A rainfall dipole mode characterized by negative correlation between subtropical southern Africa and equatorial eastern Africa is identified in instrumental observation data in the recent 100 years. The dipole mode shows a pronounced oscillation signal at a time scale of about 18 years. This study investigates the underlying dynamical mechanisms responsible for this dipole pattern.

It is found that the southern African rainfall dipole index is highly correlated to the land–sea contrast along the east coast of Africa. When the land–sea thermal contrast strengthens, the easterly flow toward the continent becomes stronger. The stronger easterly flow, via its response to east coast topography and surface heating, leads to a low pressure circulation anomaly over land south of the maximum easterly flow anomalies and thus causes more rainfall in the south.

On a decadal time scale, an ENSO-like SST pattern acts to modulate this land–sea contrast and the consequent rainfall dipole. During a “wet in the south and dry in the north” dipole, there are warm SSTs over the central Indian Ocean and cold SSTs over the western Indian Ocean. The cold SSTs over the western Indian Ocean further enhance the land–sea contrast during austral summer. Moreover, these cold western Indian Ocean SSTs also play an important role in regulating land temperature, thereby suppressing clouds and warming the land via increased shortwave radiation over the less-cloudy land. This cloud–SST coupling acts to further strengthen the land–sea contrast.

1. Introduction

Precipitation across the African continent is highly variable in its temporal and spatial distribution. Paleoclimate data from the last millennium indicate a climatic dipole with dry and wet conditions between eastern equatorial and subtropical southern Africa (Holmgren and Öberg 2006; Nicholson and Kim 1997; Tyson et al. 2002b). This dipole pattern in paleoclimate data is reminiscent of a similar feature in the present-day meteorological data as a major climate variability mode revealed in the dominant principal component (PC1) on an interannual time scale (Manatsa et al. 2011; Richard et al. 2001). Statistical analyses showed that, although ENSO affects regional rainfall variability, it failed to adequately explain this dipole rainfall anomaly pattern (Manatsa et al. 2011). Instead, they show that this rainfall dipole is strongly linked to the Indian Ocean dipole zonal mode (Saji et al. 1999; Webster et al. 1999). Their conclusion emphasizes a greater influence on the adjacent oceanic forcing for the rainfall dipole than the remote impact from ENSO. On a quasi-decadal time scale, earlier work by Allan et al. (2003) showed a statistically significant dipole pattern in January–March (JFM) and a less significant dipole pattern in October–December (OND) from the correlation between the southern African rainfall and the quasi-decadal ENSO time series.

On a longer time scale, such as decadal to multidecadal, more studies have been devoted to subregional rainfall variability. For instance, decadal variability has long been known to be a feature of the southern African climate system data (Neukom et al. 2014; Reason and Rouault 2002; Tyson 1986). The presence of the approximately 18-yr climate oscillation has been identified in instrumental and tree-ring series (Tyson et al. 2002a;
Visagie 1985), as well as in a recent precipitation reconstruction from the last 200 years (Neukom et al. 2014). A 16–20-yr band has also been observed in ocean temperatures around South Africa (Mason and Jury 1997), which appears to resemble a roughly 21-yr variability reported in Southern Hemisphere SST (Folland et al. 1986). Coral records in the tropical western Indian Ocean (Zinke et al. 2008) and subtropical western Indian Ocean (Zinke et al. 2009) also exhibit approximately 18-yr periodic variability in the last few hundred years. The presence of the decadal variability frequency in joint empirical orthogonal function analyses of global historical sea surface temperatures and mean sea level pressures is suggested to be related to the 18–20-yr rainfall signal in parts of southern Africa (Allan 2000). Reason and Rouault (2002) has also linked decadal-to-multidecadal ENSO-like SST anomalies to southern African rainfall variability. They have taken the seasonal difference in the southern Africa continent into consideration: namely, that tropical–extratropical cloud bands and their associated convection bring rainfall anomalies over eastern and northern South Africa in summer, whereas cold fronts influence the southwestern area. Given these seasonal differences, winter and summer rainfall indices and their associations with the ENSO-like decadal pattern are considered separately. They found that warmer SSTs in the tropical Pacific and Indian Oceans and offshore winds are responsible for a decreased summer rainfall over eastern South Africa at 9–13- and 18–39-yr time windows, respectively, while warm SSTs near South Africa at middle and high latitudes are favorable for increased frequency and more intense midlatitude systems, responsible for more winter rainfall to the southwest. However, the atmospheric dynamical process on the connection of SST anomaly patterns to subtropical southern African rainfall anomalies has not been clearly revealed.

