Impacts of climate change on wind erosion in southern Africa between 1991 and 2015

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September 24, 2020

Abstract

Wind erosion is the main form of soil erosion in arid and semi-arid areas. It leads to soil loss and land degradation, which aggravates ecosystem vulnerability and threatens regional sustainable development. The assessment of wind erosion and the study of its driving factors can reduce soil wind erosion and provide decision-making assistance to solve environmental problems. Southern Africa is affected by severe soil erosion, which has brought a series of development problems, such as food crises and poverty. This study used meteorological and remote sensing data, and the revised wind erosion equation model to explore the temporal and spatial dynamics of soil erosion in southern Africa from 1991 to 2015. The impact of climate dynamics on soil wind erosion was also analyzed. The results showed that wind erosion fluctuated during the study period, and it first showed a downward trend and then stabilized at a relatively low level after 2010. Soil wind erosion across 66.65% of the study area significantly decreased ($p < 0.05$) and near-surface wind speed was the most important factor. The change in wind speed had a positive impact on soil wind erosion across 68.18% of the area. Temperature and precipitation were significantly related to soil wind erosion over 18.96% and 24.63% of the area, respectively. Both can also indirectly affect soil wind erosion through their effects on vegetation cover. This study will help decision-makers to evaluate areas that are at high-risk from soil erosion in southern Africa and enable them to effectively protect fragile ecosystems.

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Acknowledgments

This study was financially supported by the National Key Research and Development Program of China (No. 2017YFA0604704).

Abstract

Wind erosion is the main form of soil erosion in arid and semi-arid areas. It leads to soil loss and land degradation, which aggravates ecosystem vulnerability and threatens regional sustainable development. The assessment of wind erosion and the study of its driving factors can reduce soil wind erosion and provide decision-making assistance to solve environmental problems. Southern Africa is affected by severe soil erosion, which has brought a series of development problems, such as food crises and poverty. This study used meteorological and remote sensing data, and the revised wind erosion equation model to explore the temporal and spatial dynamics of soil erosion in southern Africa from 1991 to 2015. The impact of climate dynamics on soil wind erosion was also analyzed. The results showed that wind erosion fluctuated during the study period, and it first showed a downward trend and then stabilized at a relatively low level after 2010. Soil wind erosion across 66.65% of the study area significantly decreased ($p < 0.05$) and near-surface wind speed was the most important factor. The change in wind speed had a positive impact on soil wind erosion across 68.18% of the area. Temperature and precipitation were significantly related to soil wind erosion over 18.96% and 24.63% of the area, respectively. Both can also indirectly affect soil wind erosion through their effects on vegetation cover. This study will help decision-makers to evaluate areas that are at high-risk from soil erosion in southern Africa and enable them to effectively protect fragile ecosystems.

Keywords : wind erosion; RWEQ; climate change; Southern Africa

1. Introduction

Land degradation caused by soil erosion is a major environmental threat across the globe and has a direct impact on global social-economic development and human wellbeing (Millennium Ecosystem Assessment, 2005; Pimentel, 2006; Montgomery, 2007). Most global land degradation occurs in arid and semi-arid areas, which account for about 40% of the total global land area (Batunacun, Nendel, Hu, & Lakes, 2018; Verón, Paruelo, & Oesterheld, 2006). Soil wind erosion is the most common form of land degradation in arid and semi-arid areas, and it continues to spread in many parts of the world, such as America, Africa, Australia, and Asia (Buschiazzo & Zobeck, 2008; Hoffmann, Funk, Reiche, & Li, 2011; Larney, Bullock, Janzen, Ellert, & Olson, 1998; Shi, Yan, Yuan, & Nearing, 2004; Webb, McGowan, Phinn, Leys, & McTainsh, 2009). It has been estimated that about $5.05 \times 10^6 km^2$ of land in the world has been degraded and desertified due to soil wind erosion. This land accounts for 46.4% of the global degraded area. Soil wind erosion has caused considerable damage to the ecosystem, resulting in the loss of soil nutrients and organic matter, and declines in land productivity (D'Odorico, Bhattachan, Davis, Ravi, & Runyan, 2013; Larney et al., 1998; Visser & Sterk, 2007). It has also produced a large number of aerosol particles, which are suspended in the atmosphere. These particles contribute to sandstorms and cause severe air pollution (Jiang, Gao, Dong, Liu, & Zhao, 2018; Kjelgaard, Chandler, & Saxton, 2004; Sharratt, Feng, & Wendling, 2007). Furthermore, land degradation has exacerbated ecological vulnerability (Lal, 2014) and has caused considerable damage to development and human health (Riksen & De Graaff, 2001).

Most studies have shown that developing countries are subject to acute soil erosion (Ananda & Herath, 2003; Pimentel et al., 1995; Rosas & Gutierrez, 2020), but the harm caused by soil erosion has not received enough attention (Borrelli et al., 2017). In sub-Saharan Africa, about 360 Mha of land, or 20%–25% of the total land area, is currently at serious risk of soil erosion (Vågen, Lal, & Singh, 2005). Severe soil erosion results in soil fertility decline and a decrease in the soil utilization rate. The cultivated land productivity loss is about 0.5–1% each year (Scherr, 1999; Sivakumar, 2007), which has caused a series of development problems, such as a decrease in food security and an increase in poverty (Cohen, Brown, & Shepherd, 2006). Around 70% of the land area in South Africa suffers from different types and degrees of degradation (Le Roux, Newby, &

Sumner, 2007), and deforestation and unreasonable reclamation mean that Namibia faces moderate or even high soil erosion risks (Klintenberg & Seely, 2004). Increasing population and climate change mean that soil erosion in southern Africa will become more serious in the future (Tamene & Le, 2015).

Soil wind erosion is a process that blows, transports, and deposits fine surface soil particles and nutrients into the atmosphere (Shao, 2008). Soil wind erosion modeling is an important means of predicting and evaluating wind erosion. It can integrate the wind erosion process and influencing factors, and help evaluate the in-situ and off-site effects of wind erosion at different spatial and temporal scales (Blanco & Lal, 2008). In the 1960s, based on Chepil and Woodruff (1959), Woodruff and Siddoway (1965) developed an empirical wind erosion (WEQ) model using wind tunnel and field measurements. After continuous improvement, the revised wind erosion equation (RWEQ) was obtained, which fully considered meteorological, vegetation, soil, roughness, and other factors, and allowed short-term soil wind erosion assessments (Tatarko, Sporcic, & Skidmore, 2013; Van Pelt, Zobeck, Potter, Stout, & Popham, 2004). The model has been widely used in European Union countries (Borrelli et al., 2017), the United States (Pi, Sharratt, Feng, & Lei, 2017; Zobeck, Parker, Haskell, & Guoding, 2000), Pampas in Argentina (Buschiazzo & Zobeck, 2008), China (Du, Xue, Wang, & Deng, 2015; Guo, Zobeck, Zhang, & Li, 2013; Hanbing Zhang et al., 2019), and Syria (Youssef, Visser, Karssenberg, Bruggeman, & Erpul, 2012). However, there have been few studies on soil wind erosion in southern Africa. At the research scale, Mhangara, Kakembo and Lim (2012) assessed the soil erosion risk for the Keiskamma basin in South Africa based on GIS and remote sensing data. For example, Shikangalah, Paton, Jetlsch and Blaum (2017) used Windhoek, Namibia, to quantify the soil erosion severity of cities in arid areas based on field survey data and Sonneveld, Everson and Veldkamp (2005) explored the dynamics of soil erosion by undertaking a remote sensing project in KwaZulu Natal, South Africa. However, the previous studies in southern Africa focused more on short-term and smaller scales, such as specific fields, cities, and watersheds, which means that there is a lack of long-term wind erosion studies at the regional scale.

