphere. Thermospheric perturbations can arise from external forcing sources to which the thermosphere is coupled. The earth's thermosphere-ionosphere system is coupled from above by interactions with incoming solar radiations and magnetospheric electric fields, and coupled to layers below by tides, gravity and planetary waves as shown in

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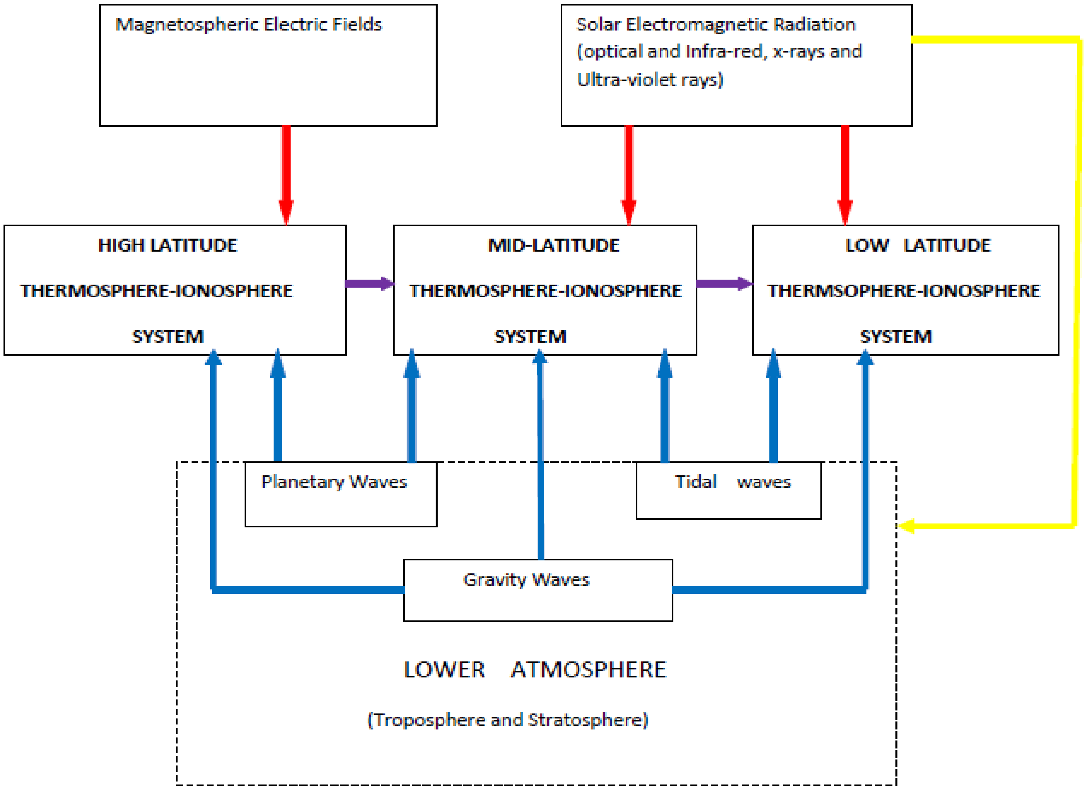

Figure 1. Thermosphere-Ionospheric interactions.

Figure 1.

Thermospheric dynamics varies with solar cycle, solar flux, geomagnetic activity and change in seasons. The high latitude of the earth's thermosphere is the site of interesting phenomena. Charged particles coming from the sun are funneled into the earth's upper atmosphere by the earth's geomagnetic field. Thermodynamic and electrodynamic processes influence thermospheric wind behavior in high latitudes as there exists strong coupling between neutral particles and the plasma of the ionosphere in the auroral regions of the earth's atmosphere (Lühr and Marker, 2013). Effects of solar disturbances are first observed in the high latitudes before onward propagation through mid to equatorial latitudes. The wind field and strength of earth's high latitude is significantly modified by geomagnetic activity (Smith et al., 1988). It is the neutral wind parameter that has not received the much needed attention in regard to the many issues pertaining to the forecasting of ionospheric weather (Meriwether, 2006).

Information on thermospheric composition and prevailing winds has been obtained using data from Fabry-Perot Inteferometers, Incoherent scatter radars and satellites (e.g. Emery et al., 1999; Thayer et al., 1987; Killeen et al., 1988; Aruliah et al., 1996; Fejer et al., 2000; Emmert et al., 2002; Liu et al., 2006; Häusler et al., 2007; Sutton et al., 2005; Sivla and McCreadie, 2014). The interferometer technique has its limitation arising from uncertainty in emission height, restriction to dark hours, clear sky and reduced moon phases (Lühr et al., 2007). During periods of disturbed conditions the physical assumptions used by the radar technique break down (Liu et al., 2006). Insufficient data has hampered the investigation of these parameters in the earth's upper thermosphere. Satellite observations of thermospheric winds have previously been carried out using data from the Dynamic explorer 2 satellites (e.g. Thayer et al., 1987). The investigations by Thayer al. (1987) were not detailed due to sparse sampling from the short-lived DE-2 mission in space (Lühr et al., 2011). Large density and wind data sets that can be used for upper thermospheric research have been generated from accelerometers flown in CHAMP and GRACE satellites. Investigations of thermospheric wind behaviour using data from accelerometer readings on board CHAMP satellite have been reported (e.g. Liu et al., 2006; Häusler et al., 2007; Förster et al., 2008; Sutton et al., 2005; Lühr et al., 2011; Sivla and McCreadie, 2014).

Using wind data derived from CHAMP satellite accelerometer using an iterative algorithm, Sivla and McCreadie (2014) successfully investigated seasonal diurnal thermospheric zonal wind behavior in the mid-latitudes during equinoxes. This iterative algorithm derived by Doornbos et al. (2010) is more reliable in that it avoids the restrictions and sources of error common in the direct algorithm. In this study we are extending our investigations to diurnal wind behavior in the north hemisphere high latitude (70 - 80°N) during the extreme low solar activity period (2006-2008) of solar cycle 23. The extended period of low solar activity in solar cycle 23 provides an opportunity to explore the diurnal behavior of the upper thermospheric parameters when the sun was at its ground state. A study of the earth's upper thermosphere during periods of low solar activity can go a long way in helping us understand contributions from lower layers of earth's atmosphere to variations in thermospheric parameters.

The first high latitude thermospheric wind distribution investigation using data from CHAMP was carried out by Lühr et al. (2007). In their analysis of 131 days data centered on the June solstice of 2003 in the Polar Regions at altitudes of about 400 km, seasonal differences were observed to be significant in the dayside auroral zone than on the nightside. Their findings also revealed that zonal winds at sub-auroral latitudes from noon to dawn and dusk are very low during winter conditions.

METHODOLOGY

Data sources and selection

The global Kp index is the mean value of the disturbance levels observed at 13 selected mid-latitude stations during the three-hour time intervals. According to a quasi-logarithmic scale it covers the range from 0 to 9. The geomagnetic planetary index, Ap, gives a measure of the level of geomagnetic activity over the entire Earth, for a given day. It is the daily average of the 3-hourly ap index, derived from the 3-hourly Kp values.

