Climate Variability and Change with Implications for Transportation

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Outline

ABSTRACT

The U.S. transportation system was built for the typical weather and climate experienced locally. Moderate changes in the mean climate have little impact on transportation. However, changes in weather and climate extremes can have considerable impact on transportation. Transportation relevant measures of extremes have been changing over the past several decades and are projected to continue to change in the future. Some of the changes are likely to have a positive impact on transportation and some negative.

As the climate warms, cold temperature extremes are projected to continue to decrease. Milder winter conditions would likely improve the safety record for rail, air and ships. Warm extremes, on the other hand, are projected to increase. This change would likely increase the number of roadbed and railroad track bucklings and adversely impact maintenance work. As the cold season decreases and the warm season increases, northern transportation dependent upon ice roads and permanently frozen soil would be adversely affected while the projected commercial opening of the Northwest Passage would result in clear benefits to marine transportation.

The warming would also produce a side benefit of shifting more of the precipitation from snow to rain. But not all precipitation changes are likely to be beneficial. Heavy precipitation events are projected to increase, which can cause local flooding. At the same time, summer drying in the interior of the continent is likely to contribute to low water levels in inland waterways. Strong storms, including hurricanes, are projected to increase. Coastal transportation infrastructure is vulnerable to the combined effects of storm surge and global sea-level rise.

Transportation planning operates on several different time scales. Road planners typically look out 25 years. Railroad planners consider 50 years. And bridges and underpasses are

generally designed with 100 years in mind. In all cases, planning that takes likely changes into consideration will be important.

1. INTRODUCTION

Transportation involves three different areas. The surface transportation includes cars, trucks, commuter rail, long-haul rail, and pipelines. The marine incorporates coastal and inland ferry, barge and recreational boating as well as ocean going cargo on the St. Lawrence Seaway, Panama Canal and potentially in the future the Northwest Passage. The third area, aviation, is involved not only in airports and in-flight systems but also ground transportation that is required to facilitate movement of vehicles at the airports including taxiing planes.

All of these areas are very sensitive to weather. But the sensitivity is less to the mean weather conditions than to extremes (see Appendix A). For example, all operate during light rain conditions but a blizzard can bring the sectors to a standstill. Therefore, climate variability and change mainly impact transportation through changes in extreme conditions. Two important long-term weather or climate conditions which have impacts on transportation are drought which adversely affects river barge traffic due to low water conditions and changes in Arctic sea ice conditions that may open up the Northwest Passage. Therefore, the majority of our focus will be on how climate change can impact transportation through changes in extreme weather conditions. This will include both historical analyses as well as projections for the future. However, it is important to keep in mind that weather observing stations typically measure air temperature in a shelter 1.5 meters above the grass covered ground while the relevant transportation parameter might actually be the temperature of a pair of steel rails laying on the ground in the sunlight or the temperature of a road bed at night. Therefore, these analyses and projections can only be of parameters that are approximations of the real transportation relevant parameter.

A considerable body of literature exists that identifies transportation sensitive weather conditions. Most notable among these is the Weather Information for Surface Transportation National Needs Assessment Report (Office of the Federal Coordinator for Meteorological Services and Supporting Research, 2002; hereafter cited as WIST, often including the relevant section). WIST quantifies the thresholds at which weather impacts transportation and has a short update (Office of the Federal Coordinator for Meteorological Services and Supporting Research, 2006). Also, NOAA's National Weather Service has a series of directives on forecasting that identified critical thresholds that are relevant to transportation. See Appendix B for the synthesis of all NWS transportation relevant forecasting directives. The US Global Change Research Program conducted National Assessments of the Potential Consequences of Climate Variability and Change. Several of the eighteen assessments contain information relevant to transportation particularly for the regions of Alaska, California, the Great Lakes, Gulf Coast, and the Pacific Northwest. An assessment with more extensive transportation relevant information is the Metropolitan East Coast Assessment (Gornitz and Couch, 2000). In addition, the US Department of Transportation conducted a Workshop on Transportation and Climate change in October 2002 (Potter, 2002). That workshop dealt with aspects of climate variability and change of greatest relevance for transportation, particularly for freight and railroads, and also as identified for the Gulf and Atlantic, Alaska, and Mississippi Regions.

The results from these workshops and assessments allowed us to focus on changes in weather conditions that are directly relevant to transportation. Weather sensitive aspects of transportation already consider and, to a large extent, have adapted to the current climate variability. Therefore, the analysis presented in this paper focuses primarily on climate change rather than climate variability.

2. DATA, MODEL OUTPUT AND ANALYSES TECHNIQUE

The analyses presented in this paper examine both observational data and model output using several different techniques.

2.1 Historical daily data

Daily maximum temperature, minimum temperature and precipitation were analyzed from 1950 through 2005. The historical analysis presented uses a data set and tools developed for an analysis of North American extremes. While the analysis is limited to the United States, data from Canada and Mexico were included in some border grid boxes. The data set from Canada is the homogeneity adjusted temperature and precipitation data sets (Vincent et al., 2002; Mekis and Hogg, 1999). For the U.S. and Mexico, homogeneity adjusted daily data sets are not yet available. Instead great care was taken to identify any station time series with discontinuities and remove them from the analysis as described below. The data from Mexico came from the Servicio Meteorológico Nacional of Mexico and the data for the US came from the Global Historical Climatology Network (GHCN) Daily data set (NOAA 2006). For data from the contiguous United States (CONUS) the homogeneity test of Menne and Williams (2005) was applied and all station time series that did not pass that test were removed from consideration. For stations in Alaska, Hawaii, Puerto Rico, the U.S. Virgin Islands and Mexico where adequate neighboring station data might not be available, the homogeneity test of Wang (2003) was used as well as subjective graphical assessments and metadata analyses. Again station time series that did not pass these homogeneity tests were removed from consideration. As the longer the time series the greater the likelihood of inhomogeneities in the climate record, data prior to 1950 were not analyzed. These data are being made available through the North American Extremes Monitoring web page at NOAA's National Climatic Data Center (http://www.ncdc.noaa.gov/nacem/nacem.html).

Indices of transportation sensitive parameters were created on a station basis and then averaged together. For localized analyses, anomalies of the indices for all stations within 500 km of the target location were averaged together. For US time series, anomalies of station level indices were first averaged into 2.5° latitude by 2.5° longitude grid boxes. Where a grid box did not have any stations, the values of the indices from neighboring grid boxes were interpolated into that grid box in order to make the averaging area more spatially representative. This primarily happened in Alaska. The grid box values were then averaged on an area-weighted basis to create U.S. time series. The time series figures show the annual values and a smoothed line derived from a locally weighted regression (lowess filter; Cleveland et al., 1988). An advantage of a lowess filter is that it is not impacted very much by one extreme annual value that might occur in an El Niño year, and therefore depicts the underlying long-term changes quite well.

2.2 Projections of the future

The projections of transportation relevant weather or climate parameters are based on the output of global climate models.

Model climate output

For projections of the future, one needs to use global climate model output based on a realistic scenario of future greenhouse gas emissions which are being incorporated into the IPCC Fourth Assessment Report (AR4). The AR4 is anticipated being released in February of 2007. Until then the AR4 conclusions and figures are embargoed. But the global climate model output that contributed to the AR4 are available for independent analysis. The climate modeling community was asked to run simulations of the global climate in a variety of future scenarios. The resulting data, from over 25 models, was collected and archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) at the Lawrence Livermore National Laboratory. For this study, three specific scenarios of the future from this collection were analyzed and compared to model simulations of the recent past. Table 1 provides a list of the models and the number of runs of each model that were analyzed. Changes in anthropogenic forcing factors, including greenhouse gas, sulfate aerosol and ozone concentrations were all varied according to a standard IPCC specification in each model. The simulations of the recent past included volcanic aerosols and solar irradiance variations in some of the models but these were not simulated in the future scenarios by any of the models.

The three scenarios chosen for this study are taken from the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic et al., 2000). In increasing order of total greenhouse gas emissions, they are SRES B1, SRES A1B and SRES A2. The IPCC has developed numerous other scenarios based on differing economic, technological and sociological assumptions about the future. These three were selected because they span the range of little to aggressive efforts at greenhouse gas reduction and are the only ones widely used by the climate modeling community. From the IPCC Third Assessment Report (TAR; Houghton et al., 2001), the B1 scenario is "a world in which the emphasis is on local solutions to economic, social, and environmental sustainability" and features the lowest greenhouse gas concentrations, with emissions decreasing after 2050, and the least climate change of the three scenarios considered. The A1B scenario is one of a family of scenarios describing "a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology" and is midway between the other two scenarios at the end of the 21st century.

The A2 scenario envisions "a very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development" and provides a high "business as usual" estimate of greenhouse gas concentrations. The annual mean concentration of atmospheric carbon dioxide used by the climate models to simulate these future scenarios is summarized in Figure 1. This figure reveals that the A1B and A2 scenarios are quite similar over the first half of the 21st century but diverge in the second half with the A1B scenario stabilizing at around 720 ppm sometime in the mid 22nd century while the A2 scenario continues to increase at a sharp rate. On the other hand, the B1 scenario shows dramatically reduced atmospheric carbon dioxide concentrations stabilizing around 550ppm at the end of the 21st century. It should be noted that these emission scenarios do not include a dramatic increase in CO_2 or methane which might result from a possible rapid melting of permafrost.

The IPCC database at PCMDI is of high quality as it has been subjected to numerous quality control tests. For this study, data from all the models that simulated the latter half of the 20th century through the end of the 21st century were used. Many of the modeling groups performed ensemble simulations to better characterize their model's simulation. In these cases, multiple integrations of each scenario were realized by perturbing the initial conditions. The chaotic nature of the (modeled) climate system causes these integrations to diverge significantly from each other but remain statistically indistinguishable. All of the monthly mean surface air temperature and precipitation data in the IPCC/PCMDI database were used to form a multi-model ensemble. In this multi-model, each different climate model contributes equally. For any individual model that was ensemble integrated, an ensemble mean is calculated as that model's contribution to the multi-model. Hence, a climate model integrated many times contributes to the multi-model the same amount as a climate model integrated only once. Using this definition of the multi-model, the single realization models' contributions are considerably noisier than the contributions from those models with multiple realizations.

The individual climate models simulate the recent past to a widely varying degree of accuracy. However, no effort was made to use model skill to weight individual climate models' contributions to the multi-model. However, because the individual climate models have very different biases in their ability to simulate the recent past, the difference in the 21st century simulation from the simulation of the 1990-1999 for each individual climate model was calculated. In this way, the individual climate model biases in the mean climate are removed prior to formation of the multi-model. Note, however, that there can still be a wide variation in each model's response to the future climate forcing changes.

It should be kept in mind that climate models create their analyses on fairly large scales. Therefore, small scale features, such as heavy lake-effect snow on a narrow ridgeline immediately downwind of a lake, would not be simulated by a global climate model. Not only would the grid scale and topography be too coarse to resolve such a feature, but our regional assessments of model output would smooth it out even if it was present. Also, not only is the climate is imperfectly understood but also climatologists' best understanding of the physics of climate are imperfectly simulated in climate models (partly because the computational demands would be too great to go to, for example, 1 km spatial resolution and explicit cloud microphysics). Therefore, the climate may provide surprises in the future. Generally, climatologists refer to these potential surprises as low probability events. But some of them, such as a dramatic acceleration of glacial melting and resulting sea-level rise, could be high impact.

Future extremes

The climate model output provides projections for changes in mean temperature. But how do these changes in means impact extremes? The program on the NOAA's National Climatic Data Center (NCDC) CD ROM *Probabilities of Temperature Extremes in the U.S.A.* (NOAA, 1999) was used to estimate the probability that a threshold temperature will occur for one or more consecutive days, and/or the probability that a threshold temperature will be exceeded for any number of days for a station in a given month or season, based on statistics from the observed climate combined with model projections. In this software, the observed climate was defined as the period from 1948 - 1997. In order to determine how the probabilities might change given a climate change projection, the monthly mean, average variance, persistence and interannual variance can be adjusted. As climate models projections have indicated little change in variance, the change in the mean is the dominant factor in climate change. Therefore, the historically observed average variance, persistence and interannual variance were used.

In order to provide assessments for a particular year in the future and have that year be representative of the time period, the interannual variability in the mean model projections was smoothed applying a 13 point binomial filter to each season's projections for each region. Since the model output were adjusted to be anomalies from a different base period, 1990 – 1997, the difference in mean temperature between the 1948 – 1997 base period and the 1990 – 1997 base period had to be factored in. Seasonal means from the SRES A2 scenario were then obtained for the current year (2007), 25 years into the future (2032), 50 years into the future (2057), and for approximately 90 years into the future (2099). As the A2 scenario has the greatest forcing, the reader is encouraged to examine these figures in light of the differences in projections for the other scenarios shown to estimate what the projected changes in extremes might be from other scenarios (e.g., for the south-central CONUS, temperature projections for 90 years in the future under the B1 scenario could be considered approximately represented by the 50 years in the future projections of extremes under the A2 scenario).

2.3 Integrating the Analyses

All these potential analyses can create far more information than is appropriate to present. To limit the amount of information provided, many of the analyses presented will be examples: an analysis of one particular transportation relevant index at a particular location can be viewed as a case study directly applicable to that particular city but with the expectation that other cities could have their extremes varying in similar fashion.

3. CHANGES IN TEMPERATURE WILL IMPACT TRANSPORTATION

The US temperatures have been rising over the last century, with more rapid increases since 1970 than earlier as shown in Figure 2, which is courtesy of and regularly updated by NOAA's National Climatic Data Center Climate Monitoring Branch (http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html). While much of the observed warming prior to 1950 was likely due to natural climate variation, North American temperature changes since 1950 are unlikely to be due to natural climate variability alone (Karoly et al., 2003). Indeed, the effects of sulfate aerosols and greenhouse gases have been detected in the North American temperature time series (Stott, 2003; Zwiers and Zhang, 2003). Examination of Figure 3 helps explain which changes on a global basis are due to natural causes and which to anthropogenic. It is clear that anthropogenic forcing is needed to explain the warming after 1970 while a combination of natural forcing and anthropogenic forcing are required prior to 1970. If the climate change seen after 1970 or so (see Figure 4) is primarily a result of anthropogenic climate forcings, which continue to increase, then it is reasonable to view the observed changes after 1970s as somewhat indicative of what might be expected in the near future.

3.1 Temperature projections

The global climate models were run under different scenarios. As examination of Figure 5 reveals, the scenario one uses for future CO_2 emissions greatly impacts global climate model projections. But for the next 30 years, the uncertainties are primarily model related and not due to different emissions scenarios. Even if atmospheric concentrations remained at the current levels, the models would still project similar warming over the next couple decades. For reasons stated earlier, analysis using the business as usual scenario of SRES A2 is more widely used in this analysis. Figure 6 shows the mean temperature projection for each region and the one and two standard deviations range of projections for scenarios B1 (Figure 6a), A1B (Figure 6b) and A2 (Figure 6c). To put these projected changes into historical perspective, note that the smoothed CONUS temperature time series has a range of ~1.5°C[1] while the projections shown in Figure 6c are two to four times that amount.

Model projections for one point or grid box are not as robust as projections that incorporate information from several grid boxes. Therefore, fairly large regions were selected as indicated in Figure 6. The modeled data were regridded to a fine grid that could then be averaged up into regions. These regions were defined by latitude and longitude and therefore, as indicated in Figure 6, do not correspond to state borders. The regions selected were deemed, based on past

[1] To convert between Celsius and Fahrenheit, note that the freezing point of water is 0°C or 32°F and boiling is 100°C or 212°F. Therefore, the freezing to boiling range is 100°C or 180°F. Ergo, 1°C change is equivalent to 1.8°F change which means that a 1.5°C change is equal to 2.7°F. To convert a Celsius temperature directly to Fahrenheit, multiply by 1.8 and then add 32. To convert from Fahrenheit to Celsius, first subtract 32 and then divide by 1.8.

experience in analyzing model output, to be about as small as regions can be and still provide robust model results. While climate variability at a point is likely to be greater than what one might conclude from regional analysis, climate change could be greater or lesser. For the regions selected for this analysis, the temperature projections are generally similar, but not identical, for neighboring regions.

Figure 7 shows the mean and standard deviation for the different model runs for the eastern region using the A2 scenario. In addition to the mean value the figures shows the variability in the form of one standard deviation across models (sigma, σ), which would include 68% of normally distributed data, and the two σ value which would incorporate 95% of the data. The top panel shows annual values. The bottom panel shows values for smoothed time series. All future panels will just show the smoothed version because it better reflects how most people think about projections. For example, if one drew a line from the starting value to the top or the bottom of the two σ contour, that would be a fairly plausible interpretation of extreme model runs if one was using the smoothed time series. But that approach would be invalid using annual values because what the boundaries reveal are near the extremes of annual deviations from the long-term change. It should also be kept in mind that actual changes in climate are unlikely to be as gradual as assessment of the line depicting the median of the climate model output might imply.

In the following analysis, seasonal projections rather than annual will be used. Generally the projections for the four seasons track each other fairly well. However, as shown in Figure 8, they start to diverge after 50 years with summer and fall showing somewhat more warming.

3.2 More hot days

On stepping outside into the hot California sun, an expert on climate change detection was asked whether that day's near record temperature was due to global warming. He replied that one could not determine whether any particular day's high temperature was due to anthropogenic climate change. But then added that hot days like that give us the privilege of seeing the kind of weather our children will have to normally endure as such high temperatures will be part of the legacy of our greenhouse gas emissions.

While the projections shown in Figure 6 are for mean annual temperature, similar projected increases can be expected for summer temperatures resulting in more hot summer days. High maximum temperature in the summer has a variety of impacts on transportation.

Analysis of Figures 9a and b indicates that the number of days with temperature above 32.2°C (90°F) and 37.7°C (100°F) has been increasing since 1970. It also reveals that the current values are not quite equal to readings during the early 1950s when several areas, particularly the south-central US, had severe droughts. Figure 9c shows somewhat different analysis of hot days by assessing the change in the number of July (the warmest month of the year) above the 90th percentile in maximum and minimum temperature, with minimum temperature showing a greater increase since the 1960s. Figures 9d and e reveal projections for extremely hot days. In these figures we show the changes in the twenty year return value for the annual maximum daily-averaged surface air temperature based on climate models using the 1990- 1999 period to the 2090-2099 period under the A1B scenario. The twenty year return value is that temperature that is reached or exceed on average every twenty years over a long period of time. Such temperatures are truly rare events as they are expected to be reached only three or four times of the course of a human lifetime. Figure 9d shows the change in this quantity. To put this projected warming in perspective we show in figure 9e the number of times the 1990-1999 return values would occur on average in a 20 year time period under the 2090-2099 A1B forcing. (By definition, this field is unity under the 1990-1999 conditions as the 20-year event would only occur once in the 20 years.) Over most of the CONUS region, the present day return value temperatures would be reached or exceeded ten times or more in a twenty year interval or in short, every other year or more frequently. Hence, the rare high temperature event becomes a commonplace event in this scenario. In Alaska, the change in frequency of the extreme event is not as large (unlike the change in the mean which is larger in Alaska than the changes in the mid-latitudes). Analysis of Figure 9f reveals that median model results from all three scenarios project increases in heat waves over the CONUS. The heat wave duration index shown in this figure is defined as in Frich et al. (2002) as the annual maximum period greater than 5 consecutive days with maximum temperature greater than 5°C above the 1961-1990 average maximum temperature for that day of the year.

For examples of what may occur in the future with extremely high temperatures, four cities are examined with the first two being Dallas, TX and Minneapolis, MN. The analysis of the historic data within 500 km of these cities are for thresholds less than that used for projections in an effort to minimize the number of years with no exceedances of the designated threshold. The top panel of both Figures 10 and 11 are anomaly time series, from stations within 500 km of the cities named. For Dallas, the time series is the number of days above 37.7°C (100°F) and for Minneapolis 32.2°C (90°F). Unlike the national average, neither of these two locations have distinct increasing values for the last few decades – certainly not compared to their year to year variability. Looking towards the future, the bottom panel of Figures 10 and 11 show how the probability of exceeding particular thresholds is likely to change. For Dallas, the threshold used was 43.3°C (110°F) and for Minneapolis it was 37.7°C (100°F). Dallas did not actually reach 110°F in any of the last three summers (June, July and August of 2004-2006). It did hit 109°F in the summer of 2003 and 110°F in September 2000. However, back in summer of 1980 (which has a spike in the top panel of Figure 10) it reached 110 three times. Minneapolis officially reached 100°F once in the summer of 2006 and none during the previous three summers. As Figures 10 and 11 indicate in these example locations, like most of the US, have projections that indicate the probability of having a hot summer day will be increasing.

Two additional locations were examined. The first is Honolulu, HI. Examination of Figure 12 indicates that very warm July days, days with maximum temperature exceeding the 90th percentile, have been increasing slightly. Projections for the number of days above 32.2°C (90°F) indicates that hot days are projected to increase in the future. The historical data record indicates that Honolulu summer maximum temperature reached or exceeded 90°F 23 times in 2003, 29 times in 2004, 46 times in 2005 and once in 2006. The software package used to calculate probabilities of days exceeding thresholds was not able to be run at San Juan, PR. However, as indicated in Figure 13, the number of days exceeding the 90th percentile of maximum temperature in July has been increasing since 1970.

Hot weather adversely impacts transportation

Impacts Maintenance

High temperature limits the number of hours that road crew maintenance personnel can work. Restrictions begin typically at 29.5°C (85°F) (WIST Appendix B-1). Depending on the humidity and heat stress index, it can lead to possible heat exhaustion at 40.5°C (105°F; WIST Appendix B-1). Increasing frequency of high temperatures will thus limit outdoor maintenance work.

Impacts infrastructure materials, load restrictions

Although pavement temperature may significantly exceed ambient temperature, air temperature over 32°C (90°F; WIST Appendix B-1) is a significant threshold. Sustained high temperatures can cause roadway buckling, demonstrated by the prolonged heat wave in July 2000 wherein three lanes on Interstate 80 in the San Francisco Bay Area buckled due to thermal expansion, shutting down the freeway (du Vair et al., 2002; US National Assessment – California Region). Materials used in roadways and bridges have a limited range of tolerance to heat, yet polymers are being developed to extend the range. Bridges can be particularly subject to extra stresses from extended periods of elevated temperatures. The New York metro area, for example, with over 2000 bridges, experiences heavy congestion, which can, with excess vehicle loadings, increase structure stress (Zimmerman 2002). High pavement temperature increases the risk of tire bow-outs, especially in heavily loaded vehicles (WIST 4-46).

Rail buckling

Air temperature above 43°C (110°F) can lead to equipment failure (WIST Appendix B-1; Changnon, 2006) especially for rails, depending on the degree of difference from the neutral installation temperature (WIST Appendix B-2). Neutral temperature, generally set when the rail is laid, is the point where rail is neither expanding nor contracting. Railways protect track from buckling by establishing the target neutral temperature to be about 22°C (40°F) less than the maximum expected rail temperature (J. Bertrand 2006, pers. comm., Jim Bertrand is a Railway Safety Inspector with Transport Canada). Track is designed to withstand the internal forces resulting from a 33°C (60°F) change in rail temperature. So if rail heats more than 33°C (60°F) above its neutral temperature then a thermal misalignment, track buckle or sun kink may result and derailments are possible. Lower speed and shorter trains, to shorten braking distance, and lighter loads to reduce track stress are operational impacts. Track alignment problems were a significant cause of accidents of weather-related factors (Rossetti, 2002), and a strategy to deliberately heat rails to more than 38°C (100°F), a practice in Florida today, may be undertaken elsewhere to increase the neutral temperature and decrease the impact of higher ambient air temperatures (Caldwell et al., 2002).