Wind speed, temperature, and precipitation are the main climatic factors affecting wind erosion (Chi, Zhao, Kuang, & He, 2019; Du, Wang, & Xue, 2017; Gao, Ci, & Yu, 2002). The wind is the major driving force influencing soil wind erosion, and the near-surface wind transportation of soil particles in arid and semi-arid regions can strongly influence the wind erosion process (Pi et al., 2017; Tegen, Lacis, & Fung, 1996; G. Zhang et al., 2019). Temperature and precipitation can determine the stability of soil surface particles and alter the balance between moisture and energy at the soil surface. Drought also makes the soil more prone to wind erosion (Mckenna Neuman, 2003; Haiyan Zhang et al., 2018).

Due to a lack of relevant data, studies on the influence factors affecting soil wind erosion in southern Africa have focused more on the qualitative assessment and estimation of single indicators, such as precipitation and vegetation. However, they have not previously considered the effects of multiple determinants (Kakembo & Rowntree, 2003; Meadows, 2003). Therefore, this study estimated soil wind erosion based on the RWEQ model in southern Africa and used trend analysis methods to reveal the changes in soil wind erosion. This study also used correlation analysis methods to identify the influences of climate factors on wind erosion. The aims of this study were to (1) estimate the distribution of soil wind erosion and its temporal and spatial changes in southern Africa from 1991 to 2015 and (2) explore the impacts of climate factor dynamics, such as temperature, precipitation, and wind speed, on soil wind erosion.

2. Materials and Methods

2.1 Study area and data sources

The study area was located in southern Africa and had a total area of 2.67×10^6 km^2. It contained five countries: Namibia, Botswana, Eswatini, South Africa, and Lesotho (Fig. 1), with a population of approximately 65.74 million people (FAO, 2019). Southern Africa is one of the most underdeveloped regions in the world. In 2015, the total regional Gross Domestic Product (GDP) was 349.759 billion (current US$), which accounted for 0.47% of global GDP. The proportion of people in poverty (the international standard poverty line is US $1.9 per day) is 13.4%–28.4%, which is higher than the global average poverty population of 9.6% (WDI, 2019). The altitude in the region ranges from -251 m to 3473 m. The central South African plateau is high and the surrounding coastal areas are relatively low. The Namib Desert and the Kalahari Desert are located on the western coast and central basin, respectively. According to the Koppen climate classification, southern Africa is dominated by arid steppe and arid desert. The average annual temperature is 13.8 degC, the average summer maximum temperature is 34.7 +- 0.05 degC (Conradie, Woodborne, Cunningham, & McKechnie, 2019), and the average annual precipitation ranges from 299.9 to 570.4 mm. The rainfall has distinct seasonal differences and the rainy season in most areas is mainly concentrated in the summer (November to February) (Pohl, Macron, & Monerie, 2017). It has been predicted that southern Africa will become drier in the future, annual rainfall will decrease, and drought frequency will increase (Arnell, Hudson, & Jones, 2003; Hulme, Doherty, Ngara, New, & Lister, 2001; Kusangaya, Warburton, Archer van Garderen, & Jewitt, 2014).

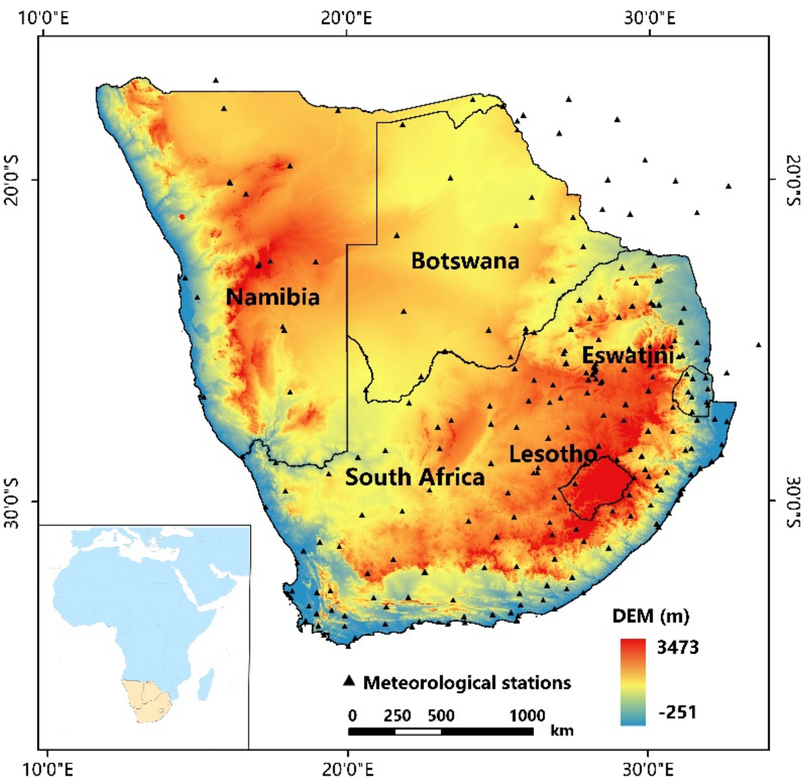

Fig. 1 Geographical location of the study area, including political borders and main topographic features.

The temperature, precipitation, wind speed, and other meteorological data used in this study were all derived from the Global Surface of Daily Meteorological Data produced by the National Centers for Environmental Information (NOAA, https://www.ncdc.noaa.gov/). More than 200 meteorological stations in southern Africa and its surrounding areas were selected. The data covered 1991–2015 and ANUSPLIN 4.3 (https://fennerschool.anu.edu.au/research/products/anusplin) was used to spatially interpolate the information. The Digital Elevation Model (DEM) was provided by the Shuttle Radar Topography Mission and has a resolution of 90 m (http://srtm.csi.cgiar.org/srtmdata/); the soil properties were determined using 250 m resolution raster data from the International Soil Reference and Information Center and included sand, clay, silt, and organic matter contents (https://soilgrids.org/); the $CaCO_3$ data came from the Harmonized World Soil Database (HWSD v1.2) with a resolution of 1 km (http://www.fao.org/soils-portal/soil-survey/); the vegetation data were obtained from the standard normalized vegetation index (NDVI) in GIMMS 3g and covered 1991–2015 with a spatial resolution of 8 km; and the vegetation coverage was calculated by the maximum synthesis method (https://ecocast.arc.nasa.gov/data/pub/gimms/). The land use/cover data came from the European Space Agency and its Climate Change Initiative (CCI-LC) project provided global land use data with a resolution of 300 m (http://maps.elie.ucl.ac.be/CCI/viewer/). All data were uniformly resampled to a spatial resolution of 8 km.