Over equatorial eastern Africa, previous studies present clear evidence of the importance of the tropical Indian Ocean in modulating rainfall variability in observations (Black et al. 2003; Clark et al. 2003) and in climate model simulations (Goddard and Graham 1999; Latif et al. 1999). SST patterns associated with the zonal mode of variability, the Indian Ocean dipole (IOD; Tierney et al. 2013; Webster et al. 1999), and associated changes in local atmospheric circulation are implicated in several flooding events (Behera and Yamagata 2001; Black et al. 2003; Hastenrath 2007; Latif et al. 1999). Black et al. (2003) propose that the indirect ENSO–East African rainfall relationship via modulation of the tropical Indian Ocean can explain interdecadal variations in East African rainfall, with both ENSO and the IOD suppressed from the mid-1940s to the early 1960s. A precipitation record for the last 200 years for southern Africa (south of 10°S) also confirms a strong relationship between the summer rainfall and SSTs in the Indian Ocean (Neukom et al. 2014). A recent study revealed that at the decadal–centennial time scale, wet and dry conditions in equatorial eastern Africa are controlled by the variability of the Walker circulation over the Indian Ocean, with wet conditions linked to ascending motion over East Africa and the western Indian Ocean and descending motion over the eastern Indian Ocean (Tierney et al. 2013). The climate model simulations for the last millennium show that the low-frequency oscillations in the eastern and western Indian Ocean basins are capable of affecting the Walker circulation there that is independent of the Walker circulation variability over the Pacific. Significant correlations are found in the 50-yr low-pass-filtered fields representing the association of wet conditions with warm SSTs in the western Indian Ocean and cool SSTs in the eastern Indian Ocean and western Pacific warm pool. It is not certain, however, if the change in the Walker circulation can also be related to the north–south rainfall dipole pattern over southern Africa.

It is difficult to examine the underlying dynamics of the dipole mode beyond the instrumental time period because of a lack of observational data. One suitable approach may be to study the decadal–multidecadal time scale by using present-day reanalysis products with adequate spatial and temporal resolutions. A better understanding of the underlying mechanisms responsible for the dipole-mode variability at these time scales may help to interpret the longer-time-scale oscillation of this dipole as seen in proxies during the last millennium (Holmgren and Öberg 2006) via modeling experiments. Currently, there are eight contemporary global reanalyses [ERA-40, ERA-Interim, JRA-25, MERRA, the Climate Forecast System Reanalysis (CFSR), NCEP-R1, NCEP R-2, and the Twentieth Century Reanalysis version 2 (20CRv2)] available, and these reanalyses differ in their atmospheric forecast models, data assimilation systems, assimilated observation data, and SST and sea ice forcing, as well as in their temporal coverage. A recent evaluation of reanalyzed southern African precipitation shows that the newly released NCEP 20CRv2 (herein called 20CR) is most representative of the rainfall dipole mode over southern Africa, as identified in station observations and in terms of its seasonal cycle and temporal variability at intraseasonal, interannual, and decadal time scales (Zhang et al. 2013). Furthermore, the 20CR encompasses the last 140 years, making it the longest among all available reanalyses, which suits our focus on decadal-scale variability.
2. Data and methods

a. CRU TS3.1 precipitation data (1901–2009) and HadISST (1871–2008)

In this study, we use the gridded precipitation dataset Climate Research Unit (CRU) Time Series version 3.10 (CRU TS3.1) from the University of East Anglia (Mitchell and Jones 2005). This dataset is statistically interpolated from monthly station observations to regular terrestrial grids at 0.5° spatial resolution. It encompasses the period 1901–2009, which facilitates the examination of interannual-decadal variability. The CRU data have also been compared with other observation-based precipitation data, such as GPCC and GPCP, for the period during which we have compared observation data with the reanalyses (Zhang et al. 2013). The climatology and the variability patterns prove to be very similar among these observational datasets.