Previous research has indicated that potential buckling of weak and strong track exists with rail temperatures of 47°C (116°F) and in excess of 54°C (130°F), respectively (J. Betrand 2006, pers. comm.). Whether a track is weak or strong depends on the type of rail (e.g., continuously welded or not), ties, fasteners etc. used. Rail may heat as much as 28°C (50°F) hotter than the ambient air temperature but on a typical warm afternoon the rail temperatures are normally about 17-22°C (30-40°F) warmer than ambient. Therefore, ambient air temperatures of 24.5°C (76°F; 116°F minus 40°F to account for the tracks being warmer than the air) for weak track and 32.2°C (90°F; 130°F minus 40°F) for strong track can be considered proxy indicators for important track temperature thresholds (Rossetti, 2002). However, orientation of the track matters greatly also because the sides of rails laid east-west will heat at considerably greater rates at low sun angle than north-south tracks. In the spring, the first occurrence of air temperature at 21-24°C (70-75°F) for long haul rail and at 29.5°C (85°F) for transit rail is relevant as frequent rail inspections may be begun at those thresholds.

Aviation

As for aviation, high temperature, combined with moisture and field elevation is used to calculate “density altitude”, used to quantify engine combustion efficiency and the needed runway length for take-off and landing at specified aircraft loads. On hot summer days at high altitude airports, such as at Denver International, aircraft may have to burn fuel, unloading weight, in order to have a safe take-off roll. Airport runways are, of course, designed to the climatological conditions of temperature, moisture, wind velocity, and visibility; therefore, for example, higher altitude airports have longer runways. Still, with more days of higher temperatures, the number of days of limited operations at high altitude airports will increase, essentially at airports in the intermountain west (Arizona, Colorado, Idaho, Montana, New Mexico, Nevada, Utah and Wyoming). Moist air, being less dense than dry air, also contributes to higher density altitude, but temperature is a more important factor in the calculation. For aircraft that use up most of the pavement on even the longest runways, even a 1 or 2% increase in density altitude from increased moisture may put those aircraft out of commission for daytime operations on certain days. With more days of higher temperatures, the number of days of limited operations at high altitude airports would be expected to increase.

3.3 Fewer cold days

As the converse of more hot days, the mean model projections shown in Figure 6 also implies fewer cold winter days. As analysis of Figure 14 indicates, the coldest days of the year have been decreasing across the US since 1970 as determined by maximum or minimum temperature. To illustrate the future changes that a decrease in cold days could bring about, three example cities were chosen with quite different parameters. The first is Billings, MT for minimum temperatures less -27.7°C (-18°F). Figure 15 shows the historical anomaly time series for the number of days less than this threshold for stations within 500 km of Billings (top) and the probability of getting below this value during the winter in the future. The historical temperature record indicates that the town of Billings did not actually reach this threshold for the winters of 2002/3 to 2005/6 but did report -17°F (-27.2°C) once in 2003 and again in 2005. The threshold of -27.7°C is based on an approximate threshold for public safety, including the safety of the traveling public. As noted in Appendix B, the NWS in the Western Region is concerned that frigid temperatures along with sustained wind speeds of at least 15 mph create dangerous wind chill readings and they use the benchmark value of -18°F (-27.7°C) or colder.

Figure 16 reveals that the number of days with minimum temperature less than freezing has been decreasing since 1970 for the stations within 500 km of Phoenix, AZ. Projections of the future also indicate that days with minimum temperature below freezing in Phoenix will become very rare. During the winters of 2002/3 to 2005/6, the Phoenix minimum temperature reached freezing twice, both in the winter of 2003/4. In the Washington, DC area the number of winter days with the maximum temperature being less than freezing has held fairly steady since 1970 although they are projected to decrease in the future (see Figure 17). The observational record indicates that Washington, DC had a daily maximum temperature less than or equal to freezing 13 times in the winter of 2002/3, 15 times in 2003/4, 11 times in 2004/5 and three times in 2005/6.

Mixed impacts from fewer cold days

Fewer lower temperatures would have a positive impact on outdoor maintenance. Wind chill affects exposed personnel and wind chills below -29°C (-20°F) severely limits ground crew work at airports (WIST 4-53) and along roadways (WIST Appendix B-1). Air temperature at the cold extremes can also have substantial effects on the railway sector of surface transportation (WIST p 4-21). The first occurrence of a low temperature at 0°C (32°F) for a season can produce rail contractions that can cause gaps and misalignment in the track. Rail contraction continues as the temperature drops further in winter.

Unimproved roads in national forests, grasslands, and wild lands (with more kilometers than the interstate highways) were developed with typical temperature and precipitation regimes in mind; often relying on frozen roads in the colder months for access. Because frozen roads are less susceptible to damage by trucks, they are legally allowed to carry 10 percent heavier loads (Caldwell et al., 2002). Warmer weather will reduce the time this exception is permitted. Logging and hauling operations usually conducted on frozen or snow-packed roads are affected by melt and thaw. Thawing may penetrate and damage structural support of roads and shut down heavy truck hauling (WIST p 4-18, and Appendix B-1).

Alaska Region

Mean annual ground temperatures commonly differ from mean annual air temperatures by several degrees. Thus, ambient air temperature is but a proxy for the ground temperatures that are the real variable important to transportation. A mean annual ground temperature less than 0°C defines the presence of permafrost. When the mean annual ground temperature rises above 0°C, the permafrost starts to thaw from the surface down, and given time, disappears (Williams and Wallis, 1995).

Roadways and railways built on permafrost have been damaged as the permafrost has begun to melt and ground settlement has occurred. Ground settlement occurs at a high rate in the ice-rich, fine-grained frozen ground common in much of Alaska (Smith and Levasseur, 2002). Costly increases in repairs for roads damaged from accelerated permafrost thawing have been observed (Smith and Levasseur, 2002; US National Assessment - Alaska Region). Increased slope instability, landslides and erosion in the Mackenzie Basin, for example, damages roads and bridges. Along the shorelines, subsidence from permafrost thaw has resulted in some bluff shorelines retreating at rates of up to five meters or more per year (Smith and Levasseur, 2002). The Alaskan-Canadian Highway was built entirely on permafrost in WWII, and the Alaska rail that serves the lower 48 States follows its route. So permafrost thaw, in response to fewer lower temperatures has serious consequences for transportation infrastructure.

Experiments in frozen tunnels by the Cold Regions Research and Engineering Lab reveal that natural permafrost at ground temperatures between -1.1 to -0.5°C (30-31°F), thaw differentially, leading to sink holes and wide areas of subsidence, or thermokarst. Special foundation designs with insulating underneath are necessary to keep the heat from buildings from thawing the permafrost. Normally, the permafrost provides for relatively stable foundations. But even in the high arctic, where the mean ground temperature may be -10°C or colder, a degree or two rise of mean ground surface temperature will cause an increase in summer thawing of 10 cm or so while in areas that are not as cold as the high arctic a degree or two warming of the mean ground surface temperature can cause the thawing layer to increase substantially, to a meter or more, disrupting foundations in roads and airstrips (Williams and Wallis, 1995). Hence, the widely used Alaskan engineering references on climate and ground conditions, some based on measurements from the 1950s, need to be updated (Rossetti 2002).

Oil pipelines, which are inherently warm, are liable to cause thawing and subsidence. The TransAlaska running from Prudhoe Bay to Valdez, is elevated above the permafrost for the most part, on steel piles which contain a self-cooling device, to avoid thawing ice-rich permafrost (Williams and Wallis, 1995). In some sections where the permafrost has thawed, like in the Prudhoe Bay oil fields, thermopiles, running in reverse, are used to exchange heat from the ground below to the oil, to keep the oil warm for flow. Even so, the warming of frozen ground (as opposed to thawing) reduces the bearing capacity of piles or other footings in permafrost. Thus failures may occur even though the pile may still be within permafrost, if the temperature rises to -1° or -2°C (Williams and Wallis, 1995). Gas pipelines, designed to carry gas chilled to below 0°C, have little effect on the permafrost, nor the permafrost on them. Differential heating of the permafrost may cause heaving of the soil, representing the continuing and longer term threat to gas and oil pipelines. Pipelines have an expected operational life of some decades. Because very extensive areas of permafrost have temperature near 0°C, a rise of mean air temperature of only a couple degrees would cause the disappearance of permafrost, with obvious impacts on the structures on which it depends.

Less cold positively impacts marine transportation

Fewer days with low temperatures would positively affect the marine transportation sector. In the simplest sense, air temperature of 0°C (32°F) or less impacts water-borne operations as water that splashes or sprays freezes on contact with vessels, decks, riggings, and accumulates as ice (WIST 4-28) making operations on deck dangerous, and limiting the period for efficient transport. Ice fog can be extremely dangerous, stopping all deck activity, including aircraft to deck operations.

Less time with cold temperatures would lead to less sea ice and that would also have a positive impact on marine transportation. Ice jams can cause flooding and may require icebreaking operations to alleviate them (WIST 4-27). Less ice lowers the risk of hull damage to vessels and port facilities (WIST 4 -29). In Cook Inlet in Alaska, for example, freezing of brackish water create sediment-laden ice blocks that travel for distances over 100 km and are very dangerous to ships in winter (Smith and Levasseur, 2002). The combination of thaw subsidence of permafrost shores, with some bluff shorelines retreat rates of up to five meters or more per year, with sea-level rise, and ice blocks makes for complex coastal dynamics. But if Arctic Ocean ice conditions continue to become less severe, prospects are for increased international trade through Alaskan water via the Northern Sea Route (Smith and Levasseur, 2002).

Great Lakes Region

In the Great Lakes, a reduction in ice cover, resulting from fewer lower temperatures, could theoretically enable a longer navigation season. Historically the Great Lakes commercial navigation season extends from late March through mid-January, though marine trade on the Lower Lakes not utilizing the Soo Locks (which are closed from January 15 to March 25) or the St. Lawrence Seaway and Welland Canal locks (which are closed from late December to early April) is able to continue in the winter months in periods when there is little or no ice (D. Knight, pers. comm.; Dave Knight is the Program Manager, Transportation and Sustainable Development, Great Lakes Commission) . While the marine transportation sector would likely benefit from the increased vessel utilization and reduced costs of ice-breaking in a milder winter scenario, this may be offset by reduced carrying capacity due to lower water levels and restricted draft depths (Caldwell et al., 2002).

Midwest Region

Winter conditions in the Midwest bring ice to the Mississippi River which commonly stops barge traffic north of the Iowa/Missouri border. This is somewhat unpredictable, but recent years seem to be milder than what was experienced in years past, allowing traffic to continue to move later into December and earlier in March, though no quantitative records on transport have been found to document this (W. Gretten, 2006 pers. comm.; William Gretten is the Operations Manager, Mississippi River Project, Rock Island District, US Army Corps of Engineers). Less inland ice, for example on Lake Pepin of the Mississippi, lowers risk to flooding.

3.4 Warmer temperatures may open up the Northwest Passage

A sea route from Europe to the Far East that avoids Cape Horn or the Cape of Good Hope inspired many explorers in the 16th and early 17th Century. All the explorers found the fabled Northwest Passage through the Arctic archipelago of Canada blocked by ice. But that might not always be the case. Indeed, some boats have already traversed the recently more open Northwest Passage.

Observations of Arctic sea ice indicate a striking thinning (Rothrock and Zhang, 2005) and overall downward trend in extent (Stoeve et al., 2005). An analysis of IPCC AR4 model simulations indicates projections for an accelerated reduction in ice, though large uncertainties exist in the projected rates (Zhang and Walsh, 2006). This means that specific predictions for when climate change would open the Northwest Passage for commercial transportation also hold a great deal of uncertainty. O'Neil (2006) in a Canadian newspaper article summed up the projections nicely as follows.

The earliest projected date was 2015 by Vice-Admiral Ron Buck the Vice-Chief of the Canadian Defense Staff. John Falkingham, chief of forecast operations at the Canadian Ice Service, a division of Environment Canada stated that the Northwest Passage will become accessible for summertime shipping on a fairly certain basis towards the end of this century and gives the 2070-2080-2090 time frame. But Falkingham also noted that the definition of commercial traffic can be used loosely. Many cruise ships currently travel great distances into the passage in the summer, and the Russian cruise ship Kapitan Khlebnikov, an icebreaker, frequently goes right through the passage. Greg Flato, who heads Environment Canada's Victoria-based Canadian Centre for Climate Modelling and Analysis, indicates that projections based on various models from scientific groups around the world range from as early as 2030 to as late as the early 22nd Century. But, the international shipping industry and its insurers are unlikely to risk using the route for years to come due to risk of hard-to-see chunks of ice damaging their vessels. According to Birchall (2006), those who predict an ice-reduced or ice-free Northwest Passage often tend to oversimplify the nature of the ice regimes in the archipelago, thus exaggerating the potential for increased shipping.

A Northwest Passage would positively impact transportation

Routes from Europe to the Far East would save 4000 to 7000 km going through the Northwest Passage compared to the Panama Canal. Not only would an open Northwest Passage allow ships to avoid a longer route through the Panama Canal, container ships, oil tankers and other ocean-going vessels too wide to fit through the Panama Canal would especially benefit from a Northwest Passage (Caldwell et al., 2002; Mills and Andry, 2002).

3.5 Seasonal changes can have impacts

It is not just the extremes of temperature that can have an impact on transportation. Some annual occurrences of particular conditions are also relevant. As Figure 18 shows, there is considerable variability in the number of freeze-thaw days but no distinct trend. However, the time of year that freeze-thaw days occur could be expected to change to earlier in the spring and later in the fall. This would be in keeping with the analysis presented in Figure 19. This is the length of time between the first time in the year that maximum daily temperature reaches 21.1°C (70°F) and the last day of the year when this occurs. The length of this time period has been increasing since 1970 and could be expected to increase further in the future.

Analysis of two locations in Alaska focus on the season changes in frozen conditions. The top panel in Figure 20 reveals that the number of days with maximum temperature below freezing has been decreasing since 1970 around Barrow, AK. The bottom panel indicates that the probability of maximum temperatures equal to or greater than freezing in May in Barrow is projected to increase in the future. The observational record for Barrow indicates that maximum daily temperatures in May were equal to or greater than freezing nine times in 2003, 16 times in

2004, six times in 2005 and 19 times in 2006. Similarly, Figure 21 indicates a decrease in the number of days with maximum temperature less than or equal to freezing for stations within 500 km of Anchorage, AK and the projected probability of freezing or (below) daily maximum temperatures at Anchorage in March will decrease as well. The Anchorage daily data indicate that daily maximum temperature in March was equal to or below freezing nine times in 2003, 16 times in 2004, six times in 2005 and 19 times in 2006.

Impacts of non-extreme seasonal changes on transportation

Springtime load restrictions

As roadways begin to thaw during the period of the year when the temperature swings below and above freezing, restrictions must be places on weights vehicles can carry to avoid structural damage due to subsidence and the loss of bearing capacity (Williams and Wallis, 1995). Freezing and thawing of subsurface soils in cold regions results in hundreds of millions of dollars in damage to roadways in the U. S. yearly. State departments of transportation attempt to mitigate damage by placing load restrictions on roads prone to this problem, attempting to implement restrictions such that the impact to commercial traffic is minimized while the structural integrity of the roadway is maintained. Research efforts to both predict soil temperatures, using heat exchange and long-range atmospheric models, and to develop effective operational decisions on specifying when to place spring load restrictions, demonstrate the importance of spring thaw conditions to the roadway sector of transportation (Hanson, 2006; Pisano et al., 2005).

The relationship between air temperature and ground thaw is complicated, but generally, in the absence of permafrost, winter freezing extends deeper under colder conditions. Freezing rarely extends to more than a meter or two, but heavy snow cover can insulate the ground and result in less freezing and higher mean annual ground temperature (Williams and Wallis, 1995). Soil temperature at the freezing point is an important threshold for the railway and pipeline sectors, along with air temperature varying around the freezing point, as it is under these conditions that the ground heaves, most prevalently during the spring thaw (WIST 4-38). The period of springtime load restrictions is climate dependent. As thaw begins earlier in the year with shorter winters and longer summers, the period of springtime load restrictions may be reduced in some areas, but may expand in areas with shorter winters but longer thaw seasons.

An additional seasonal aspect to transportation comes from the use of ice roads in remote locations. Hauling heaving machinery into remote mines can best be done in the north when the roads are frozen. The analysis presented in Figures 20 and 21 indicate that the seasonal ice roads are likely to be useable during a shorter period of the year.

4. CHANGES IN PRECIPITATION WILL IMPACT TRANSPORTATION

Changes in precipitation can impact transportation in a myriad of different ways depending on how precipitation changes.

4.1 Precipitation projections

Figure 22 shows the mean precipitation projected for the Eastern U.S. from the AR4 model runs for the three different scenarios. Interestingly, the different scenarios of future greenhouse gas emissions do not have much impact on projected changes in precipitation. While these mean projections show a slight increase in precipitation over the 1990-1997 values, the uncertainty in these projections is quite high as illustrated by Figure 23. Figure 23a show the annual precipitation projections from scenario B1. A1B results are in Figure 23b and Figure 23c show the results for scenario A2. Winter and summer precipitation projections from scenario A2 are shown in Figures 23d and e. For almost all regions, some models are projecting an increase in precipitation, some a decrease and some project total precipitation staying about the same. It should be noted, though, that the uncertainties in precipitation projections are probably greatest in Hawaii as the model resolution is too large to include island topography and island topography is a key aspect of the precipitation regime there. While the total amount of future precipitation for most regions is quite uncertain, there are a few aspects of precipitation that have greater certainty, such as increases in heavy precipitation, a shift from snow to rain in a warming climate and changes that can impact droughts. These topics are discussed in the following sections.

Independent of projected changes, using more data, more recent data and improved analyses techniques can provide quite different values for 100 year return period precipitation events, as illustrated in Figures 24 and 25. Ergo, transportation planning should make use of as up to date precipitation analyses as possible.

4.2 Heavy precipitation events are increasing

Figure 26 shows no secular change in the number of days with precipitation. Yet the magnitude of the highest precipitation event has been increasing since 1970 as shown in Figure 27a, though the extreme precipitation experienced during the El Niño event of 1982-83 stands out as quite a significant departure. Figure 27b and c are of analysis of model projected extreme precipitation. The extreme assessed is the 20-year return period maximum one day precipitation total. Figure 27b shows the predicted percentage change in this value from the 1990-1999 forcing to the 2090-2099 A1B forcing. Figure 27c shows the number of times over a 20-year period using 2090-2099 forcing that the extreme 20-year return period daily precipitation total calculated under 1990-1999 forcing would occur. Similar to the discussion of figure 9e, the present day rare precipitation event would be realized much more often in this scenario. A

Simple Daily Intensity Index averaged over the United States, as shown in Figure 28a, reveals that on days that precipitation does occur, the amount is becoming greater. Median model projections for the future over the CONUS, Figure 28b, indicate that the Simple Daily Intensity Index is expected to continue to increase over the next century. The total annual precipitation that fell on days with precipitation greater or equal to the 95th percentile, shown in Figure 29a, has considerable year to year variability but also shows marked increases since 1970. Figure 29b indicates that the fraction of precipitation from days with precipitation greater than the 95th percentile (calculated for the 1961-90 base period) is projected to increase for all three emission scenarios. According to the median model results, the highest annual five-day precipitation event is projected to increase for the CONUS under all three scenarios evaluated (Figure 29c). These observed increases in heavy precipitation events are not only in keeping with observational analyzes, such as Groisman et al. (2005), but with model projections for the future. The IPCC TAR indicates that the intensity of precipitation events is projected to increase in the future (Cubash et al., 2001). More recently, Barnett et al. (2006) found that simulations of the Hadley Center climate model project a decrease in average precipitation yet an increase in the frequency of extremely wet days.

Heavy precipitation adversely impacts transportation

Precipitation frequency-intensity-duration impacts transportation and drives design specifications. Heavy precipitation effects most transit sector activities. Heavy precipitation, whether snow or rain, constitutes the most costly weather situation to railroad transportation (Changnon 2006). Rain of sufficient intensity and duration can result in road submersion, and flooded low-lying underpasses. Flooding causes road scouring, road washout, damages railbed support structures, causes overflow onto tracks, and causes mudslides that damage tracks (WIST

4-54, Rossetti 2002). Winter rain with accompanying mudslides has caused yearly washouts of Highway 1 in California and has closed coastal railways; rail and road undercutting could lead to permanent closures of some infrastructure (du Vair et al., 2002). Intense precipitation may scour pipeline roadbeds, unearth buried pipelines, stretch lines, and damage lines by impacts of foreign objects (WIST 4-36). Erosion from the combined effects of turbulent seas and heavy precipitation causes damage to coastal roads and pipelines (du Vair et al., 2002).

Because intense precipitation events can result in flooding that can damage or destroy structures in most transportation sectors, an understanding of the precipitation intensity-frequency-duration values is warranted. Probabilistic estimates of rainfall intensities for a range of durations (5 minutes to 24 hours) for return periods, or recurrence intervals, of 20, 50 and 100 years have been used by civil engineers for designs of transportation related infrastructure such as road culverts, storm water drainage systems, rail and roadbed design.

These probabilistic estimates of precipitation date from the 1960/1970s, for much of the country and are in process of being updated, utilizing more data, both spatially and temporally (Bonnin et al., 2003). Maps showing locations where the 24-hour duration 100-year return period storms have changed show significant area in both the East and West sections similar to results shown in Figures 24 and 25 (Bonnin et al., 2003). It is likely that most of the differences shown in these maps are due to data processing techniques alone, but in any case, the engineering design criteria and flood maps, derived from older probabilistic estimates of precipitation are obsolete.

It is important to note that while the technique uses a longer period of record, which allows more confidence in the projections of rainfall frequency estimates, the technique does not incorporate projections of climate change. Nonetheless, the more recent analyses being conducted now (see http://www.nws.noaa.gov/oh/hdsc/) provide better estimates on which to base design decisions (Bonnin et al., 2003).

A record-breaking 24-hour rainstorm in July of 1996 that resulted in flash flooding in Chicago and its suburbs illustrates the effect of intensive rainfall on the transportation system. Chicago is the nation's rail hub with nearly 90% of all freight traffic going through it (Changnon, 1999). Extensive travel delays occurred on metropolitan highways and railroads, commuters were unable to reach Chicago for up to three days and more than 300 freight trains were delayed or re-routed. Streets and bridges were also damaged (Changnon 1999). An analysis of precipitation events in the Mississippi Delta Region (Burkett, 2002) shows increases in more intense events (rainfall greater than two inches or more or 5 cm per day) as well as average annual precipitation increasing overall by 20-30% over the past 100 years.

Any amount of liquid precipitation effects roadway transportation because of concerns with traction (WIST 4-45) but also because premature deterioration of concrete bridges, parking garages and other structures may be magnified in areas with more frequent precipitation events (Caldwell et al., 2002).

4.3 Warmer temperatures mean longer rain season and shorter snow season

As temperatures increase, the number of days below freezing will decrease. This will decrease the length of the snow season. Longer ice-free conditions in the Great Lakes might be assumed to lead to more or stronger lake-effect snowstorms. However, analysis of conditions in global climate models related to heavy lake-effect snowstorms downwind of Lake Erie indicated that heavy lake-effect snowstorms decrease in the model projections and be replaced in part by heavy lake-effect rain events (Kunkel et al., 2002). However, the authors also expressed concerns about the validity of the projections for these conditions. Indeed, Ellis and Johnson

(2004) state that research has determined there was an increase in snowfall over portions of the past century across those areas of the Great Lakes region that are subject to lake-effect snowfall and that this increase in snowfall came at the expense of rainfall events. Warmer minimum temperatures in northern winters may increase the likelihood of conditions conducive to ice, rather than snow events (Sato and Robeson, 2005).

Detailed analysis of the historical data record for the western CONUS found a regional trend toward smaller ratios of winter-total snowfall water equivalent to winter-total precipitation during the period 1949-2004 (Knowles et al., 2006). However, looking at a longer period, 1901-2000, and at snowstorms rather than snow, Changnon et al. (2006) found that the temporal distribution of snowstorms exhibited wide fluctuations, with downward 100-yr trends in the lower Midwest, South, and West Coast. Upward trends occurred in the upper Midwest, East, and Northeast, and the CONUS trend for 1901-2000 was upward, corresponding to trends in strong cyclonic activity.