2.2 Revised wind erosion equation

The RWEQ model is an empirically-based model developed by the United States Department of Agriculture to estimate soil loss in farmland at a height of 2 m (Fryrear et al., 2000). When the wind force is greater than the resistance, the soil particles will move, and when the wind force is less than the resistance, the soil will not be eroded by wind. The RWEQ model is based on the WEQ and includes its experience and process components. It can predict and simulate wind erosion processes by combining existing data sets and computer models (Jarrah, Mayel, Tatarko, Funk, & Kuka, 2020). Compared to other complexity models that have more parameters, the RWEQ model has a relatively simple structure and has been widely used to estimate the transport capacity of long-term and large-scale aeolian sediments (Borrelli et al., 2017; Guo et al., 2013; Youssef et al., 2012; Zobeck et al., 2000). The model calculation is as follows:

$$SL = \frac{2x}{S^2} Q_{\max} e^{-\left(\frac{x}{s}\right)^2} \quad (1)$$

$$Q_{\max} = 109.8(WF \times EF \times SCF \times K' \times COG) \quad (2)$$

$$S = 150.7(WF \times EF \times SCF \times K' \times COG)^{-0.3711} \quad (3)$$

where SL is the wind erosion modulus (kg/m^2); $Q_{\max}$ is the maximum sand transport capacity (kg/m); and s is the critical field length (m), which is the distance at which 63% of the maximum transport capacity is reached. WF is the weather factor (kg/m); EF, K', and SCF are the soil erodibility factor, the soil crust factor, and the soil roughness factor, respectively (dimensionless); and COG is the combined vegetation factor, which is also non-dimensional.

The equations for each factor are

$$WF = W_f \times \frac{\rho}{g} \times SW \times SD \quad (4)$$

$$EF = \frac{29.09 + 0.31Sa + 0.17Si + 0.33\frac{\mathrm{Sa}}{\mathrm{Cl}} - 2.59OM - 0.95\mathrm{CaCO_3}}{100} \quad (5)$$

$$SCF = \frac{1}{1 + 0.0066Cl^2 + 0.021\mathrm{OM}^2} \quad (6)$$

$$COG = \mathrm{SLR}_f \times \mathrm{SLR}_s \times \mathrm{SLR}_c \quad (7)$$

where W_f is the total wind factor (m^3/s^3); ρ is the air density (kg/m); g is the acceleration due to gravity (m/s); SW is soil wetness (dimensionless); SDis the snow cover factor; Sa is the sand content (5.5%–93.6%); Si is the silt content (0.5%–69.5%);Sa/Cl is the sand to clay ratio (1.2%–53.0%); OM is organic matter (0.18%–4.79%); $\mathrm{CaCO_3}$ is calcium carbonate (0.0%–25.2%); Cl is clay content (0.32%–4.74%);SLR_f is the flat residues; SLR_s is the standing residues; and SLR_c is the crop canopy. In this study, the crop seedlings that provide partial canopy cover and protect the soil were calculated as the effects of vegetation cover on wind erosion.

2.3 Statistical methods

2.3.1 Trend analysis

Sen's slope analysis method was used to calculate the soil wind erosion trend between 1991 and 2015. This method is a non-parametric test that only requires the independence of sample data and does not need to fit the normal distribution (Gilbert, 1987). The trend degree, β, is defined as follows:

$$\beta = Median\left(\frac{x_j - x_i}{j-i}\right) \qquad \forall j > i \quad (8)$$

where $1 < j < i < n$. When $\beta > 0$, the sequence change trend is upward, but when $\beta < 0$, then it has a downward trend. Sinceβ is a non-normalized parameter, it can only show the size of the changing trend. It cannot judge the significance of the trend change for a time series. Therefore, the Mann-Kendall method needs to be used to test the significance of the trend (Kendall, 1948). Finally,$\alpha < 0.05$ and $\alpha < 0.1$ were considered very significant and significant, respectively, and the rest were not significant.

2.3.2 Correlation analysis

The relationships between variables include definite relationships and uncertain relationships. A statistical uncertainty analysis was used in this study, and the Pearson's correlation coefficient revealed the relationship between soil wind erosion and its dominant factors. The Pearson's correlation coefficient is a common linear correlation coefficient and is also known as the product-moment coefficient of correlation. Generally, r represents the degree of linear correlation between variables X and Y, and ranges from −1 to 1. There is a negative correlation when $r < 0$, whereas $r > 0$ means a positive correlation. The significance level was p < 0.1 and the formula is expressed as follows:

$$r_{\mathrm{XY}} = \frac{\sum_{i=1}^{n}(X_i - X)(Y_i - Y)}{\sqrt{\sum_{i=1}^{n}(X_i - X)^2 \times \sum_{i=1}^{n}(Y_i - Y)^2}} \quad (9)$$

2.3.3 Partial correlation analysis

Soil wind erosion is affected by a variety of factors, and the relationships between multiple factors are complicated. This study used a partial correlation analysis, assuming other independent variables remained constant, to examine the correlation between an independent variable and the dependent variable. It aims to exclude interference by other factors so that the results reflect the influence degree of an independent variable on the dependent variable (Schielzeth, 2010). For example, if there are three sets of variables: x, y, and z, then a partial correlation analysis can be used to study the relationship between the variables and is calculated as follows:

$$r_{xy\bullet z} = \frac{r_{\mathrm{xy}} - r_{\mathrm{xz}} r_{\mathrm{yz}}}{\sqrt{(1 - r_{\mathrm{xz}}{}^2)(1 - r_{\mathrm{yz}}{}^2)}} \quad (10)$$

where $r_{xy\bullet z}$ means that when variable z is fixed, the correlation coefficient is between x and y; andr_{xy}, r_{xz}, and r_{yz} represent the correlation coefficients between variables x and y, $x$and z, and y and z, respectively. A t-test was used to test the partial correlation coefficient.

3. Results

3.1 Wind erosion distribution

The spatial distribution of soil wind erosion in southern Africa is shown in Fig. 2. The average wind erosion modulus was 0–169.87 t/ha/a from 1991 to 2015 and the spatial distribution was heterogeneous. The soil wind erosion in most parts of South Africa is relatively light, with a modulus of less than 10 t/ha/a. However, the areas with severe soil erosion are in the Namib desert, which is a narrow strip along the western coastal area, and the Kahalari Basin, which is the border area between Namibia, southern Botswana, and South Africa, has an average wind erosion modulus of more than 90 t/ha/a. The strong wind, erodible soil texture, and sparse vegetation mean that soil erosion in these areas is very serious. The soil wind erosion had roughly the same spatial distribution at certain times (Figs. 2b–2f). The proportion of the area with a wind erosion modulus greater than 60 t/ha/a (very high erosion hazard) gradually decreased from 20.36% in 1991–1995 to 15.92% in 2001–2005 and 8.78% in 2011–2015. The wind erosion modulus in the western and central regions was always higher than that in the other regions, but severe soil erosion greatly improved after 2000 in the eastern coastal area, that is, the northeastern part of South Africa and Eswatini.

