Storm Precipitation in the United States. Part II: Soil Erosion Characteristics

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ABSTRACT

Soil erosion is a major global challenge. An increased understanding of the mechanisms driving soil erosion, especially the storms that produce it, is vital to reducing the impact on agriculture and the environment. The objective of this work was to study the spatial distribution and time trends of the soil erosion characteristics of storms, including the maximum 30-min precipitation intensity ($I_{30}$), storm kinetic energy of the falling precipitation (KE), and the storm erosivity index (EI) using a long-term 15-min precipitation database. This is the first time that such an extensive climatology of soil erosion characteristics of storms has been produced. The highest mean $I_{30}$, KE, and EI values occurred in all seasons in the southeastern United States, while the lowest occurred predominantly in the interior west. The lowest mean $I_{30}$, KE, and EI values typically occurred in winter, and the highest occurred in summer. The exception to this was along the West Coast where winter storms exhibited the largest mean KE and EI values. Linear regression was used to identify trends in mean storm erosion characteristics for nine U.S. zones over the 31-yr study period. The south-central United States showed increases for all three storm characteristics for all four seasons. On the other hand, higher elevations along the West Coast showed strong decreases in all three storm characteristics across all seasons. The primary agricultural region in the central United States showed significant increases in fall and winter mean EI when there is less vegetative cover. These results underscore the need to update the storm climatology that is related to soil erosion on a regular basis to reflect changes over time.

1. Introduction

Soil erosion is a major challenge in the United States and the world (Oldeman 1994; Pimental et al. 1995; Nearing 2001). An increased understanding of the mechanisms driving soil erosion, especially the storms that produce it, is vital to reducing its impact on agriculture and the environment. The potential for climate change, in the form of changing storm characteristics, is an additional challenge to the management of soil erosion. A recent study (Soil and Water Conservation Society 2003) discussed the implications of possible climate change and suggested the following three approaches to begin addressing the issue: 1) update the climate parameters in conservation tools, 2) investigate the damages likely to occur as a result of a changed precipitation regime, and 3) evaluate the benefits of including the risks from extreme rain events in the conservation-planning process.

Groisman et al. (2004) reviewed changes in precipitation for the contiguous United States, noting that overall precipitation had increased by 7% between 1908 and 2002. Heavier precipitation events at the 95th and 99th percentile had increased even more, by 14% and 20%, respectively. Furthermore, most of these changes occurred in the last 30 yr of record (Soil and Water Conservation Society 2003). The Groisman et al. study noted that the increases in precipitation were...
largely confined to spring, summer, and fall, which is
the period when heavier events are likely to occur.
While they were focused on the more extreme daily
events and the annual totals, these results have serious
implications for individual storm events and their ero-
sive potential.

Other studies have examined the potential changes
in future rainfall erosivity using coupled atmosphere–
ocean global climate models as guidance for climate
change in the twenty-first century (e.g., Nearing 2001;
Pruski and Nearing 2002). While there were regional
differences in the results, Nearing (2001) found that
erosion over the United States increased between 16%
and 58% in projections over the next 80 yr, depending
on the methodology applied. Pruski and Nearing (2002)
used the Water Erosion Prediction Project (WEPP)
model and output from two global climate models to
to examine changes in soil erosion in response to climate
change. As expected, erosion increased in those areas
where precipitation increased. However, the relation-
ship became more complex in areas with decreased pre-
cipitation. For example, decreased precipitation could
decrease vegetation, leading to increased erosion. In a
summary of climate change and soil erosion rates,
Nearing et al. (2004) noted that soil erosion rates can be
expected to increase by 1.7% for each 1% increase in
annual precipitation. Clearly, these studies point to the
need to closely examine present-day storm erosivity in
the United States and its observed change over time.
Prior to this study, no such modern climatology for the
United States has been produced.