Changing from snow to rain positively impacts transportation

Frozen precipitation has the greatest impact of all weather parameters on transportation activities across all sectors (WIST 4-15). Freezing and frozen precipitation cause the greatest expenditure of resources in areas where such precipitation occurs (WIST 4-43). A decrease in frozen precipitation would have a positive impact on roadway safety, costs of maintenance and efficiency. Frozen precipitation can curtail on-deck activities in the marine transportation sector, impact the safety of personnel, and pose risks to cargo and equipment underway and at port (WIST 4-27). Milder winter conditions would likely improve the safety record for rail, air, ships, and roads. In 2000 about 300,000 road collisions, resulting in injuries, occurred during rain, snow or sleet (Mills and Andrey, 2002), although the statistics are not considered to be complete.

Frozen precipitation is so important to roadway surface transportation sectors that a storm severity index for winter weather has been developed for gauging the effectiveness of garage operations for anti-icing and other winter highway maintenance actions (Carmichael and Gallus, 2003) and a highly detailed winter maintenance operational support system, that includes fine scale weather and heat exchange models, is being developed by DOT (Pisano et al., 2005). In the Lake Erie snowbelt, for example, record snows in 1989 resulted in a 60% increase in costs for person-hours spent on snow and ice control on Interstate 90. Lake ports had higher operating costs and loss of shipments, yet non-transportation related business had only minor disruptions (Schmidlin, 1993).

Frozen precipitation generally has negative impacts on transportation sectors, adversely impacting pipeline operations by freezing valves, and complicating inspection of buried pipeline (WIST 4-35). Ice buildup on the third rail or catenary lines (overhead wires) on rails can cause delays and slower speeds (WIST p 4-44). And frozen precipitation can cause aircraft icing, lowering the aerodynamic performance of aircraft dramatically reducing lift. Aircraft operations may cease altogether when freezing precipitation is moderate or greater (WIST 4-51).

West Coast Region

California's transportation infrastructure could be sensitive to even modest changes in precipitation regime (from frozen to liquid) due to climate change. Climate models indicate that as temperature rises, more precipitation tends to fall as rain rather than snow, leading to immediate runoff, increasing the risks of floods, landslides, slope failures and consequent damage to roadways, especially rural roadways in the winter and spring months (du Vair et al., 2002). Navigable rivers with both rainfall and snowmelt responses would probably see greater winter volume flows with associated greater risk of flooding (US National Assessment - Pacific Northwest Region) and lower summer flows.

4.4 Non-coastal flooding and droughts

While coastal flooding can result from a combination of sea-level rise and storm surge, non-coastal flooding is a direct result of precipitation. Droughts are primarily from the lack of precipitation although increased evaporation in response to higher temperatures contributes as well. Both can impact transportation.

Odd as it may seem at first thought, model projections imply that there will likely be more droughts and more floods in the future. The IPCC TAR states that “there is a general drying of the mid-continent areas during summer in terms of decreases in soil moisture, and this is ascribed to a combination of increased temperature and potential evaporation not being balanced by precipitation” (Cubash et al., 2001). This summer drying is also found in the more recent climate models (e.g., Meehl et al., 2006) and would make droughts more likely. This prospect of droughts can also be deduced from the analysis of the temperature and precipitation projections shown in Figures 6 and 23. These figures indicate that it is quite certain that temperature will go up but there is no certainty that precipitation will go up. An increase in temperature will result in an increase in evaporation or at least potential evaporation. Without a corresponding increase in precipitation, there would be drying.

On the other hand, IPCC TAR also indicates that “precipitation extremes increase more than the mean and that means a decrease in return period for the extreme precipitation events almost everywhere (e.g., 20 to 10 years over North America)” (Cubash et al., 2001). Often floods are caused by widespread precipitation, particularly spring rain falling on melting snow which can be above ground which cannot absorb the water because it is still frozen, rather than localized heavy precipitation. Some of the increase in flooding is due simply to an increase in impervious surfaces. But still there is an increasing risk of great floods, those that exceed the 100 year return period, on large river basins (Milly et al., 2002).

Impacts of flooding on transportation

A 100-year flood denotes that there is a one percent chance of occurrence of that magnitude flood in any given year. The flood mapping by the Federal Emergency Management Agency is largely based on older outdated analysis (see Figures 24 and 25), with about 45% of the country's flood maps based on either outdated precipitation intensity-frequency-duration estimates developed in the 1960/1970s, or on USGS stream flow data, with a small portion (10%) on historical station data alone (Bonnin et al., 2003). In many areas, the magnitude of a 100-year storm flood plain recalculated using more recent data, will be greater than that calculated using data from an earlier period of less intense storminess. Structures whose design was based on the standards established from the 1960s/1970s, may not meet design criteria for a 100-year storm calculated using more recent data. The extensive rainfall in June 2006 in the Washington DC area caused flooding that closed roads and buildings and halted some metro lines is a case in point. Repaving to raise the roadbeds, and increase drainage of underpasses was undertaken in Montana following extensive flooding in 1993. The area of a 100-year flood on today's maps for Hampton Roads, Virginia, the nation's 39th most populous Metropolitan Statistical Area, becomes a 50-year return period (Shen et al., 2005). Increased flood elevations may be one of the first effects of climate change in the New York region (Zimmerman, 2002). Local or widespread flooding can hamper port operations and endanger inland waterway activities, including lock operations (WIST 4-27).

Mississippi River region

On the Upper Mississippi, the climate conditions that impact navigation are related to floods, from above normal precipitation and ice from below normal temperatures. Floods can stop navigation for days, or as in 1993, many weeks at a time, as the lock structures that are required to pass traffic around the dams can be completely submerged and inoperable (W. Gretten, 2006 pers. comm.). The long-lived El Niño event of 1992-1993 contributed to the large-scale atmospheric features associated with the many months of frequent occurrences of prolonged and excessive precipitation over wide areas of the basin.

An extensive study of the three states of Mississippi, Missouri, and Ohio which are centers of the complex riverine transportation systems, reveal a climatic shift to more multi-day periods of heavy rain since the 1920s and show a systematic, long-term increase in both flood incidence and magnitude (Changnon et al., 2001). Given that half the grain exported from the US rides on barges in this river system, climatic shifts here have great impact. During the El Niño floods of 1993, over 6,400 km (4000 miles) of rail track was laid idle (Rossetti 2002), including in Kansas City, the second largest rail hub following Chicago (Changnon 2006). Extreme flood events in the Gulf Coast region were experienced during the 2005 hurricane season. Another example, Hurricane George in 1997, prevented ships from reaching ports and disrupted freight transportation in all modes (US National Assessment - Gulf Coast Region).

Not only would river transportation in this region be adversely impacted increases in flooding caused by the projected increases in heavy multi-day precipitation events but it would also be adversely impacted low water levels in summer caused by projected mid-continent drying.

Impacts of droughts on transportation

Precipitation deficits lower water levels which adversely affect the use of inland waterways, particularly for barge traffic (WIST F-25). The system of locks and dams on the Upper Mississippi River generally maintain a nine-foot minimum navigation depth upstream of their location, at all times regardless of river flow. Drought has much more of an influence on commercial navigation on the lower portion of the river from St Louis to the Gulf where there are no locks and dams. Channel depths in the lower reach of the Mississippi River are entirely dependent on river flows, i.e. there is a direct relationship of river flow to river stage (W. Gretten, 2006 pers. comm.). The 1988 drought stranded over 4000 barges and as a result railroads saw an increased business in hauling grains and other bulk commodities (du Vair et al., 2002; Changnon, 2006). The effect of drought was such that following the drought of 1988, operational procedures on the upper Mississippi and particularly on the Missouri River were modified to guide the release of water upstream by taking into account the needs of the river downstream of the locks and dams (USACE, 2006).

Reduced water depth in channels in the Great Lakes-St. Lawrence Seaway system, not just from droughts but from general decrease in mid continent rain and increased evaporation due to higher temperatures, would translate into the need for light loading to decrease the ships' draft (Quinn, 2002).

5. CHANGING SEA-LEVEL WILL IMPACT TRANSPORTATION

5.1 Projected changes in sea-level

Sea-level rise has a bit of enigma associated with it. This is true for both historical and projected sea-level rise. Historically there are problems reconciling the observed changes with the estimated contributions from different sources such as thermal expansion and melting of polar ice (Munk, 2002). Projected increases in sea-level from the IPCC TAR (Church et al., 2001), as shown in Figure 30, seem quite reasonable: they start off slowly and accelerate over time. The enigma comes from the latest analysis of observed sea-level changes based on data from tide gauges and satellite altimeter indicating that since the start of the satellite altimetry (1993) the sea-level has been rising faster than the IPCC projected (Church and White, 2006). The 1993-2005 rate of sea-level rise is 3 mm per year which is 1.6 times as fast as the IPCC TAR projects for the period 1990-2010 of 1.9 mm per year (see Table 2). A rate of 3 mm per year is equivalent to 0.3 meters in 100 years which, at a linear rate, is roughly equivalent to the total TAR projected change over 100 years achieved with an accelerating rate of sea-level rise as shown in Figure 30.

It is beyond the scope of this paper to reconcile these differences. There are many possibilities including short-term variability in sea-level rise during the last decade that makes extrapolating a linear trend into the future inappropriate. There is, of course, uncertainty in any estimate. Most of the projected sea-level rise is due to thermal expansion. Should the melting of the polar ice caps accelerate, sea-level would rise much higher. IPCC TAR does not anticipate polar ice cap melting to contribute more than a few mm per year over the next few centuries (Church et al., 2001). However, Hansen (2006) notes that existing ice sheet models can not reproduce the ice sheet collapse of ~14,000 years ago when sea-level rose at an average rate of one meter every 20 years for 400 years and that the last time the Earth was 3°C warmer than today, during the Middle Pliocene about 3 million years ago, sea-level was about 25 meters (80 feet) higher than it is today. Currently the rapid melting of Greenland, which would have a very high impact, is not impossible but is considered unlikely and is therefore not incorporated model projections of sea-level rise. Despite the enigma described above, until the IPCC Fourth

Assessment Report is released, projections from the TAR are the most authoritative estimates to use.

5.2 Global Sea-level Rise Impacts Transportation

Transportation infrastructure can influence patterns of development of coastal regions far beyond the life cycle of the road, rail, bridge or even airport; thus the ability of coastal regions to adapt to climate change may be helped or hindered by the decisions that transportation officials make today (Titus 2002). Future transportation planning should account for projected changes in the coastlines. According to the Bruun Rule, shorelines retreat so as to maintain a constant slope, and at some estimates, move inland roughly 150 times for every unit sea-level rises (Leatherman et al., 2000, Bruun, 1962). Thus, for half a meter of world wide, or eustatic sea-level rise, sandy shores could retreat 75 meters. To illustrate lands vulnerable to sea-level rise, a Coastal Vulnerability Index has been developed (USGS Fact Sheet 076-00, 2000), mapping areas by amount of projected rise.

Predicting shoreline retreat and land loss rates are critical to planning future coastal infrastructure. Although the Bruun rule is useful as a conceptual model, rigorous application of coastal geology and climatology models are necessary for risk analysis at specific locations. Careful risk analysis may be required for infrastructure such as airports built long ago in coastal areas. See Table 3 for a list of major airports with elevation at and below 22 ft mean sea-level. The 22 ft mean sea-level threshold for the table was chosen because 22 ft was the level of an airport that was determined to have the potential of being impacted by climate-dependent local sea-level rise in Gornitz and Couch (2000). However, all the coastal airports in Table 3 do not have equal vulnerability or need for protection from sea-level rise. Indeed, no individual airport vulnerability assessment was made. Many structures on the ocean coast are designed for a working economic life of 50 years or less. A list of these structures includes airports, levees and canals, seaports, port structures, navigation channels, turning basins, docking areas and navigation gates, piers, wharfs, dry docks and wet docks (NRC, 1987). Thus for these, repairs, replacement, and re-design, which take place relatively frequently can take into account sea-level rise (Titus, 2002).

5.3 Local Sea-level Rise is Most Important

More important to transportation than eustatic change in sea-level, is the local apparent change in sea-level, in the most likely scenario (Titus, 2002; Burkett, 2002). Local apparent sea-level rise estimates consider the vertical movement of land, and coastal erosion. Coastal erosion, in turn, is driven by sea-level rise. To estimate local sea-level rise, subsidence in the Gulf and uplift along the New England coasts are important factors (NRC, 1987). Figure 31 illustrates that, due to these factors, different regions can have quite different local sea-level rise.

According to the WIST Assessment Report, with regard to the marine transportation sector, vessel captains concerned about clearance in shallow water must take actions based on differences in local sea-level amounting to mere inches. NOAA's National Ocean Service (NOS) provides real-time observations on water levels, tides, and currents to support the marine transportation sector for nowcasts and forecasts of water levels. To maximize cargo loads, mariners often time their port arrivals for best under-keel clearance conditions. A few more inches of draft can mean additional thousands to millions of dollars to a shipper (WIST Assessment Report p. F-20, ES-4).

With that in mind, the effect of sea-level rise might be projected to positively affect the transport of freight, allowing for heavier loads, but not completely. In California's Bay area, for example, increased temperatures result in more precipitation falling as rain rather than snow in the winter, and in earlier spring snowmelts. Interannual and interdecadal precipitation variations lead to fresher salinities in the bay in wet seasons and much more saline waters in dry seasons. With increased runoff in wet periods, the salinity of the bay could drop, lowering the sea's buoyancy, the levels at which ships float, and thus offsetting the benefit of sea-level rise as far as cargo load goes (du Vair et al., 2002).

West Coast Region

Drainage problems at low-lying airports will worsen with a rise in relative mean sea-level. Levees protecting the Sacramento airport, for example, may be at even greater risk of erosion from wind wave and wakes (NRC, 1987). Los Angeles hosts the busiest container port in the US (US National Assessment – California Region) with over 100 ports serving ocean-going vessels (defined as 19.1 m (30 feet) in depth). Changes in tide range and currents occur with changes in relative sea-level and disproportionately increased seiche heights may be produced. The effect of these on moorings and cargo handling for inter-modal transportation needs to be studied (NRC, 1987). Sea-level with respect to dock level is an important consideration at both wet and dry docks, general cargo docks and container berths for clearance of dock cranes and other structures. It may be advisable to incorporate anticipated sea-level rise in the design of future port modifications (NRC, 1987).

Local sea-level rise itself is less important than any changes in the frequency and intensity of storms. In coastal California, where El Niño associated sea-level rise is roughly 30 cm, maximum sea-level variation due to tides or storm surge (60 cm and 300 cm) is large compared to anticipated climate-change local sea-level rise (20 cm). California airports in San Francisco, Santa Barbara, and Oakland, with field elevations of 3.4, 3.0, and 1.8 m (11, 10, and 6 feet), respectively, could be inundated under conditions of extreme high tides coupled with flood conditions and exacerbated by local sea-level rise. So sea-level rise is important in assessing inundation scenarios. “If future climate change results in changes in storm frequency and the inter-annual variability in sea-level and storm frequency, the impact on coastal infrastructure may be far different from what we would anticipate based on long term sea-level rise alone” (US National Assessment – California Region).

Gulf and Atlantic Coast Regions

Several studies, which use model projections of sea-level rise, and were conducted for coastal areas along the Gulf and Atlantic having important transportation infrastructures, make estimates of areas likely to be below sea-level at time frames of 25, 50, and 100 years (Kana et al., 1984; Leatherman et al., 2000; Dingerson, 2005; Gornitz 1991; Gornitz and Couch 2000; Titus, 2002). These estimates show important transportation infrastructures will be permanently inundated barring mitigation techniques such as the building of defensive barrier sea walls. The Hampton Roads, VA, area for example, home of the largest naval base in the world, has two civilian airports, a military transportation control center, several military bases employing over 100,000 people connected by extensive bridge and tunnel networks, and the second largest cargo port on the East Coast, all located within inundation areas of local sea-level rise at the high probability mean scenario (Rygel, 2005; Dingerson, 2005). Tide gauges in the nearby Chesapeake Bay indicate sea-level rise in this area is twice the global average.

Building on earlier work in the National Assessments, further analyses of local sea-level rise, establishing both the base level and projecting climate change scenarios, are done for case studies in the mid and upper Atlantic area including Adirondack Park in New York, Hampton Roads area of Virginia, Cape Cod area of Massachusetts, and Cape May area of New Jersey by the Consortium for Atlantic Regional Assessment (CARA; Dempsey and Fisher, 2005). Studies like these which map the permanent inundation areas can be compared or overlaid with the location of important transportation infrastructure. Many East Coast railroads have been in their present location for 150 years when the land was higher relative to local sea-level and many tracks, signals, and stations are already low enough to be flooded during severe storms (Titus 2002). More frequent flooding of highways and railroads near estuaries during high tides and storms may be experienced as sea-level rises. Raising the level of these infrastructures by reballasting and adding pavement may be necessary, especially for those already experiencing flooding. The clearance above high water will gradually diminish for rail and road bridges across water in the tidal zone (NRC, 1987).

The transportation of goods through pipelines at fluid loading and unloading docks at ports along the Atlantic and Gulf coasts will need to consider sea-level rise, especially at ports that depend on jointed-pipe loading arms, as opposed to more flexible hose connections. Corrosion rates of pipelines would be affected if groundwater rose above pipelines (NRC, 1987).

Great Lakes and Lawrence Seaway

Unlike the sea coasts, most models indicate that the Great Lakes water levels fall instead of rise under the influence of climate change as drier, warmer conditions lead to relatively higher evaporation rates (Quinn, 2002; Caldwell et al., 2002; Mills and Andrey, 2002). The Great Lakes - St. Lawrence water transportation system, supporting annual shipments of 200 million tons through 145 ports and terminals, responds to even small changes in lake-levels. Ocean going and inter-lake vessels lose 100 and 270 tons of capacity, respectively for every inch of draft lost (U.S. National Assessment – Great Lakes Region). Shifts in modes of transportation (from marine to rail or road) may result.

Hawaii

Temporary disruptions of transportation at the Honolulu airport would result from a 0.6 m (1.9 foot) rise in relative mean sea-level while a 1.5 m (4.8 foot) rise would cause frequent and prolonged disruptions if no remedial works such as levees were emplaced (NRC, 1987).

5.4 Sea-level Rise exacerbates storm surge

Storm surge is the abnormal rise in sea-level accompanying a hurricane or other intense storm, above the level of the normal or astronomic tide. It can be exacerbated by tidal piling, abnormally high water levels from successive incoming tides that do not completely drain because of strong winds or waves persisting through successive tide cycles. Storm surge and abnormally high or low tides are primarily of greatest concern to port operation, mooring facilities, and moored vessels. For ferries, there is an increased risk of grounding (WIST 4-29).

Flooding from coastal storms results from a combination of storm surge and intense precipitation. Storm surge has been estimated or modeled using the USACE WES model, the NWS Sea, Lake and Overland Surge from Hurricanes (SLOSH) model, and more recently with the Advanced CIRCulation Model (ADCIRC; Westerink et al., 1994). These models do not include wind-waves on top of the surge. Storm surge here refers to the "local, instantaneous sea-level elevation that exceeds the predicted tide and which is attributable to the effects of low barometric pressure and high wind associated with storms, excluding the effect of waves" (Flick, 1991).

Storm surge models, when updated, show wider areas of 100-year floodplains

USACE models are based on the Standard Hurricane Project model, which uses wind fields, or pressure measurement from historical tropical storms (and also extra tropical where appropriate) to calculate standard pressure indices. These pressure indices are infrequently updated with new data, a situation similar to the precipitation intensity-frequency-duration values as discussed earlier. The pressure indices are used in models like the SLOSH to calculate the height of storm surge with specified return periods. The 100-year return period storm has been used by engineers and planners to aid in the design of coastal engineering structure, defining setback lines, and as a standard for flood elevation. Flood insurance rate maps are essentially based on the storm surge frequency curve in combination with land elevations.

The Standard Hurricane Project wind fields were reanalyzed for the New Orleans zone of Gulf of Mexico (Levinson, 2006) using the USACE ADCIRC model (Luettich et al., 1991). Using data through the 2005 hurricane season, the analysis shows a significant decrease in the central pressure, which results in greater storm surge, and higher flooding. The magnitude of the 100-year storm-surge flood (previously established using data from 1900-1956) would now re-occur at an interval of 75 years (based on data from 1900-2005; Levinson, 2006).

Gulf Coast Storm Surge

The impact of sea-level rise, the attendant shoreline retreat, and spread of the floodplain in the Charleston, South Carolina and Galveston, Texas area were examined by Kana et al. (1984) and Leatherman et al. (1983), respectively. In both studies, the amount of local sea-level rise was calculated considering global sea-level rise estimates available at that time, plus local subsidence. Galveston and Charleston have subsided different amounts, 40 and 10 cm, respectively, in the study period (Titus and Barth, 1989). Both studies determined that damage to inland structures, including transportation infrastructure, is largely dependent on storm surge elevation and penetration, exacerbated by the amount of local sea-level rise.

A medium scenario for sea-level rise that is roughly equivalent to the estimates by the IPCC TAR was used and land loss from shoreline movement was estimated using the Bruun rule (Bruun, 1962). Results were that 8% of land area would be lost by 2025 and 30% by 2075 for the

Charleston area. Because Galveston is protected by seawalls and levees, the impact would not be as great here, with 2% and 9% lost in 2025 and 2075, respectively. Next, storm surges were calculated. Three sources of information for inland coastal storm surges were used: the U.S. Army Corps of Engineers' (USACE) flood frequency curves, Federal Emergency Management Agency (FEMA) flood maps, and the National Weather Service SLOSH model. The SLOSH model will estimate storm surge for a given storm track, intensity and forward speed. In both Charleston and Galveston, the area that would be flooded, as a result of storm surge, is much greater than the area that would be flooded by local sea-level rise alone. In Charleston, the percent of the floodplain flooded by the combination of sea-level rise and storm surge would be 70% in 2025 and 84% in 2075. For Galveston, the combined sea-level rise and storm surge would cover 60% and 97% of the floodplain in 2025 and 2075 respectively (Titus and Barth, 1989). Obviously, significant damage to all coastal transportation's structures would result.

Future analysis of Galveston or Charleston, using updated USACE storm tables, modeled from more recent hurricane central pressures, might yield new results that would indicate wider floodplains at even lower return periods than 100-years than previous analyses. Moreover, important hurricane evacuation routes along the Gulf coastal plain are flooded during storm surge (Burkett, 2002). Further impacts of extreme weather events in the Gulf were quantified by Kaiser (2006). Pipelines in the Gulf of Mexico are shut down when a hurricane threatens, crews are evacuated, by ship or by aircraft, and refineries and processing plants close. Roughly two-thirds of the Nation's imported oil is transported onshore into Texas and Louisiana facilities (Burkett 2002).

Atlantic Region

An analysis by Titus (2002) on sea-level rise effects on Atlantic coastal transportation infrastructure states that many roads routinely flood at high tide levels. These roads would essentially become dykes as sea-level rises, and of course, no road or rail that parallels a coast can be considered an evacuation route.

Transportation systems of the New York-New Jersey-Connecticut metropolitan regions have been shown to be vulnerable to significant extratropical cyclones**,** or nor'easters (Zimmerman 2002). For example, the nor'easter of December 1992 severely handicapped, if not completely put out of service, the transportation systems throughout the area. Roadways were flooded, trains delayed or cancelled, bus service cancelled, airports closed due to high winds, piers, marinas, sea walls, and roads were destroyed by coastal flooding and surf that was driven by hurricane force winds and exacerbated by astronomical high tide. Thousands of boats were destroyed or significantly damaged (NOAA, 1992).