The geomagnetic indices are retrieved from the World data Centre (WDC) for Geomagnetism, Kyoto (wdc.kugi.kyoto-u.ac.jp/wdc/sec3.html) whereas the absolute solar flux at 10.7 cm is obtained from National Geophysical Data Centre (http://www.ngdc.noaa.gov).

CHAMP was in a polar orbit and took 130 days to cover all local times and latitudes (Liu et al., 2006). The crossings of the latitude bands during the ascending and descending motions took place at different longitudes due the earth's rotation. The relative position of the sun and the polar orbiting satellite changes little during the day so satellite measurements at the same geographic latitude although at different longitudes are within a small range of local time (Zhang and Shepherd, 2002). The tilting of the satellite orbit and latitudes establish the real local solar time coverage at particular geographic latitude.

The zonal wind used in this study is from the data derived by Doornbos et al. (2010) using an iterative algorithm. In this procedure, the modelled aerodynamic force is varied until it coincides with the observed acceleration (Ritter et al., 2010). Data at high latitudes from 70 - 80° north was selected for this study. The data covers the solar minimum period from 1st January, 2006 to 31st December, 2008, a total of 1096 days. The earth's thermosphere has significant seasonal variations, thus the need to group the wind into appropriate seasons; the March equinox (February, March, April), the September equinox (August, September, October), the June solstice (May, June, July) and December solstice (November, December, January). This period spanning over three years provides enough data for detecting the diurnal variations at the different seasons. In general, solar activity may be different between March equinox and September equinox of a year (Chen et al., 2012), thus the need to separate the equinox seasons.

Figure 2 shows the distribution of the wind speeds within the selected latitude band. The selected data is then binned into local time bins and averaged to find the mean speeds. The number of measurements in each local time bin each of the seasons is displayed in Figure 3.

RESULTS

Figure 4 shows the Kp index, sunspot number, Ap index, geomagnetic and solar flux proxy variation during the period of study. The solar flux values are generally less than 100 s.f.u.. This period was characterized by very low Kp index values.

The standard deviations in Figure 5 show the variability of the averaged winds. These deviations represented by the vertical bars are deviations of the winds for each one hour interval. The March and September equinox averaged winds show large standard deviations occurring in the late afternoon from about 1400 LT to 2100 LT. The large morning deviations during equinoxes are observed from 0200 LT to about 0800 LT. The deviation variation pattern is not well ordered during the June solstice. A large deviation during the June solstice is observed at 1200 LT and 1300 LT, with the largest occurring at 2300 LT. The December deviation pattern is similar to the March variation.

Equinox variation

During the March equinox season, maximum westward wind speeds going up to 260 m/s are observed at 0700 LT while eastward speeds of 145 m/s occur at 2000 LT. The west east switch in wind direction is observed to occur at about 1500 LT while east west switch is observed at about 2330 LT.

The September equinox maximum westward and eastward speeds going above 250 and 200 m/s are observed at 0800 and 2000 LT, respectively. Change in wind direction from west to east occurred at about 1430 LT, while the change from east to west is observed at about 2330 LT.

Solstice variation

In the June solstice period, switch in wind direction from west to east is observed at 1600 LT, while the westward switch is observed at 2230 LT. Maximum westward speeds of about 295 m/s occurred at 0600 LT while maximum eastward speeds going close to 90 m/s is occurred at 1900 LT.

For the December solstice season east to west switch was observed at about 0130 LT while change in direction

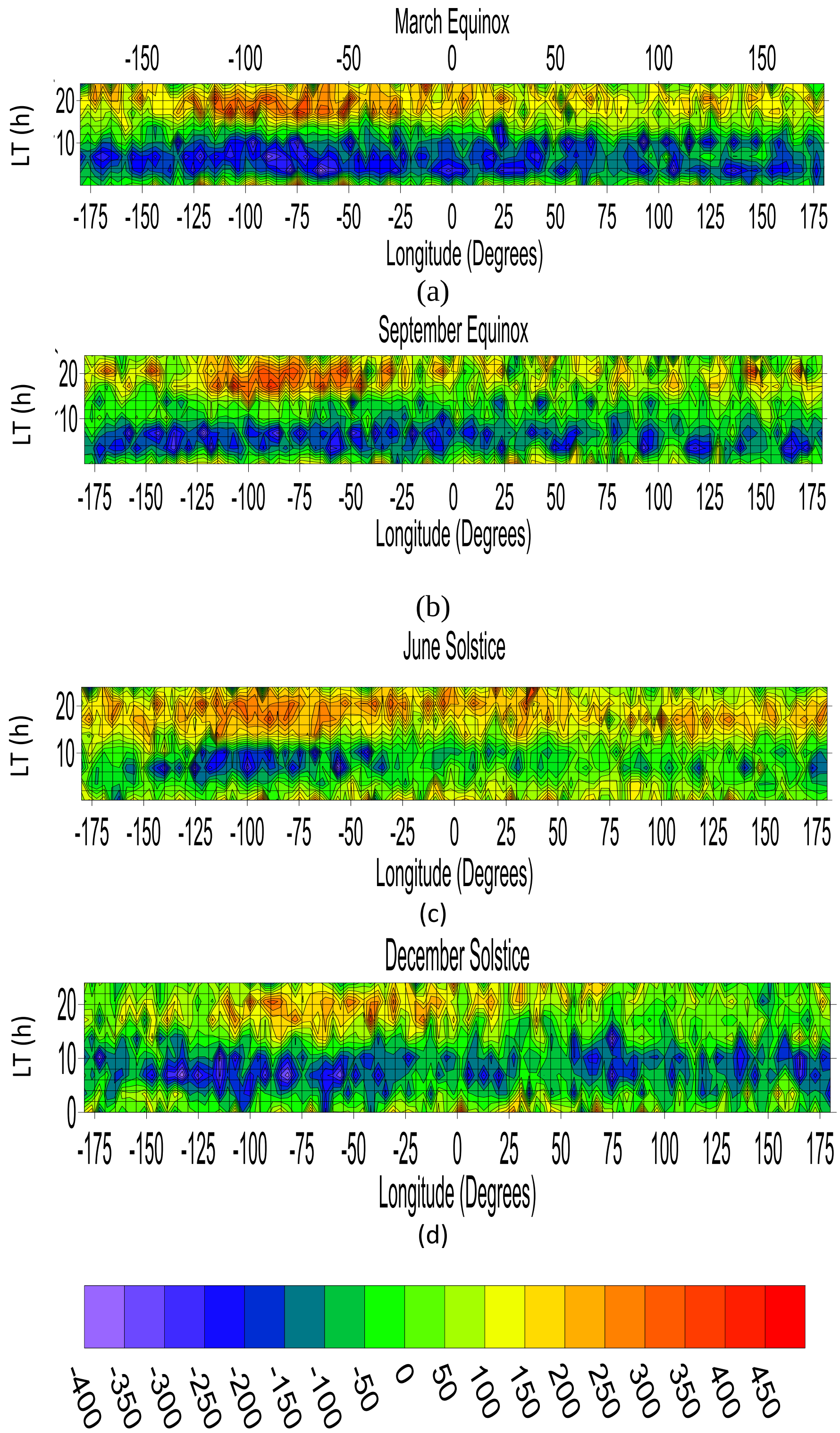

Figure 2. Distribution of the zonal wind speeds within the selected latitude band for the different seasons (a) March Equinox (b) September Equinox (c) June Solstice and (d) December Solstice.

from west to east was observed at 1400 LT. Maximum westward speeds of about 240 m/s occurred at 0800 LT while maximum eastward speeds of about 160 m/s occurred at 1900 LT.