Palecki et al. (2005, hereinafter Part I) examined the
meteorological characteristics of storm precipitation.
Our objective was to study the spatial distribution and
time trends of the storm erosion characteristics of rain-
storms in the conterminous United States, including the
storm maximum 30-min precipitation intensity \(I_{30}\),
storm kinetic energy (KE), and the storm erosivity in-
dex (EI). Storm erosional characteristics for each of the
four climatological seasons of winter (December–Janu-
ary–February), spring (March–April–May), summer
(June–July–August), and fall (September–October–
November) were examined. The storm erosion charac-
teristics were grouped into nine zones, representing co-
herent seasonal cycles of storm precipitation character-
istics (Fig. 1).

2. Data and methods

Storm soil erosion characteristics were computed us-
ing the National Climatic Data Center (NCDC) 15-min
precipitation database as measured by a network of
Fischer–Porter weighing-bucket gauges (Hammer
1998). This network of unshielded gauges has remained
unchanged during its operation within the period of this
study (1972–2002). In a review of the U.S. climate net-
work, Groisman and Legates (1994) examined the ac-
curacy of precipitation measurements. They concluded
that gauges underestimate the actual precipitation,
largely because of wind-induced turbulence. The prob-
lem is worst in winter and northern latitudes, because
the snowfall catchment is especially sensitive to wind.
No attempt was made here to identify or adjust for such
biases on a storm-by-storm basis. However, this inher-
ent limitation of the data should be kept in mind while
considering the results of this study, especially for win-
ter.

While approximately 3700 stations are included in
the 15-min precipitation database, many stations had
missing records, and some had record lengths of less
than 10 yr. The database was first screened to identify
stations with a record length of greater than 20 yr and
with less than 25% missing data, resulting in the final
selection of 1505 stations in the conterminous United
States.

Each 15-min record includes quality control flags in-
dicating missing data, accumulated data, and data
flagged by NCDC for quality control reasons (Hammer
1998). In computing the storm soil erosion characteris-
tics, only storms that had no flags present and were
separated from flagged or missing data by more than 6
h were used. The “6 h between storms” rule has been
used extensively in previous work (e.g., Huff 1967;
Wischmeier and Smith 1978; Renard et al. 1997).

Once each storm was identified, \(I_{30}\), KE, and EI were
computed. The \(I_{30}\) was computed by summing the pre-
cipitation in each consecutive pair of 15-min periods
during a storm and multiplying the greatest 30-min total
precipitation by 2 to get the rate in millimeters per
hour. The resulting rate was then adjusted by 1.034 to

Fig. 1. Storm precipitation characteristic cluster zones. Stations in zones 8 and 9 on the West Coast are intermingled but separated
by elevation (see text). For a more detailed rendering of zones 8
and 9, please see Fig. 1 in Part I.
represent a maximum 30-min precipitation rate that would be obtained from break-point data (Hollinger et al. 2002). Break-point precipitation data are reported as time segments of an equal intensity rather than amounts at fixed time intervals, and, therefore, can capture the true 30-min maximum of a storm.

The KE, a measure of the accumulated kinetic energy of the precipitation as it strikes the ground, has been computed using a power-law equation (Uijlenhoet and Stricker 1999), a logarithmic function (Wischmeier and Smith 1958), and an exponential equation (Kinnell 1980; Brown and Foster 1987; Renard et al. 1997). In a critical literature appraisal, van Dijk et al. (2002) conclude that the exponential equation is the best estimate of kinetic energy because it places an upper limit on kinetic energy at high precipitation intensities (Hudson 1963; Barauah 1973; Carter et al. 1974; Wischmeier and Smith 1978; Kinnell 1980; Rosewell 1986; Brown and Foster 1987). The total KE (MJ ha\(^{-1}\)) is calculated after Renard and Freimund (1994),

\[
KE_k = \sum_{r=1}^{s} e_r \Delta V_r,
\]

