Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century

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ABSTRACT: The erosive power of rainfall can be expected to change as climate changes. Such erosive changes are likely to have significant impacts on local and national soil conservation strategies. This study uses results of climate change scenarios from two coupled Atmosphere-Ocean Global Climate Models to investigate the possible levels and patterns of change that might be expected over the 21st century. Results of this study suggest the potential for changes in rainfall erosivity across much of the continental United States during the coming century. The magnitude of change (positive or negative) across the country over an 80 year period averaged between 16–58%, depending upon the method used to make the predictions. Some areas of the country showed increases and others showed decreases in erosivity. Spatial distributions of calculated erosivity changes indicated areas of both consistency and inconsistency between the two climate models.

Keywords: Atmosphere-ocean global climate models, precipitation, RUSLE, soil erosion

Soil erosion rates may change in response to changes in climate for a variety of reasons, including climatic effects on plant biomass production, plant residue decomposition rates, soil microbial activity, evapotranspiration rates, soil surface sealing and crusting, and shifts in land use necessary to accommodate a new climatic regime (Williams et al. 1996). However, the most consequential effect of climate change on water erosion will be in changes of erosive power, or erosivity, of rainfall.

Studies using erosion simulation models (Nearing et al. 1989; Flanagan and Nearing 1995) indicate that erosion response is much more sensitive to the rainfall amount and intensity than to other environmental variables (Nearing et al. 1990). Warmer atmospheric temperatures associated with greenhouse warming are expected to lead to a more vigorous hydrological cycle, including more extreme rainfall events (IPCC 1995). Such a process may already be taking place in the United States. Historical weather records analyzed by Karl et al. (1996) indicate that since 1910 there has been a steady increase in area of the United States affected by extreme precipitation events (> 50.8mm in a 24 hr period), and there is less than one chance in a thousand that this observed trend could occur in a quasi-stationary climate. Karl et al. (1996) also observed an increase in proportion of the country experiencing a greater than normal number of wet days.

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Atmosphere-Ocean Global Climate models also indicate potential changes in rainfall patterns, with changes in both the number of wet days and percentage of precipitation coming in intense convective storms as opposed to longer duration, less intense storms (McFarlane et al. 1992; Johns et al. 1997).

Rainfall erosivity is strongly correlated to the product of total rainstorm energy and maximum 30 minute rainfall intensity during a storm (Wischmeier and Smith 1978). The relationship first derived by Wischmeier and Smith has proved to be robust and is still used today in the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997), which is the current technology applied in the United States for conservation planning and compliance. Studies using a physically-based, continuous simulation model of erosion have also substantiated the geographic trends of published R factors for several parts of the United States (Baffaut et al. 1996).

A direct computation of the rainfall erosivity factor, R, for the RUSLE model requires long term data for rainfall amounts and intensities. Current global circulation models do not provide details requisite for a direct computation of R factors (McFarlane et al. 1992; Johns et al. 1997). However, the models do provide scenarios of monthly and annual changes in total precipitation around the world.

Renard and Freimund (1994) evaluated erosivity at 155 locations within the continental United States, and developed statistical relationships between the R factor and both total annual precipitation at the location and a modified Fournier coefficient (Fournier 1960; Arnoldus 1977), F, calculated from monthly rainfall amounts as

$$F = \frac{\sum_{i=1}^{12} P_i^2}{P} \qquad (1)$$

where p_i (mm) is the average monthly precipitation and P (mm) is the average annual precipitation.

Derived relationships between R factor and P developed by Renard and Freimund (1994) were

$$\text{R factor} = 0.04830P^{1.610} \quad (r^2 = 0.81) \qquad (2)$$[1]

and

$$\text{R factor} = 587.8 - 1.219P + 0.004105P^2 \quad (r^2 = 0.73) \qquad (3)$$

and the relationships between R factor and F were

$$\text{R factor} = 0.7397F^{1.847} \quad (r^2 = 0.81) \qquad (4)$$[2]

and

$$\text{R factor} = 95.77 - 6.081 + 0.04770F^2 \quad (r^2 = 0.75) \qquad (5)$$

where the R factor is in units of (MJ mm ha^{-1} yr^{-1}).

Equations 2 and 4 provided a better fit on the lower end of the data range, and equations 3 and 5 fit better on the upper end; therefore, Renard and Freimund (1994) recommended using equation 2 when P was < 850 mm and equation 3 when P was > 850 mm. Likewise, they recommended using equation 4 when F was < 55 mm and equation 5 when F was > 55 mm.

The objective of this study was to estimate potential changes in rainfall erosivity in the United States during the 21st century under global climate change scenarios generated from two coupled Atmosphere-Ocean Global Climate models.

Methods and Materials

Two coupled Atmosphere-Ocean Global Climate models from which results were used were developed by the

UK Hadley Centre and the Canadian Centre for Climate Modelling and Analysis.