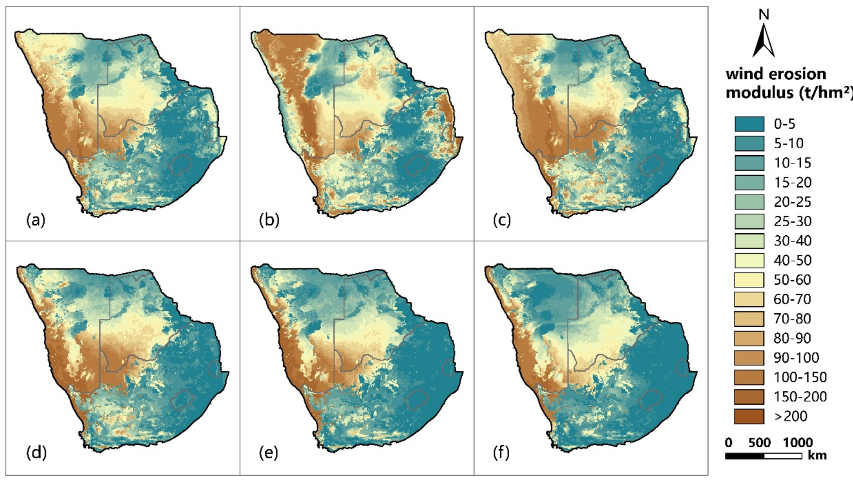

Fig. 2 Spatial distribution of the average wind erosion moduli in southern Africa for (a) 1991–2015; (b) 1991–1995; (c) 1996–2000; (d) 2001–2005; (e) 2006–2010; and (f) 2011–2015.

3.2 Temporal-spatial trends for wind erosion

The soil erosion modulus in southern Africa fluctuated from 1991 to 2015, but the temporal changes showed a significant downward trend (Fig. 3a) with an average annual decrease of 0.99 t/ha/a, and a maximum soil loss of 61.01 t/ha in 1995. In general, wind erosion in southern Africa can be divided into three phases. From 1991 to 2000, the amount of wind erosion fluctuated around 46.40 t/ha/a; from 2001–2010, it fell significantly at an average rate of 1.95 t/ha/a; and then it stabilized after 2010. According to Sen's trend test (Fig. 3b), 70.84% of the southern Africa study area showed a downward trend in annual average soil erosion. This decrease was significant across 66.65% of the area ($p < 0.05$), but 7.1% of the area showed a significant increase ($p < 0.05$). The Namib Desert along the western coastal area only had severe soil wind erosion at certain times during the study period (Fig. 2); In the central part of the study area, such as Botswana and Lesotho, the soil wind erosion modulus in local areas showed an increasing trend, but the soil wind erosion modulus showed no significant change over 21.11% of the area.

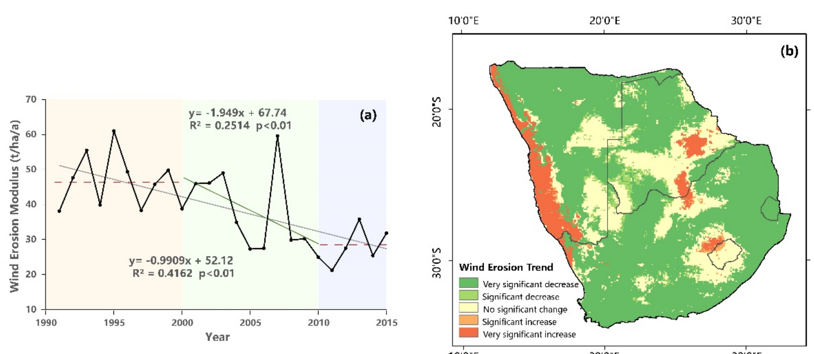

Fig. 3 Wind erosion dynamics in southern Africa from 1991 to 2015.

(a) Annual average wind erosion trend; (b) spatial distribution of the wind erosion trend.

3.3 Impacts of climate change on wind erosion

Soil wind erosion in southern Africa is the result of both climatic conditions and human activities. The control variable method was used to explore the impact of climate dynamics on soil wind erosion. The average climatic conditions from 1991 to 2015, instead of the actual climatic conditions, were used as the model input to obtain SL'. Therefore, there is a difference between the actual results and the soil wind erosion estimated in 3.1, which was only affected by climate dynamics. Wind speed is the main driving force behind soil wind erosion. However, temperature and precipitation also have an influence on wind erosion because they affect soil moisture and vegetation coverage. Therefore, this study used mean annual temperature, annual precipitation, and annual average maximum wind speed as the main climatic factors in a partial correlation analysis that revealed the influence of the different climatic factors on soil wind erosion.

From 1991 to 2015, the annual average temperature and precipitation in southern Africa did not significantly change, but temperature, precipitation, and soil wind erosion were significantly related across local, smaller areas. The annual average temperature in southern Africa gradually decreased from northwest to southeast (Fig. 4c), and the Kalahari Desert and its surrounding basins were the main high-temperature areas. In general, temperature had a more significant impact on soil wind erosion in areas with higher annual average temperatures. Around 18.69% of southern Africa was affected by temperature (Fig. 4e), and temperature and wind erosion were significantly negatively correlated across 12.71% of the area ($p < 0.05$). For example, the high temperature and precipitation in the eastern part of the study area may promote the growth of vegetation, which would reduce soil wind erosion to a certain extent. The annual precipitation in southern Africa increased from west to east, and the annual precipitation in the subtropical monsoon climate region in the southeast was generally higher than in the rest of the study area (Fig. 4d). There was a negative correlation between soil wind erosion and precipitation across 23.96% of the area (Fig. 4f), particularly near the Kalahari Basin in the central region and Eswatini in the east. Arid and semi-arid areas with annual precipitation less than 400 mm are prone to wind erosion. However, a rise in precipitation may increase the vegetation coverage to a certain extent, which would reduce soil wind erosion. There was no significant correlation between soil wind erosion, and temperature and precipitation in 81.31% and 75.37% of southern Africa, respectively. Therefore, temperature and precipitation are not direct determinants of soil wind erosion, but they probably have an indirect impact on wind erosion because they affect vegetation growth.