The monthly-mean 1°-grid global sea surface temperature data from HadISST1.1 (Rayner et al. 2003), which are also used to drive the atmospheric forecast model for 20CR, are used to investigate the influence of the SST on atmospheric variability.

b. 20CR for 1871–2008

We use 20CR for our atmospheric dynamics diagnoses, following the recent evaluation for reanalyzed precipitation in contemporary reanalyses by Zhang et al. (2013). In addition to the precipitation data, the 6-h analyzed water vapor and wind fields from 20CR are used for analyzing the moisture transport. The monthly-mean total cloud cover and downward shortwave solar radiation are used to investigate the impacts of clouds on land surface temperature.

The 20CR utilizes an ensemble Kalman filter system to assimilate surface pressure observations (Compo et al. 2011). Ensembles of short-term forecasts are generated using an atmospheric general circulation model from the NCEP operational Climate Forecast System (Saha et al. 2006) operating on an irregular Gaussian grid corresponding to a T62 horizontal resolution (grid spacing of approximately 2° × 2°), with 28 vertical levels, with the top level at 0.2 hPa. The atmosphere model is driven by time-evolving SST and sea ice distributions from the HadISST dataset (Rayner et al. 2003). The model assimilates observations of surface pressure and sea level pressure every 6 h from the International Surface Pressure Databank (ISPD), which incorporates pressure observations extracted from leading international archives of meteorological variables and contributed national and international collections.

Our study domain (0°–34°S, 6°–53°E) encompasses southern Africa: namely, the African continent south of the equator as well as Madagascar. When discussing the dipole mode over southern Africa in the remaining part of the paper, we refer to equatorial eastern Africa and subtropical southeastern Africa as the north and south regions, respectively. Since CRU data are only available over land, rainfall data over oceans in 20CR are masked out to facilitate comparisons. For related atmospheric circulation and SST patterns, we use the global analysis. To homogenize the temporal window of study for all variables, we choose to concentrate our study over the period 1901–2008.

The area-averaged rainfall index is weighted in the latitude dimension by the difference between the sine of the latitude at the northern and southern edges of the grid box. Both the correlation and regression are subjected to Student’s t significance test.

3. Observed dipole pattern of rainfall anomalies over southern Africa

The CRU observational data show that southern Africa receives 939 mm of precipitation annually (1901–2008 mean). December–March (DJFM) is the major rainy season with total precipitation of about 576 mm, which contributes 60% of the annual precipitation (Zhang et al. 2013). Here we consider the entire southern African continent as a whole and choose a statistical average of December–March to represent the majority of rainfall during the year without concerning the distinction of the long rainy season during March–May and short rainy season in October and November over equatorial eastern Africa.

The dipole pattern over southern Africa has been identified with only one proxy collected from the eastern equatorial region and two proxies from the southern African subcontinent. These proxy records indicate dry and wet conditions according to the contained-water-isotope signal or biogenic composition. The two subtropical southern African records from a stalagmite proxy in Cold Air Cave and a sediment proxy from Lake Malawi show in-phase variation for dry and wet conditions during the last millennium, while the eastern African record from Lake Naivasha shows an antiphase relationship during several centennial periods (Holmgren and Öberg 2006). A dipole-like response in rainfall over southern Africa also has been shown in relation to Indian Ocean coral records (Zinke et al. 2009). To confirm the findings with these proxies, we have plotted the one-point correlation map between a grid box closest to the Cold Air Cave (24°S, 29°E) where a stalagmite proxy is located (Holmgren et al. 2003) and rainfall anomalies over all the other grid boxes over southern Africa (Fig. 1a). A dipole pattern between subtropical southern
Africa and tropical eastern Africa is shown in the correlation map. The dipole pattern also shows up (Fig. 1b) when we choose the grid box close to the sediment proxy from Lake Naivasha (0.8°S, 36°E) (Vershuren et al. 2000). It indicates the statistical ability of these proxies to represent the long time variations of climate over southern Africa. In Fig. 1c, we first computed a rainfall index for the domain 20°–30°S, 25°–35°E, and then calculated the one-point correlation map for southern Africa with this index. The correlation maps indeed do show a dipole pattern over the region in both the DJFM-mean (Fig. 1c) and annual-mean (Fig. 1d) rainfall fields, with significant positive correlations over subtropical southern Africa south of 12°S and significant negative correlations over equatorial eastern Africa, including part of Madagascar as well as the southern part of the Congo region along the Atlantic coast (but less significant in the annual-mean map).

