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ABSRACT

Though the facts of global climate change are beyond doubt, there has been relatively limited information about its local consequences. Global climate models and their derivatives have provided often differing and unspecific indications. This paper demonstrates an effective approach for the determination of local and seasonal effects of global climate change using data for the United States. Examples are given for specific weather station sites and for sites across the U.S. in five longitudinal strips divided into four latitudinal strips. Mean temperature and precipitation data are subjected to thirty year moving averaging and linear time trend lines are estimated, for which, in almost all instances, the estimated coefficients are highly significant.

While in some locations there have been significant weather effects of climate changes, in other locations the effects have been small and may even be perverse. Linear extrapolation into the future of the results for individual sites seems reliable, based on past experience.

Local weather patterns and local topographies modify the local effects of global climate change. An immediate implication of the results reported here is that there are significant local differences in the type and degree of adaptation to global climate change that should be considered.

I.   Introduction

Though the facts of global climate change are beyond doubt, there has been relatively limited information about its local consequences.[1] This paper demonstrates an approach for the determination of the local and seasonal effects of global climate change using data for the United States. The paper shows that, while in some locations there have been and will be significant climate changes, in other locations the effects will be small and may even be perverse. The diversity in effects will, in turn, have personal and general economic consequences, especially in household adjustments, agricultural productivity, health effects, infrastructure requirements and, perhaps, political support for both mitigation and adaptation measures.

Denials of global warming, in spite of the urgent warnings, may stem in part from the failure of people to believe they are experiencing it in their local weather. The ups and downs of the daily weather obscure weather trends, unless they are followed closely, and only climate scientists do that. The reality is that global warming has been going on for years. In addition to the evidence of it in global weather patterns there is evidence in local weather, as well. This paper shows and uses that evidence, but, somewhat surprisingly, it is, in fact, quite diverse.

The urgent warnings of global climate change have been accompanied by the desire of private persons, public officials with responsibilities that may be affected by changes in the climate, electric power companies, farmers and other climate-related businesses all want to know what it will mean to them in their particular locations. This paper responds to these interests by utilizing past local weather information that is readily available for the United States to show

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[1]   The urgent interest in the effects of global warming in particular locations and the uncertainty in currently available forecasts are discussed in, "Vital Details of Global Warming Are Eluding Forecasters," Science, vol. 334, 14 Oct., 2011.

climate trends. Local weathers have reflected the continuing climate change, just as future

weathers are expected to reflect future climate change. The idea of simply looking at what has

actually happened in response to climate change in order to gain insight into future changes

seems obvious. Yet, to the best of this author's knowledge, and most surprisingly, this tactic has

not previously been followed in a systematic manner.

It will not be a revelation to climate scientists that the local effects of general warming

are quite diverse. Yet the degree of variability may be surprising. However, the variability of

local responses should not be interpreted as signifying the relative unimportance of general

climate change. While, in some places, the effects are indeed small, as shown below, in other

locations they are quite significant. Moreover, although the climate change records and

projections differ substantially across localities, those differences do not in themselves carry

welfare implications. Those implications depend on many other specific local factors, including

the potential for adaptations, and are not pursued in this paper.

Climate scientists have, by no means, neglected regional climate projections, as

evidenced by their prominence in IPCC records. The Third and Fourth Annual Reports have

extensive discussion of the issues.[2] This is not the place to review in detail the approaches

considered but it can be said that ingenious methods have been tried, yet with expressed

skepticism of their success.[3] None of them, however, use the simple, yet effectual approach to

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[1]IPCC Third Assessment Report, http://www.grida.no/publications/other/ipcc_tar/;   IPCC
Fourth Assessment Report,
http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#1

[3]Christensen, J.H., et al. (2007), "AOGCM (Atmosphere Ocean General Climate Models)
projections provide plausible future regional climate scenarios, although methods to establish the
reliability of the regional AOGCM scales have yet to mature. The spread within an ensemble of
AOGCMs is often used to characterize the uncertainty in projected future climate changes "

be followed here. That may be the result of several factors: (1) the preference for science-based and relatively long term projection methods, (2) the desire to find methods of general applicability and the perceived limitations of heuristic methods and (3) dissatisfaction with the scarcity of multi-decadal data sets. None of these concerns inhibit the approach to be demonstrated below, although no attempt will be made to provide science based explanations of the observations.

The paper will proceed by describing the data used and then will present detailed results for two specific localities which exemplify the range of local reactions to global climate change. These will make more comprehensible the subsequent condensed results comparing some of the estimated changes across the U.S.

II.   Data

The data to be used for the temperatures and precipitation in the United States come from U.S. National Weather Service weather stations.[4] There are as many as several thousand of these stations across the country, with varying periods of observation, which sometimes span seven or eight decades. Although the weather service data cover the entire year, this paper will focus on the weather data for January and July, as winter and summer months. Since the annual data are very, "noisy," the analysis will be based on 30 year moving averages of the temperature and precipitation observations, which smooth the often wide annual variations, particularly in the precipitation records.[5]

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[4] NOAA, National Climate Data Center, Washington, D.C.