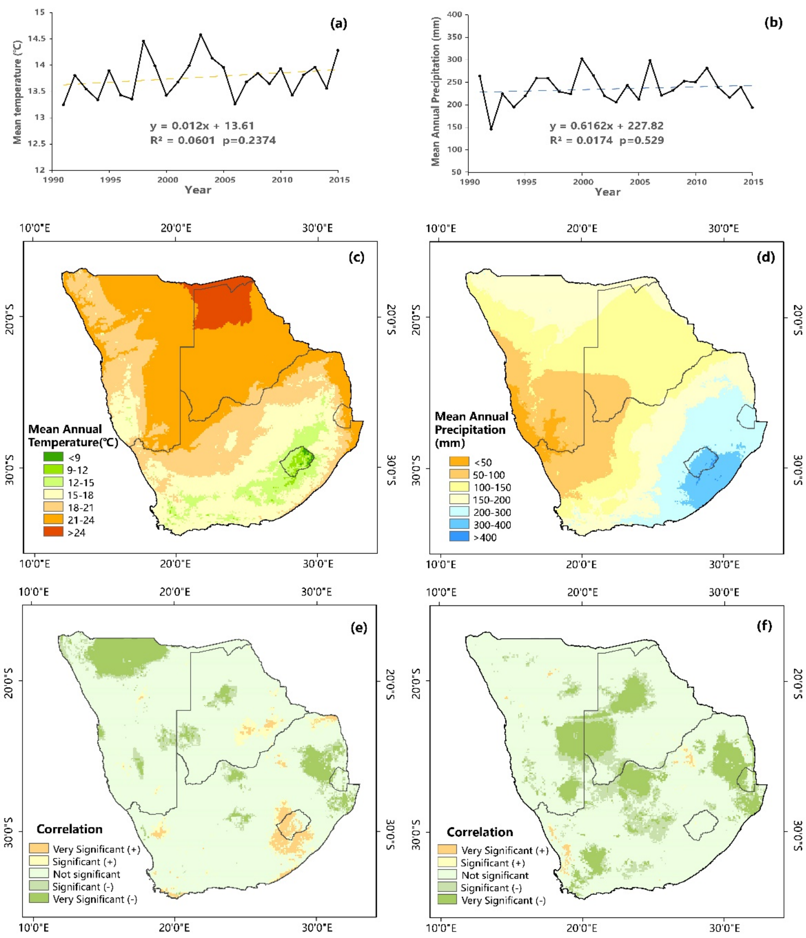

Fig. 4 Relationships between wind erosion, and temperature and precipitation in southern Africa due to temporal changes in the (a) mean annual temperature and (b) annual precipitation. Spatial distributions of (c) mean annual temperature and (d) annual precipitation. Spatial patterns of the partial correlations between wind erosion, and (e) mean annual temperature and (f) annual precipitation.

The annual maximum wind speed in southern Africa showed a clear downward trend from 1991 to 2015, with a decline rate of 0.0742 m/s/a ($r^2 = 0.87$, $p < 0.01$) (Fig. 5a). A significant drop in the wind speed led to a reduction in soil wind erosion (Fig. 3a). There was a significant positive correlation ($p < 0.1$) between the annual wind erosion modulus and the annual average maximum wind speed across 68.18% of southern Africa (Fig. 5b), mainly distributed in the Kalahari Basin of South Africa and southern Botswana. A slight rise in wind speed in 2003–2004 and 2006–2007 led to an increase in the average annual wind erosion modulus, which suggested that wind speed had a strong influence on wind erosion spatial distribution and temporal changes. However, near-surface wind speed is not the main factor affecting soil erosion in the Western Coastal Namib area where the soil erosion is more likely to be affected by the surface rock structure and lower vegetation coverage.

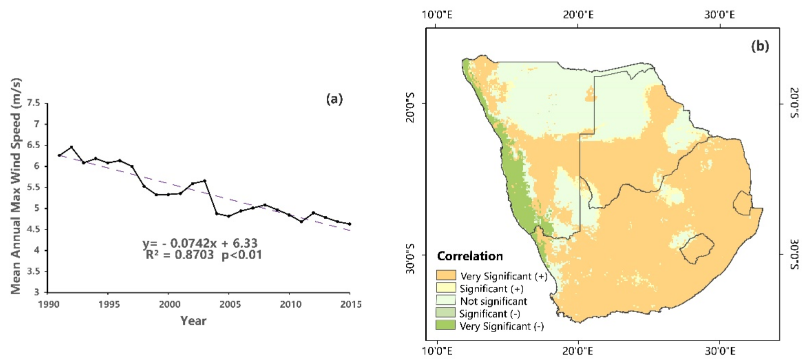

Fig. 5 Relationships between wind erosion and mean annual maximum wind speed in southern Africa from 1991 to 2015. (a) Temporal changes in mean annual maximum wind speed and (b) spatial patterns of the partial correlations between wind erosion and mean annual maximum wind speed.

4. Discussion

4.1 Climate dynamics in southern Africa

Since the 1870s, the increase in atmospheric water demand and changes to atmospheric circulation patterns have led to more frequent droughts in Africa (Dai, 2011). In particular, since 1980, the area suffering from severe drought has continued to increase (Rouault & Richard, 2005), and the irrational utilization of limited natural resources and population growth will further aggravate the risk of drought in the future (Ahmadalipour, Moradkhani, Castelletti, & Magliocca, 2019). Southern Africa was subjected to severe droughts in 2003 and 2007 (Rouault & Richard, 2005; Winkler, Gessner, & Hochschild, 2017); and serious drought events have occurred in local areas (Masih, Maskey, Mussá, & Trambauer, 2014), such as Namibia in 1995, South Africa in 1995 and 2003, and Lesotho and Eswatini in 2007. These events may have led to greater soil erosion across southern Africa in these years. Southern Africa has a noticeable rising temperature trend with the minimum temperature rising higher than the maximum temperature, especially in Namibia (Collins, 2011; Hulme et al., 2001). There are great uncertainties surrounding the multi-year rainfall intensity in southern Africa, but the average precipitation in the region has significantly decreased, the rainy season has shortened, and the rainfall intensity has weakened (Kusangaya et al., 2014; Nicholson, 2001a, 2001b). Over the last 30 years, the near-surface wind speed in southern Africa has shown a downward trend (Horton, Skinner, Singh, & Diffenbaugh, 2014; Torralba, Doblas-Reyes, & Gonzalez-Reviriego, 2017; Wu, Zha, Zhao, & Yang, 2018), and aerosol emissions have decreased the near-surface wind speed in sub-Saharan Africa by 0.05 m/s (Bichet, Wild, Folini, & Schär, 2012). During 1993–2010, the data derived from meteorological stations in the South Africa showed an average decrease in near-surface wind speed of 0.21 m/s/decade (Kruger, Goliger, Retief, & Sekele, 2010), which may be one of the reasons for the decrease in annual average soil erosion in southern Africa. In addition, vegetation productivity and desertification in sub-Saharan Africa may be influenced by global climate change, which is partly caused by the North Atlantic Oscillation and the El Niño Southern Oscillation (ENSO) (Oba, Post, & Stenseth, 2001). For example, in 2002, 2003, and 2015, the ENSO led to drought in southern Africa (Gizaw & Gan, 2017; Winkler et al., 2017), which was probably further linked to soil wind erosion.

4.2 Relationship between vegetation and wind erosion

Temperature and precipitation can have a direct impact on soil wind erosion. However, vegetation growth, which is dominated by the temporal and spatial water and heat patterns, can also indirectly affect soil wind erosion (Miao, Yang, Chen, & Gao, 2012). A correlation analysis between the average annual fractional vegetation cover (FVC), annual temperature, and annual precipitation showed that in southern Africa, temperature and FVC were negatively correlated across 91.8% of the total area (Fig. 6a). However, in most areas (approximately 88.3% of the total area), FVC had a positive correlation with precipitation (Fig. 6b). The correlations between different FVC values, and temperature and precipitation were also different (Figs. 6c, 6d). When the FVC is below 0.4: the negative correlation between FVC and temperature increases. In contrast, when FVC is greater than 0.4: the influence of temperature on FVC decreases as FVC increases. For example, the Kalahari Basin, which is in the middle of the study area and sparsely covered by shrubs and herbs, has a vegetation coverage of between 0.2 and 0.4 (Fig. 7a). The negative correlation between FVC and temperature and the positive correlation with precipitation were clearly more robust than in other regions (Figs. 6a, 6b). The high temperatures and reduced rainfall make this area hotter and drier, which reduces vegetation growth. In contrast, an increase in precipitation promotes the growth of vegetation. However, in the southern coastal area with a marine climate, the rise in temperature under warm and humid climate conditions increases FVC, but the increase in precipitation actually inhibits vegetation growth.