where \(e_r\) is the kinetic energy (MJ ha\(^{-1}\) mm\(^{-1}\)), \(\Delta V_r\) is the precipitation depth (mm) of a given storm increment, and the summation is over the storm increments (1 to \(s\)). The number of increments (\(s\)) is determined by the storm length and data resolution. In this case where 15-min data are used, if a storm lasts 2 h, then \(s = 8\). The kinetic energy \(e_r\) is computed with the continuous exponential equation from Renard and Freimund (1994), as modified by McGregor et al. (1995):

\[
e_r = 0.29[1 - 0.72 \exp(-0.082i_r)],
\]

where \(i_r\) is the precipitation intensity (mm h\(^{-1}\)) for a particular storm increment. The McGregor et al. (1995) modification changed the exponential coefficient to 0.082 from 0.05 (Renard and Freimund 1994). The total EI (MJ mm ha\(^{-1}\) h\(^{-1}\)) is computed as

\[
EI = KE(I_{30}).
\]

The Fischer–Porter weighing-bucket gauge will measure snowfall events. However, the concepts of the kinetic energy of the falling precipitation and storm erosivity are not meaningful in these situations. A portion of these gauges is not collocated with climatological sites that collect temperature and snowfall data. Furthermore, those climatological sites that are collocated with gauges report only once a day, with the exact time varying from site to site. As a result, individual snow “storms” cannot be reliably identified and removed from the analysis. Therefore, the results for winter in colder climates may not always represent the potential for soil erosion.

Seasonal mean storm precipitation total, storm duration, storm intensity, and storm maximum 15-min intensity examined in Part I, as well as \(I_{30}\), KE, and EI statistics for each of the four seasons for each station, were input into a cluster analysis using Ward’s method to identify regions with homogeneous seasonal cycles of storm characteristics (Part I). This resulted in nine spatially coherent clusters or zones across the conterminous United States. (Fig. 1). Stations in West Coast zones 8 and 9 are intermixed, with zone 8 predominantly at lower elevations and interior valleys and zone 9 at higher elevations. There are also two zone 8 enclaves in northern Idaho and near Phoenix, Arizona. For a more detailed map of zones 8 and 9, see Fig. 1 in Part I.

In addition to studying the seasonal mean erosional characteristics in each zone, the statistical distribution of storm characteristics is very useful for constructing storm time series to be used in erosion modeling. The probability density function (PDF) of each storm characteristic was determined by testing the fit of two equation families to the empirical probability bins for each season and zone and finding the most appropriate fit. The first equation that is used is the double exponential:

\[
y = ae^{-(x-b)/c} + ce^{-(x-b)/d}.
\]

The coefficients \(a, b, c,\) and \(d\) are fit using nonlinear regression procedures in TableCurve 2D (SYSTAT 2002). The second equation is a more general family of curves that can be derived from the transformed general form

\[
\ln y = a + bx^\beta(\ln x)^\gamma + cx^\gamma(\ln x)^\gamma.
\]

Parameters \(\beta, \gamma,\) and \(\gamma\) define the general form of the equation, and the coefficients \(a, b,\) and \(c\) are fit using linear regression procedures from TableCurve 2D (SYSTAT 2002). Examples of the fit of these curves to the data are presented in Part I. Because of the potential usefulness of these curves, an appendix has been created with the coefficients of the best-fit curve to each empirical distribution, and the range of data where the distribution fits well.

The storm characteristics were analyzed in two ways in the following section. The nonextreme events were analyzed by the mean values and fitted distributions, while the extreme events were characterized by the 10-yr storm. The mean for each storm characteristic was calculated by season for all of the storms recorded at all of the stations in each of the nine zones. Then, the
means were compared statistically with the Student’s t test to determine both regions with similar characteristics by season, and seasons with similar characteristics by region.