The most current UK Hadley Centre model, HadCM3 (Gordon et al. 2000; Pope et al. 2000; Wood et al. 1999), is the third generation of Atmosphere-Ocean Global Climate models produced by the Hadley Centre. It simulates a 1% increase in greenhouse gases for the study period, and the effects of sulphate aerosols. The model also considers the effects of minor trace gases, CH_4, N_2O, CFC11, CFC12, and HCFC22 (Edwards and Slingo 1996), a parameterization of simple background aerosol climatology (Cusack et al. 1998), and several other improvements over the previous Hadley Centre model, HadCM2. Results from the model are reported on a 2.5° latitude by 3.75° longitude grid.

The Canadian Global Coupled model, CGCM1 (Boer et al. 2000), is composed of an atmospheric component based on the model GCMII (McFarlane et al. 1992) coupled with an ocean component based on the model GFDL MOM1.1 (Boer et al. 2000). We used results from the simulation GHG + A1, which incorporated an increase of atmospheric concentration of greenhouse gases (GHG) corresponding to a rate of increase of 1% per year for the study period, and the direct forcing effect of sulphate aerosols (Reader and Boer 1998). Data from this model were presented on a Gaussian 3.75° by 3.75° grid.

Changes in rainfall erosivity for the two models were computed for two time intervals, 40 yr and 80 yr. In the first case, erosivity values from 2040–2059 were compared those from 2000–2019, and in the second case erosivity values from 2080–2099 were compared to those from 2000–2019. Ideally, it would have been advantageous to also compare results for future predictions of erosivity to historical values. However, results from the climate change models are an integrated average over the grid square, thus using an historical record from a specific location within the grid would not be a compatible comparison with the information for the entire grid. Using the period of 2000–2019 to represent current conditions should provide conservative results on erosivity changes.

Erosivity changes were computed in two ways. First, as a function of change in average annual precipitation for the 20 yr periods, using equations 2 and 3. Second, as a function of the Fournier coefficient for the 20 yr periods using equations 4 and 5. Erosivity values were mapped only for the 80 yr results. Maps were constructed on a rectangular grid following the manner in which the data were extracted from the climate change models. No attempt was made to limit the coverage of maps to the continental boundaries because many of the grid squares on the boundary covered only a small portion of the land area, and it was not possible with our mapping software to plot a partial grid square. Rather than decide on which grid squares to retain and which to eliminate along the boundary, we simply plotted all squares.

Results and Discussion

Erosivity results calculated from the Hadley Centre model analyses indicated a general increase in rainfall erosivity over large parts of the eastern United States, including most of New England and the mid Atlantic states as far south as Georgia, as well as a general increase across the northern states of the U.S. and southern Canada (Figures 1 and 2). Hadley Centre results also indicated a tendency for erosivity increases over parts of Arizona and New Mexico. Decreases in erosivity were indicated in other parts of the southwestern U.S., including parts of California, Nevada, Utah, and western Arizona. Decreases were also shown over eastern Texas and a large portion of the southern central plains from Texas to Nebraska.

Erosivity results calculated from the Canadian Centre for Climate Modelling and Analysis model also showed an increase in erosivity across the northern U.S., including New England, and southern Canada (Figures 3 and 4). The Canadian Centre model results also indicated a reduction in erosivity across much of the southern plains, again from Texas to Nebraska, but extending somewhat west of the corresponding area shown in the Hadley Centre results.

The Canadian Centre model did not show consistent results for the southeastern United States. Results of the computations using annual precipitation (Figure 3) indicate changes in parts of the southeast U.S. tending toward lower erosivity, corresponding to a tendency toward a decrease in the annual precipitation in that region (equations 2 and 3). Results of the erosivity computations using the Fournier coefficient indicate the possibility of little change or increases

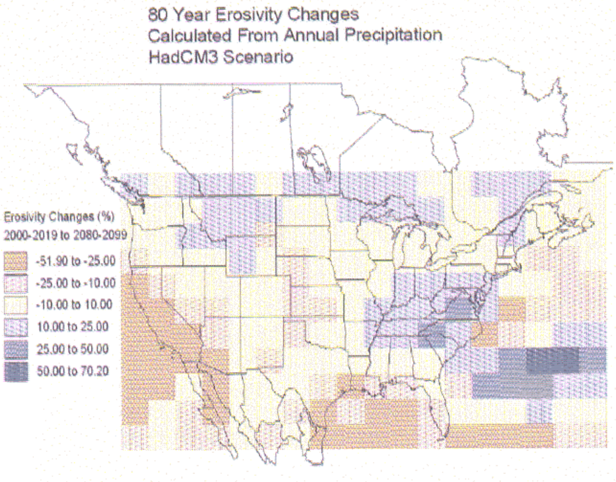

Figure 1. Potential erosivity changes, RP, from 2000-2019 to 2080-2099 calculated from average annual precipitation (Hadley Centre HadCM3 model scenario).