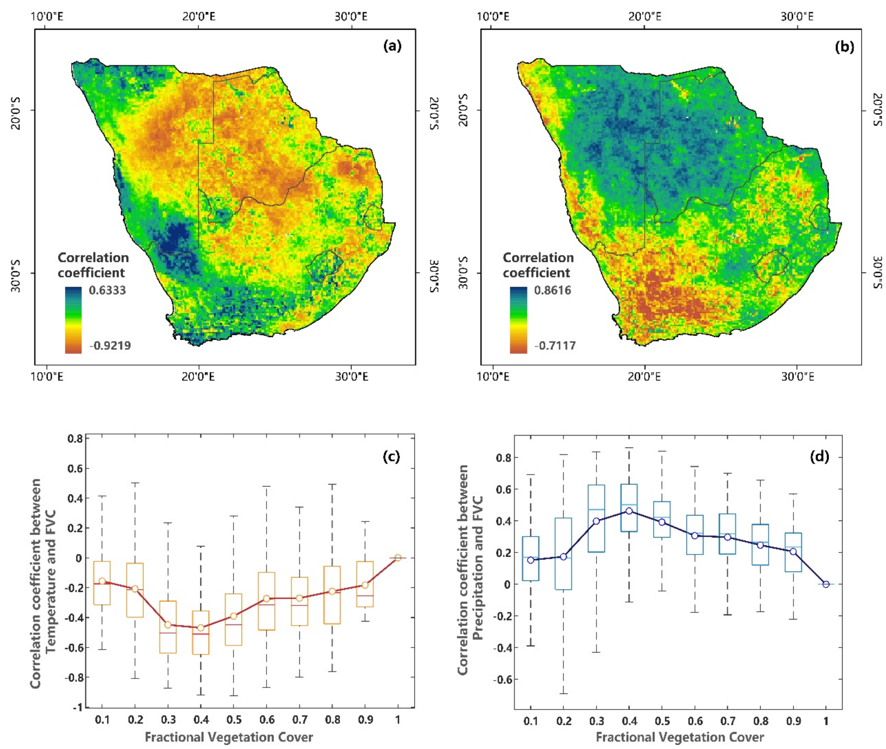

Fig. 6 Relationships between the fractional vegetation cover (FVC), and (a) temperature and (b) precipitation. Relevance analysis between the different FVC, and (c) temperature and (d) precipitation.

In general, FVC in southern Africa increased from west to east (Fig. 7a). The areas with higher FVCs were in the subtropical monsoon climate zone of eastern South Africa. The marine climate zone in the south and the western coastal areas with sparse vegetation also suffered from severe soil erosion. Vegetation can reduce near-surface wind speed, intercept moving sand particles, and protect and fix the topsoil. Furthermore, an increase in FVC effectively helps to slow down soil nutrient loss, reduces dust entrainment, and inhibits soil wind erosion (D. Li et al., 2018; Yan et al., 2013). The data showed that FVC was significantly negatively correlated with soil wind erosion across 47.2% of southern Africa (Fig. 7b). These areas were mainly distributed in the Kalahari Basin in the central part of the study area where FVC was around 0.4. The FVC is also strongly affected by temperature and precipitation (Figs. 6a, 6b). Therefore, the influence of temperature and precipitation on the soil wind erosion modulus may be related to different FVC values. The soil wind erosion modulus is strongly affected by the FVC when the FVC has a strong correlation with temperature and precipitation in an area. That is to say, the changes in temperature and precipitation have a more noticeable impact on soil wind erosion in these areas.

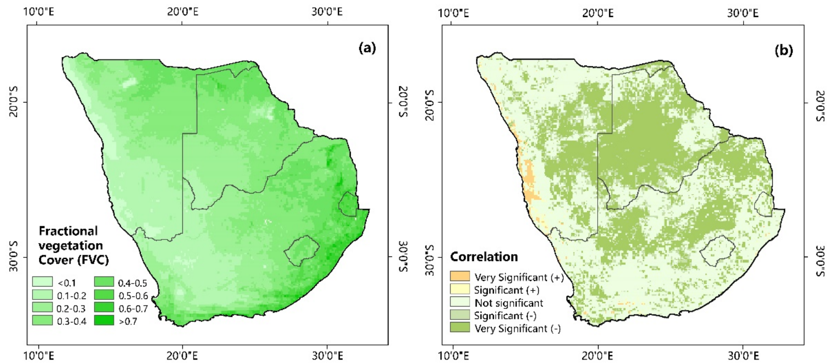

Fig. 7 Relationships between wind erosion and fractional vegetation cover (FVC) in southern Africa between 1991 and 2015. (a) Spatial distribution of FVC, and (b) spatial pattern for the correlations between wind erosion and mean annual FVC.

4.3 Uncertainties and limitations

Soil wind erosion is a common environmental problem in arid and semi-arid areas across the world (Dewitte, Jones, Elbelrhiti, Horion, & Montanarella, 2012). The relationship between dust emission sources and soil erosion caused by wind in arid and semi-arid areas has been previously reported (Bullard, Baddock, McTainsh, & Leys, 2008; Gillette & Hanson, 1989; F. R. Li, Zhao, Zhang, Zhang, & Shirato, 2004), but there are still challenges in quantifying the temporal and spatial soil wind erosion patterns on a larger, regional scale. This study assessed the changes in soil wind erosion across southern Africa between 1991 and 2015 (Fig. 2). The results showed that the spatial and temporal patterns for soil wind erosion were basically the same as those obtained by different methods. The inland areas of southern Africa and the Namib Desert were the major areas affected by soil wind erosion (Goudie, 2008; Symeonakis & Drake, 2010). Wiggs and Holmes (2011) conducted a field assessment of dust deposition on farmland in Free State, South Africa, and the erosion modulus from August 7 to November 13, 2007 was about 0.4819 t/ha, which was similar to this study (0.69 t/ha). In addition, previous studies on large-scale spatial patterns for dust emissions also showed that there was significant soil wind erosion in southern Africa (Luo, Mahowald, & Corral, 2003; Shao et al., 2011). However, there are still uncertainties in the model calculation results due to the low availability of higher resolution data for southern Africa.

This study focused on analyzing the temporal and spatial patterns for soil wind erosion and its influence factors rather than the precise calculation of the amount of soil wind erosion at a certain point in time or place. This meant that the results of this article are referenceable. In addition, this study analyzed annual average temperature, annual precipitation, and near-surface wind speed in order to reveal the impact of long-term climate dynamics on soil wind erosion. However, less attention was paid to the possible impact of a single climate event on soil wind erosion. Future research should concentrate on the effects of specific climate events, such as extreme drought or precipitation caused by the ENSO, on soil wind erosion.