The mean 10-yr storm for each zone and season was derived from the 10-yr storms that were calculated for each station within the zone. The station 10-yr storms were generated by fitting the two-parameter Gumbel distribution to the annual extreme series of the storm characteristic using L-moments software (Hosking 1991). The 10-yr interval was examined because of the programmatic importance of this return frequency that is specified in government soil erosion mitigation policies (e.g., Renard et al. 1997). The mean 10-yr return interval estimate and two standard error bounds were generated for each zone and season from the individual stations.

Trends in the three mean storm erosion characteristics for each zone were evaluated using linear regression with time. The input data were annual time series of 31 values for the period of 1972–2002, derived by computing the averages of all of the sites in each zone. Using the resulting regression equations, the change in each storm characteristic from 1972 to 2002 was calculated as the regression estimate for 2002, minus the regression estimate for 1972, divided by the 1972 estimate. This is then expressed as a percent change over the 31-yr period, giving an indication of the relative size of the change.

3. Results and discussion

a. Maximum 30-min precipitation intensity

The $I_{30}$ of a storm is a useful indicator of the storm’s intensity at its peak. The mean and 10-yr $I_{30}$ values are shown in Table 1. The highest amounts occurred in all seasons in zone 1, the one closest to the Gulf of Mexico, which is a major source of atmospheric moisture for storms and the scene of frequent tropical storms. The values generally decrease when moving farther away from the Gulf of Mexico. The lowest values are in the interior west and West Coast. In general, the lowest values occurred in winter and the highest were in summer, except for zone 9 when the higher values were in winter.

The probability density functions (PDFs) of the $I_{30}$ for all seasons and zones are shown in Fig. 2. The PDFs illustrate the response of $I_{30}$ in the tails of the distributions as well as the central tendencies. There is a general pattern of higher intensities in summer, largely due to the convective nature of the storms during that season. Zones 4–6 are generally skewed toward less intense $I_{30}$ amounts. In most cases the probabilities are similar for spring, summer, and fall, whereas winter is clearly different, because nonconvective precipitation processes tend to dominate. The largest difference among the seasons can be found in zone 6 in the northern United States.

b. Storm kinetic energy

The mean and 10-yr total KE of the falling precipitation (in MJ ha$^{-1}$) is shown in Table 2. In general, the largest values occurred in summer and fall, and the lowest were in winter in zones 1–7. Zones 8 and 9 had higher average values in winter, reflecting their West Coast maritime climate of wet winters and dry summers.