[5] The use of moving averages naturally raises concerns about autocorrelation in the data. This concern will be taken up when results are presented.

While for most weather stations the reporting periods cover a relatively few years, as noted, some weather stations have had reporting periods of almost a century to the present. Reports from many stations start in the 1940's, but long period reporting starting in the 1950's seems most common. So the data series are long enough, in many cases, to provide for reasonably reliable statistical estimates of rates of change.

Climate change is induced by the atmospheric accumulation of greenhouse gases. The magnitude of this accumulation is measured by the AGGI, the Annual Greenhouse Gas Index. This measures the total radiative forcing of atmospheric greenhouse gases.   In the charts to be shown, temperatures are related to the year of observation rather than the AGGI, however. This was done in order to show the manner in which mean temperatures have changed over time, rather than in relation to the AGGI, which would be less familiar to non- climate scientists. Since the AGGI has increased almost linearly over time for many years, there is an implicit relation of yearly temperatures to the AGGI.[6]

Two Examples of Local Effects of Climate Change

Before showing the results of estimating the climate changes that have occurred in the last fifty or sixty years across the U.S., it will be useful to examine results for two particular weather station sites: Des Moines, Iowa and Liberal, Kansas. Figure 1 traces the thirty year moving averages of the mean January and July temperatures and precipitation in DesMoines and shows their linear trends.[7] The closeness of the linear trends to the temperature averages is

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[6] See Hofman, D.J., et al, (2006)

[7] The dating of the thirty year moving average points differ from a more general practice of identifying those points with the mid-date of the thirty years. However, it seems to this author that identifying the last date of the thirty year average indicates more clearly the span that is covered.

obvious and the estimated regression coefficients on the year variable are all significant at the 1

% level, except for the July temperature.

Figure 1
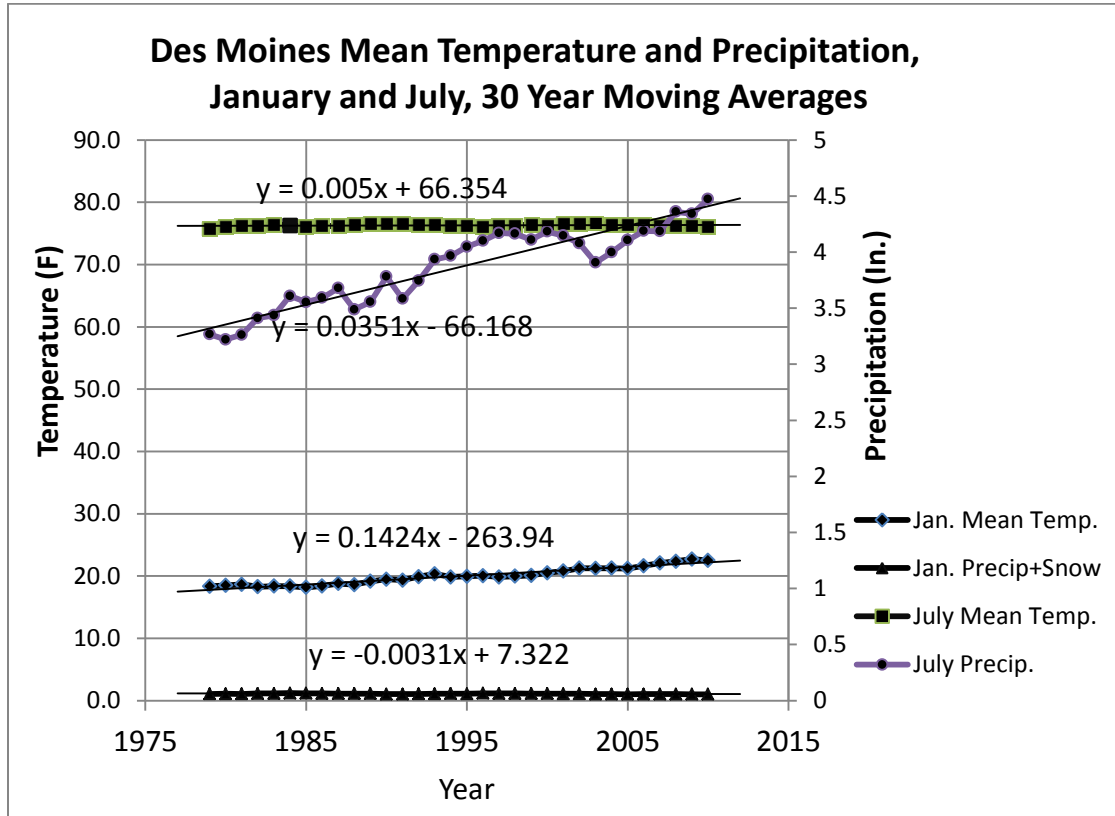
The trend of the January mean temperature indicates an average temperature increase of

slightly more than 0.14 degrees per year, or 1.4 degrees every ten years or 14 degrees in a

hundred years. Measured in degrees Celsius, it is about 7.7 degrees in a hundred years, if the

linearity assumption holds and greenhouse gas concentrations continue to rise as in the past This

increase in average mean temperatures is somewhat higher than the mean, "business as usual,"

projection of many global climate models.