The Metro New York Hurricane Transportation Study (MYHTS, 1995), undertaken following the December 1992 extratropical storm, provides an excellent assessment of transportation infrastructure impacts by computing storm surge heights associated with worst-case storm tracks for hurricanes (using the SLOSH model). The lowest critical elevations of transportations systems, airport runways, entry to tunnels, bridge approaches, ventilation shafts of subways, were compared to the elevation of the storm surge levels. Sixteen important transportation infrastructures including the Holland Tunnel, the Throngs Next Bridge, JFK Airport, and the Red Hook Marine Terminal were examined (MNYHTS, 1995; Jacob et al., 2001). All the structures' critical elevations were below the surge level of category 3 and 4 hurricanes, and 12 of 16 were below the surge level of category 2 hurricanes. Modeling a worst-case-track (the track that would result in the strongest winds over populated areas and the highest storm surge where it would do the most damage) category 3 hurricane, storm surge height at JFK airport, for example, was calculated at 6.4 m (21 feet); but the critical field elevation is 4 m (13 feet). The 1938 hurricane that crossed Long Island was probably a category 4, but not a worse-case path event. The study (which used the 1929 reference sea-level datum), concluded that many of the transportation facilities' operations will be flooded during worst-case track scenarios of Categories 1-4 under present climate conditions.

The worst case hurricane tracks were used in the study (MNYHTS, 1995), with no regard to the probability of occurrence, and did not include nor'easters. The surge crest height of a nor'easter, while in general not as high as a hurricane, can potentially cause severe flooding, similar to hurricanes, as the volume of water entering tunnel shafts is time dependent and a nor'easter's effects can last for days, over several tidal cycles.

Building upon the MNYHTS study, climate-dependent local sea-level rise was examined for the Metropolitan East Coast (MEC) region (Gornitz and Couch, 2000). Sea-level rise projections for the region were calculated using a suite of climate model (GCM) projections, making adjustments for local land subsidence, and shoreline retreat (using the Bruun Rule). Storm surge levels were also modeled, accounting for the wind field generated by both hurricanes and nor'easters (as estimated by the Standard Hurricane Project Model). Future coastal flood heights and return intervals were then calculated using U. S. Army Corps of Engineers WES model. The WES Implicit Flooding Model does not include rain fall (Cialone, 1991). Although the sea-level rise would permanently inundate only a narrow strip of land, below the 1.5 m (five-foot) contour level, the 100-year flood level in New York City, presently close to the 3 m (10-foot) contour, could rise to 3.7 m (12 feet) by the 2020s and nearly 4.3 m (14 feet) by the 2080s (Gornitz and Couch, 2000).

The return period for what is now a 100-year storm could be between 5.5 and 50 years, depending on the model scenario used in the study. The greater frequency of severe flooding episodes would adversely affect highways, rail, harbors, airports, and evacuation routes, many of which are close to present-day flood levels. The storm surge calculations did not include the height of wind driven waves on top of the surge; the climate models were based on the Second Assessment Report of the IPCC; and the climate change scenarios assumed no changes in the number and strength of extratropical and tropical cyclones. The study concluded that rising ocean levels are likely to exacerbate storm impacts, with a marked reduction in the flood return period, putting vital transportation infrastructure at risk.

Using storm surge calculations for the metropolitan east coast region (Gornitz and Couch, 2000), vulnerability of transportation systems in the same region were examined (Jacob et al., 2001). In it, sea-level rise projections for the first and last decades of this century were superimposed on the storm surge heights of 5, 50, and 500 year return-period floods. The elevation of the storm surges were compared to the lowest critical elevations of 15 transportation structures (some examined in MNYHTS 1995) including three airports and bridges and four tunnels (Jacob et al., 2001). From this study, by the end of the century, flooding may occur at least once every five years at half of the facilities at or below 3 m (10 feet) critical elevation. La Guardia airport, with a field elevation of 6.7 m (22 feet), but a lowest critical elevation of 2 m (6.8 feet; MNYHTS 1995) would flood at a 5-year return period storm presently, were it not protected by sea-walls. The JFK airport was shown to be flooded only with a 500-year recurrence storm and the Newark airport would flood at a 50-year storm at the end of the century. The lowest critical elevation for the Throgs Neck Bridge, for example, would be underwater at the 50-year storm with sea-levels projected at the end of century, while the Bronx

Whitestone and Triborough bridges would be threatened in a 500-year storm at the end of the century, if at all.

A similar study done for the Boston Metropolitan area (Suarez et al., 2005) concluded that delays and trips lost in the climate change scenario was not enough to justify the cost of infrastructure improvements. However, this study, unlike the MNYHTS, did not use minimum critical elevation, did not account for coastal erosion with local sea-level rise, used the outdated probabilistic precipitation estimates and did not estimate storm surge flooding.

Coastal California

During the ENSO event of the winter of 1982-1983, both the number and intensity of storms increased on coastal California. More than 12 ocean piers in California were destroyed or severely damaged. When piers and wharfs are designed for a 50-year life, which includes local sea-level rise, the expected magnitude of the consequences to coastal piers from sea-level rise is relatively minor compared to potential damages if the number and intensity of storms increases with climate change (NRC, 1987). Storm events related to the 1998 ENSO event shut down major rail lines, interstate highways, and ruptured gas and oil pipelines (U.S. National Assessment – California Region).

Coastal Airports

Airports constructed on landfill in bays (San Francisco, Oakland, La Guardia Field, and Boston) are partially protected by levees. A significant increase in relative mean sea-level could result in overtopping during severe storms. Needed adjustments, placing more material on levees, resulting from relative mean sea-level rise may be made as part of routine maintenance (NRC, 1987), but the degree of the eventual problem is specific to the site. Twenty-three airports with routine airline traffic are at or below 6.7 m (22 feet) mean sea-level (see Table 3); 6.7 m (22 feet) being the level of La Guardia airport which was discussed in MNYHTS (1995). Of 750 airports where traffic is sufficient to warrant an automatic weather station, about 50 of these presently have field elevations below 6.7 m (approximately 7%, excluding some private fields and some military installations). The lowest-critical-elevation for these airports is not routinely available. Plans for future airport development of the Next Generation Air Transportation System (NGATS 2006) must surely account for local sea-level rise.

6. STORMS AND THE IMPACT FROM STORMS ARE EXPECTED TO CHANGE

There are several aspects of storms that are relevant to transportation: precipitation, winds and wind-induced storm surge. All three tend to get much worse during strong storms. Strong storms tend to have longer periods of intense precipitation and wind damage increases exponentially with wind speed. The Saffir-Simpson Hurricane Scale goes from Categories 1 to 5. Category 1 has winds of 119-153 km/hr (74-95 mph) while Category 5 has winds greater than 249 km/hr (155 mph). The primary concern with hurricanes is for strong storms of categories 3, 4 and 5. These storms have a lot more destructive energy. The formula for kinetic energy is one half the mass times the square of the velocity. So while a Category 5 storm may have winds twice as fast as a Category 1 storm, there is over 4 times as much kinetic energy in the Category 5 storm's wind.

6.1 Projected changes in hurricanes and tropical storms

The link between global climate change and the number and/or intensity of tropical cyclones is still being debated (Curry et al., 2006; Eilperin 2006). Several papers have recently been published on the subject (e.g., Trenberth and Shea (2006), Anthes et al. (2006), Pielke et al., 2006), Emanuel (2005), Landsea (2005), Santer et al. (2006), Klotzbach (2006), etc.) that come to different conclusions. The reasons for the lack of agreement may be partially because all sources of information on hurricanes have problems. “While the observations have their limitations (Pielke, 2005; Landsea, 2005), it is also clear that the modeling to date has not been at sufficient horizontal resolution to capture the details of tropical cyclone behavior (Schrope, 2005), nor perhaps the effects of subsurface warming of the ocean” (Pittock, 2006). Nevertheless, there is solid theoretical and model analysis that indicates, since hurricanes are essentially heat engines, warming the oceans will provide more energy resulting in stronger storms but not necessarily more storms (Knutson and Tuleya, 2004) and model evidence suggesting that the increases in greenhouse gases is the dominant influence in the observed century-scale increase in sea surface temperatures in the tropical cyclogenesis regions (Santer et al., 2006). While there is still a question of how much change is likely (Michaels et al., 2005), the model projected warming of the hurricane cyclogenesis region is quite large compared to changes in the last century. While it is probable that global climate change will increase the number of intense hurricanes hitting the United States, how large the changes would be is uncertain. It is certain, however, that the number Atlantic hurricanes varies considerably year to year as well as decade to decade and that the fairly quiet time of the 1970s and 1980s (see Figure 32) is unlikely to provide appropriate guidance for planning for future hurricanes.

Hurricanes and tropical Storms Impacts on Transportation

Following Hurricanes Katrina and Rita, it is clear that Gulf Coast oil refineries are susceptible to hurricane damage and the resulting rise in fuel prices can impact all transportation sectors. The pipeline sector of surface transportation cites tropical cyclones as having the most impact of any weather parameter (WIST p. 4-5). Sea bed scouring, flooding, under water landslides and other consequences of tropical cyclones adversely affect the pipeline transportation sector (WIST 4-34). Pipelines in the Gulf of Mexico were buried largely during a period of minimal tropical cyclone activity. Built to standards meeting the 100-year return period storm, pipeline infrastructure may be particularly vulnerable to increases in tropical storm intensity or frequency (Burkett 2002). Whether this can be attributed to normal climate variability or to some forcing mechanism, projecting forward in time any increase in tropical storm occurrence in the Gulf puts pipeline transportation infrastructure at risk. High winds, seas and tides restrict or suspend movement of barge traffic between offshore drill sites and coastal pumping facilities (WIST 4-37).

Tropical cyclones have, of course, also great impact on Marine transportation. As ships cannot generally stay in port without sustaining damage, sortie decisions are taken, and ships must be moved to open water to wait out the storm, thus spending more time at sea (WIST 4-29).

6.2 Extra-Tropical Cyclones and Mesoscale Storms Adversely Impact Transportation

Extratropical or mid-latitude cyclones are commonly known as areas of low-pressure on weather maps and are about a 1000 km in size. In meteorology, mesoscale refers to weather systems in the few hundred km range which is smaller than the synoptic-scale low or high pressure center but larger than a typical individual thunderstorm. Mesoscale storms such as mesoscale convective systems or super cells generate tornadoes, large hail and damaging winds.

Bernstein et al. (1998) compared surface observations of freezing precipitation and pilot reports of severe in-flight aircraft icing for the continental United States to the location of surface weather features, including airmasses of different origin and position relative to fronts, low-pressure centers and troughs. They determined that the airmasses found along the east and west coasts of the US are the most efficient producers of freezing precipitation and pilot reports of severe icing, respectively, and that the areas ahead of surface warm fronts are the most efficient producers of both of these phenomena. Warm fronts are commonly associated with extra-tropical cyclones.

Fewer but more intense extra-tropical storms projected

The IPCC TAR noted that there could be an increase in the number of intense extratropical storms and a decrease in the number of weaker storms (Cubash et al., 2001). The IPCC AR4 models simulated a reduction in the total number of mid-latitude cyclones and an increase in the number of intense storms. This is a robust result, which essentially all the models exhibit (Lambert and Fyfe, 2006). Associated with these changes comes an increase in ocean wave height in some regions. For example, "in general, global warming is associated with more frequent occurrence of the positive phase of the North Atlantic Oscillation (NAO) and strong cyclones, which leads to increases of wave heights in the northeast Atlantic" (Wang et al., 2004). Again using climate model output, Wang and Swail (2005) found similar areas of large increases in wave height in the north Pacific.

Analysis of the conditions that cause mesoscale systems in the U.S. to produce hail results in a time series fairly similar to the U.S. temperature time series shown in Figure 2, decreasing from 1950 to the 1970s and then increasing (Brooks and Dotzek, 2006). There is a hint of a similar change in tornadoes but the change is small and the year to year variability is high. Projecting these conditions into the future, it is reasonable to expect that severe storms associated with hail could continue to increase as hail is directly related to updraft speed and updraft speed is related to humidity at the surface. Tornadoes on the other hand are also related to downdrafts and changes in wind speed or direction with height (known as shear) which is more complex. These conditions have not yet been analyzed in climate model output (H. Brooks, 2006 pers. comm.).

Extra-tropical and mesoscale storm impacts on transportation

An examination of railroad accidents related to weather conditions shows that storm related events (particularly soft roadbed) was a significant factor (Rossetti, 2002). Increased storminess may bring the most important consideration to rail operations in the future, especially as aircraft take offs and landing failures can lead to modal shifts. Alternately, an increase in flooding from storms may force freight to switch from barges to trains. Severe weather has a secondary impact of increased ridership on buses and commuter trains when snowstorms or other severe weather occur (WIST p 4-40)

The presence of lightning halts some rail sector activities, such as refueling (WIST p 4-24) and halts most ground based aviation transportation sector activity. Hail greater than one inch can damage exposed aircraft and causes operational delays and cancellations (WIST 4-52). Microbursts and gust fronts can affect airport ground operations, primarily through delays in takeoffs, approaches and landings (WIST 4-53). *USA Today* reported (May 12, 2006) that the number of airline flight delays in April 2006 was 30% higher at the nation's 35 busiest airports than the same period one year earlier, mostly due to thunderstorms. Railroads sustain damage and washouts from flash floods and river floods, washouts, storm surges, and heavy rains.

6.3 Visibility

Generally for transportation, a change in visibility from 10 km to 5 km does not have a significant impact. However, when visibility drops to less than ~400 m (a quarter mile) it does have a significant impact on transportation. Times with such low visibility are primarily associated with fog, heavy precipitation, and blowing snow although smoke from wildfires can also drastically reduce visibility.

Projected changes in visibility

While visibility has been observed at airports throughout the US, the changes in observing practices make it inappropriate to examine long-term changes in low visibility without a major effort to assess the data's homogeneity and make adjustments where necessary, which is beyond the scope of this paper. So no historical analysis is presented. Global climate models do not evaluate transportation relevant visibility either. However, some information is available.

For example, as stated earlier, the number of storms is projected to decrease but the number of intense storms is projected to increase. This change would be anticipated to increase the time with low visibility as the standard relationship between snowfall intensity and visibility is that 400 m (1/4 mile) or less visibility corresponds to heavy snowfall intensity (Rasmussen et al., 1999). Projections of drying in the interior of continents would imply that there might be increases in blowing dust. Wildfires also impact visibility and have resulted in the closing of interstate highways. Westerling et al. (2006) documented that forest wildfire risks in the American West are strongly associated with increased spring and summer temperatures and an earlier spring melt. As pointed out by Running (2006) and section 3 above, these are exactly the conditions models are projecting for the future. Therefore, it is likely that wildfire induced decreases in visibility are likely to become more frequent.

Hanesiak and Wang (2005) examined changes in visibility related parameters at 15 stations in the Canadian arctic whose data they carefully homogenized. For the period 1953-2004, blowing snow generally decreased while fog increased in the southwestern portion of the Canadian arctic and generally decreased elsewhere. It is uncertain from a theoretical standpoint how the occurrence of fog might change. Therefore, while the number of low visibility events associated with intense storms and fires might be projected to increase, it is uncertain whether the total number of occurrences of low visibility would increase, decrease or stay the same in the projected climate of the future.

Visibility impacts on transportation

Visibility can be reduced because of storminess, higher water vapor, and secondary effects of drought. Smoke from fires fueled by drought caused low enough visibility to close highways and airborne dust has been a factor in a major traffic accidents.

Generally only a problem when under 400 m (¼ mile), low visibility can impact all sectors of surface transportation (WIST p 4-18). Visibility thresholds for rail, whether long haul or transit, are based on the stopping distance. As the visibility drops, the train speed must be reduced (WIST 4-25). For transit rail, visibility threshold can be as high as 3.8 km (3 miles). For pipelines, low visibility disrupts safe surveillance of the facilities (WIST 4-38) but more importantly, it disrupts fuel delivery and restricts or suspends pumping (WIST Appendix B-4). At airports, flight operations are greatly slowed with low visibility (WIST 4-54). In the marine transportation sector, two-way navigation can be suspended with visibility under 800 m (½ mile) and all vessel movements stopped with visibility under 400 m (¼ mile). Intense precipitation reduces visibility and clutters the radar of ships underway. Sun glare's bright reflected sunlight limits visibility and affects all marine activities, resulting in adjusting heading and reducing speed (WIST Appendix B-3).

Although not a great deal can be seen vis-à-vis climate change and visibility, it is important to note that levels of visibility that have the most impact on transportation, less than 400 m, have a definite time-of-day bias. Low visibilities tend to occur around 7 AM, which coincides with peak traffic flow on highways in metropolitan regions. The time of day combined with high traffic volume is cited by troopers in many incidences such as in June 2006 when low visibility triggered a series of wrecks involving more than 80 cars, trucks and buses in 44 collisions along a five mile stretch of Interstate 40. Warmer ocean temperatures may lead to more events of low visibility caused by sea fog in coastal areas.

6.4 Winds not associated with storms

The influence of winds on transportation is primarily high winds with adverse impacts. As people in the prairie states and, of course, Chicago, can attest, not all strong wind events are associated with storms.

Projected changes in winds

Primarily for the purpose of examining projected changes in wind energy potential, Pryor et al. (2005a) examined five state-of-the-art Atmosphere-Ocean General Circulation Models. They used a downscaling approach which links surface wind speeds, which the models might not do well, with parameters such as sea-level pressure gradients and upper air relative vorticity which the models handle better. They focused on northern Europe and concluded that there was no significant difference in the wind regimes from 1961-1990 and 2046-2065 though they did find a slight general decrease in wind energy density for the 2081-2100 period. However, the analysis by Bogardi and Matyasovszky (1996) using an earlier generation of climate models and focusing on Nebraska found that “the basic tendency of change under 2 x CO_2 climate is a considerable increase of wind speed from the beginning of summer to the end of winter and a somewhat smaller wind decrease in spring.” Focusing only on the stronger winds which would be most relevant to transportation, Kharin and Zwiers (2000) found that extreme wind speed in the extratropics changes only modestly in transient climate model runs. Given the mix of these results and Pryor et al.’s (2005b) conclusion that “the uncertainty of the projected wind changes is relatively high," no clear projection for future changes in transportation relevant winds can be made.

The impact of winds on transportation

The critical threshold for winds for the roadway sector of surface transportation is 80 kph (50 mph), with the exception of high profile transport of manufactured homes, which stop travel when winds exceed 40 kph (25 mph; WIST p 4-19, p 4-24), and transit vehicles, who have moderate risk at ~38 kph (30 mph; WIST 4-47). Winds of 56 kph (35 mph) can topple double loaded rail cars. Wind speeds above 97 kph (60 mph) restrict barge and tanker operations, disrupting fuel deliveries, and can cause physical damage to the pipeline systems. (WIST 4-38)

Critical wind thresholds for the marine transportation sector are lower than for surface transportation. Small boat handling becomes difficult at 37 kph (20 knots) and suspension of operations is recommended at 56 kph (30 knots). Large ocean-going vessels begin to modify their operations at 56 kph (30 knots). Wind damage at port facilities is possible at speeds above 46 kph (25 knots), and likely at speeds above 83 kph (45 knots). When wave heights, driven by wind, reach 1.8 – 3.7 m (6-12 feet), damage to port facilities is likely. At heights of 3.1-3.7 m (10-12 feet) and greater, there is risk of structural damage to larger vessels and their cargo (WIST 4-31). With waves higher than 3.7 m (12 feet), the seafloor pipelines can be damaged or destroyed (WIST Appendix B-4).

Wind direction can also impact transportation by raising the fuel use for travel into the wind and lowering for traveling with the wind.

Aviation impacts from surface winds at airports and flight level winds are not assessed here.

7. SUMMARY AND CONCLUSIONS

The U.S. transportation system was built for the typical weather and climate experienced locally. Moderate changes in the mean climate have little impact on transportation. However, changes in weather and climate extremes can have considerable impact on transportation. Transportation relevant measures of extremes have been changing over the past several decades and are projected to continue to change in the future. Some of the changes are likely to have a positive impact on transportation and some negative.

As the climate warms, cold temperature extremes are projected to continue to decrease. Milder winter conditions would likely improve the safety record for rail, air and ships. Warm extremes, on the other hand, are projected to increase. This change would likely increase the number of roadbed and railroad track buckling and adversely impact maintenance work. As the cold season decreases and the warm season increases, northern transportation dependent upon ice roads and permanently frozen soil would be adversely affected while the projected commercial opening of the Northwest Passage would result in clear benefits to marine transportation.

The warming would also produce a side benefit of shifting more of the precipitation from snow to rain. But not all precipitation changes are likely to be beneficial. Heavy precipitation events are projected to increase, which can cause local flooding. At the same time, summer drying in the interior of the continent is likely to contribute to low water levels in inland waterways. Strong storms, including hurricanes, are projected to increase. Coastal transportation infrastructure is vulnerable to the combined effects of storm surge and global sea-level rise.

Transportation planning operates on several different time scales. Road planners typically look out 25 years. Railroad planners consider 50 years. And bridges and underpasses are generally designed with 100 years in mind. In all cases, planning that takes likely changes into consideration will be important.

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REFERENCES

Anthes R. A., R. W. Corell, G. Holland, J. W. Hurrell, M. C. MacCracken and K. E. Trenberth, 2006: Hurricanes and global warming - Potential linkages and consequences, *Bull. Amer. Meteorol. Soc.*, **87**, 623-628.

Barnett D. N., S. J. Brown, J. M. Murphy, D. M. H. Sexton and M. J. Webb, 2006: Quantifying uncertainty in changes in extreme event frequency in response to doubled CO2 using a large ensemble of GCM simulations, *Climate Dynamics*, **26**, 489-511.

Bernstein, B.C., T.A. Omeron, M.K. Politovich and F. McDonough, 1998: Surface weather features associated with freezing precipitation and severe in-flight aircraft icing. *Atmos. Res.*, **46**, 57-73.

Birchall, S. J., 2006: Canadian sovereignty: climate change and politics in the Arctic, *Arctic*, **59**, June 2006, p. iii-iv.

Bogardi, I., and I. Matyasovszky, 1996: Estimating daily wind speed under climate change. *Solar Energy*, **57**, 239-248.

Bonnin, Geoffrey M., B. Lin and T. Parzybok, 2003: Updating NOAA/NWS Rainfall Frequency Atlases. *Symposium on Observing and Understanding the Variability of Water in Weather and Climate*, Long Beach, CA, 9-13 February.

Brooks, H. E. and N. Dotzek, 2006: The spatial distribution of severe convective storms and analysis of their secular changes. *Climate Extremes and Society*, Henry Diaz and Richard Murnane (Eds.), Cambridge Univ. Press, in press.

Bruun, P., 1962: Sea-level Rise as a Cause of Shore Erosion. *Journal of the Waterways and Harbors Division,* **88**, 117-130.

Burkett, V. R., 2002: Potential Impacts of Climate Change and Variability on Transportation in the Gulf Coast / Mississippi Delta Region. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*. U.S. Dept. of Transportation, Workshop, 1-2 October, http://climate.volpe.dot.gov/workshop1002/.

Caldwell, H., K. H. Quinn, et al., 2002: Impacts of Global Climate Change on Freight, In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1-2 October, http://climate.volpe.dot.gov/workshop1002/.

Carmichael, C. G and W. A. Gallus, Jr., 2004: A winter weather index for estimating winter roadway maintenance coasts in the Midwest, *J. Applied Meteorology,* **43**, 1783-1790.

Changnon, S. A., K. E. Kunkel and K. Andsager, 2001. Causes for record high flood losses in the central United States. *Water International,* **26**, 223-230.

Changnon, S. A. 2006: *Railroads and Weather: From Fogs to Floods and Heat to Hurricanes, the Impacts of Weather and Climate on American Railroading.* Amer. Meteor. Soc., Boston, MA. 125 pp.

Changnon, S. A, 1999: Record flood-producing rainstorms of 17-18 July 1996 in the Chicago metropolitan area. Part III: Impacts and responses to the flash flooding, *J. Applied Meteorology*, **38**, 257-265.

Changnon, S.A., D. Changnon and T.R. Karl, 2006: Temporal and spatial characteristics of snowstorms in the contiguous United States. *J. Appl. Meteorol. and Climatol.,* **45**, 1141-1155.

Church, J. A., J. M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. T. Nhuan, D. Qin, P. L. Woodworth, 2001: Changes in Sea-level, in *Climate Change 2001: The Scientific Basis--Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 639-694, Cambridge Univ. Press, New York.

Church, J. A. and N. J. White, 2006: A 20th century acceleration in global sea-level rise. *Geophys. Res. Lett.,* **33**, L01602, doi:10.1029/2005GL024826.