The PDFs of the average KE for all seasons and zones are shown in Fig. 3. In most cases, there are smaller differences between the seasons than in the PDFs for $I_{30}$. In the east, larger KE values are found in zones 1–3, with the distribution becoming more skewed toward smaller KE values in zones 4–7 as distance increases from the important moisture source of the Gulf.
TABLE 2. The KE (MJ ha⁻¹) mean and 10-yr storm interval estimate bounded by 2 times the standard error for each zone and season. Zones with the same superscript letter in a column are not significantly different at α = 0.05, and zones with the same superscript number for a season in the same row are not significantly different at α = 0.05.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Mean Winter</th>
<th>Mean Spring</th>
<th>Mean Summer</th>
<th>Mean Fall</th>
<th>10-yr KE Winter</th>
<th>10-yr KE Spring</th>
<th>10-yr KE Summer</th>
<th>10-yr KE Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.46</td>
<td>3.89</td>
<td>3.20</td>
<td>3.64</td>
<td>25.7 ± 1.1</td>
<td>30.8 ± 1.4</td>
<td>27.3 ± 1.0</td>
<td>31.4 ± 1.2</td>
</tr>
<tr>
<td>2</td>
<td>2.78</td>
<td>3.23</td>
<td>3.08</td>
<td>3.50</td>
<td>20.0 ± 0.7</td>
<td>24.4 ± 0.6</td>
<td>23.2 ± 0.6</td>
<td>27.0 ± 0.8</td>
</tr>
<tr>
<td>3</td>
<td>1.54</td>
<td>2.39</td>
<td>2.69</td>
<td>2.63</td>
<td>9.6 ± 1.1</td>
<td>16.8 ± 1.3</td>
<td>21.3 ± 1.2</td>
<td>19.8 ± 1.4</td>
</tr>
<tr>
<td>4</td>
<td>2.18</td>
<td>2.44</td>
<td>2.81</td>
<td>2.85</td>
<td>14.8 ± 0.5</td>
<td>18.6 ± 0.4</td>
<td>22.1 ± 0.4</td>
<td>21.9 ± 0.5</td>
</tr>
<tr>
<td>5</td>
<td>1.33</td>
<td>1.90</td>
<td>2.63</td>
<td>2.07</td>
<td>8.3 ± 0.4</td>
<td>14.3 ± 0.4</td>
<td>20.8 ± 0.4</td>
<td>15.6 ± 0.4</td>
</tr>
<tr>
<td>6</td>
<td>1.44</td>
<td>1.71</td>
<td>2.19</td>
<td>1.99</td>
<td>10.2 ± 0.4</td>
<td>12.4 ± 0.4</td>
<td>17.3 ± 0.4</td>
<td>15.8 ± 0.5</td>
</tr>
<tr>
<td>7</td>
<td>1.09</td>
<td>1.21</td>
<td>1.56</td>
<td>1.33</td>
<td>5.5 ± 0.4</td>
<td>8.3 ± 0.3</td>
<td>10.9 ± 0.4</td>
<td>8.6 ± 0.4</td>
</tr>
<tr>
<td>8</td>
<td>2.22</td>
<td>1.54</td>
<td>1.38</td>
<td>2.00</td>
<td>20.3 ± 1.8</td>
<td>13.1 ± 1.0</td>
<td>7.7 ± 0.6</td>
<td>15.3 ± 1.2</td>
</tr>
<tr>
<td>9</td>
<td>3.53</td>
<td>2.21</td>
<td>1.62</td>
<td>3.00</td>
<td>31.4 ± 2.1</td>
<td>19.2 ± 1.3</td>
<td>9.0 ± 0.7</td>
<td>22.2 ± 1.5</td>
</tr>
</tbody>
</table>

Fig. 2. Maximum $I_{50}$ probability density distributions for all nine zones and four seasons.
of Mexico. In zones 1–5, summer and fall tend to have higher KE values; winter and fall are more dominant in zones 6–9.

c. Storm erosivity index

The mean and 10-yr EI (MJ mm ha⁻¹ h⁻¹) is the result of multiplying the $I_{30}$ by the KE (Table 3) and is considered to be highly correlated to rainfall erosivity (Wischmeier and Smith 1978). Spring values were slightly higher in zone 1, and summer was highest in zones 2–7. Only zones 8 and 9 had the highest values in winter.

The PDFs for EI are shown in Fig. 4. In zones 1–3, the differences between the seasons are relatively small. In zones 4–7, the differences between seasons become greater, with summer producing the highest numbers and winter producing the smallest numbers. In zones 8 and 9, the roles reverse, with summer contributing to lower amounts while fall and winter play a larger role.

The spatial patterns of storm characteristics were generally coherent. High values along the Gulf of Mexico reflect the influence of the Gulf as a source of moisture in all seasons. The influence of this moisture source region decreased away from the coast. The seasonal patterns of storm characteristics were also similar with warm season precipitation events having the largest magnitudes for all three storm erosion characteristics. The exception to this was the West Coast (zones 8 and 9), where winter events were more energetic. Most of this area is known for a West Coast maritime climate with wet winters and a dry, warm summer season. Storm erosion characteristics were lowest in magnitude in zone 7 in all seasons except summer, when zones 8 and 9 were the lowest. Zone 7 is the interior west and
Table 3. The EI (MJ mm ha\(^{-1}\) h\(^{-1}\)) mean and 10-yr storm interval estimate bounded by 2 times the standard error, for each zone and season. Zones with the same superscript letter in a column are not significantly different at \(\alpha = 0.05\), and zones with the same superscript number for a season in the same row are not significantly different at \(\alpha = 0.05\).