Based on the regional dipole pattern shown in the one-point correlation maps in Fig. 1c, we constructed time series of rainfall anomalies over subtropical southern Africa (averaged over 20°–30°S, 25°–35°E) and equatorial eastern Africa (averaged over 0°–10°S, 30°–40°E). A 10-yr low-pass filter is applied to the rainfall index time series in order to depict decadal variability. The difference between the two filtered time

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**Fig. 1.** One-point correlation maps between DJFM-mean rainfall anomalies over southern Africa and (a) a grid box close to a stalagmite proxy record in Cold Air Cave (−24°S, 29°E); (b) a grid box close to Lake Naivasha (−0.8°S, 36°E) (Vershuren et al. 2000); (c) rainfall index averaged over the domain 20°–30°S, 25°–35°E; and (d) as in (c), but for annual-mean rainfall. Correlations are calculated for the period 1901–2008 from CRU data. The shading highlights the areas where the correlations are significant at the 95% confidence level. The green boxes in (c) indicate the areas used for computing the rainfall dipole index.
A series of mean rainfall anomalies over subtropical southern Africa and that over equatorial eastern Africa is then defined as a rainfall dipole index (black curves in Fig. 2). The same analysis procedure has been applied to DJFM-mean rainfall anomalies in CRU observation data (Fig. 2a) and 20CR (Fig. 2b). Power-spectrum analyses show that the rainfall dipole index has a pronounced 18-yr oscillation both in the gridded observation and in the 20CR (figures not shown), which is very similar to the one reported in instrumental and tree-ring proxy records of the southern African climate (Tyson 1986; Visagie 1985). The 18-yr oscillation cycle in rainfall dipole variability falls well into the southern African summer rainfall decadal bands of 18–39 years as identified in Reason and Rouault (2002).

The regression maps for the rainfall variability on the decadal rainfall dipole index are shown in Fig. 3. The dipole pattern in the CRU data regression map (Fig. 3a) is quite similar to that in the one-point correlation (Fig. 1c) with some detailed regional differences because the one-point correlation analysis results in more emphasis on subtropical rainfall variability and includes subdecadal variability. The dipole pattern shown in the 20CR (Fig. 3b) is similar to that in CRU data with a negative pole over the eastern equatorial region and a positive pole over the subtropical region. The negative regression over the southern Congo along the Atlantic coast in CRU does not show up in the 20CR. It is worthwhile to point out that the nodal point of the dipole mode may shift at different time scales. For example, the nodal point is around 12°S in the observed data but was more equatorward at much longer time scales, as indicated in paleoclimate proxy data (Holmgren and Oberg 2006).

4. Dynamical processes of shifts in moisture transport and its convergence zones

We now attempt to investigate the atmospheric dynamical processes responsible for the regional rainfall anomalies using the reanalysis data. As indicated in Figs. 2 and 3, in spite of the fact that 20CR only assimilated the surface pressure, it is capable of capturing the main characteristics of the rainfall dipole mode over southern Africa, such as its spatial pattern and temporal variations, although the exact timing of the dipole-mode evolution in 20CR does not match well with the CRU observations. Therefore, we choose the 20CR to diagnose the atmospheric water vapor transport pattern associated with the rainfall dipole oscillation.

The atmospheric fields used to compute the moisture flux are 6-hourly data from winds and specific humidity in the 20CR dataset from 1901 to 2008. The horizontal resolution of these variables is 2.0°×2.0°. Both the moisture transport by the winds \(qV\) and its divergence \(\nabla \cdot qV\) are vertically integrated over nine pressure levels: 1000, 850, 700, 500, 400, 300, 200, 100, and 50 hPa. Because moisture rapidly decreases with height, the field of the vertically integrated moisture flux \(qV\) mainly represents the low-level atmospheric circulation pattern.