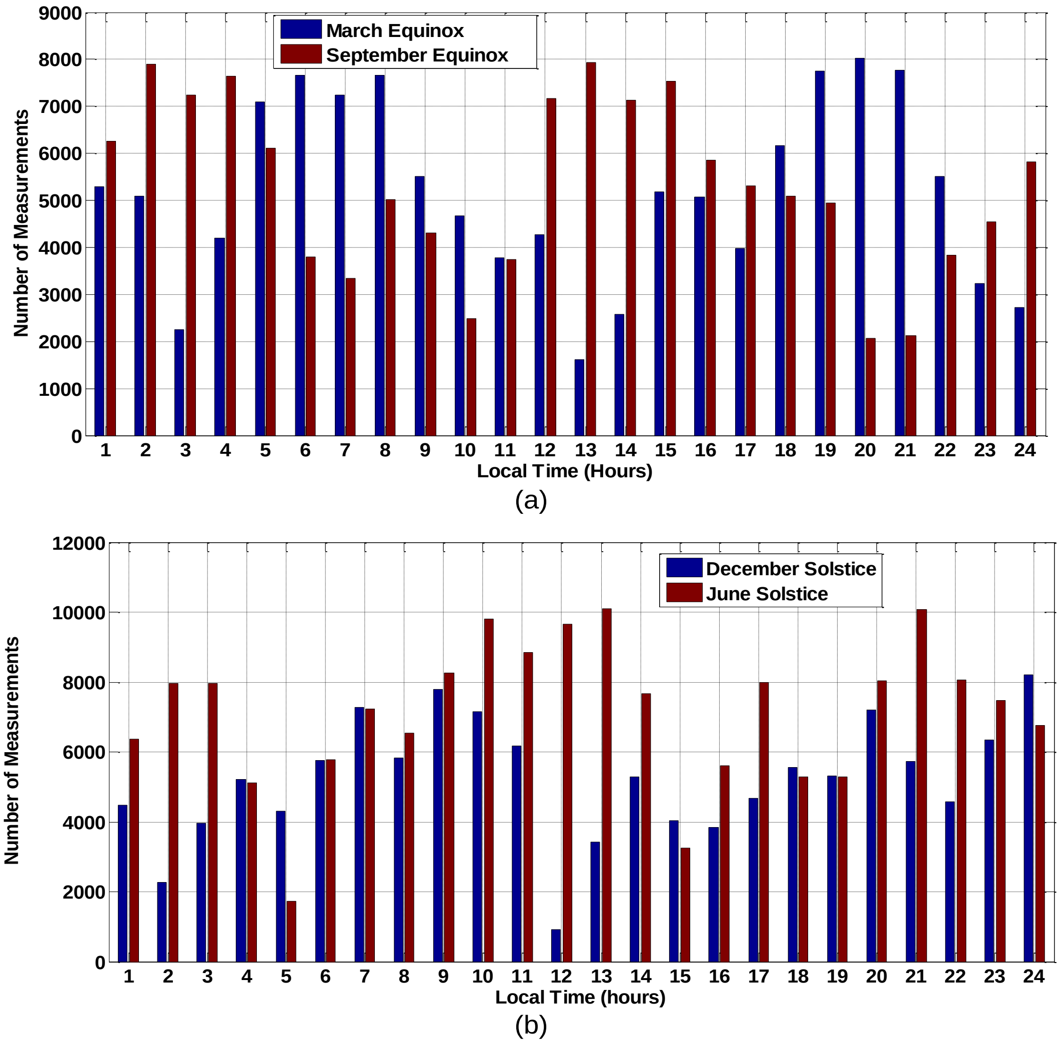

Figure 3. Number of measurements in each local time bin for (a) equinox seasons (b) solstice seasons.

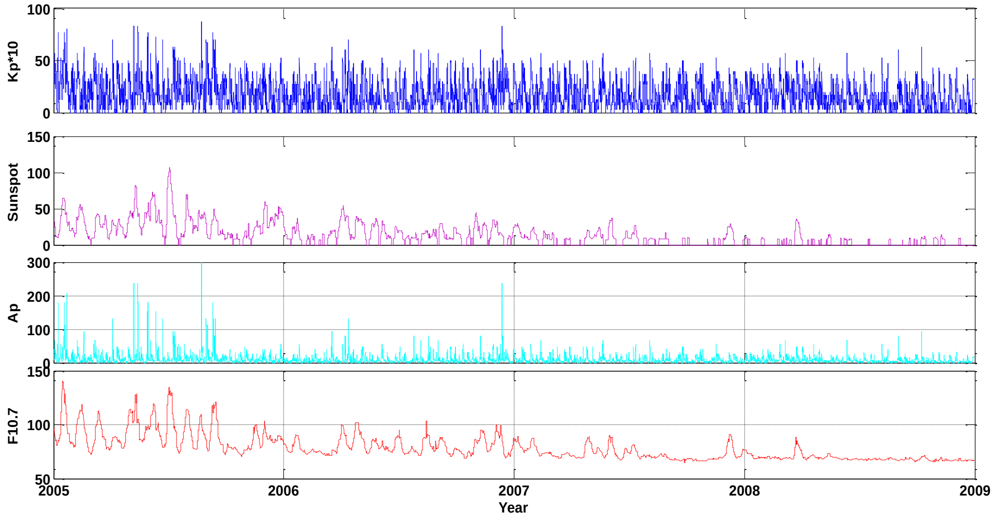

Figure 4. Variations of solar flux index, sunspot number, Ap and Kp geomagnetic activity indices.

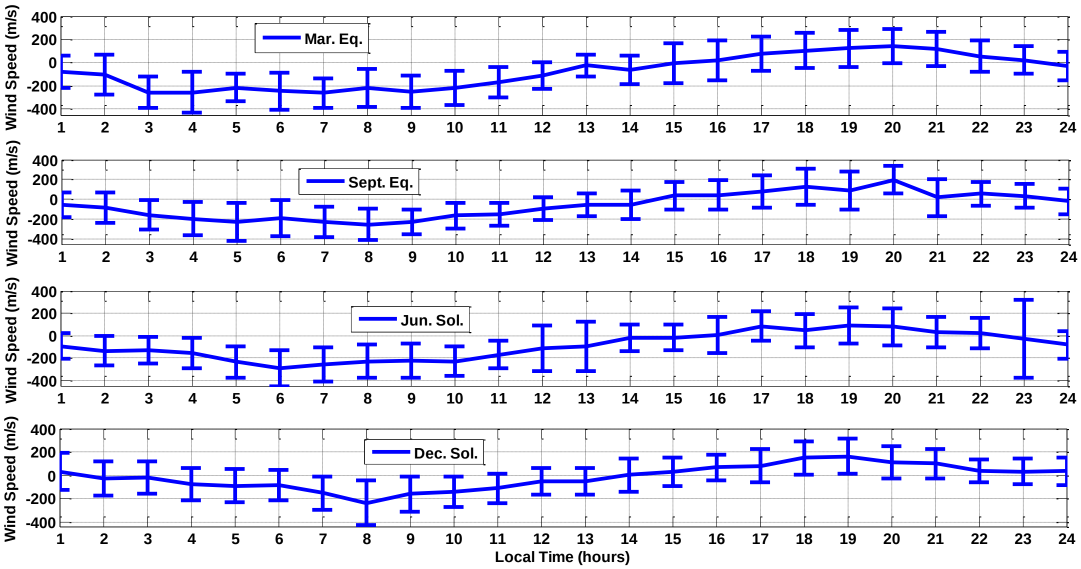

Figure 5. Diurnal zonal wind variation for the different seasons with error bars.