<table>
<thead>
<tr>
<th>Zone</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77.3</td>
<td>127.1</td>
<td>117.1</td>
<td>115.3</td>
<td>1201.2</td>
<td>2097.3</td>
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<td>96.8</td>
</tr>
<tr>
<td>2</td>
<td>45.3</td>
<td>85.9</td>
<td>103.7</td>
<td>96.8</td>
<td>668.5</td>
<td>1396.5</td>
<td>55.1</td>
<td>1588.8</td>
</tr>
<tr>
<td>3</td>
<td>18.8(^a)</td>
<td>63.6(^b)</td>
<td>83.4</td>
<td>67.5</td>
<td>225.2</td>
<td>939.8</td>
<td>122.0</td>
<td>376.2</td>
</tr>
<tr>
<td>4</td>
<td>23.9</td>
<td>42.1</td>
<td>80.8</td>
<td>56.2</td>
<td>334.8</td>
<td>758.0</td>
<td>35.5</td>
<td>1371.3</td>
</tr>
<tr>
<td>5</td>
<td>10.5</td>
<td>26.6</td>
<td>71.2</td>
<td>32.1</td>
<td>129.8</td>
<td>526.7</td>
<td>25.3</td>
<td>1272.7</td>
</tr>
<tr>
<td>6</td>
<td>9.9</td>
<td>16.3</td>
<td>43.1</td>
<td>23.6</td>
<td>139.0</td>
<td>288.9</td>
<td>15.9</td>
<td>807.6</td>
</tr>
<tr>
<td>7</td>
<td>7.3</td>
<td>10.5</td>
<td>28.6(^a)</td>
<td>13.0</td>
<td>61.7</td>
<td>159.5</td>
<td>12.4</td>
<td>480.5</td>
</tr>
<tr>
<td>8</td>
<td>19.6(^a)</td>
<td>11.6</td>
<td>14.9</td>
<td>18.0</td>
<td>335.9</td>
<td>190.4</td>
<td>19.2</td>
<td>165.2</td>
</tr>
<tr>
<td>9</td>
<td>18.8</td>
<td>19.8</td>
<td>17.5(^a)</td>
<td>32.1</td>
<td>629.9</td>
<td>322.6</td>
<td>37.2</td>
<td>177.6</td>
</tr>
</tbody>
</table>

Fig. 4. The EI probability density distributions for all nine zones and four seasons.
the Great Plains—an area known for being the driest in the United States in all seasons. These storm erosion characteristic patterns are explained by the seasonal water availability from source regions, the atmospheric water vapor capacity (a function of temperature), and predominant precipitation mechanisms (convective or stratiform).

d. Trends in mean storm erosion characteristics

The results of the trend analysis of mean storm characteristics are summarized in Table 4. Mean $I_{30}$ increased across zones 1–5 during the winter, decreased in zones 1–3 in spring and summer, and increased in zones 4–8 in spring and summer. Zone 3 winters experienced the largest percent increase during the study period, 19.5%. The three zones closest to the Gulf of Mexico showed evidence of decreasing $I_{30}$ amounts in spring, and to a lesser extent in summer. During spring and summer, generally small increases were found in zones 4–8. Fall showed the least spatial coherence of the four seasons with little or no changes over time, except in zone 1. Zone 4 showed upward trends in all four seasons, although only the winter trend shows any statistical significance. Along the West Coast, zone 8 showed small increases in all seasons, while at the higher elevations zone 9 showed decreases in all seasons.