Figure 4a shows the climatological-mean fields of the vertically integrated moisture transport and its divergence averaged for the rainy season (DJFM) for 1901–2008. As insolation shifts toward the Southern Hemisphere in the austral summer months, the cold air branch of the Northern Hemisphere’s Hadley cell begins to cross the equator over the vast Indian Ocean surface. Meanwhile, much stronger heating over land creates a basinwide easterly land–sea breeze that supplies most of the moisture for southern Africa from the Indian Ocean. As the northeasterly moisture transport meets the southern African subcontinent, it is forced to deflect toward the south. As a result, only a part of the moisture transport coming from the Indian Ocean gets into tropical southern Africa. To conserve absolute vorticity, airflow that curves to the south will need to have a counterclockwise circulation, which then meets the easterly flow over the Indian Ocean, leading to the strong convergence zone of moisture over Madagascar. Such a counterclockwise circulation around Madagascar...
along the east coast of the southern African subcontinent explains most of the gradual southward shift of the austral summer intertropical convergence zone (ITCZ) over the Indian Ocean. The moisture coming from the Indian Ocean that does get transported into southern Africa will interact with the topography and form a low pressure trough over the land. It reflects the response of the easterlies to strong summertime surface heating over the East African highlands, similar to the formation of continental troughs in Australia, as demonstrated by a two-layer model in earlier work by Fandry and Leslie (1984). Here, the surface heating is a dominant factor for the intensity and location of the low pressure system. The ascending motion over the low pressure center is accompanied by convergence of the moisture from the Indian Ocean into the subcontinent, explaining the continuation of the southward shift of the austral summer ITCZ from the equatorial latitudes over the Indian Ocean to the subtropical latitudes over the southern African continent.

To depict the changes in moisture transport from the Indian Ocean and the shift in convergence zones associated with the dipole mode of the southern African rainfall anomalies, we show the regression of the moisture transport and its divergence on the rainfall dipole index derived from the 20CR dataset in Fig. 2b. It appears as a significant dipole pattern in the moisture transport regression as well. During a wet period over subtropical southern Africa, there is a pronounced enhancement of moisture transport from the Indian Ocean to the equatorial latitudes over the Indian Ocean and to the subtropical latitudes over the southern African continent.

The analysis in the previous section indicates that the enhancement (reduction) of rainfall over subtropical southern Africa is linked to the strengthening (weakening) of the easterly flow over the tropical east coast. In Fig. 5a, we compare the decadal variation of the zonal component of atmospheric water vapor flux $q_u$ (black curve in Fig. 5a) averaged over the domain $0^\circ$–$10^\circ$S, $40^\circ$–$50^\circ$E with the southern African rainfall dipole index (red curve in Fig. 5a, which is identical to the black curve in Fig. 2b). The correlation coefficient between the two time series is $-0.62$, confirming that stronger (weaker) easterly flow along the coast is associated with more...
Now we wish to examine what causes decadal variability of the easterly flow along the east coast of tropical southern Africa. In a normal austral summer, the land–sea contrast of warm land and cold ocean leads to an easterly sea breeze toward the continent. Variability of Indian Ocean SSTs would act to modulate austral summer land–sea contrast, responsible for the anomalous easterly wind from the ocean to the land. The black curve in Fig. 5b shows the decadal variability of the surface temperature difference between the subtropical east coast of southern Africa and its adjacent ocean. The negative correlation between the land–sea temperature difference in Fig. 5b and easterly flow in Fig. 5a confirms the conjecture above: namely, that variability in the austral summer easterly flow over southern Africa is related to the austral summer land–sea contrast between southern Africa and the adjacent Indian Ocean. Through the easterly wind anomalies, the decadal variability of the austral summer land–sea contrast over the tropical latitudes is related to the dipole mode, as indicated by its high correlation \((r = 0.88; \text{Table 1})\) with the rainfall dipole index. Although the decadal SST variability may play a major role due to the longer memory of ocean, we found that land temperature dominates in decadal variability of land–sea contrast in the tropics. The correlation of the dipole index with land temperature is much higher than that with western Indian Ocean SST \((r = -0.33; \text{Table 1})\).