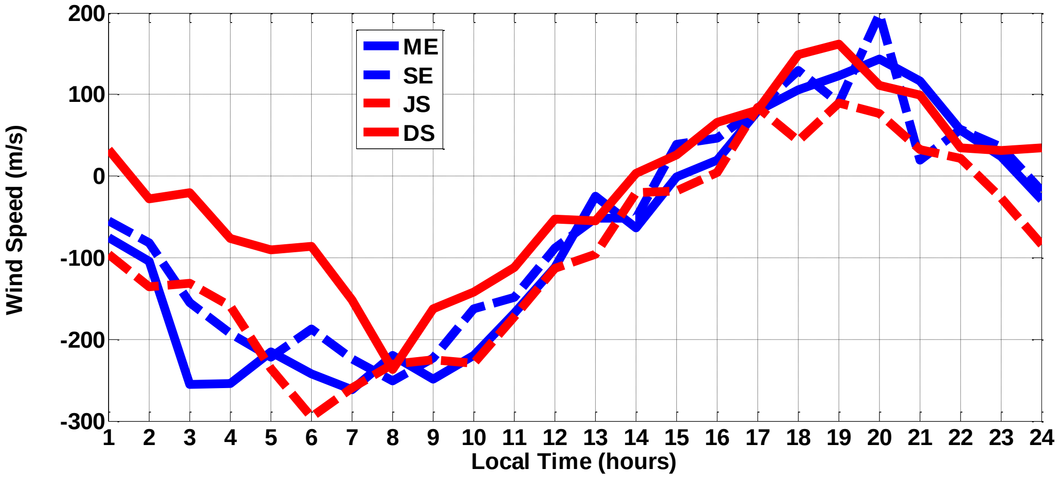

Figure 6. Comparison of the seasonal diurnal variations.

DISCUSSION

During period of extreme low solar activity the earth's ionosphere-thermosphere system is at its ground state. During this period of solar minimum, the high latitude thermospheric zonal winds may not be coupled efficiently to the pattern of ion drift movement leading to poor response to momentum forcing (Smith et al., 1988). The geomagnetic field geometry and the sun's activity have a strong influence on the processes taking place in the earth's high–latitude thermosphere (Lühr and Marker, 2013). The principal driving forces in high latitude upper themospheric zonal winds are the pressure gradient from solar heating and ion drag from ion-neutral collisions.

The December solstice averaged winds lag behind the other seasons in the westward direction and generally lead the June solstice averaged winds during the morning hours as can be seen in Figure 6. On the dawn side plasma flow is aligned with the cross-polar cap wind at high latitudes (Lühr and Marker, 2013). In the northern hemisphere, the December solstice normally experience a shorter period of sunlight due to the position of the sun, leading to less contributions from the pressure gradient force to daytime wind flow. The June solstice averaged winds generally lead the other season's averaged winds in the westward direction except the significant departure observed from 0200 to 0500 LT. They lag behind the other seasons in the eastward direction. The relative

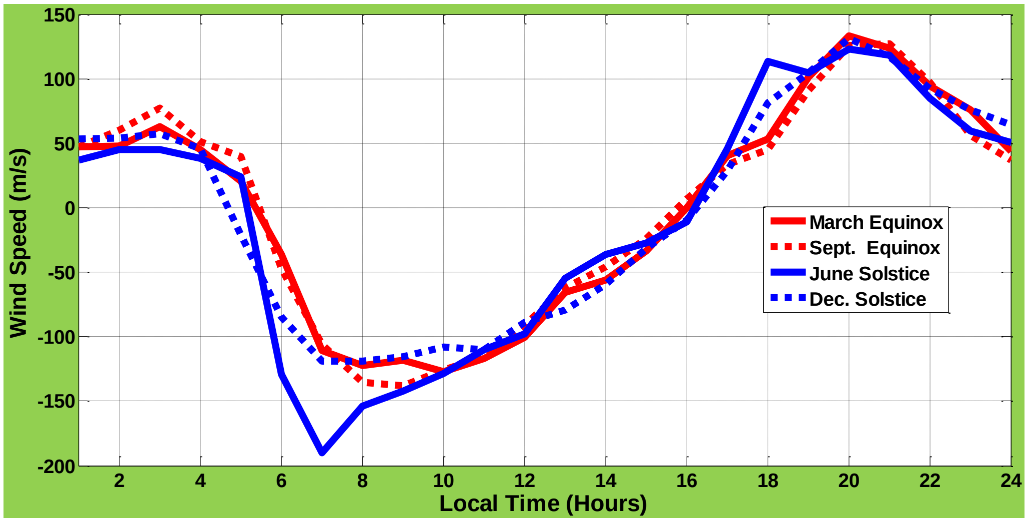

Figure 7. Zonal wind variation in the equatorial latitudes.

higher plasma density during the June solstice, March and September equinoxes may account for the relative high speeds observed in the morning. But again this does not explain the seemingly insignificant difference between the June and Equinox early morning diurnal wind variations. The eastward maximum speeds compare favorably well with those from the equatorial latitudes as can be observed in Figure 7.

Solar heating may not be principal driving force of the high latitude winds, as equinoctial asymmetry is observed generally in the wind behavior. According to Aruliah et al. (1996), the asymmetry in high latitude winds originates from a seasonal and diurnal variation in the in the cross-polar –cap electric field generated by an equivalent variation in the inclination of the geomagnetic pole with respect to the average interplanetary magnetic field orientation. This may be a possible explanation as wind variation in the equatorial latitudes using the same data sets during the same period show less asymmetry as can be seen in Figure 7.

Compared to averaged wind variation in the equatorial latitudes the change in wind direction does not take place simultaneously. The switch in direction in the high latitudes which occurs generally takes one to two hours earlier in the westward to eastward direction. The westward switch takes place four to six hours earlier than in the equatorial latitudes as can be seen in Figures 6 and 7. As explained by Lühr et al. (2011), the observed dependence of zonal wind change in direction can be partly attributed to coriolis forces which cause earlier reversals at high latitudes. Compared to equatorial zonal wind variation, our high latitude winds showed high maximum speeds during the morning hours. Maximum westward direction speeds going above 200 m/s are observed as compared to maximum westward speeds of less than 150 m/s generally observed in the equatorial latitudes. The high speeds observed in the high latitude may be attributed to the prevailing effect of the electrodynamic and hydrodynamic forces. The pressure gradient force is the principal driving force of low latitude upper thermospheric zonal winds.