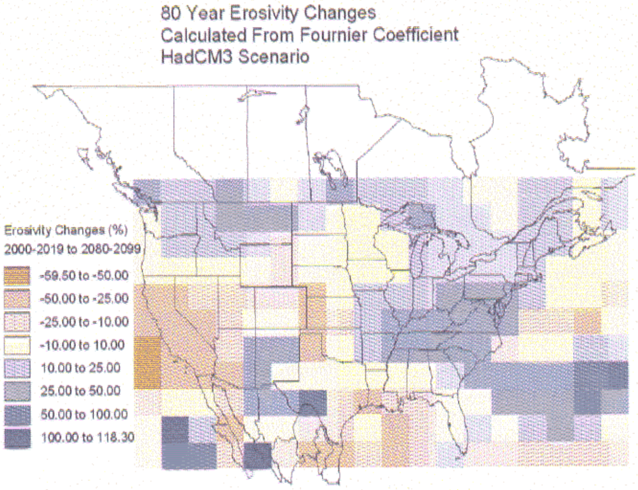

Figure 2. Potential erosivity changes, RF, from 2000-2019 to 2080-2099 calculated from the Fournier coefficient using monthly precipitation information (Hadley Centre HadCM3 model scenario).

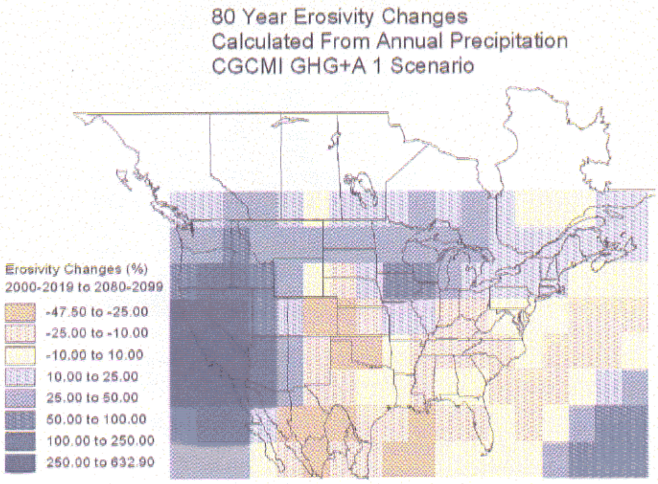

Figure 3. Potential erosivity changes, RP, from 2000-2019 to 2080-2099 calculated from average annual precipitation (Canadian Centre for Climate Modelling and Analysis CGCM1 GHG+A1 model scenario).

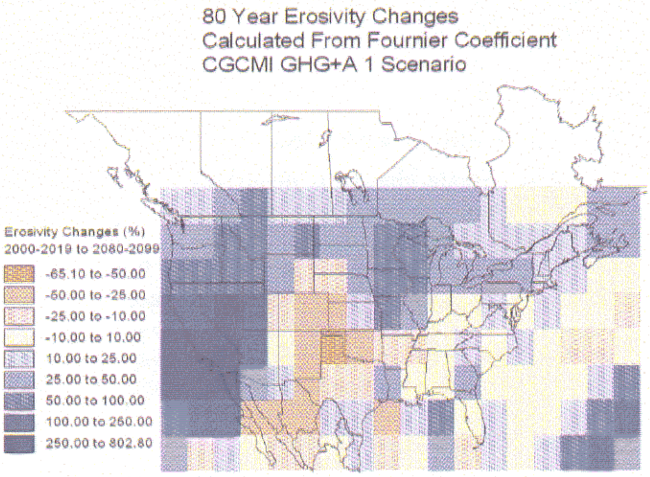

Figure 4. Potential erosivity changes, RF, from 2000-2019 to 2080-2099 calculated from the Fournier coefficient using monthly precipitation information (Canadian Centre for Climate Modelling and Analysis CGCM1 GHG+A1 model scenario).

Table 1. Percentages of map grid cells in which changes over time in erosivity values (RP) calculated using precipitation were inconsistent in sign with changes in values of erosivity (RF) calculated using the Fournier coefficient.

	Inconsistencies in Erosivity between RP and RF			
	For all Data		Where also both |RP| and |RF| > 10%	
Model Scenario	40 Yr Time Interval (%)	80 Yr Time Interval (%)	40 Yr Time Interval (%)	80 Yr Time Interval (%)
HadCM3	17.2	16.2	1.0	1.5
CGCM1 HG+A1	17.4	19.4	0.7	7.6

Table 2. Percentages of map grid cells in which changes over time in erosivity values calculated over the 40 yr time interval were inconsistent in sign with changes in erosivity values calculated over the 80 yr time interval.