There is, of course, the very important issue as to whether the linear trends can be

extrapolated into the future reliably. If a similar exercise is done for the period 1979 to 2000,

this would result in different estimates of annual increments. There is a different estimate of the constant as well. The final result is that, if the regression for the period 1979-2000 is extrapolated to 2010, the resulting mean temperature estimates would differ by one half of a degree from the actually observed temperatures. This suggests the reliability of the linear extrapolation. However, the linear extrapolation procedure also gets strong reinforcement from the observed linearity of mean temperature patterns in the Atmosphere Ocean Global Climate Models.[8]

The January mean precipitation trend is very small and just slightly negative, indicating little effect of overall climate change.

The July climate patterns for Des Moines are strikingly different from those in January. The thirty year moving averages of the mean temperatures in July are virtually constant across the years, suggesting the reason for the lack of significance of the regression coefficient on the year variable. As a result there is very little evidence in the July mean temperatures that global warming has occurred at all. Evaporative cooling due to the greater summer precipitation and the higher summer temperatures moderates summer warming. The July mean precipitation trend indicates an annual increase of 0.035 inches, which may not seem significant. But, in a hundred years it would more than double the current precipitation levels.

The second site to be examined is Liberal, Kansas (latitude 37.01, longitude 100.96), a small town in southwestern Kansas named for the generosity of an early settler, has temperature patterns that are strikingly different from those for Des Moines, as shown in Figure 2.

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[8] The linearity of the recorded year-temperature relations is a feature of the Atmosphere-Ocean Global Climate Model simulations. Christensen, et all: "In the ensemble mean AOGCM projections there is no indication of abrupt climate change, nor does the literature on individual models provide any strong suggestions of robust nonlinearities."

Figure 2

Liberal MeanTemperatures and Precipitation, January and July, 30Year Moving Averages
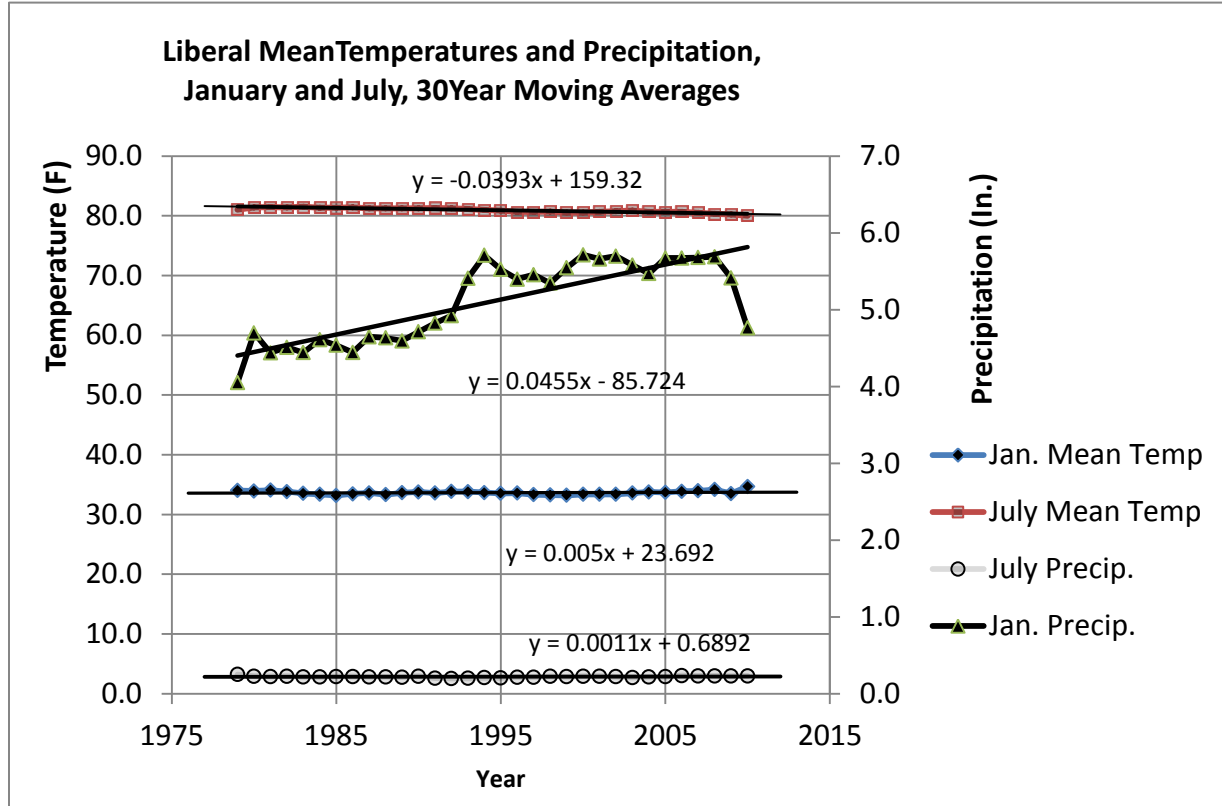
There is no evidence at all of climate change in the thirty year moving averages of mean temperatures in both January and July, as shown in Figure 2. In fact there has been a slight negative trend for the average mean temperature in January and a larger negative trend in July. Precipitation in Liberal is again volatile, but small in relative magnitude. Thus for Liberal, Kansas there has been no virtually no climate change in the last 40 years and, with the assumptions of linearity and no acceleration in the rate of greenhouse gas emissions, there will be no climate change in the future.