Conclusion

Using wind data from CHAMP accelerometer readings for three year data from 2006 to 2009, we have investigated diurnal wind variation in the north hemisphere high latitude during a period of extreme low solar activity. The main feature noticed from our analysis is the significant contributions from solar variation and ion drag to the wind patterns during this period of extreme low solar activity.

Our analysis from the plots have shown

(1) December solstice averaged winds lag other seasons in the westward direction.
(2) some degree of asymmetry in equinox averaged winds. The asymmetry is observed to be more pronounced from midnight to morning hours.
(3) reversals in averaged speed wind direction occurring earlier than in averaged wind speeds in the equatorial latitudes.
(4) fast zonal flows at dawn. Maximum averaged winds occur in the westward direction during the day and generally larger in magnitude than eastward maximum speeds occurring in the evening.

Generally, our investigations have revealed that at this period of low extreme solar minimum, the upper thermospheric longitudinally averaged zonal winds have shown some degree of coupling to the moving ion drift patterns. Considering the coupling between neutral and plasma motions, the averaging of zonal wind speeds over altitudes between 200 km and 700 km could cause smearing of reversal time at different altitudes (Liu et al., 2006), as reversal time of zonal plasma drift varies within this range (Fejer et al., 1981). Thus there is need for observations at a constant height. Satellite coverage of the upper thermospheric parameters only provide LT constructs of diurnal variations combined together over long series of days, and such samples provide global averages where composite solar time changes are mixed with the poorly known "longitude effects" (Sambou et al., 1998). Thus the needs for simultaneous wind measurements.

We recommend that further studies be carried out in geomagnetic coordinates in the north and south hemisphere using data from this algorithm. Due to the influence of electrodynamic forces there is need to present high latitude winds in geomagnetic coordinates.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENT

The authors thank Doornbos for making his data available for this study.

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Vol. 13(2), pp. 16-23, 30 January, 2018
DOI: 10.5897/IJPS2017.4701
Article Number: F5F092D55937
ISSN 1992 - 1950

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Study of the performance of a system for dry cleaning dust deposited on the surface of solar photovoltaic panels

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Received 20 November, 2017; Accepted 22 January, 2018

This study was carried out at the International Center for Training and Research in Solar Energy (CIFRES) and its main purpose was to study the performance of a solar module cleaning system. To handle this work, a measuring platform consisting of two polycrystalline (pc-Si) PV modules was designed. The modules were connected to a waterless cleaning system on the surface of the solar panels. The platform also contained a temperature sensor on the surface of the module, a pyranometer, shunt resistors (for current measurement), and an acquisition unit. This platform was exposed under real conditions and measurements of the parameters were taken in increments of ten seconds. Only one of the two modules was cleaned daily, and an evaluation of the degradation rate of the short-circuit current (I_{sc}) of the dust module with respect to the cleaned module was carried out. After one month of exposure, the analysis of the results showed a degradation rate of 17.13% of the short circuit current (I_{sc}) of the dirty module compared to the clean module. Compared to the initial conditions under the standard test conditions, a degradation of 10.16 and 24.09%, respectively for the clean module and the dirty module was obtained. This work also showed that a polynomial relation exists between the degradation rate and the dust deposition density with a coefficient of determination of 0.9933.

Key words: Photovoltaic modules, dust, short-circuit current, impact, automatic cleaning without water, degradation.

INTRODUCTION

The development of renewable energy is currently a political requirement. In the short term, an energy deficit from known resources is not predictable, but long-term scenarios already exist that require an overall reduction in the production of pollutants, particularly CO_2. These problems have led to an unbridled race towards new

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forms of energy. The development of renewable energies in Senegal, in this context is a matter of securing the energy supply and the reduction of dependence on imports of fossil fuels. However, the use of these forms of energy has long been marginal, in particular, that of solar photovoltaic whose capacity installed in the year 2000 was 850 KWc. The total installed capacity reached 2.3 MWc in 2005 and was close to 4 MWc in 2010 (0.7% of the total installed capacity) (PANER, 2015). With the advent of a new political alternation in 2012, the implementation of the Emergent Senegal Plan (PSE) has been witnessed, which aims at the country development by 2035. This plan targets the energy sector as an economic development pillar and the reduction of social and territorial inequalities. For example, there has been a proliferation of photovoltaic solar power plants (Bokhole 20 MW, Malicounda 20 MW, Sakal 30 MW and several ongoing projects to validate), which positions the country as a leader in the field at the sub-regional level. However, the development of solar photovoltaic field is encountering a number of difficulties. In terms of operation, solar panels need to be exposed to the open air. Consequently, dust, bird droppings, marine spray, pollen and of course pollution are all external phenomena that can gradually be deposited on the surface of the solar panels. In time, this accumulation of dirt and dust form a thin layer on the photovoltaic cells. This layer, depending on its thickness, can hide the exposure to the sun and thus cause a reduction in the current and voltage generated by the solar panels, greatly reducing the performance of solar panels. This phenomenon is further amplified because the area focused of focus is located in the Sahelian zone characterized by periodic dust storms.

Analysis of the AERONET data at four 4 stations in the Sahel (Dakar, Agoufou, Banizoumbou and Ouagadougou) shows that the Sahel is affected by dust throughout the year (Drame et al., 2013). These dust deposits affect solar photovoltaic installations by causing disturbances in the distribution of energy. Ndiaye et al. (2013) were able to show a maximum power degradation of 18 and 78% for polycrystalline (pc-Si) and monocrystalline (mc-Si), respectively. The phenomenon of dust deposition from surrounding environment on the glazing of PV panels is a major constraint in the cost of maintenance and operating (M & O) for solar plants (Lopez-Garcia et al., 2016). Currently, the panels are cleaned using laborers which is expensive, uses significant amounts of water resources, and often results in mistakes that damage the panels (Al Shehri et al., 2014).

Dry cleaning is one such technology, aiming to mitigate the impact of dust mitigation by removing deposited dust. This solution offers promises in mitigating the impact, but it is important to recognize that synergistic technologies that could actually reduce dust accumulation are also an important topic of research and development (Al Shehri et al., 2017). Figure 1 shows the various methods that can be used to clean the surface of solar panels including natural cleaning, automatic cleaning, manual cleaning, and passive surface cleaning (Sayyah et al., 2014). This paper work presents the system used to clean the solar panels as well as the methodological approach. The degradation over time of the short-circuit current (I_{sc}) of the two modules is evaluated as well as the evolution of the difference between the short-circuit current (I_{sc}) of the two modules as a function of time. The conclusion will deal with the evolution of degradation as a function of the amount of dust on the surface of the modules.

MATERIALS AND METHODS

Dust is generally a term used for any particulate matter that is less than 500 μm in diameter, which compares the size of an optical fiber used for communication or 10 times the diameter of a hair strand (Field et al., 2015). It greatly affects the operation of solar installations. To mitigate this effect, cleaning methods are increasingly developed in order to limit the losses due to dust and dirt. Figures 2a (Ecoppia, 2014) and 2b (Häberlin et al., 2012) show dry cleaning via robots and FWG700 Panel washer, respectively.