	Inconsistencies in Erosivity between 40 and 80 Yr Time Intervals			
	For all Data		Where also Both the 40 yr |R| and the 80 yr |R| > 10%	
Model Scenario	RP (%)	RF (%)	RP (%)	RF (%)
HadCM3	16.2	15.2	1.5	1.0
CGCM1 HG+A1	7.6	23.6	0	5.6

Table 3. Average magnitudes (absolute values) of erosivity change.

	Average Magnitude of Change			
	40 yr Time Interval		80 yr Time Interval	
Model Scenario	RP (%)	RF (%)	RP (%)	RF (%)
HadCM3	11.8	16.5	15.9	20.9
CGCM1 HG+A1	23.4	29.1	53.4	58.3

over part of the region for the 80 yr comparison (Figure 4). Calculated increases in erosivity using the Fournier coefficient (equations 4 and 5) suggest a change in the distribution of rainfall patterns through the year.

Erosivity results calculated from the Canadian Centre for Climate Modelling and Analysis show major differences compared to the results from the Hadley results in the southwestern United States, including California, Arizona, Nevada, and Utah. Whereas the Hadley Centre model results suggest a definite trend toward lower erosivity in this area (Figures 1 and 2), the Canadian Centre for Climate Modelling and Analysis model results suggest a definite, strong trend toward greater erosivity through the 21st century in this area (Figures 3 and 4).

Inconsistency in predictions between the two sets of equations (equations 2 and 3 vs. equations 4 and 5) was of the same general magnitude for the two models (Table 1). Overall, between 16–20% of the calculations resulted in negative values of the R factor changes calculated by equations 2 and 3, RP, when the R factor changes calculated by equations 4 and 5, RF, was positive, or vice versa. For the cases where both |RP| and |RF| were greater than 10%, those percentages were much smaller, although 7.6% of the pairs were inconsistent in this case for the Canadian model results for the 80 yr time interval (2000–2019 to 2080–2099). Inconsistencies between results of RP and RF are expected, since RP is based on total annual precipitation and RF is based on monthly distributions of precipitation. Both relationships are statistically based, and we have no rationale for favoring one over the other.

One might expect a consistent trend for the change of erosivity as a function of time, and in general this was true (Table 2). In this case, the Canadian model exhibited more inconsistency as a function of time when using monthly precipitation values to calculate erosivity, though it was consistent temporally in terms of erosivity calculated using annual precipitation.

The RF values tended to show a somewhat greater magnitude, in terms of the average of the absolute value of percent erosivity change, than did RP values (Table 3). The difference between the two models in this regard was striking. The Canadian model indicated a much greater level of erosivity change overall as compared to the Hadley Centre model (Table 3, Figures 1–4). Both models suggested erosivity changes which generally increased in magnitude from the 40–80 yr comparison.

Summary and Conclusion

Global climate change is occurring now. Historical weather records over this last century show that precipitation is increasing in terms of the number of days of rain and the intensities of rain. Statistical analyses of existing records have indicated that there is less than 1:1,000 chance that changes in precipitation patterns could have occurred under a stable climate. We expect in the future that parts of the country will become wetter, and parts will become drier. We also have good scientific reason to believe that temperature will increase in the U.S. during the next century as well. As rainfall, temperature, and atmospheric carbon dioxide levels change, so will soil erosion.

Our results indicate that changes will be significant, though varying from region to region. From the most conservative of the four methods used, we estimate that the average magnitude of change (as either increase or decrease) over the country as a whole will be 16% different from current erosivity at the location. At the other extreme, one of the four methods used predicted average magnitude of change at 58% from current conditions. Regardless of which method was used, the results suggest that at certain locations changes in erosivity will be critical (Figures 1–4).

Accuracy in predictions of erosivity changes are limited primarily by information on future changes in precipitation. Predictions made using the two coupled Atmosphere-Ocean Global Climate models gave similar trends in results in certain regions and quite divergent trends in others. It would appear from these results that more work is needed to improve predictions of future climate. At the least, it would be useful to understand why the two models give different results in certain locations, so that we might be more confident of results for regions in which the models agree.

The HadCM3 and CGCM1 models gave very divergent results for the southwestern U.S., and to a lesser extent for the southeastern U.S. This might suggest that representation of orographic effects associated with the Rocky and Appalachian Mountains may play a role in the difference between the two models. As confidence in climate change prediction improves, so will our confidence in predictions of erosivity changes.

ENDNOTES

[1] RP is the R factor changes calculated by equations 2 and 3.

[2] RF is the R factor changes calculated by equations 4 and 5.

[3] Equation 13 in the Renard and Freimund (1994) paper, which corresponds to equation 4 in this paper, contained a misprint.

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