5. Conclusion

This study used the RWEQ model to evaluate soil wind erosion and its temporal and spatial changes in southern Africa from 1991 to 2015. It also investigated the impact of climate dynamics on soil wind erosion. The results showed that the wind erosion changes in southern Africa strongly fluctuated. The overall wind erosion modulus significantly declined at the beginning of the study period, but then stabilized after 2010.

However, soil wind erosion in the western coastal areas was very serious and had an upward trend year by year. Near-surface wind speed is the dominant factor affecting soil wind erosion. The near-surface wind speed decline in southern Africa had a positive impact because it reduced soil wind erosion across 68.18% of the study area. Furthermore, soil wind erosion was significantly related to temperature and precipitation ($p < 0.05$) in only 18.96% and 24.63% of the area, respectively. In addition, the differences in vegetation cover due to temperature and precipitation also indirectly affected soil wind erosion in southern Africa. According to this multi-source data analysis, increasing the vegetation coverage in arid and semi-arid areas will effectively reduce near-surface wind speed. This will solidify the soil, which, in turn, should play a positive role in decreasing and controlling wind erosion.

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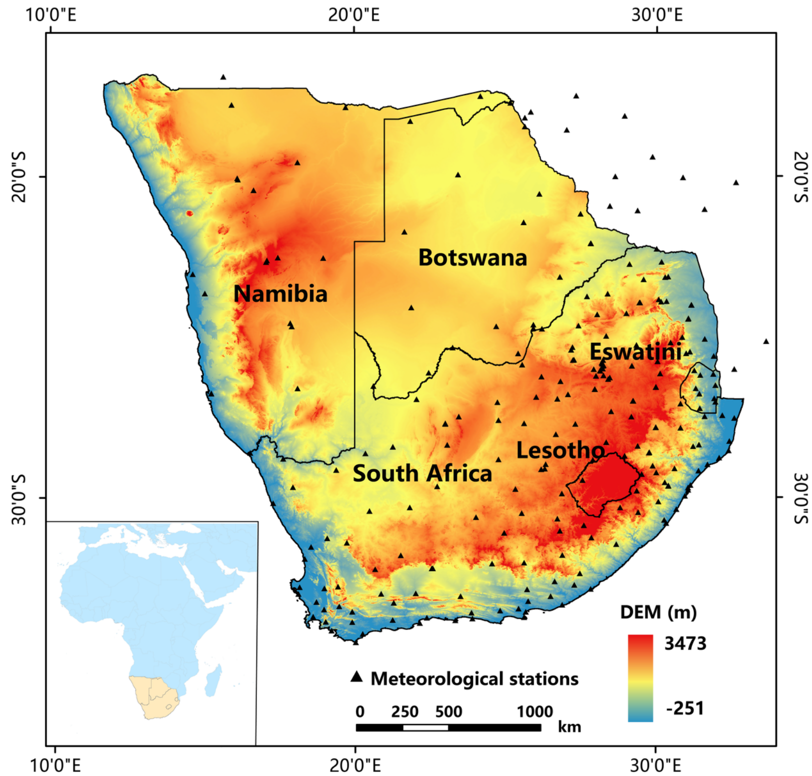
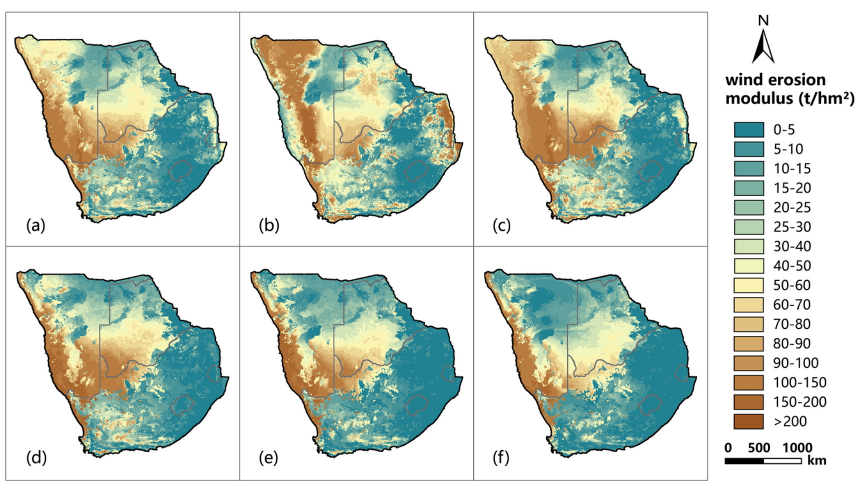
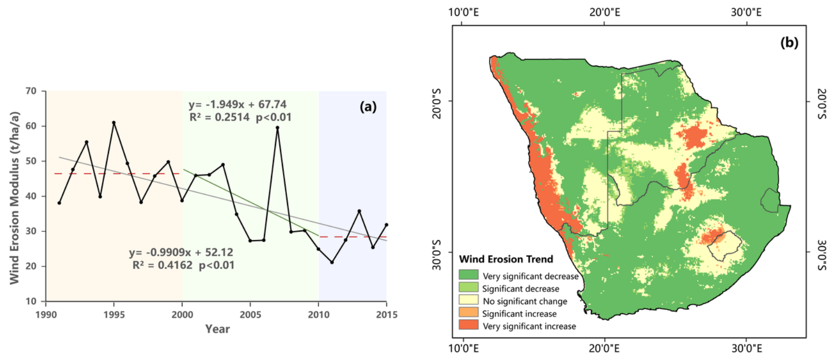
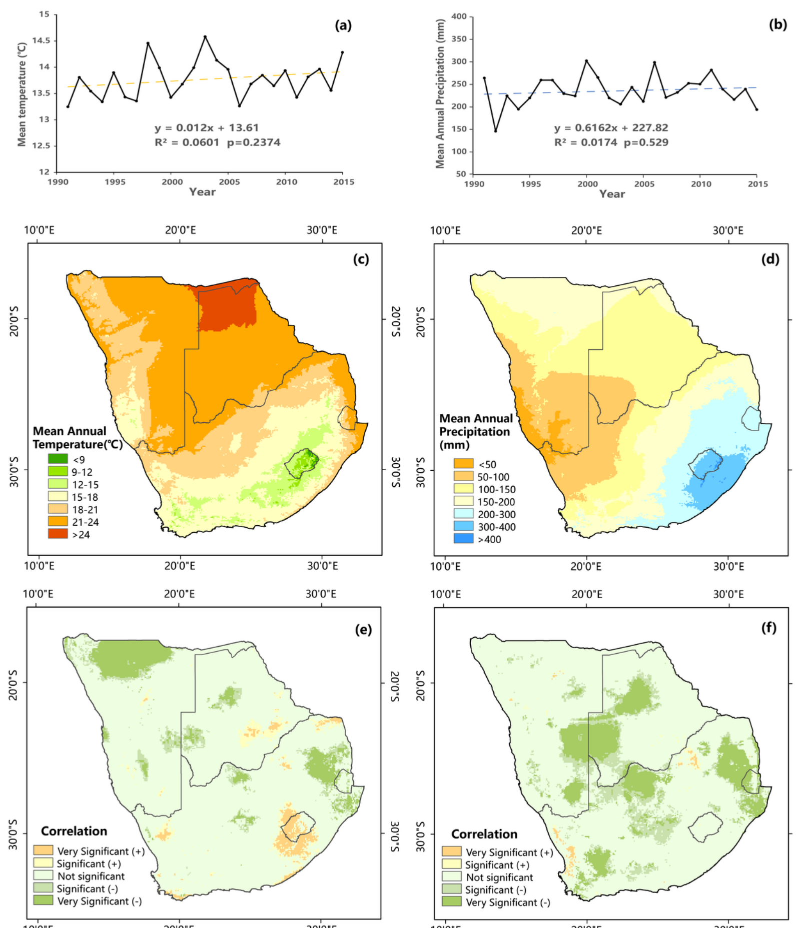