Presentation of the system

The study was performed in the laboratory of the International Center for Training and Research in Solar Energy (CIFRES) located at the Polytechnic High School of Cheikh Anta Diop University in Dakar. An experimental platform (Figure 3) was installed on the roof of the building that houses the CIFRES laboratory. It includes sensors to measure the electrical parameters of the photovoltaic modules and environmental parameters, a datalogger and the automatic cleaning system. The platform consists of the following:

(i) Two identical polycrystalline (pc-Si) solar modules inclined at 15° with a power rating of 150 W each, mounted on an aluminum support. Each of the two panels is connected to a waterless cleaning system.
(ii) Shunt resistors to measure the short-circuit current (I_{sc}) of the modules.
(iii) 12-volt AGM battery that powers the cleaning system motor.
(iv) Pyranometer to evaluate the solar radiation at the surface of the modules.
(iv) Hygro-thermometer for measurement of humidity and ambient temperature.
(v) Wind vane and an anemometer to measure the direction and speed of the wind.
(vi) Type K thermocouples to measure the temperature of the modules.

The technical specifications of the modules are given in Table 1. The waterless cleaning system consists of several components including a cleaning brush (wiper blade), cables, DC 12 V motor, scorers to determine the end of travel etc. Data storage is provided in 10 s increments using a Campbell scientific CR800 datalogger.

Presentation of the experimental protocol

The data used in this study were collected in May, 2017. Daily cleaning was carried out on one of the modules while the other was left without any cleaning action during the whole duration of the experiment. The experimental device consisted of a 12 V DC motor

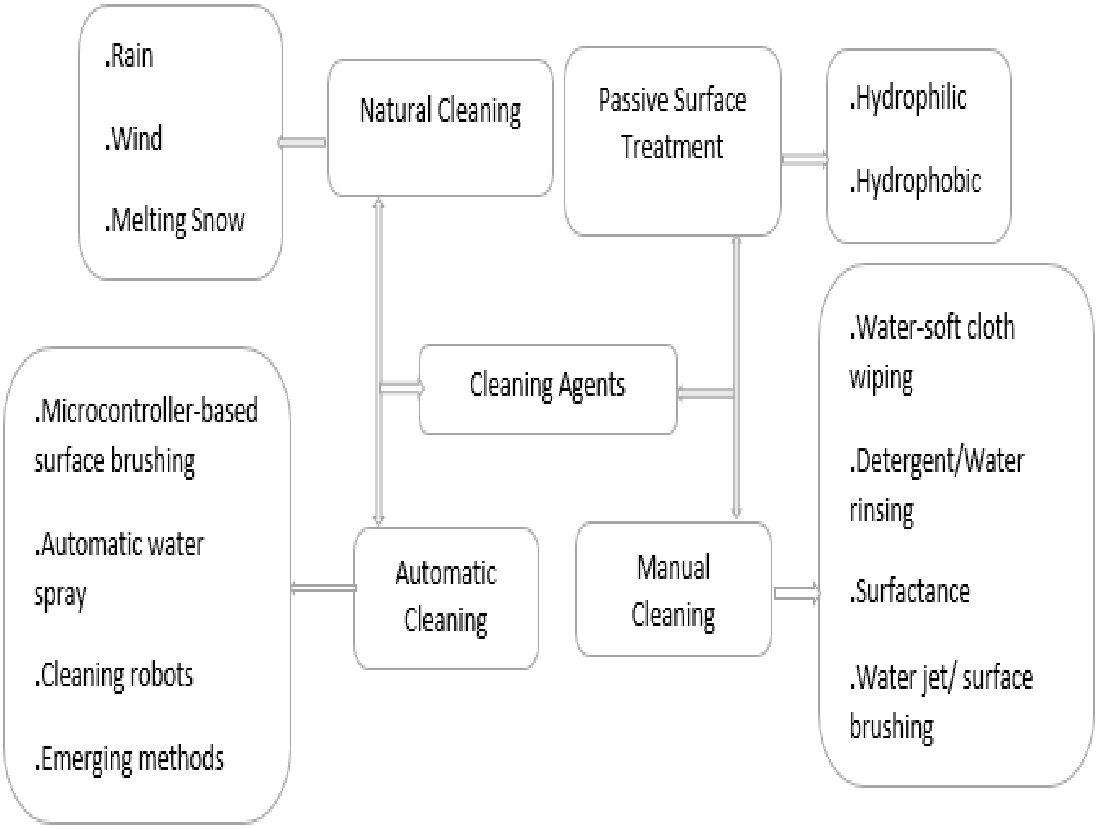

Figure 1. Different cleaning methods for removing dust from solar collectors (Sayyah et al., 2014).

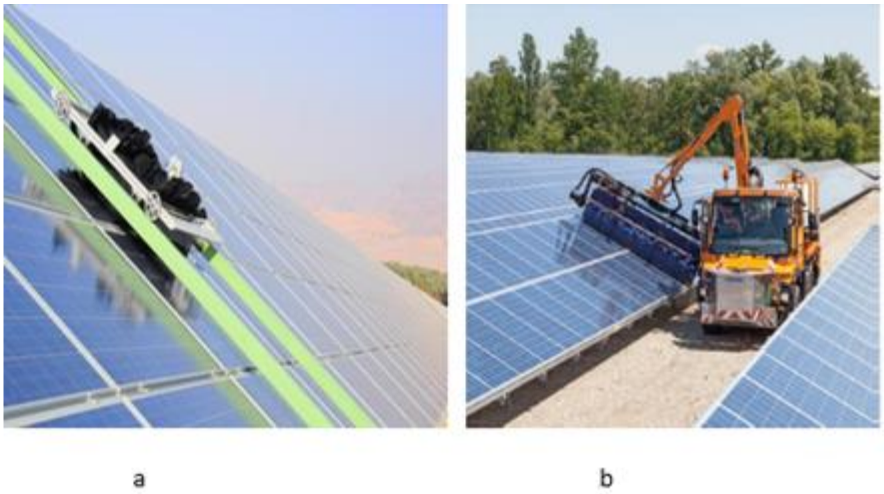

Figure 2. (a) Waterless cleaning of solar panels via robot and b) FWG panel washer.

which drives a brush placed horizontally on the surface of the PV module. The motor is controlled by a microcontroller via an L298 driver which ensures power supply to the motor in both directions of travel. The control signals are supplied by the microcontroller and an end stop detects the moment of reversal of the polarity. The Thomson L298 circuit is an interface reference for DC motors and step by step motors (UIT Nime, 2010). The L298 is a double H-bridge with logic interface that can control two DC motors. These low voltage characteristics, less than 12 V, give it an unquestionable place in integrated power circuits. The H-bridge is an electronic structure used to control the polarity across a receiver. It is composed of four switching elements generally arranged