Mean KE (Table 4) is strongly related to storm total precipitation (Part I) as shown in Eq. (1). Eastern U.S. zones 1–5 show increasing trends in mean KE during winter, while zones 6–9 show decreases. The far southern zones 1 and 2 reverse this signal with decreasing precipitation (Part I) as shown in Eq. (1). Eastern U.S. zones 1–8 in spring and summer, generally small increases were found in zones 4–8. Fall showed the least spatial coherence of the four seasons with little or no changes over time, except in zone 1. Zone 4 showed upward trends in all four seasons, although only the winter trend shows any statistical significance. Along the West Coast, zone 8 showed small increases in all seasons, while at the higher elevations zone 9 showed decreases in all seasons.

Mean KE (Table 4) is strongly related to storm total precipitation (Part I) as shown in Eq. (1). Eastern U.S. zones 1–5 show increasing trends in mean KE during winter, while zones 6–9 show decreases. The far southern zones 1 and 2 reverse this signal with decreasing trends in mean KE during the spring, as do zones 7–9 in the West. Summer and fall have quite varied trends across the conterminous United States. Zone 4 in the Midwest shows fairly consistent positive trends in mean KE in all seasons, although they are strongest in the winter. Meanwhile, zone 9 shows fairly large decreases in mean KE in all four seasons.

The high-elevation zone 9 is easy to analyze for mean EI trends, because both component parts—mean $I_{30}$ and mean KE—trend negatively in every season. Therefore, mean EI trends are strongly negative in zone 9, ranging from $-2.7\%$ in fall to $-26.6\%$ during summer. With similar reasoning, zone 4 shows consistent increases across all four seasons and all three storm characteristics. Zones 1–5 also showed increases in EI in winter, as did zones 1, 3, and 4 in fall. Increasing EI trends are also apparent in zones 5–7 during spring and summer. Zone 5 encompasses the Corn Belt, and so the 26.0%, 10.2%, and 8.3% increases in storm erosion index during winter, spring, and summer, respectively, could lead to significant impacts to agriculture and water quality. Because farm fields are less likely to be covered during these seasons, increased erosion could result. As noted in section 2, the Fischer–Porter gauge does collect snow events and, therefore, may not entirely reflect the potential for soil erosion during winter months.

The zones and seasons with consistently strong trends for all three mean storm characteristics include fall in zone 1, with large increases in $I_{30}$ and KE leading to a 42.8% increase in EI (Fig. 5a) from 1972 to 2002 (94–135 MJ mm ha$^{-1}$ h$^{-1}$, respectively). The same is true for winter in zone 3, with a 69.1% increase in mean EI (Fig. 5b) from 1972 to 2002 (from 13 to 22 MJ mm

Table 4. Trends in mean storm characteristics from 1972 to 2002 expressed as a percent change over the entire period. Entries marked with ** are significant at the $p = 0.05$ level, and those marked with * are significant at the $p = 0.10$ level.

<table>
<thead>
<tr>
<th>Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Max 30-min precipitation intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>2.3 &amp; 5.2</td>
<td>19.5*** &amp; 7.4* &amp; 4.6 &amp; -1.6 &amp; 0.2 &amp; 3.5 &amp; -1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
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ha\(^{-1}\) h\(^{-1}\)). To the west, summer in zone 7 shows increases in all three mean storm characteristics (Fig. 5c), while zone 9 shows strong decreases (Fig. 5d). The resulting changes in EI are significant—a 17% increase for zone 7 in the summer and a 26.6% decrease in zone 9 in the summer.

4. Summary and conclusions

The objective of this work was to provide a unique study of the spatial distribution and time trends of the soil erosion characteristics of individual storms, as opposed to daily or monthly precipitation, including the maximum 30-min precipitation intensity \(I_{30}\), storm kinetic energy (KE), and the storm erosivity index (EI). This is the first time that such an extensive climatology of soil erosion characteristics of storms in the United States has been produced.