Cialone, M. A. 1991: The Coastal Modeling System: A System of Numerical Models and Support Programs. In *The Coastal Engineering Technical Note CETN II-28*, U.S. Army Engineer Waterways Experiment Station, Coastal Research Center, Vicksburg, MS, 5 pp.

Cleveland, W., S. Devlin and E. Grosse, 1988: Regression by local fitting. *J. Econometrics*, **37**, 87-114.

Cubasch, U., G. A. Meehl, G. J. Boer, R. J. Stouffer, M. Dix, A. Noda, C. A. Senior, S. Raper, K. S. Yap, 2001: Projections of Future Climate Change, in *Climate Change 2001: The*

Scientific Basis—Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, pp. 525–582, Cambridge Univ. Press, New York.

Curry, J. A., P. J. Webster and G. J. Holland, 2006: Mixing politics and science in testing the hypothesis that greenhouse warming is causing a global increase in hurricane intensity, *Bull. Amer. Meteorol. Soc.*, **87**, 1025-1037.

Dempsey, R. and A. Fisher, 2005: Consortium for Atlantic Regional Assessment (CARA): Information tools for community adaptation to changes in climate or land use, *Risk Analysis*, **25**, 1495-1509.

Dingerson, L. 2005: *Predicting Future Shoreline Condition Based on Land Use Trends, Logistic Regression, and Fuzzy Logic*, Thesis, Virginia Institute of Marine Science, College of William and Mary, Gloucester, Virginia, 199 pp.

du Vair, P., D. Wickizer, and M. Burer, 2002: Climate Change and the Potential Implications for California's Transportation System. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1-2 October, http://climate.volpe.dot.gov/workshop1002/.

Ellis, A.W. and J.J. Johnson, 2004: Hydroclimatic analysis of snowfall trends associated with the North American Great Lakes. *J. Hydrometeorology*, **5**, 471-486.

Emanuel, K.: 2005: Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, **436**, 686-688.

Eilperin, J., 2006: A stormy debate: Researchers disagree over whether global warming is fueling more intense hurricanes. *The Washington Post National Weekly Edition*, **23**, (September 4-10) p 35.

Flick, R. E., 1991: Joint Occurrence of High Tide and Storm Surge in California, *World Marina '91, 1st International Conference*, ASCE/Southern California Advisory Group, Long Beach, CA, 4-8 September.

Frich, P., L. V. Alexander, P. Della-Marta, B. Gleason, M. Haylock, A. M. G. Klein Tank and T. Peterson, 2002: Observed coherent changes in climatic extremes during the 2^{nd} half of the 20^{th} century, *Climate Research*, **19**, 193-212.

Gornitz, V., 1991: Global coastal hazards from future sea-level rise, *Palaeoecology* (Global and Planetary Change Section), **89**, 379-398.

Gornitz, V. and S. Couch, 2000: Sea-level Rise and Coastal Hazards. In *Climate change and a Global City: An Assessment of the Metropolitan East Coast Region*. Washington, D.C.: United States Global Change Research Program, 21-46, http://ccsr.columbia.edu/cig/mec/03_Sea_Level_Rise_and_Coast.pdf.

Groisman, P. Y., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, V. N. Razuvaev and N. Vyacheslav, 2005: Trends in intense precipitation in the climate record. *J. Climate,* **18**, 1326-1350

Hanesiak, J. M. and X. L. Wang, 2005: Adverse-Weather Trends in the Canadian Arctic, *Journal of Climate*, **18**, 3140-3156.

Hansen, J., 2006: The treat to the planet: Actions required to avert dangerous climate change, *Solar 2006 Conference on Renewable Energy*, Denver, 10 July, ftp://ftp.giss.nasa.gov/outgoing/JEH/chartsfor_threattalk_01sept06.ppt and ftp://ftp.giss.nasa.gov/outgoing/JEH/textfor_threattalk_01sept06.pdf.

Hanson, J. L., 2006: *Spring Load Restriction Modeling*, Surface Transportation Weather Research Center, University of North Dakota, Grand Forks, ND.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu, editors, 2001: *Climate Change 2001: The Scientific Basis*, Cambridge University Press, 944 pp.

Jacob, K.H., N. Edelblum and J.Arnold, 2001: Infrastructure. Chapter 4 (pp. 47-65) plus Appendices (pp. 197-200) in: Rosenzweig, C. and W. Solecki (editors, 2001*): Climate Change and a Global City: The Potential Consequences of Climate Variability and Change - Metro East Coast*. Report for the U.S. Global Change Research Program, National Assessment of the Potential Consequences of Climate Variability and Change for the United States. Columbia Earth Institute, New York. 224 pp. ISBN 0-9713347-0-6. In web-form: http://metroeast_climate.ciesin.columbia.edu/reports/infrastructure.pdf.

Jones, P.D., 1994: Hemispheric surface air temperature variations: a reanalysis and an update to 1993. *J. Climate*, **7**, 1794-1802.

Kaiser, M. J., 2006: Empirical models of extreme weather impacts on shut-in production in the Gulf of Mexico, *Marine Technology Society Journal*, **40,** 4-14.

Kana, T. W., J. Michel M.O. Hayes, and J. R. Jensen, 1984: The physical impact of sea-level rise in the area of Charleston, South Carolina. In M.C. Barth and J.G. Titus (Eds.), *Greenhouse Effect and Sea-level Rise.* Van Nostrand Reinhold Co., New York, N.Y., 105-150. http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsSLRChallenge.html.

Karoly, D.J., K. Braganza, P.S. Stott, J.M. Arblaster, G.A. Meehl, A.J. Broccoli and K.W. Dixon, 2003: Detection of a human influence on North American climate. *Science*, **302**, 1200-1203.

Kharin, V. V. and F. W. Zwiers, 2000: Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM. *J. Climate*, **13**, 3760-3788.

Klotzbach, P. J., 2006: Trends in global tropical cyclone activity over the past twenty years (1986-2005). *Geophys. Res. Lett.*, **33**, doi:10.1029/2006GL025881.

Knowles, N., M.D. Dettinger and D.R. Cayan, 2006: Trends in snowfall versus rainfall in the western United States. *J. Climate*, **19**, 4545-4559.

Knutson, T. R. and R. E. Tuleya, 2004: Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. *J. Climate*, **17**, 3477-3495.

Kunkel, K. E., N. E Wescott and D. A. R. Kristovich, 2002: Assessment of potential effects of climate change on heavy lake-effect snowstorms near Lake Erie. *J. Great Lakes Res.,* **28**, 521-536.

Lambert, S. J. and J. C. Fyfe, 2006: Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: results from the models participating in the IPCC diagnostic exercise, *Climate Dynamics*, **26**, 713-728.

Landsea, C. W., 2005: Meteorology - Hurricanes and global warming, *Nature*, **438**, E11-E13.

Larsen, C.F., R.J. Motyka, J.T. Freymueller, K.A. Echelmeyer and E.R. Ivins, 2005: Glacial isostatic rebound, ongoing glacial wastage, and geoid change in southern Alaska. *American Geophysical Union Fall Meeting Abstracts*, G24A-08.

Leatherman, S. P., K. Zhang and B. C. Douglas. 2000: Sea-level Rise Shown to Drive Coastal Erosion. *Eos*, **81**, 55-57.

Leatherman, S. P., M. S. Kearny and B. Clow, 1983: *Assessment of Coastal Responses to Projected Sea-level Rise: Galveston Island and Bay, Texas*. URF report TR-8301; report to ICF under contract to EPA.University of Maryland.

Levinson, D.H., 2006: *Update to the Standard Project Hurricane (SPH) Indices.* Enclosure 6 of Annex 6, Louisiana Coastal Protection and Restoration, Preliminary Technical Report submitted to Congress in July 2006, 17 pp.

Luettich, R. A. Jr., J. J. Westerink and N. W. Scheffner, 1991: "*ADCIRC: An Advanced ThreeDimensional Circulation Model for Shelves, Coasts and Estuaries*," Report 1, U.S. Army Corps of Engineers Tech Report DRP-92-6, Washington, D.C. 20314-1000, 137 pp.

Meehl, G. A., et al., 2006: Climate change projections for the 21st century and climate change commitment in the CCSM3. *J. Climate*, **19**, 2597-2616.

Mekis, E., and W. D. Hogg, 1999: Rehabilitation and analysis of Canadian daily precipitation time series. *Atmosphere Ocean*, **37**, 53-85.

Menne, M. J., and C. N. Williams, Jr., 2005: Detection of undocumented changepoints using multiple test statistics and composite reference series. *J. Climate*, **18**, 4271-4286.

Michaels, P. J., P. C. Knappenberger, C. Landsea, 2005: Comments on “Impacts of CO2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Scheme”. *J. Climate*, **18**, 5179-5182.

Mills, B. and J. Andrey, 2002: Climate Change and Transportation: Potential Interactions and Impacts. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1-2 October, http://climate.volpe.dot.gov/workshop1002/.

Milly, P. C. D., R. T. Wetherald, K. A. Dunne, and T. L. Delworth, 2002: Increasing risk of great floods in a changing climate. *Nature*, **415**, 514-517.

MNYHTS, 1995: *Metro New York Hurricane Transportation Study*, Interim Technical Data Report. /US Army Corps of Engineers (USACE), the Federal Emergency Management Agency (FEMA), National Weather Service (NWS), NY/NJ/CT State Emergency Management, 75 pp.

Munk, W., 2002: Twentieth century sea level: An enigma. *Proceedings of the National Academy of Sciences*, 99, 6550-6555, doi/10.1073/pnas.0927704599.

Nakicenovic, N. et al., 2000: *Special Report on Emission Scenarios*, Intergovernmental Panel on Climate Change, Cambridge University Press, 612 pp. Available on line from http://www.grida.no/climate/ipcc/emission/.

National Research Council, 1987: *Responding to Changes in Sea-level: Engineering Implications*, Commission on Engineering and Technical Systems, National Research Council, National Academy Press, Washington, D.C., 148 pp.

Next Generation Air Transportation System (NGATS), 2006: *Weather Concept of Operations, Version 1.0*, Weather Integrated Product Team, Joint Planning and Development Office, Federal Aviation Administration and National Aeronautics and Space Administration, Washington D.C.

NOAA, 2006: Global Historical Climatology Network (GHCN) Daily data set documentation, available from NOAA's National Climatic Data Center, http://www1.ncdc.noaa.gov/pub/data/ghcn/daily/.

NOAA, 1999: *Probabilities of Temperature Extremes in the U.S.A.* CD-ROM. Available from the NOAA's National Climatic Data Center, 151 Patton Ave. Asheville, NC 28801.

NOAA, 1992: *Storm Data Publication December 1992*. Available from the NOAA's National Climatic Data Center, 151 Patton Ave. Asheville, NC 28801.

Office of the Federal Coordinator for Meteorological Services and Supporting Research, 2006: *Weather Information for Surface Transportation: Update on Weather Impacts and WIST Results*, Office of the Federal Coordinator for Meteorological Services and Supporting Research, FCM-R26-2006, Washington, D.C., http://www.ofcm.gov/r26-wist%20update/fcm-r26.htm.

Office of the Federal Coordinator for Meteorological Services and Supporting Research, 2002: *Weather Information for Surface Transportation: A National Needs Assessment Report* (WIST), Office of the Federal Coordinator for Meteorological Services and Supporting Research, FCM-R18-2002, Washington, D.C., http://www.ofcm.gov/wist_report/wist-report.htm.

O'Neil, P., 2006: Northwest Passage 'could open in 2015', *Vancouver Sun*, 12 August.

Parker, D.E., Folland, C.K. and Jackson, M., 1995: Marine surface temperature: observed variations and data requirements. *Climatic Change,* **31**, 559-600.

Pielke R., C. Landsea, M. Mayfield, J. Laver, R. Pasch, 2006: Reply to " Hurricanes and global warming - Potential linkages and consequences", *Bull. Amer. Meteorol. Soc.,* **87**, 628-631.

Pielke, R. A., Jr., 2005: Are there trends in hurricane destruction?, *Nature*, *438*, doi:10.1038/nature04426.

Pisano, P. A., A. D. Stern and W. P. Mahoney, III, 2005: The U.S. Federal Highway Administration Winter Road Maintenance Decision Support System (MDSS) Project: Overview and Results, *21st International Conference on Interactive Information*

Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, San Diego, CA., 10-13 January.

Pittock, A. B., 2006: Are scientists underestimating climate change? *Eos*, **87**, 340.

Potter, J., 2002: Workshop summary. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, 3-32. http://climate.volpe.dot.gov/workshop1002/.

Pryor, S. C., J. T. Schoof and R. J. Barthelmie, 2005a: Climate change impacts on wind speeds and wind energy density in northern Europe: empirical downscaling of multiple AOGCMs. *Climate Research*, **29**, 183-198.

Pryor, S. C., R. J. Barthelmie and E. Kjellstrom, 2005b: Potential climate change impacts on wind energy resources in northern Europe: analyses using a regional climate model. *Climate Dynamics*, **25**, 815-835.

Quinn, F. H., 2002: The Potential Impacts of Climate Change on Great Lakes Transportation. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1-2 October. http://climate.volpe.dot.gov/workshop1002/.

Rasmussen, R. M., J. Vivekanandan, J. Cole, B. Myers and C. Masters, 1999: The Estimation of Snowfall Rate Using Visibility, *J. Applied Meteorology*, **38**, 1542-1563.

Rossetti, M. A. 2002: Potential Impacts of Climate Change on Railroads. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1-2 October, http://climate.volpe.dot.gov/workshop1002/.

Rothrock D. A., J. Zhang, 2005: Arctic Ocean sea ice volume: What explains its recent depletion?, *J. Geophys. Res*., **110**, C01002, doi:10.1029/2004JC002282.

Running, S. W., 2006: Is global warming causing more, larger wildfires? *Science*, **313**, 927-928.

Rygel, L. M. 2005: *Modeling the Vulnerability of Coastal Communities to Hurricane Storm Surge with Sea-Level Rise: A Case Study of Hampton Roads, Virginia*, Thesis, Pennsylvania State University, College of Earth and Mineral Science, State College, Pennsylvania, 122 pp.

Santer, B. D., T. M. L. Wigley, P. J. Gleckler, C. Bonfils, M. F. Wehner, K. AchutaRao, T. P. Barnett, J. S. Boyle, W. Brüggemannk, M. Fiorino, N. Gillett, J. E. Hansen, P. D. Jones, S. A. Klein, G. A. Meehl, S. C. B. Raper, R.W. Reynolds, K. E. Taylor and W. M. Washington, 2006: Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions, *Proceedings of the National Academy of Sciences*, 10.1073/pnas.0602861103.

Sato, N. and S. M. Robeson, 2005: *Climate Change and its Potential Impact on Winter-Road Maintenance: Temporal Trends in Hazardous Temperature Days in the United States and Canada*, Paper 06-1515, Transportation Research Board 85th Annual Meeting Compendium of Papers CD-ROM, 13 pp.

Schmidlin, T. W., 1993: Impacts of severe winter weather during December 1989 in the Lake Erie snowbelt. *J. Climate*, **6**, 759-767.

Schrope, M., 2005: Winds of change, *Nature*, *438*, 21–22.

Shen, J., W. Gong and H. Wang, 2005: *Simulation of Hurricane Isabel using the Advanced Circulation Model for Shelves, Coasts and Estuaries (ADCIRC),* Virginia Institute of Marine Science, Department of Physical Sciences, Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA 23062.

Smith, O. P. and G. Levasseur, 2002: Impacts of Climate Change on Transportation in Alaska. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1-2 October, http://climate.volpe.dot.gov/workshop1002/.

Smith, T. M., T. C. Peterson, J. Lawrimore, and R. W. Reynolds, 2005: New Surface Temperature Analyses for Climate Monitoring. *Geophys. Res. Lett.*, **32**, L14712, doi: 10.1029/2005GL023402.

Stott, P.A., 2003: Attribution of regional-scale temperature changes to anthropogenic and natural causes. *Geophyic. Res. Lett.*, **30**, doi:10.1029/2003GL017324.

Stroeve J. C., M. C. Serreze, F. Fetterer, T. Arbetter, W. Meier, J. Maslanik, K. Knowles, 2005: Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004, *Geophys. Res. Lett.*, **32**, L04501, doi:10.1029/2004GL021810.

Suarez, P., W. Anderson, et al, 2005: *Impacts of flooding and climate change on urban transportation: A system wide performance assessment of the Boston Metro Area*. Also known as Climate's Long-term Impacts on Metro Boston (CLIMB) report of the Center for Transportation Studies, Boston University, Boston, MA.

Titus, J. G. and C. Barth, 1989: An overview of the causes and effects of sea-level rise. In M.C. Barth and J.G. Titus (Eds.), *Greenhouse Effect and Sea-level Rise.* Van Nostrand Reinhold Co., New York, N.Y., 1-56. http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsSLRChallenge.html

Titus, J., 2002: Does Sea-level Rise Matter to Transportation Along the Atlantic Coast? In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1-2 October, http://climate.volpe.dot.gov/workshop1002/.

Trenberth, K. E., and D. J. Shea, 2006: Atlantic hurricanes and natural variability in 2005, *Geophys. Res. Lett.*, 33, L12704, doi:10.1029/2006GL026894.

USACE, 2006: *Missouri River Mainstem Reservoir System Master Water Control Manual*, Environmental Assessment for the Inclusion of Technical Criteria for Spring Pulse Releases from Gavins Point Dam, Missouri River Water Management Division, U.S. Army Corps of Engineers.

USGS Fact Sheet 076-00, 2000: *National Assessment of Coastal Vulnerability to Future Sea-level Rise*. U.S. Geological Survey, Woods Hole, MA, 2 pp. http://water.usgs.gov/wid/index-hazards.html.

US National Assessment of the Potential Consequences of Climate Variability and Change, Alaska Region, Reports for the U.S. Global Change Research Program, 1999: *The Potential Consequences of Climate Variability and Change – Alaska*. The Center for Global Change and Arctic System Research, University of Alaska, Fairbanks, Alaska, http://www.usgcrp.gov/usgcrp/nacc/allreports.htm.

US National Assessment of the Potential Consequences of Climate Variability and Change, California Region, Reports for the U.S. Global Change Research Program, 2002: *The California Regional Assessment*, draft final report (dated June 2002) from the California Regional Climate Impacts Assessment, University of California, Santa Barbara. http://www.usgcrp.gov/usgcrp/nacc/allreports.htm.

US National Assessment of the Potential Consequences of Climate Variability and Change, Coastal Areas and Marine Resources, Reports for the U.S. Global Change Research Program, 2001: *Coastal Areas and Marine Resources, a Report of the National Coastal Assessment Team*, from NOAA's National Ocean Service, National Centers for Coastal Ocean Science. http://oceanservice.noaa.gov/outreach/pdfs/nccos_climate_change.pdf.

US National Assessment of the Potential Consequences of Climate Variability and Change, Great Lakes Region, Reports for the U.S. Global Change Research Program, 2000: *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change: Great Lakes Overview*. The University of Michigan, Ann Arbor, Michigan. http://www.usgcrp.gov/usgcrp/nacc/allreports.htm.

US National Assessment of the Potential Consequences of Climate Variability and Change, Gulf Coast Region, Reports for the U.S. Global Change Research Program, 2003: *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change: Gulf Coast Region.* Summary Report by Z. H. Ning, R. E.Turner, T. Doyle and K.K. Abdollahi (lead authors), published by the Gulf Coast Climate Change Assessment Council (GCRCC) and Louisiana State University (LSU) Graphic Services. http://www.usgcrp.gov/usgcrp/nacc/allreports.htm.

US National Assessment of the Potential Consequences of Climate Variability and Change, Pacific Northwest Region, Reports for the U.S. Global Change Research Program, 1999: *Impacts of Climate Variability and Change, Pacific Northwest*. National Atmospheric and Oceanic Administration, Office of Global Programs, and JISAO/SMA Climate Impacts Group, University of Washington, Seattle, WA. 100 pp. http://www.usgcrp.gov/usgcrp/nacc/allreports.htm.

Vincent, L. A., X. Zhang, B. R. Bonsal, and W. D. Hogg, 2002: Homogenization of daily temperatures over Canada. *J. Climate*, **15**, 1322-1334.

Wang, X. L., 2003: Comments on "Detection of Undocumented Changepoints: A Revision of the Two-Phase Regression Model". *J. Climate*, **16**, 3383-3385.

Wang, X. L., F. W. Zwiers, and V. R. Swail, 2004: North Atlantic Ocean wave climate change scenarios for the Twenty-First Century, *J. Climate*, **17**, 2368-2383

Wang, X. L. and V. R. Swail, 2005: Climate change signal and uncertainty in projections of ocean wave heights. *Climate Dynamics*, **26**, 109-126.

Westerink, J. J., C. A. Blain, R. Luettich and N. W. Scheffner, 1994: *ADCIRC: An advanced three-dimensional circulation model for shelves, coasts, and estuaries. Report 2: Users Manual for ADCIRC-2DDI*, Tech. Rep DRP-92-6, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, MS.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan and T. W. Swetnam, 2006: Warming and earlier spring increase in Western U.S. forest wildfire activity. *Science*, **313**, 940-943.

Williams, P. J. and M. Wallis 1995: Permafrost and Climate Change: Geotechnical Implications, *Philosophical Transactions: Physical Sciences and Engineering*, **352**, 347-358.

Zhang, X. and J. E. Walsh, 2006: Toward a seasonally ice-covered Arctic Ocean: Scenarios from the IPCC AR4 Model Simulations. *J. Climate*, **19**, 1730-1747.

Zimmerman, R., 2002: Global Climate Change and Transportation Infrastructure: Lessons from the New York Area. In *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1-2 October, http://climate.volpe.dot.gov/workshop1002/.

Zwiers, F.W. and X.B. Zhang, 2003: Toward regional-scale climate change detection. *J. Climate*, **16**, 793-797.

APPENDIX A. TRANSPORTATION WEATHER/CLIMATE PARAMETERS IDENTIFIED BY WIST

- **Precipitation Elements**
  - Freezing precipitation, snow accumulation, liquid precipitation, precipitable water vapor, soil moisture, flooding, water body depths, fire weather
- **Thunderstorm Related**
  - Severe storm cell tracks, lightning, hail
- **Temperature Related**
  - Air temperature including maximum and minimum, first occurrence of season, heat index, cooling or heating degree days
- **Winds**
  - Wind speed, upper air winds
- **Visibility**
  - Restrictions from fog, haze, dust, smog and sun glare, upper atmosphere restrictions from volcanic and desert dust
- **Sea State**
  - Tropical Cyclone including tracks and elements effecting evacuation routes, open water sea ice
  - High surf, storm surge, abnormal high or low tides, freezing spray, hurricane winds, sea state, flooding, wind wave height, sea wave height

APPENDIX B: WEATHER THRESHOLDS WITH IMPLICATIONS TO U.S. TRANSPORTATION PRIMARILY DERIVED FROM NWS FORECASTING DIRECTIVES

B.1 Surface transportation

Includes Roads, Rails, Transit and Pipelines

Temperature:

Extreme Cold: Frigid temperatures along with sustained wind speeds of at least 15 mph create dangerous wind chill readings. The benchmark value is -18°F or colder. In the Western Region, wind chill index temperatures are expected to drop below a locally determined effective temperature threshold (usually -20°F to -40°F) for more than one hour, with a wind speed at least 10 mph. The exact criteria for both temperature and duration are set locally. In Alaska, readings are -55°F at Juneau to -60°F at Fairbanks.

Extreme Heat: Heat index (combined temperature and relative humidity) of at least 115°F degrees for 3 hours or more, with minimum nighttime heat index at or above 80°F. Implications to transportation commence when the Heat Index is expected to be at least 105°F for 3 hours or more and the overnight minimum is around 80°F degrees or higher. Eastern Region local heat index criteria are based on National Guidelines associated with recommendations from the 1995 Chicago Heat Assessment. Central Region guideline values for excessive heat may be locally adjusted, especially adjusted downward for metropolitan areas, where certain groups, such as elderly people shut inside without air conditioning, place themselves at a significantly higher risk.