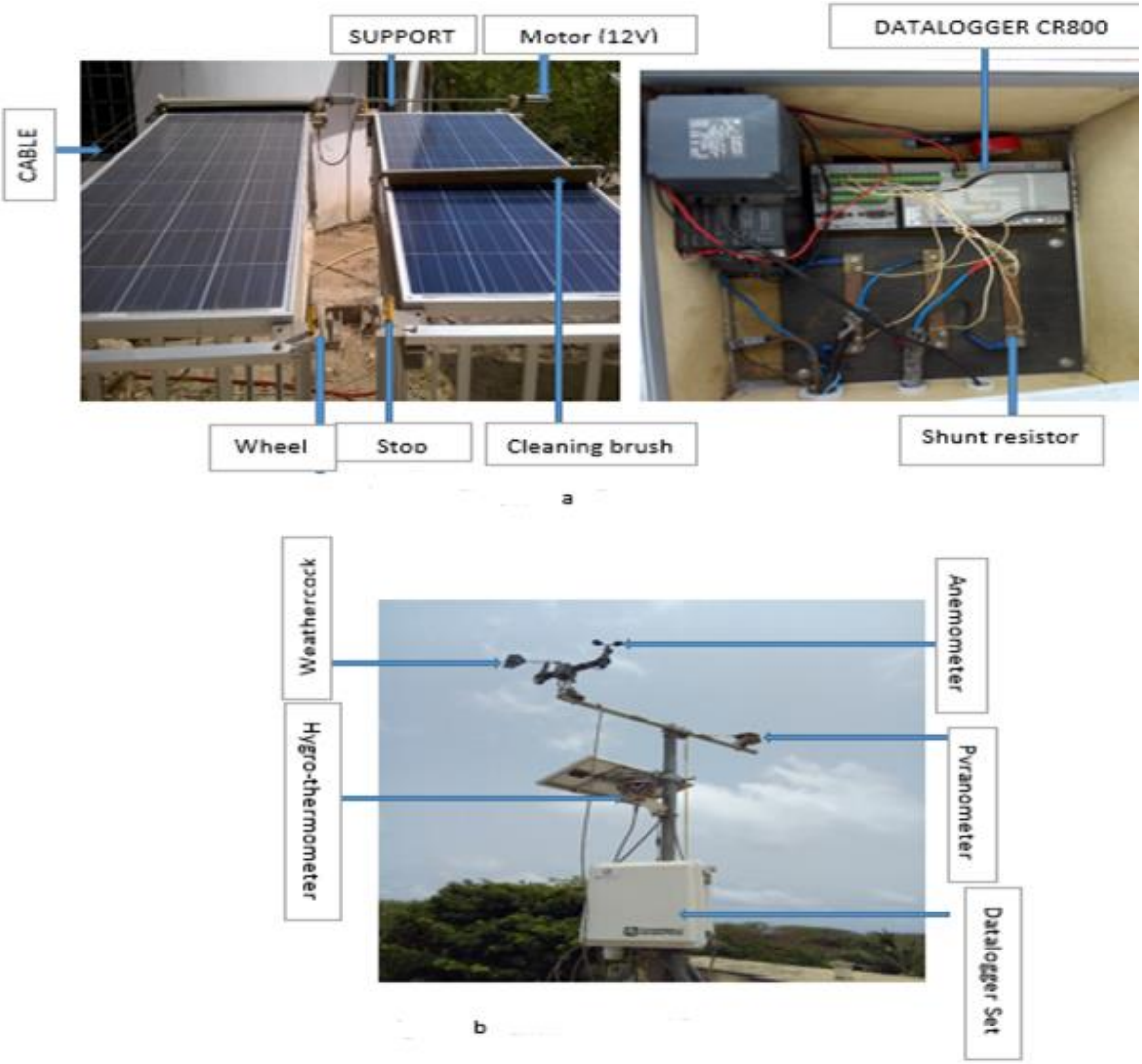

Figure 3. a) Electrical parameters platform and b) environmental parameters platform.

Table 1. Technical specification of photovoltaic modules.

Parameter	Values	Units
P_{max}	150	Watts
(I_{sc})	8.57	Amps
V_{co}	22.5	Volts
I_{max}	8.24	Amps
V_{max}	18.2	Volts
S	99	Cm²
Number of cells (*N*)	36	-
(FF)	0.78	-

schematically in a form of the letter H, hence the name. The switches may be relays, transistors, or other switching elements depending on the intended application. It reverses the direction of rotation of a DC motor. Whether starting or not, the control system depends on the detection voltage. Thus, 10 s after the system detects a voltage, the cleaning is activated. A cleaning cycle is

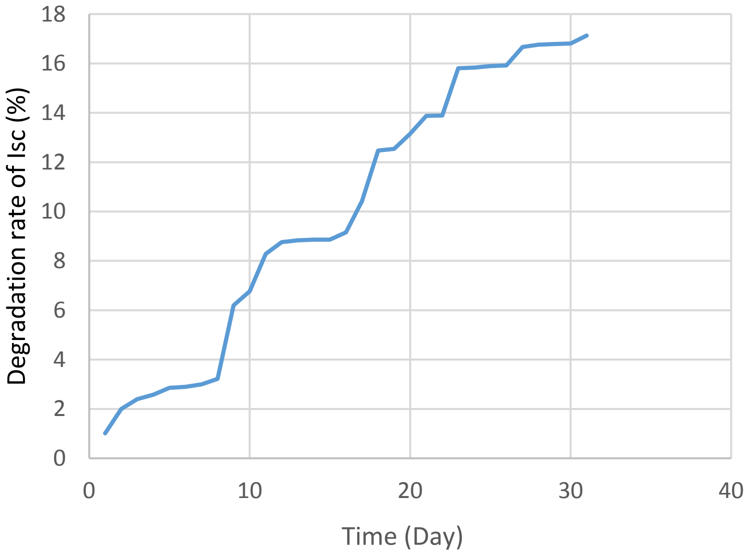

Figure 4. Evolution of the degradation rate over time.

composed of two backward and forward motion periods. When the system starts cleaning and touches the end of stroke after starting (increase of current up to about 2A), it stops because the high resistance causes a rapid increase in motor current. The use of the month of May data was motivated by the fact that this month presents interesting characteristics with strong sunshine, absence of cloud cover and a total absence of rain (Le Sénégal en Mai, 2017). The approach consists of making a comparative study between the short-circuit current of the cleaned module and that of the dirty module. After collecting data at the datalogger level, the measurements were standardized in order to eliminate temperature and sunlight effect according to the model of Equation 1 (Ndiaye et al., 2013):

$$I_{cc,s} = I_{cc;m}\left(\frac{1000}{E}\right) + \alpha\, S\left(T_{ref} - T_{mod}\right) \qquad (1)$$

With $I_{cc,s}$ equal to the standardized short-circuit current (I_{sc}), $I_{cc,m}$ as the measured short-circuit current (I_{sc}), T_{ref} representing the reference temperature, T_{mod} the module temperature, α is the current temperature coefficient, and S is the surface of the modules.

After this step, the rate of degradation of the short-circuit current of the two modules was calculated with respect to their initial conditions using Equation 2 (Ndiaye et al., 2013).

$$\Delta I_{cc} = \frac{I_{cci} - I_{cc,stc}}{I_{cci}} * 100 \qquad (2)$$

With ΔI_{cc} as the rate of degradation of the short-circuit current (I_{sc}) of the modules, I_{cci} which represents the initial short-circuit current and $I_{cc,stc}$ as the one under standard conditions.

According to Paudyal and Shakya (2016) and Al-Hasan and Ghoneim (2005), the degradation evolution is a function of the amount of dust deposition over time. This amount of deposits depends on the exposure site of the panels. Thus, the focus was on the study of the amount of dust that is deposited on the surface of the modules in our work. To do this, glasses with a surface area of 10 cm² and a weight of 96 g are positioned at the same level as the solar panels to collect dust. After a week of deposit, the glasses are weighed using a very high electronic precision balance (1 mg). The weight of the dust is equal to the difference between the weight of the clean glass and that of the glass covered with dust.