In order to supply more information about the estimation of the weather trends, regressions are presented in Table 1 for the mean temperatures and precipitation for January and

July for each one of the two weather stations based on the 30 year moving averages. As would be expected from examination of the Figures the fits of the regressions are usually very close.[9]

With the temperature and precipitation patterns showing the effects of past global warming in two particular locations as background, examples of these effects across the U.S. can now be examined with more insight. For purposes of illustration of the local effects of climate change across the United States, five longitudinal strips are created, north to south, across the U.S. Since weather stations with a useful time series of data do not line up exactly, the weather stations in each strip will have only approximately the same longitudinal positions. The Atlantic and Pacific coastal areas are identified as well as three longitudinal strips in the interior of the country, with longitudes roughly 120, 100, 93, 84, and 76.

Within each longitudinal strip four latitude strips are identified. Since in each longitudinal strip, it is not possible to find weather stations that have substantial time series of weather observations and line up with the precisely the same latitudes, the latitudes are defined in ranges: 33-35, 37-38, 41-42, 44-47.

As will be noted below, one of the observations that emerges from calculating regressions with the data is that what appear to be small differences in longitudes and latitudes are often significant in explaining the temperature and precipitation differences among the stations. So the results to be presented do reflect local differences, they are only precise for the individual stations. This is consistent with experience with the Atmosphere Ocean Global Climate Models

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[9]It can be argued, correctly, that there is substantial autocorrelation in the 30 year averaged observations and that this biases downward the standard errors and gives an erroneous view of precision in the regressions. In fact the Durban-Watson test shows such autocorrelation. This would normally be a major concern. However, an eyeball view of the regression lines in the temperature regressions for individual sites shows that they lie right on top of the data and estimation of the residuals of the regressions shows that they are, in fact, quite small.

(AOGCM) which indicate that local experiences should not be uncritically extrapolated to larger regions.[10]

The weather stations that are identified cannot be considered to be a representative sampling of weather across the country. In particular, the idiosyncratic geographical effects of each weather station have not been taken into account. The best that can be said of the weather stations that are identified is that they are an exemplification of U.S. climates. There remains, therefore, a legitimate question as to whether the particular set of examples are misleading with respect to the climate patterns that have prevailed. That question cannot be given a definitive answer. It can be said that the choice of the weather stations was made solely on the basis of their location and the length of their weather data. It is still possible that there is a bias in the choices. For example, the weather stations may have been consciously or unconsciously located to record what was regarded as, "typical," conditions. But the existence and extent of bias but cannot be known without much more investigation.

In order to condense the details shown in the previous charts, Figures 3 and 4 show for the 20 weather stations the averaged changes in temperatures from 1979 to 2008 based on the fitted trends. The left vertical axis thus shows the changes in the thirty year moving averages of the mean January and July temperatures for the longitudinal strips identified on the horizontal axis.

There are striking features in the charts. As shown in Figure 3, presenting the temperature data for January, the differences in the changes across longitudes at roughly the same latitudes

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[10] Christenson, et al, op.cit., "Some regional responses are consistent across AOGCM simulations, although for other regions the spread remains large." And, "trends in large-area and grid-box average projections of precipitation are often very different from the local trends within the area. This demonstrates the inadequacy of inferring the behavior at fine scales from that of large-area averages."

are often more than 100 per cent and in some instances much, much larger. And the differences across latitudes in roughly the same longitudes are similarly quite diverse. In general climate science analysis indicates that the effect of climate change on temperatures will increase from south to north. That is not uniformly the case in the different longitudes as shown in Chart 3. For example, the changes in temperature in Lubbock, the southernmost latitude, in longitude 100, are greater than in any other latitude except that of Pierre, at the northern most latitude. Likewise, the temperature changes in Dayton, at the second most southern latitude in longitude 84 are greater than that in any other latitude except Lansing, the second most northern latitude. In Cheboygan, at the northern most latitude, the average mean temperature actually declined slightly from 1979 to 2010.