Freeze and Frosts: Thresholds reached when an event is expected 24 to 48 hours in the future during the freeze/frost season, highlighting the potential for such an event. Whenever the minimum shelter temperature is forecast to be 32°F or less in the next 12 to 36 hours during the freeze/frost season, a Freeze Warning will be issued. Whenever the minimum shelter temperature is forecast to be 33-36°F in the next 12 to 36 hours during the freeze/frost season, on nights with light wind and good radiational cooling, a Frost Advisory will be issued. In the Western Region, in normally warm desert areas, cold temperatures for only a few hours can cause considerable damage to pipes. To distinguish these types of situations from “normal” Freeze Warnings, the local NWS Forecast Office may issue Hard Freeze Warnings when specific criteria have been established based on local research. In the Alaska Region, the frost/freeze season is locally defined and usually spans the growing season until the first hard freeze (less than 28°F) occurs toward the end of the season. Minimum shelter temperature for frost is between 33-36°F, on nights with radiational cooling conditions (e.g. light winds and clear skies).

Precipitation:

Note: While major winter storm conditions described below will have implications to transportation, even small or negligible (trace reports) amounts of frozen precipitation (snow, sleet, freezing rain) can impact surface transportation on road surfaces, especially when readings are <32°F. Implications are more pronounced during the season’s first winter event as new drivers face weather hazards not experienced while veteran drivers have not encountered driving in winter weather conditions for a number of months. Additionally, road surfaces are less likely to be treated with chemicals before the first event of season.

Heavy Snow: Snow accumulation meeting or exceeding locally defined 12 and/or 24 hour warning criteria. In most areas in the Central Region, this is defined as an average snowfall with an accumulation equaling or exceeding 6 inches or more in 12 hours or less; or an average snowfall with an accumulation equaling or exceeding 8 inches or more in 24 hours or less. In areas impacted by the Great Lakes, lake effect snows can impact surface transportation. These events can be widespread or localized lake induced snow squalls or heavy showers which produce snowfall accumulations meeting or exceeding locally defined warning criteria. Lake Effect Snow usually develops in narrow bands and impacts a limited area within a zone(s). In the Alaska Region, heavy snowfall varies from 6 inches in 12 hours to 12 inches in 12 hours, dependent upon forecast zone.

Ice Storm: Ice accumulation meeting or exceeding locally defined warning criteria (typical value is 1/4 inch or more). In the Juneau and Anchorage forecast zones in the Alaska Region, ice accumulation of 0.25 inch or greater.

Sleet: Sleet accumulation meeting or exceeding locally defined warning criteria (typical value is 1/2 inch or greater).

Flash Flood: Flash flood warnings are issued when flooding is imminent or for any high flow, overflow, or inundation. In the Southern Region, flood warnings are issued in which water rises rapidly from normal level to inundation within 6 hours of the causative event. In the Alaska Region, flash flood warnings may be warranted when ice jams during the breakup or freeze up periods are expected to cause imminent flooding which endangers life or results in property damage. Flash flooding will not commonly occur in areas with broad floodplains or in extensive braided glacial streams. Flood warnings may be issued for reaches along gauged streams, for ungauged streams and rivers within a specific geographic area, or for both. This warning will be reserved for those short-term events which require immediate action to protect lives and property, such as dangerous small stream flooding or urban flooding and dam or levee failures. The geographic areas addressed by flash flood warnings may be counties, portions of counties, river/stream basins, or other definable areas (e.g., deserts, valleys).

Sea State:

Inland Tropical Storm/Inland Hurricane Wind: In the Eastern and Southern Regions, issued for and verified by sustained winds of 39 - 73 mph, or significant public impact. Inland Hurricane Wind Warnings are issued for and verified by sustained winds of 74 mph or more, or significant public impact.

Visibility:

Dust Storm: Widespread or localized blowing dust reducing visibilities to ¼ mile or less (In the Alaska Region, for three hours or longer). Sustained winds of 25 mph or greater are usually required.

Dense (or Heavy) Fog: Per World Meteorological Organization (WMO) definition, fog restricting visibility to 1 nm or less.

Blizzard: Sustained wind or frequent gusts greater than or equal to 35 mph accompanied by falling and/or blowing snow, frequently reducing visibility to less than 1/4 mile for three hours or more.

Wildfires: criteria consists of both fuel and weather parameters. Suggested meteorological criteria for a Red Flag Event include:

a. Lightning after an extended dry period

b. Significant dry frontal passage

c. Strong winds

d. Very low relative humidity

e. Dry thunderstorms

Winds:

High Winds: Damaging or dangerous winds occur when wind speeds are sustained of

40 mph or greater for an hour or more, or a peak gust > 58 mph for any duration has been reported from reliable observing equipment. Public impact such as power outages or damage to trees, roofs, windows or cars can also be used to indicate that a high wind event has occurred. In the Central Region, criteria differ in the mountain areas in Colorado, Wyoming, and eastern Utah and in the mountain areas of the Western Region where the following conditions must be met: (1) Sustained winds of 50 mph or greater lasting 1 hour or longer, or (2) sustained winds or gusts of 75 mph or greater (for any duration). In the Alaska Region, implications to transportation commence with sustained or frequent gusts ranging from 40 mph to 50 mph at specific forecast zones with damaging conditions occurring with sustained winds or frequent gusts ranging from 50 mph in specific forecast zones to 73 mph or greater in Anchorage.

Severe Weather:

Severe Thunderstorm: Radar or satellite indication and/or reliable spotter reports of wind gusts equal to or in excess of 50 knots (58 mph) and/or hail size of 3/4 inch (penny) diameter or larger.

Tornado: Issued when there is radar or satellite indication and/or reliable spotter reports of a tornado.

B.2 Marine transportation

Includes Fresh Water and Sea Transport

Temperature: Non-Applicable

Precipitation: Non-Applicable

Sea State:

Coastal/Lakeshore Flooding: (i) (Oceanic) Coastal Flooding is the inundation of land areas adjacent to bodies of salt water connected to the Atlantic Ocean, Pacific Ocean, or Gulf of

Mexico, caused by sea waters over and above normal tidal action. This flooding may impact the immediate oceanfront, gulfs, bays, back bays, sounds, and tidal portions of river mouths and inland tidal waterways. (ii) Lakeshore Flooding is the inundation of land areas adjacent to one of the Great Lakes caused by lake water exceeding normal levels. Lakeshore flooding impacts the immediate lakefront, bays, and the interfaces of lakes and connecting waterways, such as rivers.

Freezing Spray: An accumulation of freezing water droplets on a vessel at a rate of less than 2 centimeters (cm) per hour caused by some appropriate combination of cold water, wind, cold air temperature, and vessel movement. In the Alaska Region, ice accumulating at a rate less than 0.3 inches per hour.

Heavy Freezing Spray: An accumulation of freezing water droplets on a vessel at a rate of 2 cm per hour or greater caused by some appropriate combination of cold water, wind, cold air temperature, and vessel movement. In the Alaska Region, ice accumulating at a rate greater than 0.3 inches per hour.

High Surf: A forecast of high surf conditions on oceanic shores that may pose a threat to life or property. High surf may be characterized by observations specific to a geographical area.

Rip Currents: A relatively small-scale surf-zone current moving away from the beach. Rip currents form as waves disperse along the beach causing water to become trapped between the beach and a sandbar or other underwater feature. The water converges into a narrow, river-like channel moving away from the shore at high speed.

Significant Wave Height: The average height (trough to crest) of the one-third highest waves. An experienced observer will most frequently report heights equivalent to the average of the highest one-third of all waves observed.

Storm Surge: An abnormal rise in sea-level accompanying a hurricane or other intense storm, whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone. Storm surge is usually estimated by subtracting the normal or astronomic tide from the observed storm tide.

Storm Tide: The actual level of sea water resulting from the astronomic tide combined with the storm surge.

Tidal Piling: Abnormally high water levels from successive incoming tides that do not completely drain because of strong winds or waves persisting through successive tide cycles.

Wave Steepness: The ratio of wave height to wavelength and is an indicator of wave stability. When wave steepness exceeds a 1/7 ratio; the wave typically becomes unstable and begins to break.

Sea Ice: In the Alaska, Central and Eastern Regions, any form of ice found at sea which has originated from the freezing of sea water (sea ice does not include superstructure icing). Ice formed from the freezing of the waters of the Great Lakes is considered the same as sea ice.

Tsunami: In the Pacific and Alaska Region, a warning is issued when there is an imminent threat of a tsunami from a large undersea earthquake, or following confirmation that a potentially destructive tsunami is underway. They may initially be based only on seismic information as a means of providing the earliest possible alert. Warnings advise that appropriate actions be taken in response to the tsunami threat. Such actions could include the evacuation of low-lying coastal areas and the movement of boats and ships out of harbors to deep waters.

Winds:

Brisk Wind: A small craft advisory issued for ice-covered waters.

Gale: A warning of sustained surface winds, or frequent gusts, in the range of 34 knots (39 mph) to 47 knots (54 mph) inclusive, either predicted or occurring, and not directly associated with a tropical cyclone.

Hurricane: A warning for sustained surface winds of 64 knots (74 mph) or higher associated with a hurricane are expected in a specified coastal area within 24 hours or less. A hurricane or typhoon warning can remain in effect when dangerously high water or a combination of dangerously high water and exceptionally high waves continue even though winds may be less than hurricane force.

Storm: A warning of sustained surface winds, or frequent gusts, in the range of 48 knots (55 mph) to 63 knots (73 mph) inclusive, either predicted or occurring, and not directly associated with a tropical cyclone.

Subtropical Storm: A subtropical cyclone in which the maximum 1-minute sustained surface wind is 34 knots (39 mph) or more.

Tropical Storm: A tropical cyclone in which the maximum sustained surface wind ranges from 34 to 63 knots (39 to 73 mph) inclusive.

Super Typhoon. In the Pacific Region, a typhoon having maximum sustained winds of 130 knots (150 mph) or greater.

Small Craft Advisory Thresholds

Eastern: Sustained winds ranging between 25 and 33 knots (except 20 to 25 knots, lower threshold area dependent, to 33 knots for harbors, bays, etc.) and/or seas/waves 5 to 7 feet and greater, area dependent.

Central: Sustained winds or frequent gusts (on the Great Lakes) between 22 and 33 knots inclusive, and/or seas/waves greater than 4 feet.

Southern: Sustained winds of 20 to 33 knots, and/or forecast seas 7 feet or greater that are/is expected for more than 2 hours.

Western: Sustained winds of 21 to 33 knots. A Small Craft Advisory for Hazardous Seas (SCAHS) is issued for seas 10 feet or greater.

Alaska Small Craft: An advisory for areas included in a coastal waters forecast for sustained winds from 23 to 33 knots and/or wave conditions deemed to be locally hazardous based upon expressed customer needs. An advisory may also be issued for frequent gusts from 23 to 33 knots.

Pacific Sustained winds: northwest through east/southeast winds of 25 to 33 knots for the coastal waters (30 to 33 knots for the channels between the islands); southeast through west winds of 20 to 33 knots for both coastal waters and channel winds. Swells: open ocean swells 10 feet and greater; swells 6 feet and greater with short periods (6 to 8 seconds); south swell 4 feet and greater with long periods (13 seconds and greater); north and northeast swells 5 feet and greater with long periods.

Severe Weather:

Severe Local Storm: An alert issued for the contiguous U.S. and its adjacent waters of the potential for severe thunderstorms or tornadoes.

Special Marine Warning: A warning of potentially hazardous weather conditions usually of short duration (up to 2 hours) producing sustained marine thunderstorm winds or associated gusts of 34 knots or greater; and/or hail 3/4 inch or more in diameter; and/or waterspouts affecting areas included in a Coastal Waters Forecast, a Nearshore Forecast, or an Open Lakes Forecast that is not adequately covered by existing marine warnings.

Waterspout: A rotating column of air over water whose circulation extends to the surface.

B.3 Aviation transportation

Includes Ground Transportation Systems and In-Flight Systems

Temperature:

Extreme Heat: Temperature is critically important for take offs and landings at airports because warmer air is less dense and therefore has less lift. This is especially a concern at high airports like Denver and some in Arizona. See *Extreme Heat* as described in section B.1 Surface transportation.

Precipitation:

Onset of freezing rain

Heavy Snow Warning: 6 inches or more within 12 hours or 9 inches or more within 24 hours. At Minneapolis St. Paul Airport, any time 2+ inches of snow is expected.

Winter Storm: Heavy snow combined with wind or wind chills

Flash Flood

Sea State: Non-applicable

Visibility:

Blizzard: Winds 35 mph or more with blowing snow and visibilities less than 1/4 mile (for 3 hours).

Volcanoes: In the Alaska Region, an advisory for areas included in the coastal or offshore waters forecast for an airborne ash plume resulting in ongoing deposition at the surface. There is no minimum accumulation threshold. Ashfall may originate directly from a volcanic eruption or from the resuspension (by wind) of a significant amount of relic ash.

Winds:

High Winds: Sustained 40 mph or higher (for 1 hour), or gusts 58 mph (no time limit) result in delays or cancellations of flights. Initial impacts to aviation commence with sustained winds of 20 knots or greater or winds gusts over 30 knots. At Minneapolis St. Paul Airport, implications to aviation commence from convective winds (sustained or gusts) of 35 knots or greater. At the following Western Region airports, the thresholds which have implications to aviation transportation are as follows:

AIRPORT	CRITERIA
BFR, CA	Thunderstorm within 5 nm of the airport; wind gusts >40 knots.
FAT, CA	Thunderstorm within 5 nm of the airport, wind gusts >40 knots.
FCH, CA	Thunderstorm within 5 nm of the airport, wind gusts >40 knots.
SFO, CA	Thunderstorm within 5 nm of the airport; hail >1/2 inch; wind gusts >35 knots.
SLC, UT	Thunderstorm within 5 nm of the airport.
GTF, MT	Tornado and/or Severe thunderstorm within 10 nm of the airport.
HLN, MT	Tornado and/or Severe thunderstorm within 10 nm of the airport.
SAN, CA	Thunderstorm within 5 nm of the airport; any hail; sustained winds >30 knots
PSC, WA	Thunderstorm within 5 nm of the airport; hail >1/4 inch; wind gusts >40 knots; freezing rain; visibility from snow <1/2 SM.
MFR, OR	Wind gusts >35 knots; >1/2 of snow.
GPI, MT	Tornado and/or Severe thunderstorm within 15 nm of the airport; sustained wind >30 knots and wind gusts >40 knots; snowfall >4 inches; freezing rain or drizzle; visibility from blowing snow <1/4 SM for 2 hours or more.

MSO, MT Tornado and/or Severe thunderstorm within 15 nm of the airport; sustained wind >30 knots and wind gusts >40 knots; snowfall >4 inches; freezing rain or drizzle; visibility from blowing snow <1/4 SM for 2 hours or more.

PHX, AZ Wind gusts >35 knots.

Severe Weather:

Cloud to ground lightning within 5 miles of the airport

Thunderstorms with >½ inch hail

Tornado Warning

Severe Thunderstorm Warning

B.4 National Weather Service Forecasting Directives from which the information in Appendix B was derived

NWS, 2005: National Weather Service Alaska Region Supplement 03-2002, Applicable to NWSI 10-301, National Weather Service/NOAA, Washington. http://www.nws.noaa.gov/directives/010/010.htm

NWS, 2004: National Weather Service Marine and Coastal Weather Services, Policy Directive 10-3, Instruction 10-301, Operations and Services, National Weather Service/NOAA, Washington. http://www.nws.noaa.gov/directives/010/010.htm

NWS, 2006: National Weather Service Fire Weather Services, Policy Directive 10-4, Instruction 10-401, Operations and Services, National Weather Service/NOAA, *Washington.* http://www.nws.noaa.gov/directives/010/010.htm

NWS, 2003: National Weather Service Tsunami Warning Services, Policy Directive 10-7, Operations and Services, National Weather Service/NOAA, Washington.

http://www.nws.noaa.gov/directives/010/010.htm then link to: http://wcatwc.arh.noaa.gov/definition.htm

NWS, 2003: National Weather Service, Aviation Weather Services, Policy Directive 10-8, Instruction 10-801, Operations and Services, National Weather Service/NOAA, Washington. http://www.nws.noaa.gov/directives/010/010.htm

NWS, 2004: National Weather Service, Public Weather Services, Policy Directive 10-5,Instruction 10-513,10- 515, Operations and Services, National Weather Service/NOAA, Washington. http://www.nws.noaa.gov/directives/010/010.htm

NWS, 2004: National Weather Service, Hydrologic Services Program, Policy Directive 10-9, Instruction 10-922, Operations and Services, National Weather Service/NOAA, Washington. http://www.nws.noaa.gov/directives/010/010.htm

Table 1. Models and the number of model runs used in the analysis.

Institution	Country	Model name	# of B1 runs	# of A1B runs	# of A2 runs
Bjerknes Centre for Climate Research	Norway	BCCR-BCM2.0	1	1	1
National Center for Atmospheric Research	USA	CCSM3	9	7	4
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1(T47)	5	5	5
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1(T63)	1	1	0
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3	1	1	1
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0	1	1	1
Max Planck Institute for Meteorology	Germany	ECHAM5/ MPI-OM	3	4	3
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group.	Germany / Korea	ECHO-G	3	3	3
LASG / Institute of Atmospheric Physics	China	FGOALS-g1.0	3	3	0
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.0	1	1	1
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.1	1	1	1
NASA / Goddard Institute for Space Studies	USA	GISS-EH	0	4	0
NASA / Goddard Institute for Space Studies	USA	GISS-ER	1	5	1
Institute for Numerical Mathematics	Russia	INM-CM3.0	1	1	1
Institut Pierre Simon Laplace	France	IPSL-CM4	1	1	1
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2 (hires)	1	1	0
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2 (medres)	3	3	3
Meteorological Research Institute	Japan	MRI-CGCM2.3.2	5	5	5
National Center for Atmospheric Research	USA	PCM	4	4	4
Hadley Centre for Climate Prediction and Research / Met Office	UK	UKMO-HadCM3	1	1	1
Hadley Centre for Climate Prediction and Research / Met Office	UK	UKMO-HadGEM1	0	1	1

Table 2. Projected sea-level rise from the IPCC Third Assessment Report for emission scenarios A2, A1B and B1. In mm.

Year	A2	A1B	B1
1990	0	0	0
2000	17	17	17
2010	38	37	38
2020	61	61	62
2030	88	91	89
2040	120	127	118
2050	157	167	150
2060	201	210	183
2070	250	256	216
2080	304	301	249
2090	362	345	281
2100	424	387	310

Table 3. Major Airports at or below 22 feet above mean sea-level. Field Elevations were verified by using www.NavAir.com. Airport lists with weather stations were referenced from public files at NOAA's National Climatic Data Center.

City	**St**	**Airport**	**Field Elev m msl**	**Field Elev ft msl**	**Id**
KEY WEST	FL	KEY WEST INTERNATIONAL	1.2	4	EYW
OAKLAND	CA	METROPOLITAN OAKLAND INTERNATIONAL	1.8	6	OAK
NEW ORLEANS	LA	LOUIS ARMSTRONG NEW ORLEANS INTERNATIONAL	1.8	6	MSY
SAN JUAN	PR	SAN JUAN LUIS MUÑOZ MARIN INTERNATIONAL AIRPORT	3.1	10	SJU
SANTA BARBARA	CA	SANTA BARBARA MUNICIPAL	3.1	10	SBA
SAN FRANCISCO	CA	SAN FRANCISCO INTERNATIONAL	3.4	11	SFO
FORT LAUDERDALE	FL	FORT LAUDERDALE/HOLLYWOOD INTERNATIONAL	3.4	11	FLL
MIAMI	FL	MIAMI INTERNATIONAL	3.7	12	MIA
HONOLULU	HI	HONOLULU INTERNATIONAL	4.0	13	HNL
NEW YORK	NY	JOHN F KENNEDY INTERNATIONAL	4.0	13	JFK
NEW HAVEN	CT	TWEED-NEW HAVEN	4.3	14	HVN
SAN DIEGO	CA	SAN DIEGO INTERNATIONAL-LINDBERGH FIELD	4.6	15	SAN
WASHINGTON	DC	RONALD REAGAN WASHINGTON NATIONAL	4.9	16	DCA
BEAUMONT/PORT ARTHUR	TX	SOUTHEAST TEXAS REGIONAL	4.9	16	BPT
NEWARK	NJ	NEWARK LIBERTY INTERNATIONAL	5.5	18	EWR
SEATTLE	WA	BOEING FIELD/KING COUNTY INTERNATIONAL	5.5	18	BFI
JUNEAU	AK	JUNEAU INTERNATIONAL	5.8	19	JNU
HARTFORD	CT	HARTFORD-BRAINARD	5.8	19	HFD
WEST PALM BEACH	FL	PALM BEACH INTERNATIONAL	5.8	19	PBI
BOSTON	MA	GENERAL E.L. LOGAN INTERNATIONAL	6.1	20	BOS
PHILADELPHIA	PA	PHILADELPHIA INTERNATIONAL	6.1	21	PHL
SACRAMENTO	CA	SACRAMENTO EXECUTIVE	6.1	21	SAC
NEW YORK	NY	LA GUARDIA	6.7	22	LGA

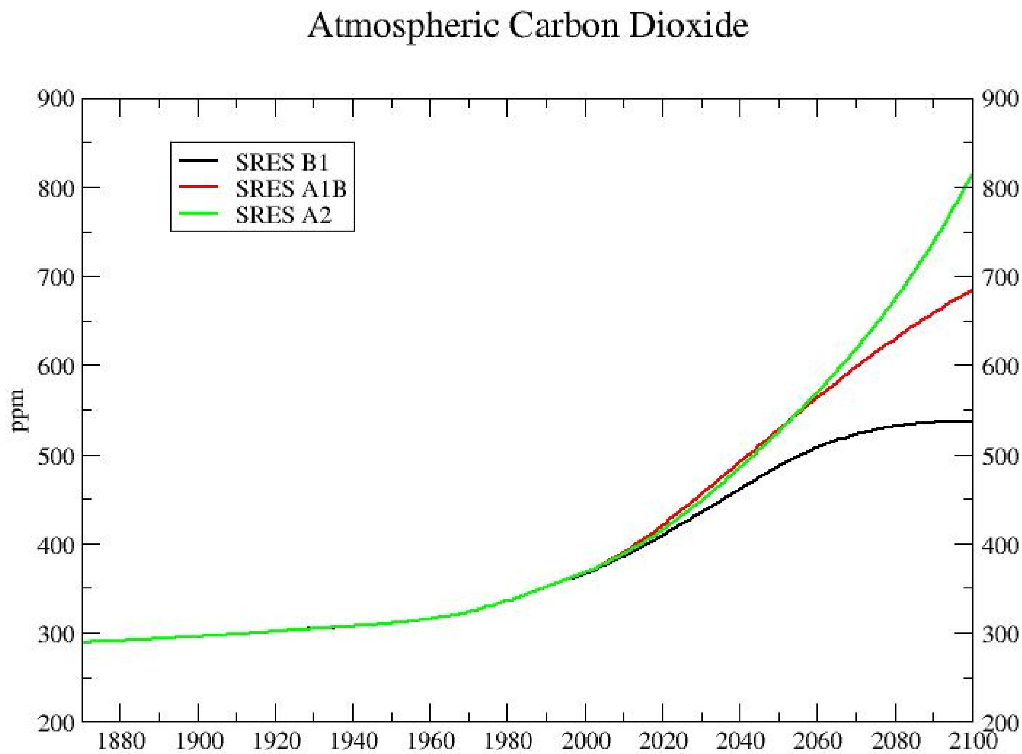


Figure 1. Atmospheric CO_2 concentration from historical observations and three different scenarios which reflect different expectations for future population growth, economic expansion, energy efficiency improvements, etc.