RESULTS AND DISCUSSION

Figure 4 represents the evolution of the degradation rate of the dirty module with respect to the specific module over time. The measurements were carried out under the real conditions. It was found that degradation increases over time due to dust accumulation on the surface of the dirty panel. Thus, after one month of exposure, a maximum degradation of 17.13% of the dirty module relative to the clean module was noted. The effect of dust on the long-term performance degradation of PV modules, which had been left without any cleaning procedure, was investigated in a recent (Tanesab et al., 2015) study in Perth, Australia. Although the degradation was mostly due to non-dust related factors such as corrosion, a significant contribution of 16 to 29% was recorded due to dust with a fairly uniform impact on the performance degradation of PV technologies. This degradation of the short circuit current (I_{sc}) of the dirty module with respect to the clean module shows the importance of cleaning the surface of the solar modules.

Figure 5 shows the degradation rates over time of the two modules with respect to their initial values. The short-circuit currents (I_{sc}) collected at the platform was standardized in order to eliminate the effect of sunshine and temperature and was compared to the initial short-circuit current (I_{sc}) (new module). Thus, even if the clean module was cleaned automatically every day, one can still notice some degradation due to other factors different from the dust. Indeed, according to Adelstein and Sekulic

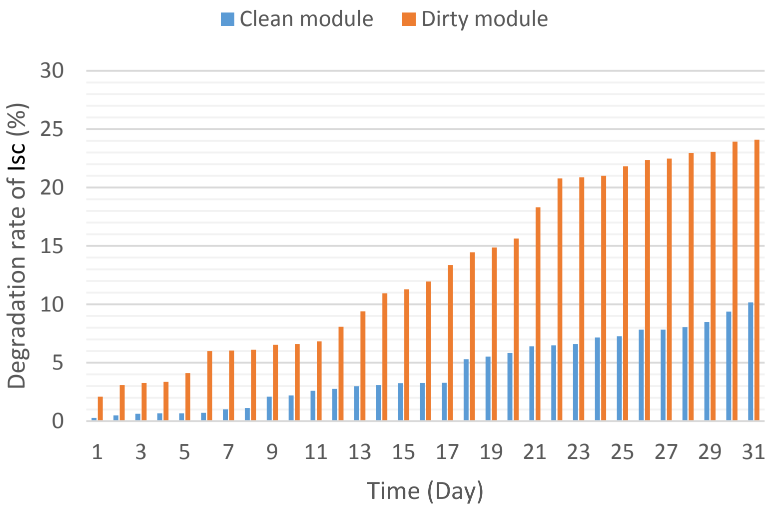

Figure 5. Evolution of the degradation as a function of time for the clean module and the dirty module.

(2005) the electrical parameters of the modules vary according to climatic conditions and gradually degrade over time. This explains the rate of degradation noted at the level of the clean module which reaches the maximum value of 10.16%. However, it should also be noted that the modules had been used about two years before the start of the experiments, which may explain the high value of the degradation. Similarly, the first concern is that dry cleaning may not be as effective as wet cleaning technologies. This is because the water or other chemicals involved in wet cleaning serve as a medium through which dust layers containing salt or similar chemical deposits can be dissolved and the fluid also serves as a medium through which these particles can be transported away from the surface. In dry cleaning, the only method for releasing dried layers of dusty materials is through friction, and air is the only medium through which they can be transported from the surface (Al Shehri et al., 2016).

In Figure 5, there is an increase in the degradation of the short-circuit current (I_{sc}) for the two modules. This degradation is much more significant for the dirty module than for the clean module. Thus the degradation rates can reach maximum values of 10.16 and 24.09% for the clean module and the dirty module, respectively. Indeed, according to Ndiaye et al. (2013), dust induces a generally non-uniform shading on the surface of the PV modules and thus the chains of photovoltaic cells do not receive the same intensity of sunshine. Consequently, they do not have the same behavior and the characteristics of the modules are modified. Some mechanical methods to remove dust from the surface of PV module covers include mechanical wiping, blowing, and the use of removable covers were reviewed. Al Shehri et al. (2016) reviewed different dry cleaning mechanisms that use robotic systems. It was reported that dry cleaning methods using nylon brushes did not affect the optical characteristics of the PV glass surface after equivalent simulation of 20 years.

Williams et al. (2007) reported that the use of mechanical vibration to remove dust resulted in a restoration of 95% of the power-generating capacity of the photovoltaic module. Fernandez et al. (2007) designed a robotic dust wiper supported by a high performance brush to clean surfaces from deposited Martian dust particles. The results showed that the cleaning efficiency was above 93%.

Figure 6 shows the evolution of the degree of degradation of the dirty module as a function of the amount of dust that settles on the surface of the solar panels. After 4 four weeks of collecting dust, we see an increase in the degradation rate of the dirty module depending on the amount of dust that is deposited. Thus, a polynomial regression line is obtained which shows the relationship between degradation and dust deposition density with a regression coefficient of $R^2 = 0.9933$.

Conclusion

The purpose of this study was to suggest a solar photovoltaic solar panel cleaning solution. It was carried out at the Polytechnic Higher School of the University of Dakar and made a comparative study of the short-circuit current of the module cleaned with a waterless cleaning system of the modules and a module without any cleaning action. The month of May that was chosen has very good environmental characteristics. During this study period of 31 days we were able to note a significant rate of degradation of the short circuit current (I_{sc}) of the dirty module.

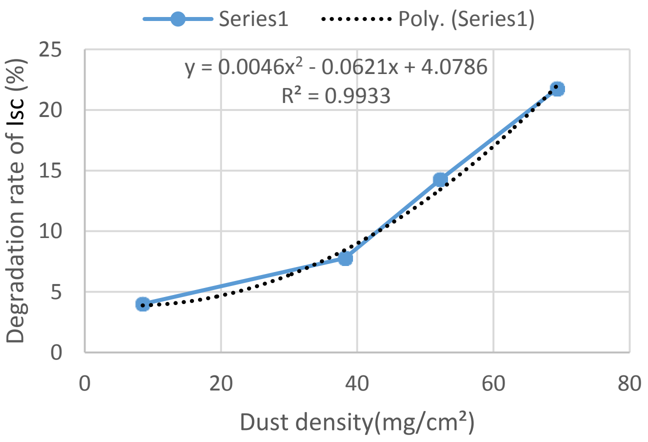

Figure 6. Evolution of degradation as a function of the density of dust deposits.

In this paper the cleaning system and the methodological approach were presented. Interesting results have been found as the proposal of automatic cleaning to limit the effect of dust on the surface of the modules. The following results were thus obtained:

(i) A degradation rate of 17.13% of the dirty module compared to the clean module.
(ii) Degradations of 10.16 and 24.09%, respectively, for the clean module and dirty module.
(iii) A polynomial relation between the degradation and the density of dust deposits on the surface of the modules is determined with a coefficient of determination of 0.9933.

In the continuation of this study, it would be interesting to evaluate the cost of the system to see if the process of cleaning the surface of the modules is profitable or not for the owners and in addition, determine appropriate cleaning frequencies for solar photovoltaic installations.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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