Erosional characteristics for each of the four traditional seasons of spring (March–April–May), summer (June–July–August), fall (September–October–November), and winter (December–January–February) were examined. The storm soil erosion characteristics were computed using the NCDC 15-min precipitation database. Because of the challenges in the spatial distribution, length of record, and quality of individual stations, the storm characteristics were aggregated by zones derived from a cluster analysis to create more robust spatial and temporal patterns and to allow for the use of standard statistical testing.

The highest mean \(I_{30}\), KE, and EI values occurred in all seasons in the southeastern United States, while the lowest occurred predominantly in the interior west. The lowest mean \(I_{30}\), KE, and EI values typically occurred in winter, while the highest occurred in summer. The exception to this was along the West Coast, where winter storms exhibited the largest mean KE and EI values. Storm erosion characteristics were lowest in magnitude in zone 7 in all seasons except summer, when zones 8 and 9 were lowest. These storm erosion characteristic patterns are explained by the underlying physical processes that are present during the seasons.

![Fig. 5. Selected statistically significant trends in EI for (a) fall in zone 1, (b) winter in zone 3, (c) summer in zone 7, and (d) summer in zone 9.](image)
Trends in mean storm characteristics for each zone were evaluated using linear regression. Because EI is the product of $I_{SO}$ and KE, the trends in those two parameters are reflected in EI. Previous research mentioned in section 2 has shown that EI is closely related to soil erosion. Zone 9 showed downward trends in all four seasons, while zone 4 showed upward trends in all four seasons. Mean EI increased through most of zones 1–5 in fall and winter, a time when fallow farm fields may be more vulnerable to soil erosion. Meanwhile, increasing trends in mean EI are evident for spring and summer in zones 5–7. Further examination of the physical processes driving these changes is warranted because they may lead to insights on potential future changes.

This study shows that the storm characteristics related to soil erosion ($I_{SO}$, KE, and EI) reflect the underlying processes that also drive total precipitation, processes such as orographic features and proximity to oceans, especially the warm Gulf of Mexico. More challenging for U.S. conservation policy and practices are the significant changes in storm erosivity characteristics that have occurred during the period of 1972–2002. As a result, some portions of the country, for example, the Corn Belt located in zone 5, may be more vulnerable to soil erosion over the course of the 31-yr study period.

In addition to long-term climate variability and change, preliminary research by Palecki et al. (2002) suggests that storm characteristics are sensitive to largescale interannual climate variability, for example, with the Pacific decadal oscillation (PDO). A further examination of the impacts of climate variability issues related to storm soil erosion characteristics is currently underway, including the influence of El Niño–Southern Oscillation events. The 31-yr record used in this study is too short to determine if the noted changes in storm

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errosion characteristics are part of long-term climate change or are driven by slow oscillations in teleconnection patterns, such as PDO. However, these results suggest that the changes in the risk of soil erosion are large enough over time that climate change and variability must be actively built into soil conservation policy and practices. One way of doing this is to immediately and regularly update the climatic parameters in critical conservation planning tools and to continue to do so to reflect current climate conditions as suggested by the Soil and Water Conservation Society (2003).

Acknowledgments. This work was supported by Cooperative Agreement AG 68-7482-7-306 between the National Water and Climate Center (NWCC) of the U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS); and National Oceanic and Atmospheric Administration (NOAA) Cooperative Agreement NA67RJ0146. The constructive comments of and discussions with Greg Johnson are greatly appreciated. Dan Wilks provided valuable insight on fitting probability density functions to the storm characteristics. The views expressed herein are those of the authors and do not necessarily reflect those of the USDA-NRCS NWCC, NOAA, or the ISWS.

APPENDIX

Coefficients of PDF Curves by Zone and Season

In Tables A1–A3, the equations that best fit the probability distribution for each variable, season, and zone are identified as either Eq. (4) or Eq. (5) (see section 2). The appropriate parameters are identified for cases using Eq. (5), and the regression coeffi-
coefficients for the best fit of an analytical curve to the empirical PDF are given for all of the equations.

REFERENCES