Table 1[11]

Des Moines	Lat 41.32		Long 93.43		
January			July		
mean temp	Coef.	Std. Err	mean temp	Coef.	Std. Err.
year	0.1419***	0.0080	year	0.0050	0.0038
constant	-262.9713***	16.0114	constant	66.3536***	7.5245
$R^2 = 0.9332$			$R^2 = 0.0722$		
precipitation+snow	Coef.	Std. Err	precipitation	Coef.	Std. Err
year	-0.0040***	0.0008	year	0.0351***	0.0020
constant	9.1235***	1.5520	constant	-66.1680***	3.9277
$R^2 = 0.4079$			$R^2 = 0.8772$		

Liberal	Lat 37.01		Long 100.56		
January			July		
mean temp	Coef.	Std.Err.	mean temp	Coef.	Std.Err.
year	-0.0192***	0.0062	year	-0.0141***	0.004347
constant	71.9995***	12.2402	constant	108.9836***	8.660838
R^2	0.2576		R^2	0.2201	
precipitation + snow	Coef.	Std.Err.	precipitation	Coef.	Std.Err.
year	0.0266***	0.005691	year	-0.0101***	0.002232
constant	-47.8576***	11.33995	constant	23.0894***	4.43781
R^2	0.2576		R^2	0.2201	

Figure 2 indicates that temperature changes are often higher in the interior of the continent than in the coastal areas at the same latitudes. That, again, would not be surprising to climate scientists, but there are exceptions. It is clearly the case that the variability of temperature changes in the coastal longitudes is less than in the interior longitudes.

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[11] The regression coefficients in this Table differ slightly from those shown in the Figures, presumably because of slightly different estimating procedures in Excel, used for the figures, and Stata, used for Table 1. *** indicates significance at 1%.
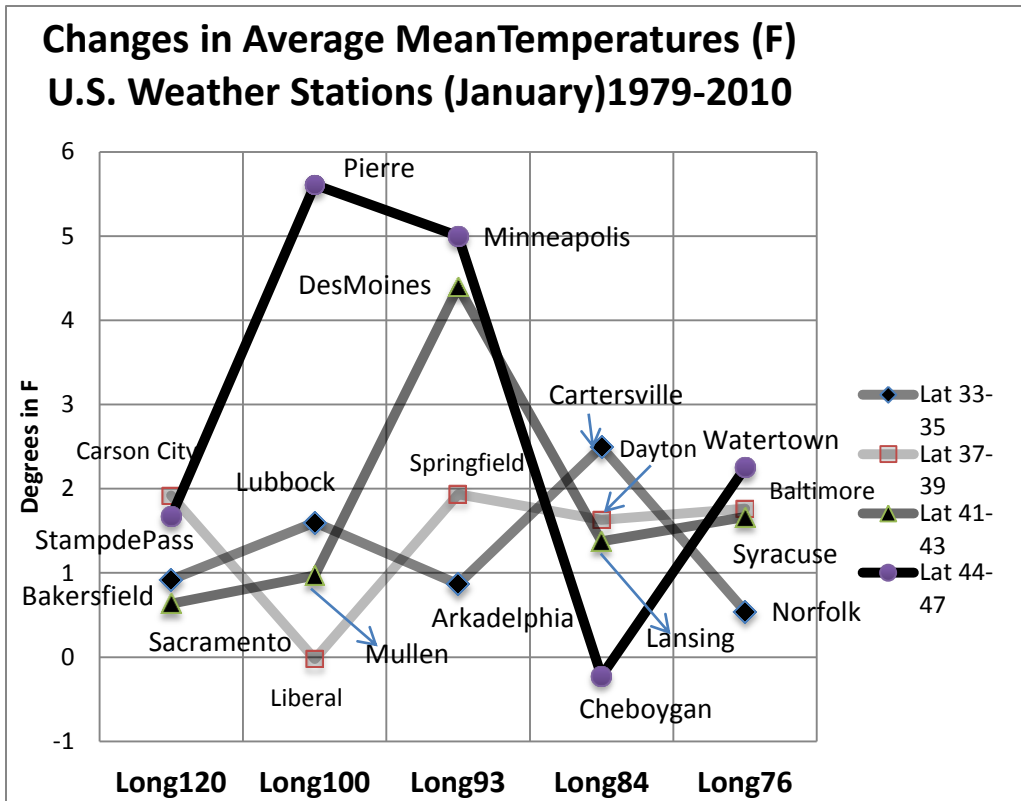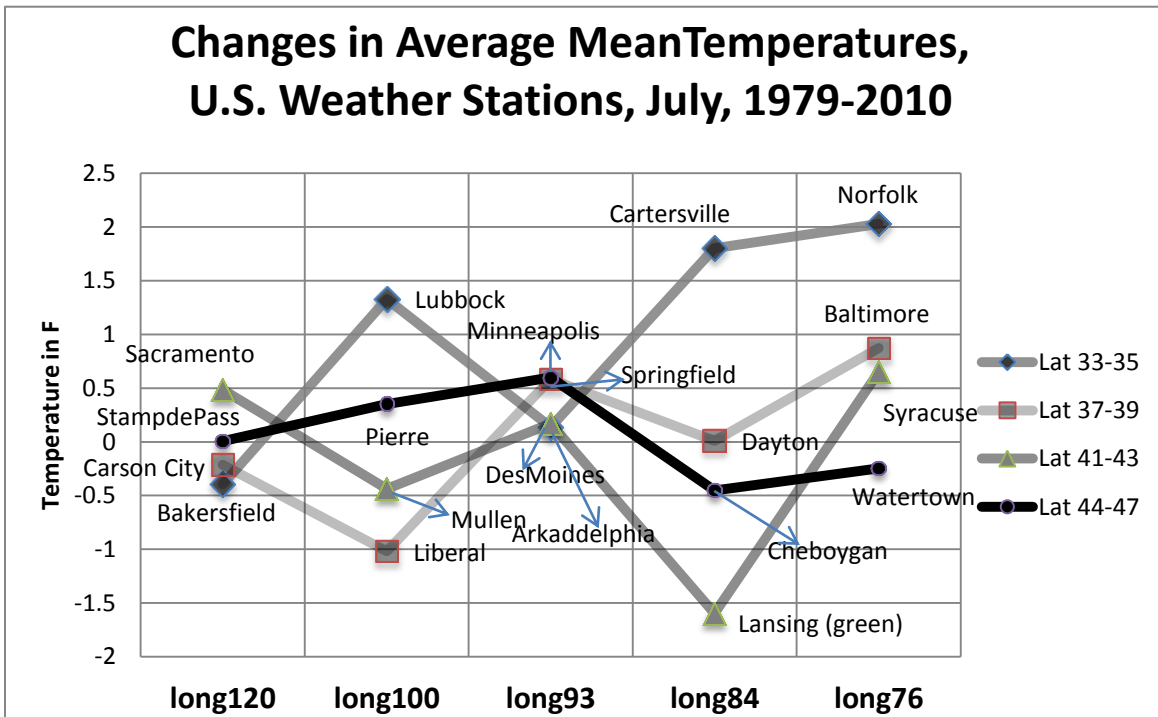
Figure 3