To understand how land temperature can play an important role on a decadal time scale, in Fig. 6 we show the correlation map of the global DJFM-mean SST anomaly with the rainfall dipole index over the period 1901–2008. The correlation map displays a similar ENSO-like pattern as identified by Allan (2000) on a decadal time scale. Warm SSTs appear from the warm pool from the western equatorial Pacific to the South Pacific, and from the central to southern Indian Ocean, while cool SSTs are observed over the tropical western Indian Ocean. The warmer SST over the central Indian Ocean provides more moisture supply in the Indian

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**Fig. 4.** The DJFM-mean vertically integrated moisture flux (vectors) and its divergence (shading) derived from NCEP 20CR data: (a) 1901–2008 mean and (b) regression against the southern African rainfall dipole index. In (b), only the regressed moisture flux divergence anomalies that are significant at the 95% confidence level are displayed.
Ocean basin when the strengthened southward flow passes through it. Meanwhile, there is less moisture supply to equatorial eastern Africa because of cold SST over the adjacent western Indian Ocean. The colder SST will further amplify the land–sea contrast during austral summer, because the strengthened easterlies due to a stronger land–sea contrast would act to enhance evaporation feedback that causes a further SST cooling. Thus, this land–ocean interaction induces a positive feedback. We also found pronounced reduction in total cloud cover (Fig. 7a) due to less moisture. As a result, more solar radiation (Fig. 7b) reaches the equatorial region and leads to rapid warming over the land there in austral summer. Meanwhile, the warm land enhances the surface heating; subsequently, the southward deflection of easterlies becomes stronger and deepens the low pressure trough, as shown in Fig. 4b.

The results presented in Figs. 5–7 strongly suggest that the SSTs over the central Indian Ocean are important to the moisture supply in the Indian Ocean basin, whereas the decadal variability of the rainfall dipole oscillation over the southern African continent is related to the western Indian Ocean SST through its modulation of the austral summer land–ocean contrast, which in turn modulates the land–sea breeze and moisture transport toward the continent.

6. Conclusions

A rainfall dipole mode characterized by a negative correlation between subtropical southern Africa and equatorial eastern Africa in austral summer is identified in instrumental observation data. The dipole shows a pronounced decadal oscillation in both station and reanalysis data. Our results show that an ENSO-like SST anomaly pattern is related to the decadal variability of the rainfall dipole. During a wet phase of the dipole pattern, with wet conditions in the subtropical region and dry conditions in the tropical region, the ENSO-like SST pattern exhibits warm conditions over the central Indian Ocean but cold conditions in the western Indian Ocean. The cold SSTs in the western part are crucial for the land–sea temperature gradient that modulates the rainfall dipole. The cold SST in the west further enhances cold ocean temperature through a positive dynamical feedback that involves an intensified land–ocean contrast, an intensified easterly wind, and a strong evaporational cooling feedback. Meanwhile, cold SST also enhances the warm land temperature by suppressing clouds and increasing the incoming shortwave solar radiation, thus amplifying the warm land–cold ocean contrast and strengthening
the easterly flow toward the continent. The stronger easterly flow via its interaction with the topography causes a deep trough circulation into subtropical southern Africa, which is responsible for a rainier summer in the south and a less rainy summer in the north. The opposite situation occurs when the ENSO-like pattern shows cold SST over the central Indian Ocean and warm SST over the western Indian Ocean. The condition of a warm SST anomaly in the western tropical Indian Ocean contributes to a weaker land–ocean thermal contrast, a weaker easterly wind, and a shallow trough circulation that remains in equatorial southern Africa. This gives rise to more rainfall in the north and less rainfall in the south.

Our results further substantiate the earlier findings of Reason and Rouault (2002) that link rainfall over southern Africa with the ENSO-like decadal variability. We confirm that not only the subtropical southern African rainfall but also a rainfall dipole that is connected with the rainfall in the tropical region is associated with the ENSO-like SST. By using the NCEP 20CR data, we have illustrated how the ocean–atmosphere–land interaction leads to the dipole oscillation. The evidence presented in this work further suggests that it is the SST anomaly in the western Indian Ocean along the east coast of tropical Africa that directly influences decadal rainfall variability over southern Africa.

**FIG. 6.** Spatial correlations between global SSTs and the decadal southern African rainfall dipole index for the period 1901–2008 for the DJFM mean. SST data are from HadISST1.0. The absolute correlation values above 0.19 are significant at the 95% confidence level.

**FIG. 7.** Spatial correlations of (a) total cloud cover and (b) downward shortwave radiation with the decadal southern African rainfall dipole index for the period 1901–2008 for the DJFM mean. Total cloud cover and downward shortwave radiation are from NCEP 20CR. The absolute correlation values above 0.19 are significant at the 95% confidence level.
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