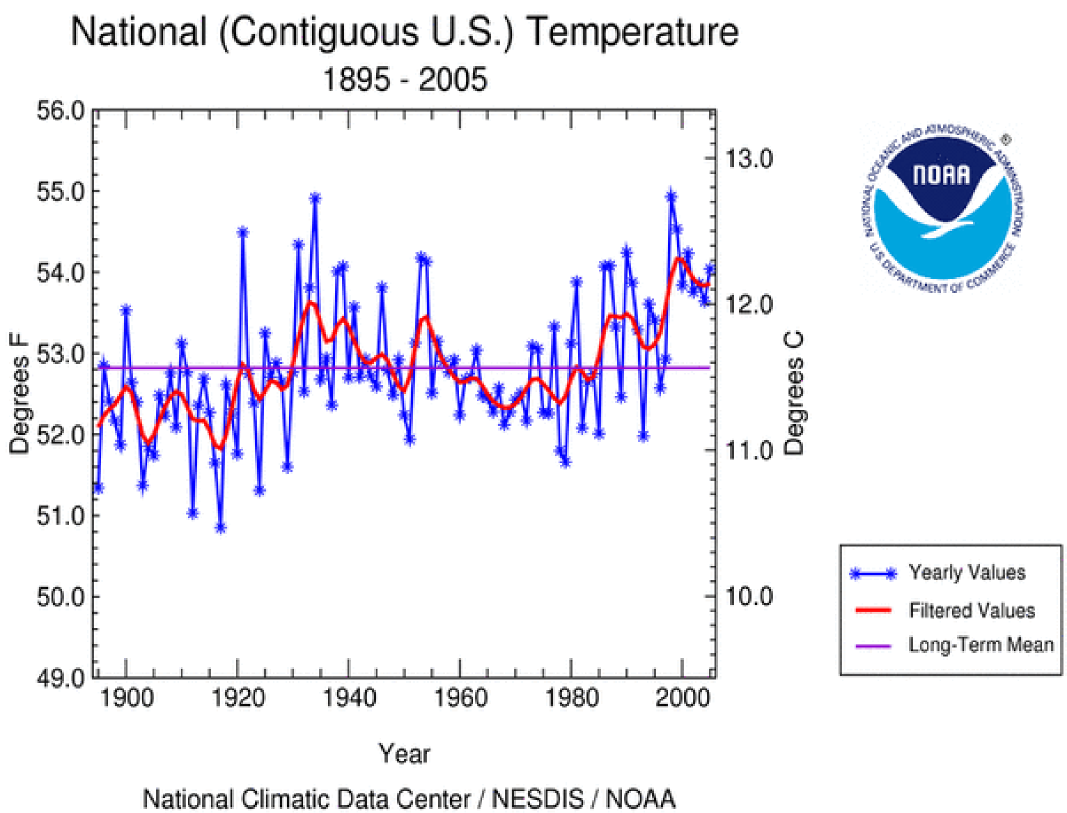


Figure 2. Area-averaged mean temperature time series for the contiguous United States.

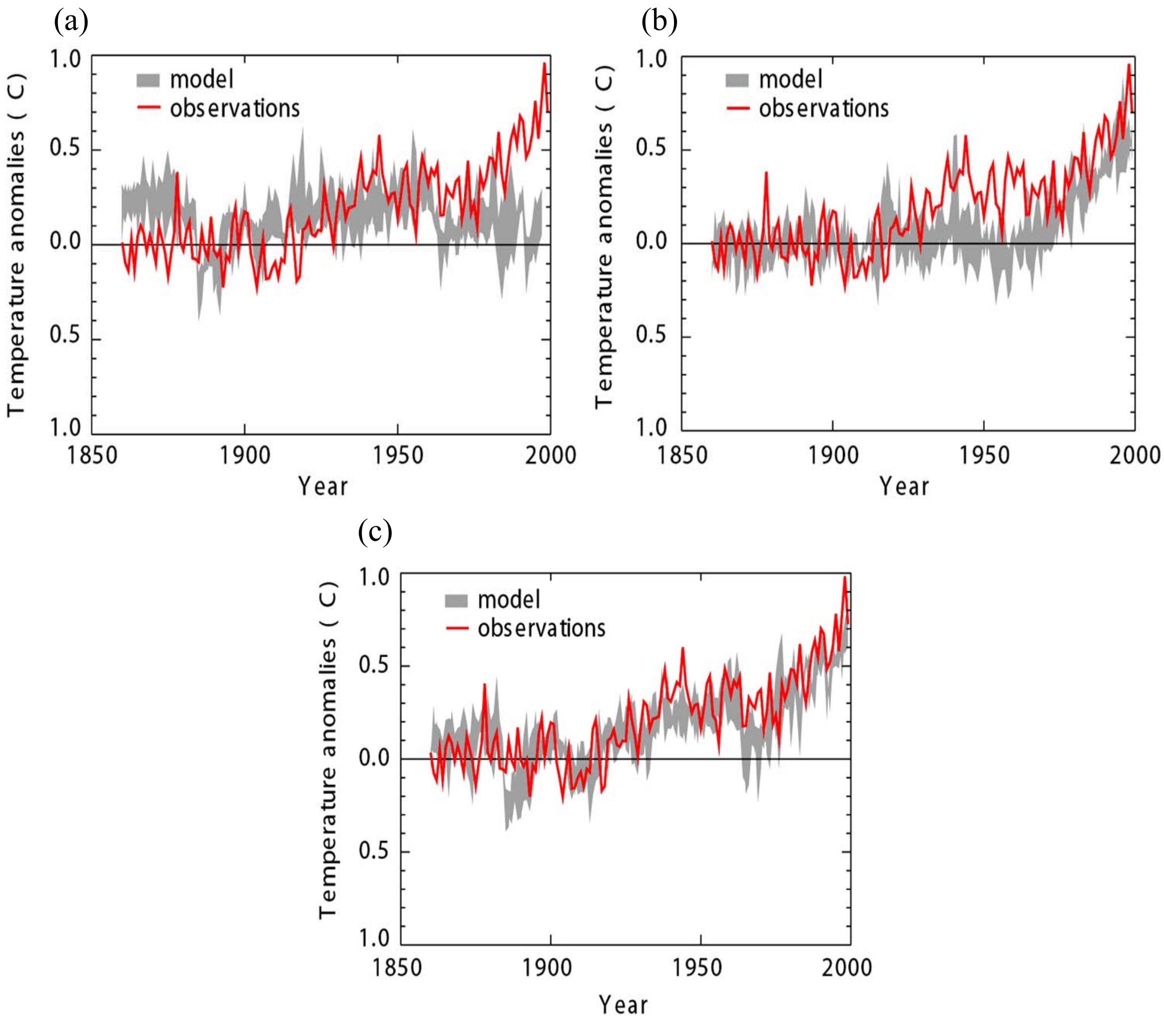


Figure 3. Climate model simulations of global air temperature for the period 1860-2000. In (a) the models only had natural forcings such as changes in solar irradiance and volcanic aerosols and did a poor job of representing global temperatures after ~1970. In (b) the models only had anthropogenic forcing and did a fairly good job of representing global temperatures after 1970 but not for the few decades preceding 1970. In (c) the models included both natural and anthropogenic forcings and reproduces the global air temperature time series quite well. From IPCC TAR (Houghton et al., 2001).

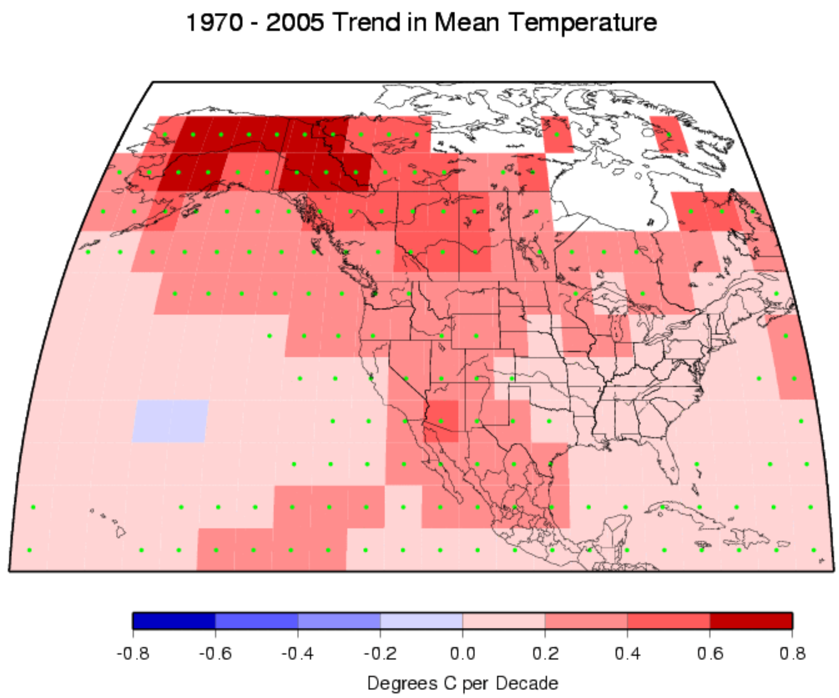


Figure 4. Trends in mean temperature for the US and surrounding areas since 1970. When the trend in a 5° latitude by 5° longitude grid box is statistically significant at the 95% level, a green dot is put in the center of the box. Data from Smith et al. (2005).

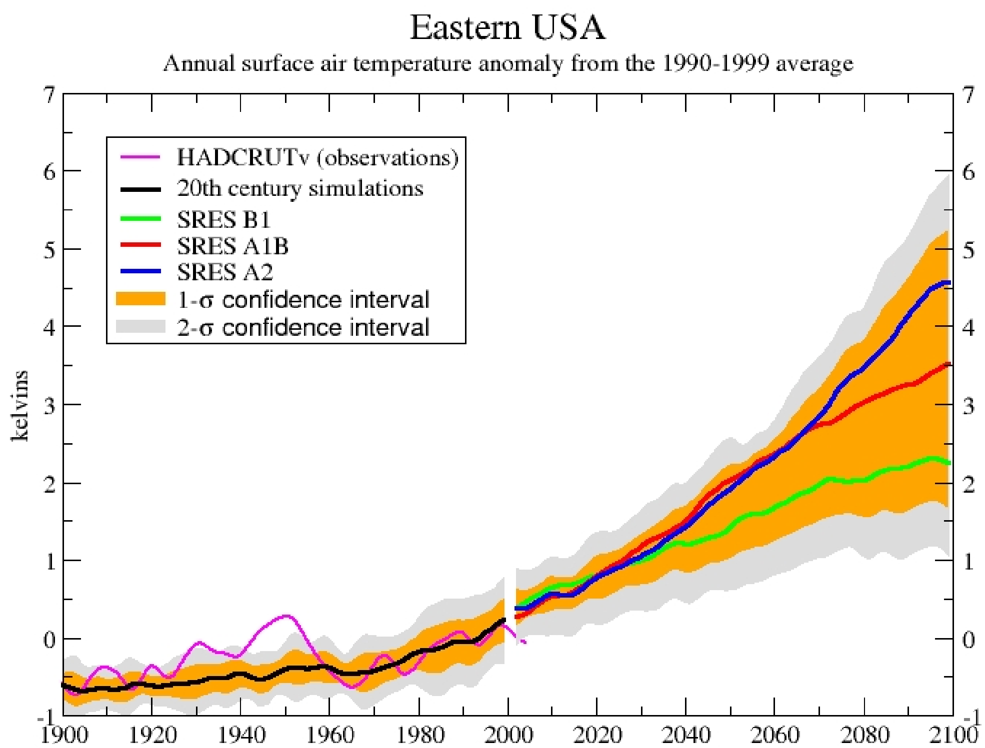


Figure 5. The CO_2 emissions scenario makes considerable difference in terms of climate projections. This figure for the Eastern US is fairly typical of all the different regions. Scenario B1 has the least warming and A2 has the most. Which scenario is most realistic estimate of technology and the global economy for the next 100 years? We have chosen to use scenario A2. It should be kept in mind when looking at results based on scenario A2 that A2 and A1B are very similar out to the year 2060 after which A2 is definitely higher. The differences between the observations and historical model runs is caused by some of the models did not incorporate solar variability or volcanic aerosols. HADCRUTv is a combination of land air temperature anomalies (Jones, 1994, CRUTEM1) and sea surface temperature anomalies (Parker et al., 1995).

Temperature Projections using Scenario B1

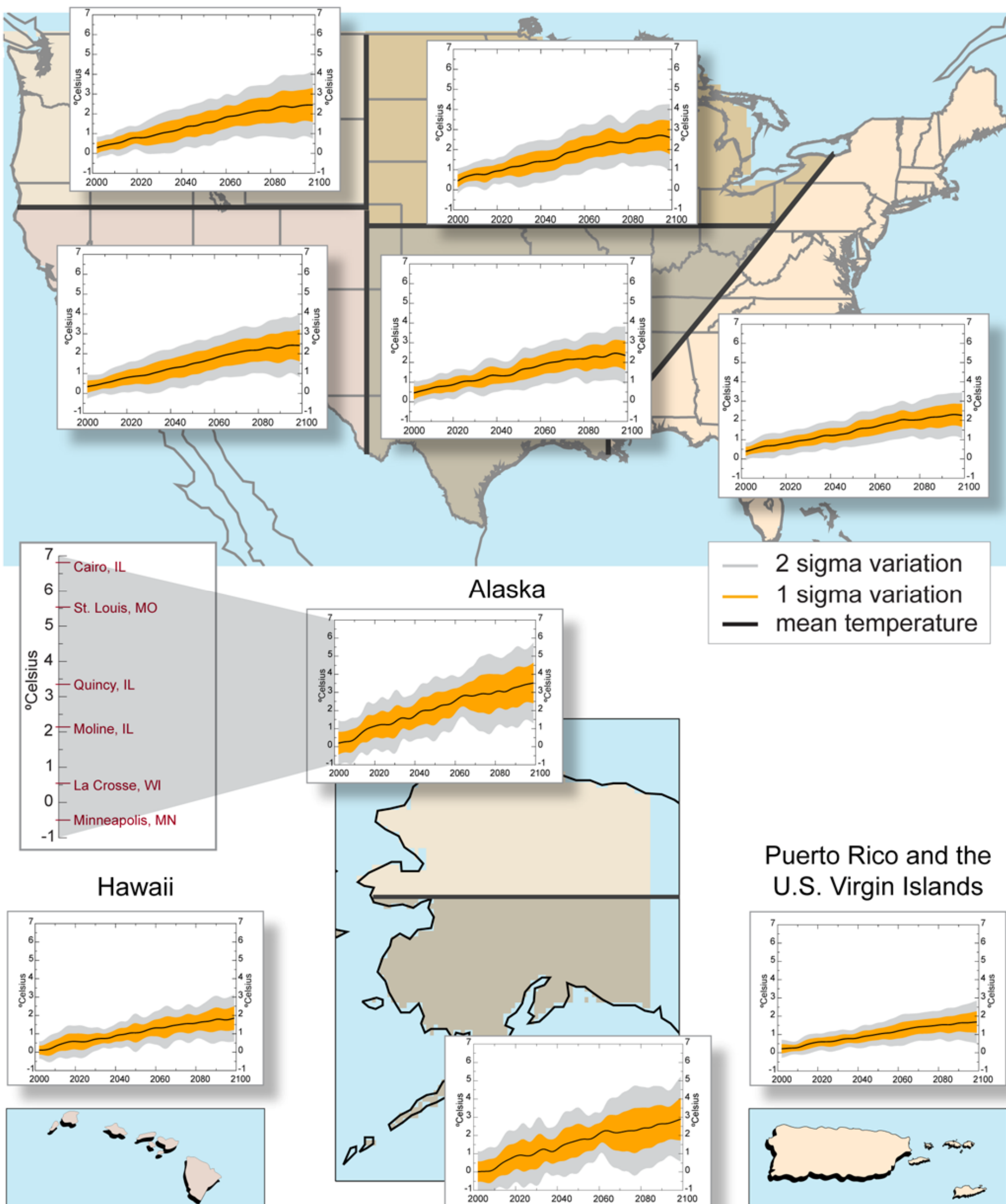


Figure 6a.

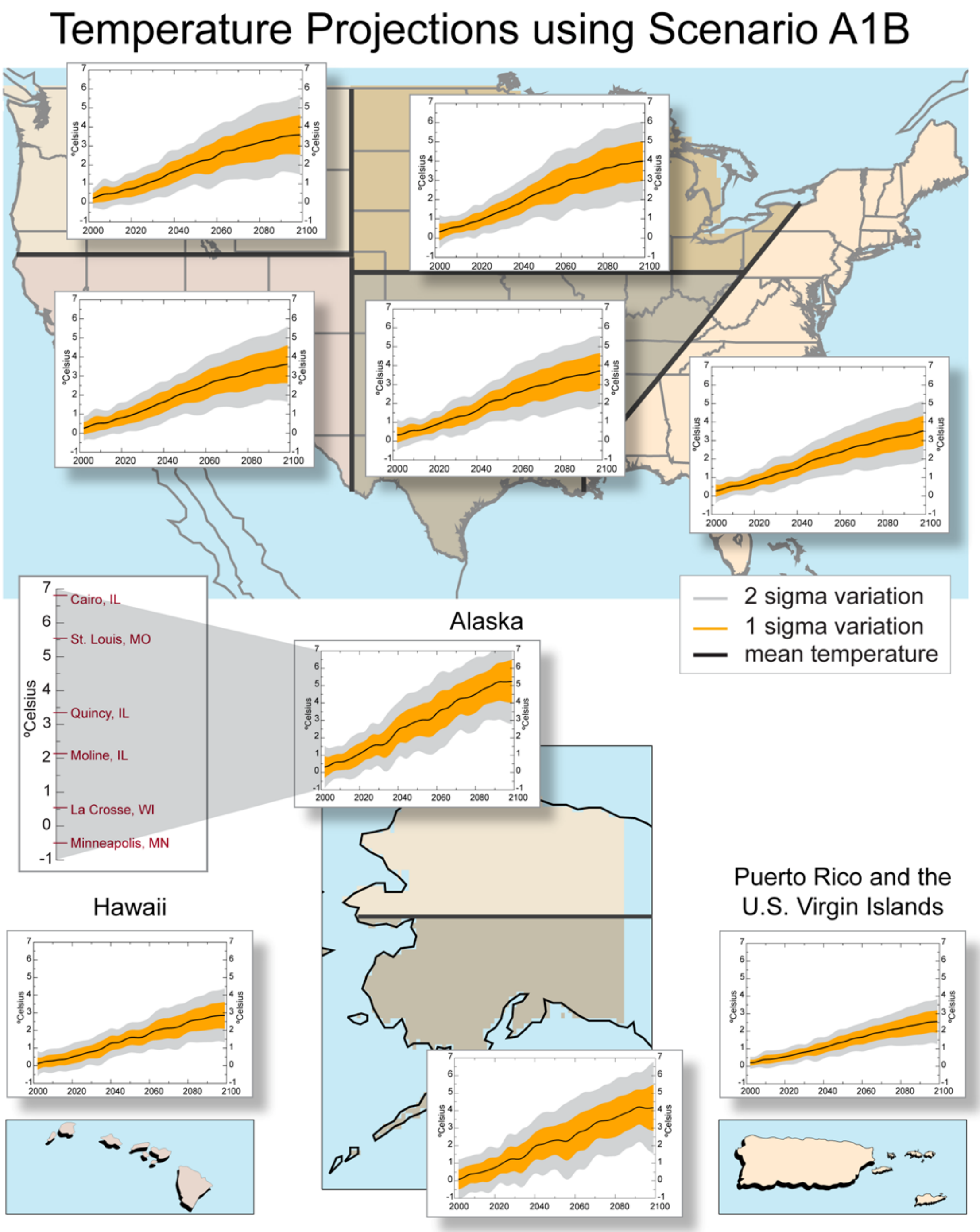

Temperature Projections using Scenario A1B
Alaska
Hawaii
Puerto Rico and the U.S. Virgin Islands
2 sigma variation
1 sigma variation
mean temperature
°Celsius
Cairo, IL
St. Louis, MO
Quincy, IL
Moline, IL
La Crosse, WI
Minneapolis, MN

Figure 6b.

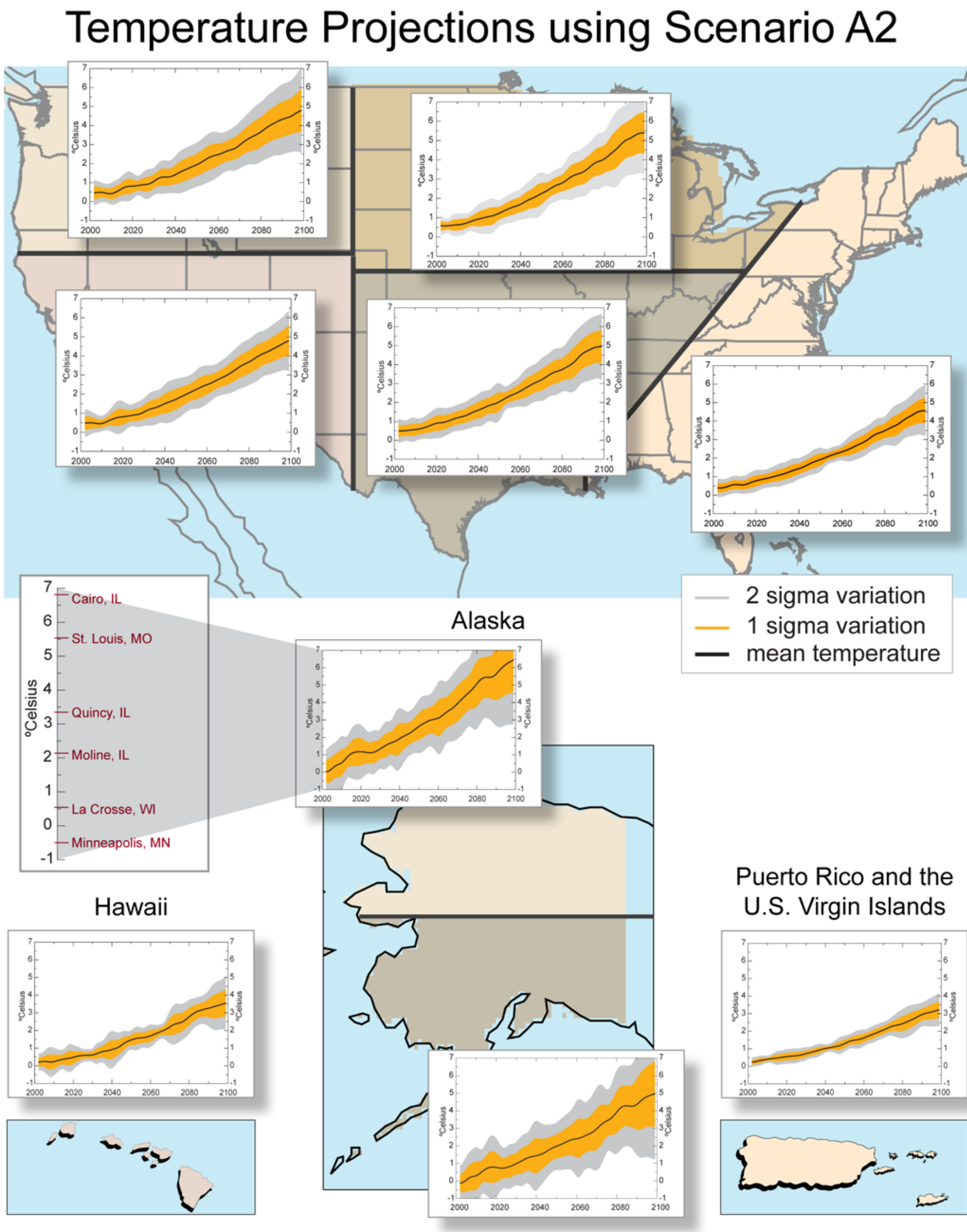
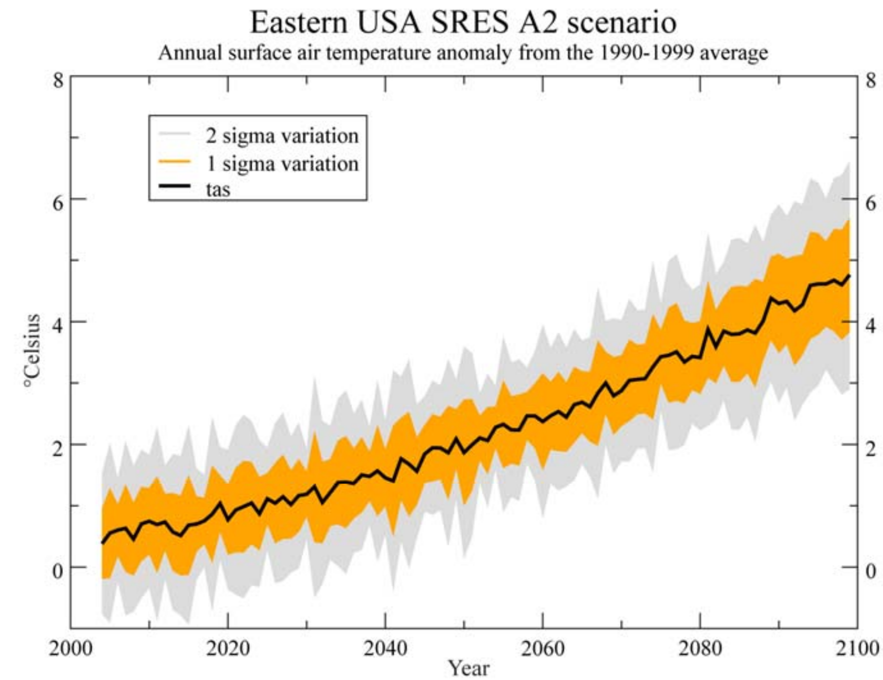


Figure 6c.