Changes in Average MeanTemperatures (F)
U.S. Weather Stations (January)1979-2010

Figure 4

Changes in Average MeanTemperatures,
U.S. Weather Stations, July, 1979-2010

Turning to Figure 4, the picture presented for July is quite different from that for January, as would be expected from the previous examination of just two sites. The temperature increases are much more modest and there are even stations for which there are reductions in average temperatures. Only for Norfolk are the temperature increases as much as two degrees. There are temperature decreases in seven of the twenty weather stations in the 31 years, enough to suggest that there is some systematic influence, rather than idiosyncratic effects. The variability in temperature changes on the west coast are smaller than those in any other longitude and the variability on the east coast is still larger. Yet the variability in the longitude 84 weather stations is the greatest. The only clear north to south pattern is on the east coast, where the climate change variation increases from north to south, reversing the January pattern.

Figures 5 and 6 show the precipitation changes in the weather stations across the U.S. Except for a few outliers the averaged changes in precipitation plus snow recorded in the 20 weather stations in January and July, the changes are strikingly modest, one inch or less. An increase of one inch of rain and snow in 31 years, would be 3.2 inches in 100 years, under the continued assumption of linearity.
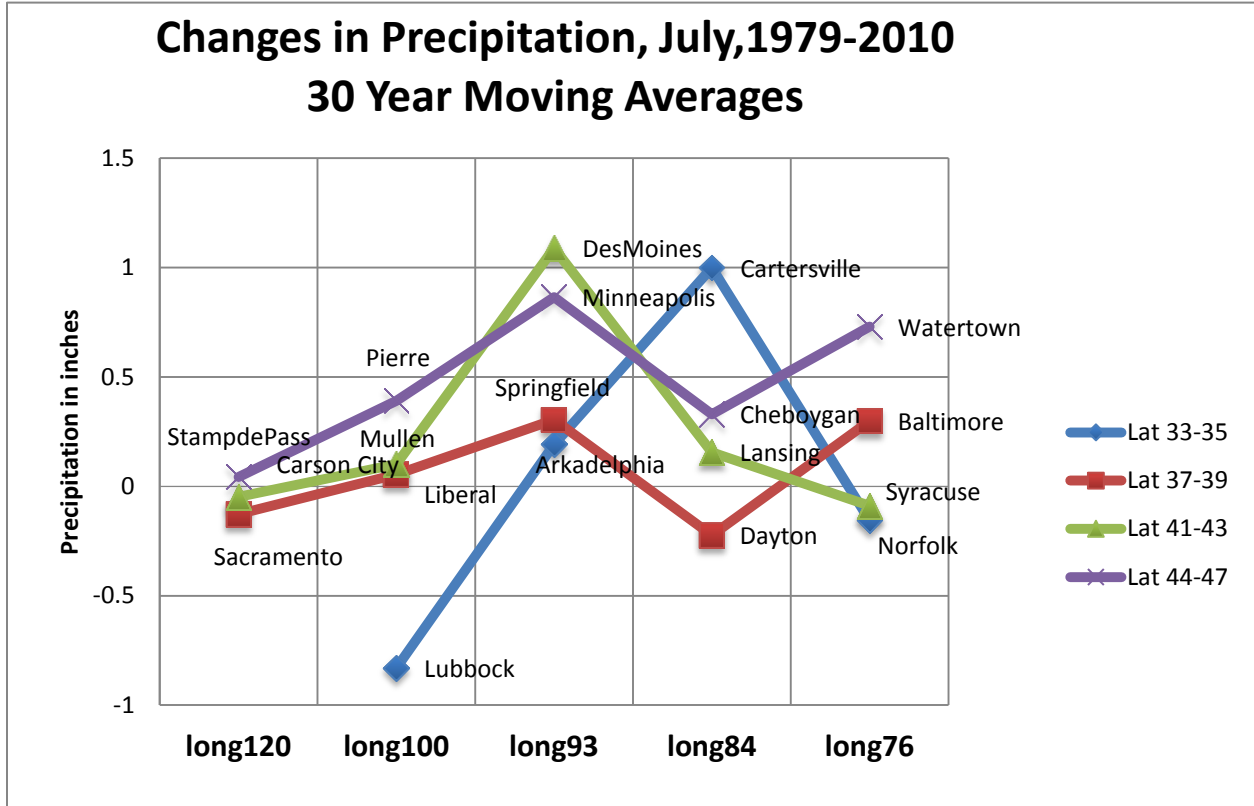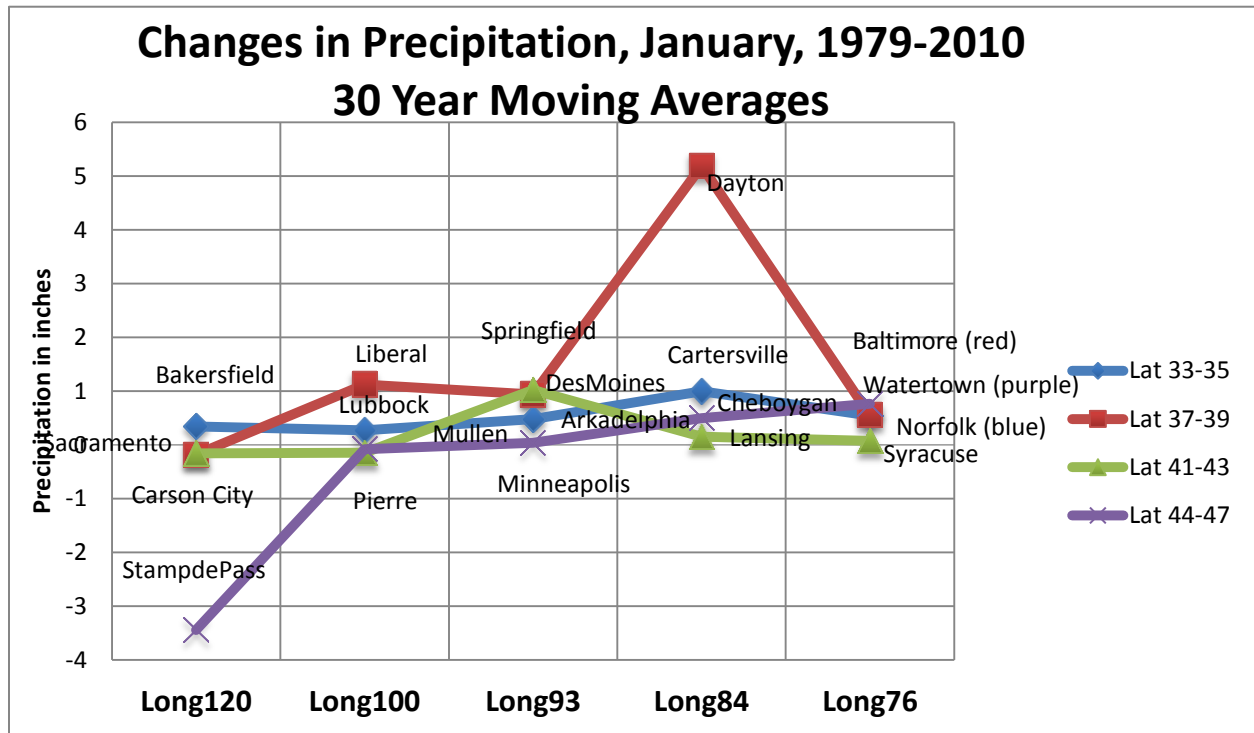
Figure 5

Changes in Precipitation, July,1979-2010
30 Year Moving Averages

Figure 6

Changes in Precipitation, January, 1979-2010
30 Year Moving Averages

While 3.2 inches is certainly noticeable, it is equivalent to only two or three heavy rainstorms. The Stampede Pass and Dayton outliers in January reflect some particularly heavy rainstorms in the early years of the twenty-first century, that even thirty year averaging could not hide. In two longitudes there was actually a decrease in the January precipitation over the thirty one years. There is also a suggestion from the charts that the latitude 38-39 weather stations had relatively the largest increases in rainfall and snow in January,

The July rainfall is relatively modest at many stations, being mainly less than one inch. However, there is greater variability than in the January patterns in some longitudes and lesser in others, again with some stations recording actual reductions in the averages. In general, it appears that agricultural productivity would not be strongly affected by the precipitation changes associated with climate change.