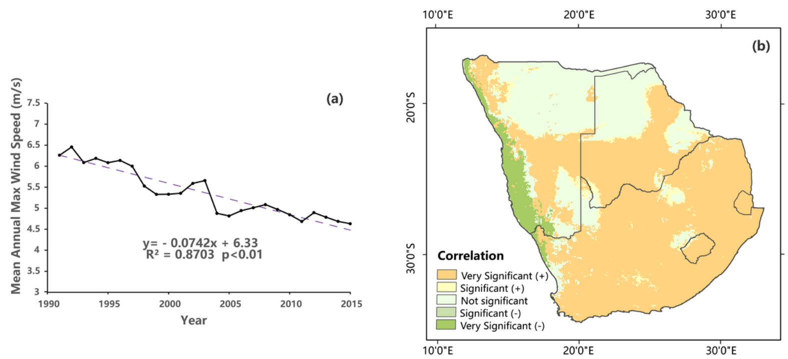
10'0"E
20'0"E
30'0"E
20'0"S
30'0"S
Namibia
Botswana
Eswatini
Lesotho
South Africa
DEM (m)
3473
-251
Meteorological stations
0 250 500 1000
km

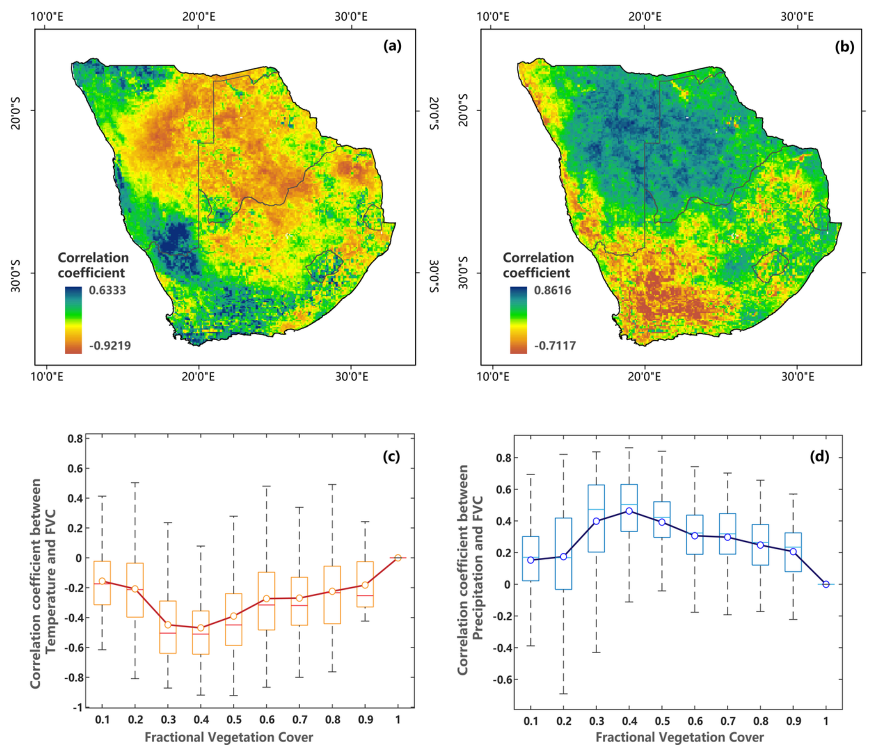


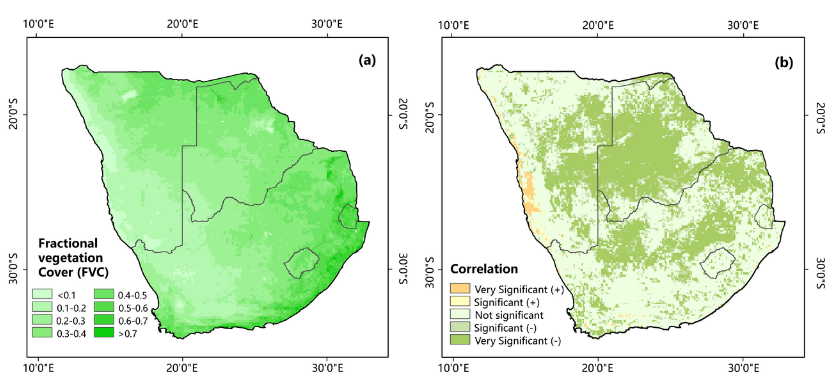
(a)
(b)
(c)
(d)
(e)
(f)
N
wind erosion modulus (t/hm²)
0-5
5-10
10-15
15-20
20-25
25-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
100-150
150-200
>200
0 500 1000
km


(a)
Wind Erosion Modulus (t/ha/a)
Year
y= -1.949x + 67.74
R² = 0.2514 p<0.01
y= -0.9909x + 52.12
R² = 0.4162 p<0.01
(b)
Wind Erosion Trend
Very significant decrease
Significant decrease
No significant change
Significant increase
Very significant increase
10°0'E
20°0'E
30°0'E
20°0'S
30°0'S


(a)
Mean temperature (℃)
Year
y = 0.012x + 13.61
R² = 0.0601 p=0.2374
(b)
Mean Annual Precipitation (mm)
Year
y = 0.6162x + 227.82
R² = 0.0174 p=0.529
(c)
Mean Annual Temperature(℃)
<9
9-12
12-15
15-18
18-21
21-24
>24
(d)
Mean Annual Precipitation (mm)
<50
50-100
100-150
150-200
200-300
300-400
>400
(e)
(f)
Correlation
Very Significant (+)
Significant (+)
Not significant
Significant (-)
Very Significant (-)
10°0'E
20°0'E
30°0'E
20°0'S
30°0'S


(a)
Mean Annual Max Wind Speed (m/s)
Year
y= - 0.0742x + 6.33
R² = 0.8703 p<0.01
(b)
Correlation
Very Significant (+)
Significant (+)
Not significant
Significant (-)
Very Significant (-)


(a)
Correlation coefficient
0.6333
-0.9219
(b)
Correlation coefficient
0.8616
-0.7117
(c)
Correlation coefficient between Temperature and FVC
Fractional Vegetation Cover
(d)
Correlation coefficient between Precipitation and FVC
Fractional Vegetation Cover


(a)
Fractional vegetation Cover (FVC)
<0.1
0.1-0.2
0.2-0.3
0.3-0.4
0.4-0.5
0.5-0.6
0.6-0.7
>0.7
(b)
Correlation
Very Significant (+)
Significant (+)
Not significant
Significant (-)
Very Significant (-)