In order to compare the influence of latitudinal and longitudinal locations, a panel regression was estimated which include all twenty weather stations, separately for January and July. The results are summarized in Table 2 below.

Both random effects and fixed effects estimates were made and the outcomes were quite similar, and the AGGI variable was included in the random effects regression. In addition an index number for each station was included to catch effects specific to each weather station. Only these random effects estimates are reported.

The estimated coefficients in the regression for mean temperature in January are all significant and the overall R^2 is high. The coefficients in the mean temperature regression for July are significant, except for that on the AGGI variable and, again, R^2 is high. In the

regressions for precipitation, the coefficient estimates were, with the exception of that for AGGI in January, were significant, though usually at lower levels of confidence.

An important feature of the regressions is that, in every case, the coefficient on the index, the identification number for each individual weather station, is significant. The coefficient is quite large in the mean temperature regression for January, a winter month in which the warming effects of climate change are expected to be relatively large. The relatively large coefficient on the index variable indicates again the importance of the divergent local effects on weather.

Table 2

Panel Regressions For All Weather Stations, 1979-2009

January mean temperature	Coef.	January precipitation	Coef.
aggi	1.2495*	aggi	0.3362
	-0.3045		-0.3035
longitude	1.1589*	longitude	0.1788*
	-0.0255		(-0.0332)
latitude	-1.4862*	latitude	0.2816*
	-0.0195		(-0.0379)
index	2.4921*	index	0.3256*
	-0.0659		(-0.0771)
constant	-49.4858*	constant	-29.2789
	-3.6396		(-5.0582)
overall R^2	0.9505	overall R^2	0.2514

July mean temperature	Coef.	July precipitation	Coef.
aggi	0.116	aggi	1.0005*
	(-0.4113)		(-0.3332)
longitude	-0.4897*	longitude	-0.0585**
	(-0.0482)		(-0.0246)
latitude	-1.5029*	latitude	-0.1539*
	(-0.0500)		(-0.0234)
index	-1.2592*	index	0.1515***
	(-0.1135)		(-0.0828)
constant	193.6036*	constant	11.6443*
	-7.1361		(-3.3810)
overall R^2	0.7579	overall R^2	0.3497

Summary

This is paper simply presents some facts of climate change in the U.S. over the last thirty one years. The facts lead to interesting generalizations. Most of the evidence provided will not be surprising to climate scientists in its general features: latitudinal and longitudinal variability of the impact of climate change, the greater degree of warming in the winter than in the summer and the moderating effects of locations close to oceans. What may be surprising is the extent of the variability across close locations. This variability has been difficult, if not impossible, to discern reliably with existing models, yet emerges quickly from the examination of just what has actually happened. It implies that local conditions, perhaps of weather circulation patterns or topographical elements, are of great importance in determining local effects of climate change. For example, in 2008 in five provinces the specifically local residuals in a panel regression against mean temperature are greater than the influence of the AGGI. And in another four provinces, the specifically local effects are virtually the same as the effect of the AGGI. This substantial local variability in turn implies that the attempt to identify regional effects of climate change with atmosphere-ocean general climate models that cannot embody local influences will not be successful.

A further implication of the evidence is that in many locations there will be little need for local adaptation to climate change, at least in the near future, if two assumptions are correct: first, that there will be no increase in the rate of growth of greenhouse gas emissions and, second, that the pattern of linearity of temperature and precipitation change with global warming will continue. The first assumption depends on the political will to avoid higher rates of greenhouse gas emissions. The second assumption falls out of the current climate science as well as the patterns described here. These conclusions are relevant for average climate effects, which are

relevant for planning adaptations to climate change. They do not, of course, rule out annual changes in weather that differ from the average.

The great concern with local and regional adaptation to climate change is, to some extent, the result of the common inference, or directly stated proposition, that climate change will directly and significantly affect everyone.   The direct effects are clear for Des Moines and certainly Minneapolis, as shown above, and for many other locations. However, in many other locations those direct effects will be small and may even be perverse. There may, of course, be indirect effects, which, in some cases may turn out to be substantial.

Thus, the simple facts presented here imply quite different local needs to adjust to climate conditions as, overall, the climate warms. That, of course, does not rule out local decisions to help mitigate greenhouse gas emissions to reduce global warming.   For many locations, the best projection would be that climate change for the next many decades will be of an order of magnitude of a few degrees Fahrenheit. However, if climate change reduces the viability of life in tropical or semitropical regions with substantial populations, the indirect effects could well affect Des Moines.

There is much left to be done in determining the local effects of climate change. This paper suggests how important it is to know those effects.