Figure 6. Model temperature projections smoothed with a 13-year filter and their one and two σ ranges. To help put the projected changes into perspective, the relative differences in mean annual temperatures for six cities have been plotted on the same scale. (a) Scenario B1, (b) scenario A1B, (c) scenario A2.



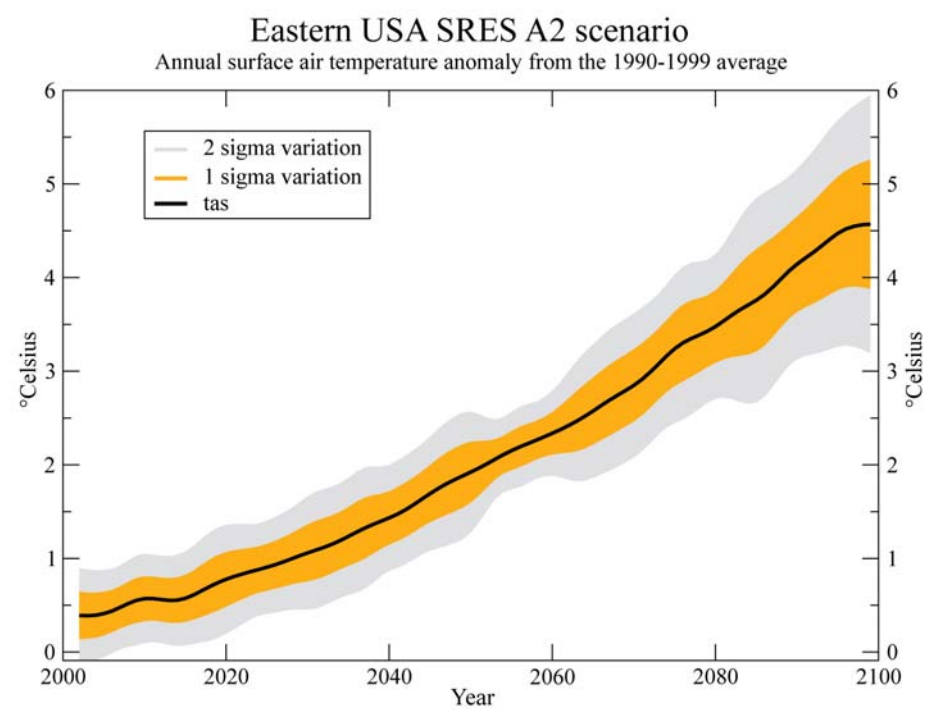


Figure 7. Top time series of the scenario A2 for the eastern region showing annual values for the mean and standard deviations (one standard deviation (sigma, σ) includes 68% of normally distributed data; two σ incorporate 95%). Bottom the same but for time series that have been smoothed.

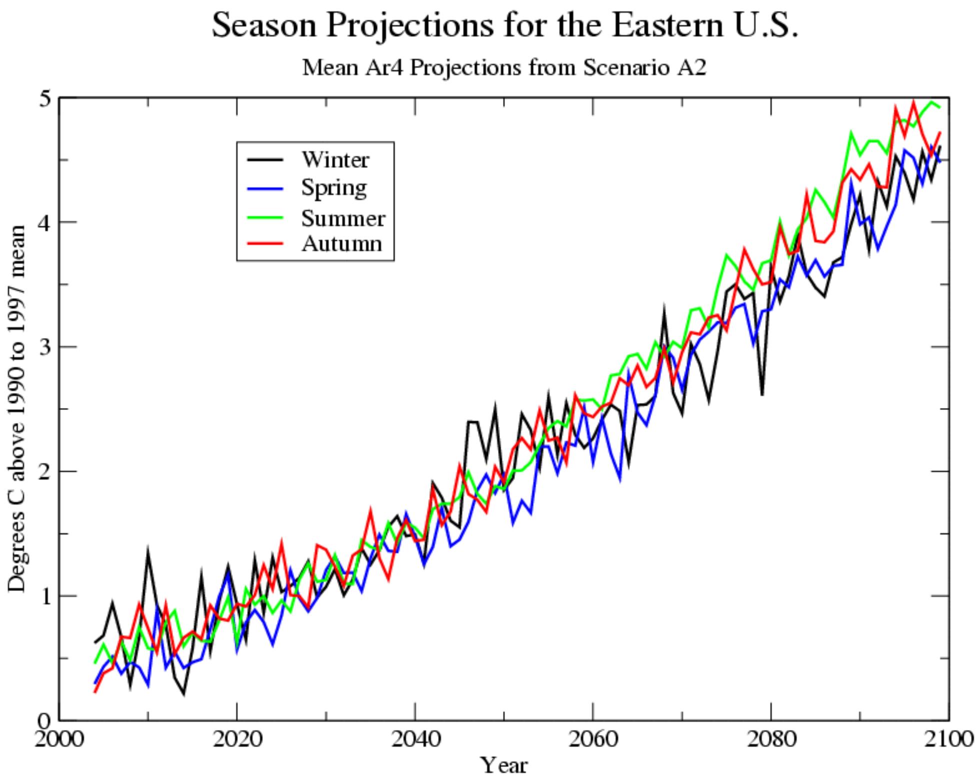
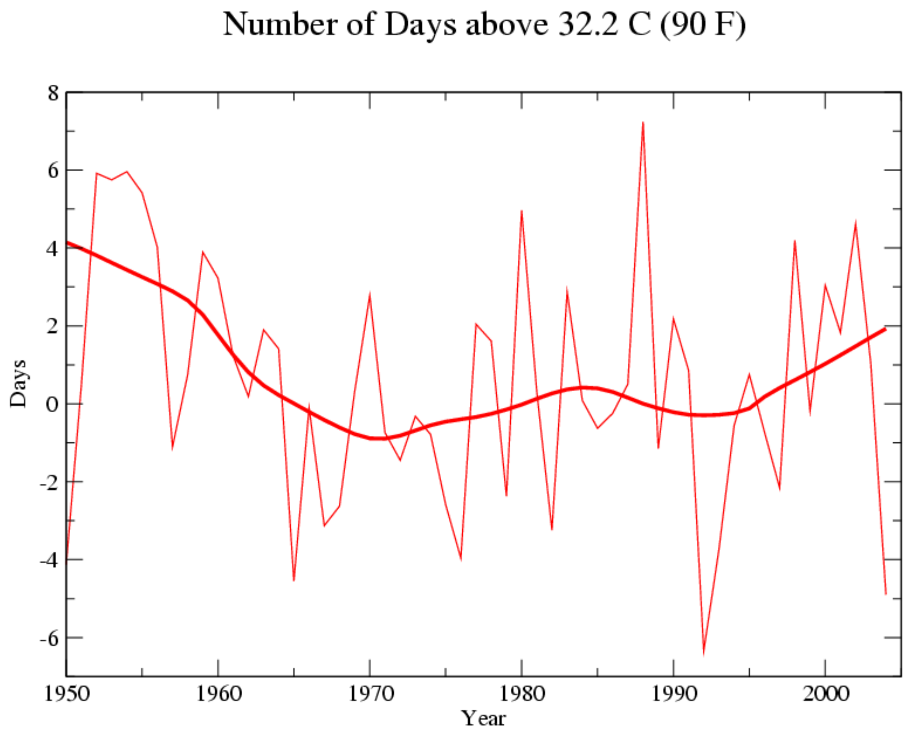


Figure 8. Median seasonal projections for the Eastern U.S. show very similar trends until ~2055 after which the summer and autumn projections show somewhat more warming.



Number of Days above 32.2 C (90 F)
Days
Year
8
6
4
2
0
-2
-4
-6
1950
1960
1970
1980
1990
2000

Figure 9a

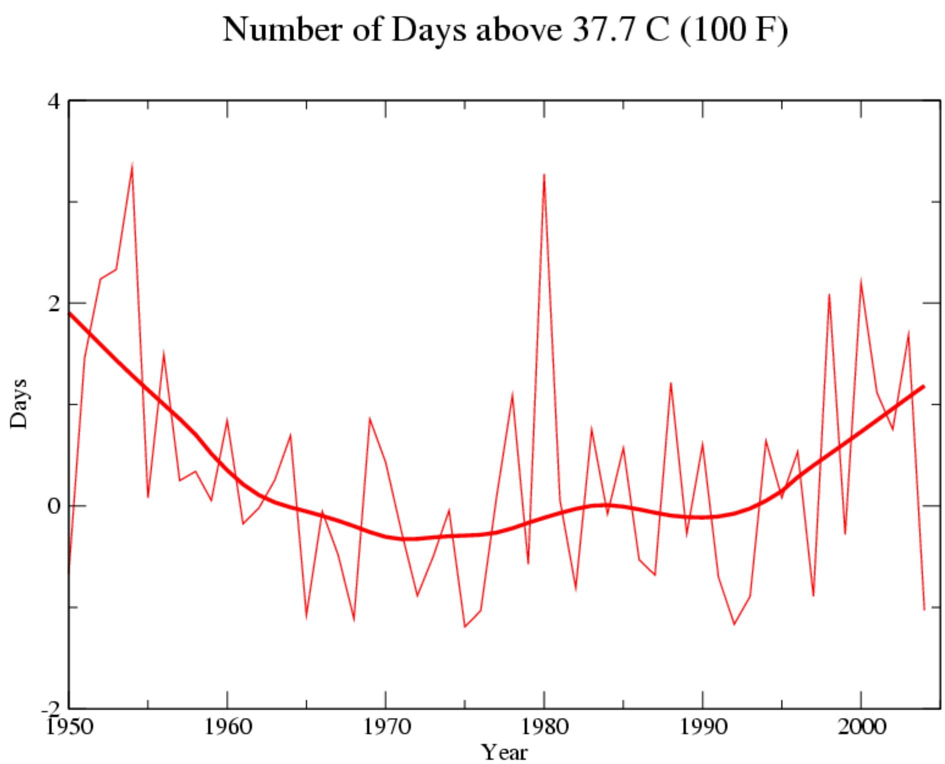
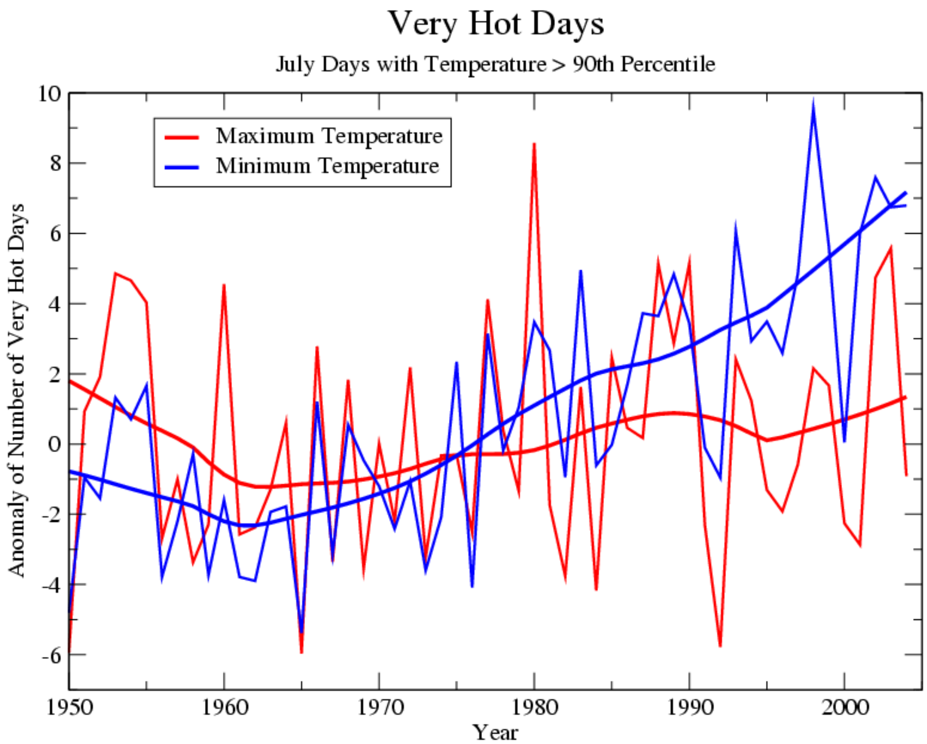
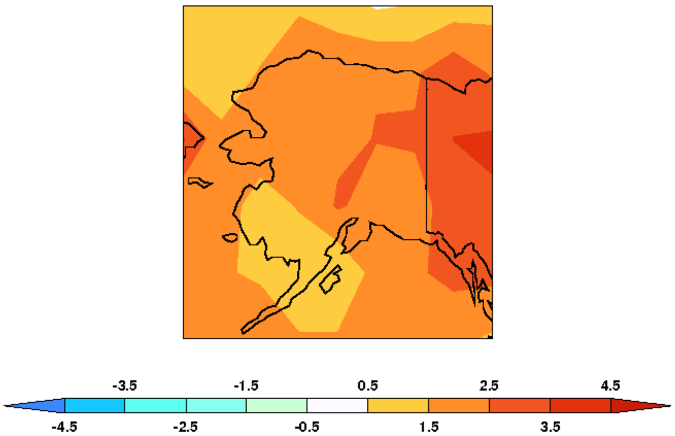

Number of Days above 37.7 C (100 F)
4
2
0
-2
Days
1950
1960
1970
1980
1990
2000
Year

Figure 9b.



Very Hot Days
July Days with Temperature > 90th Percentile
Maximum Temperature
Minimum Temperature
Anomaly of Number of Very Hot Days
Year
10
8
6
4
2
0
-2
-4
-6
1950
1960
1970
1980
1990
2000

Figure 9c.



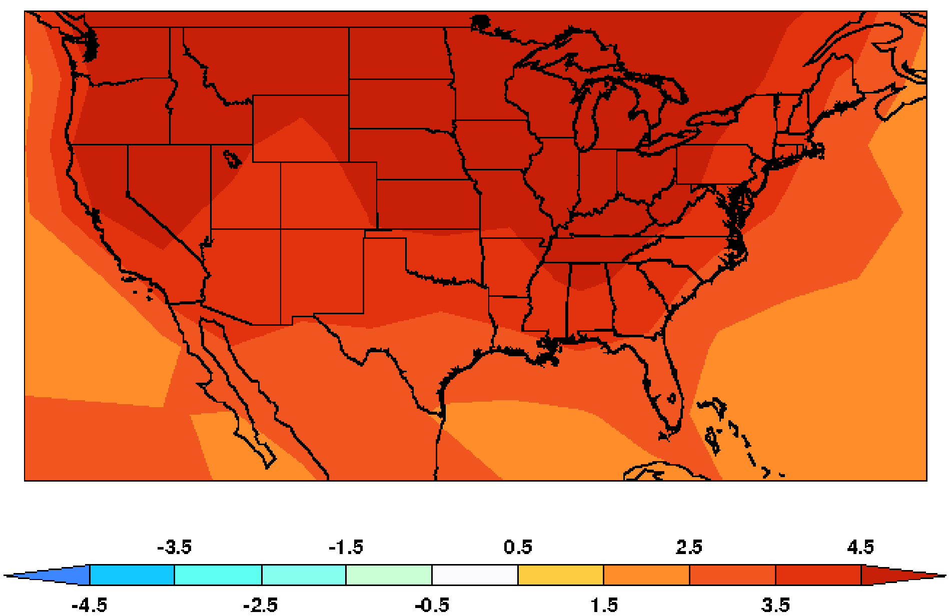


Figure 9d.

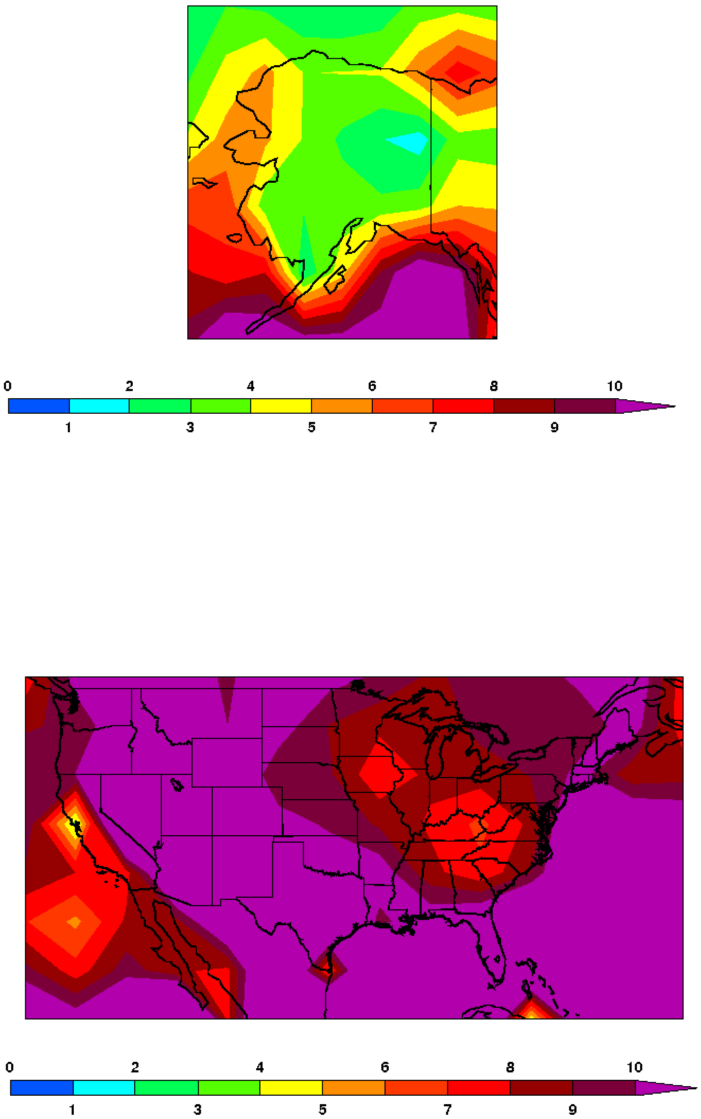


Figure 9e

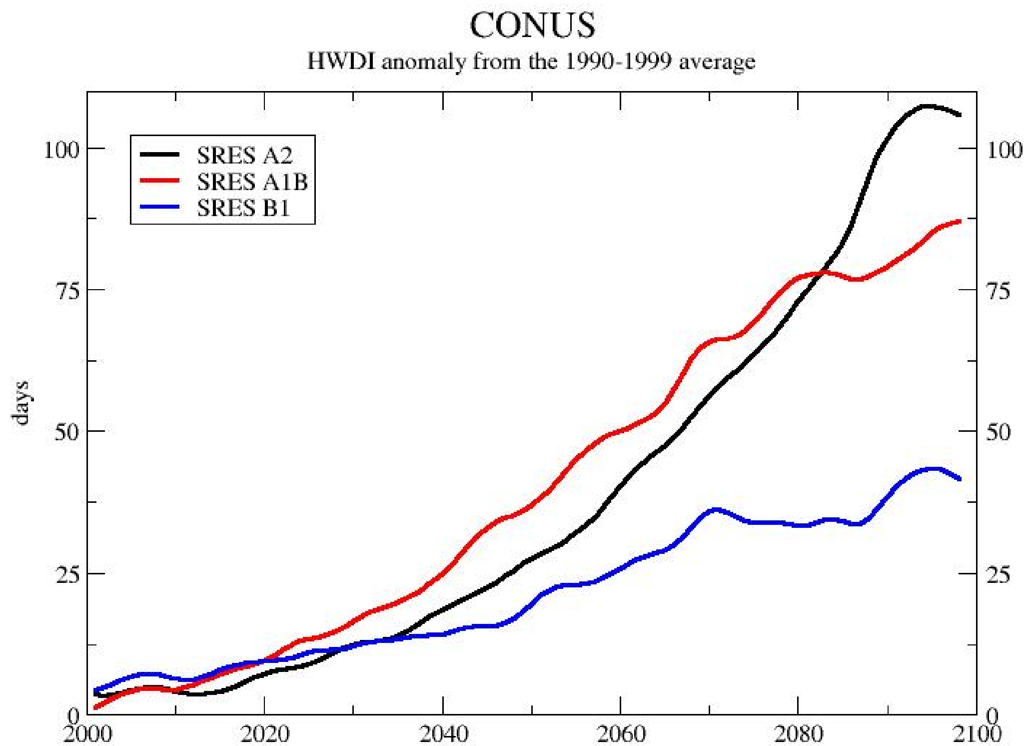
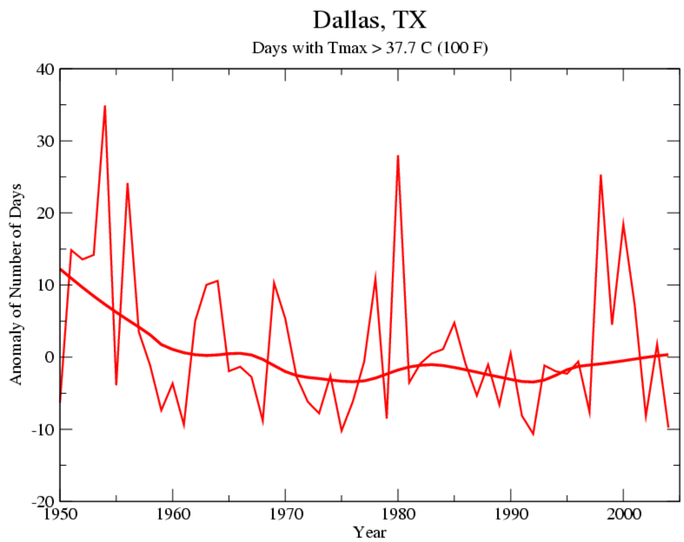


Figure 9f

Figure 9. Nationally, the number of days with high temperatures decreased from 1950 to 1970 and has been increasing since then. Area averaged anomaly time series for the U.S.: (a) is days above 32.2°C (90°F), (b) the middle panel is days above 37.7°C (100°F). (c) The bottom panel shows the warmest 10% of July maximum and minimum temperatures at each station. Note the number of days above the 90th percentile in minimum temperature is rising faster than maximum temperature. (d) Model projected changes (in Degrees C) in the annual maximum daily averaged surface temperature from 1990-1999 to 2090-2099 using scenario A1B. (e) The number of times in 20 years that the 1990-1999 20-year return period daily maximum surface air temperature would occur using the 2090-2099 forcing from scenario A1B. (f) Median model results from all three scenarios indicate a projected increase in heat waves over the CONUS. Heat waves were defined, as in Frich et al. (2002) as the annual maximum period greater than 5 consecutive days with maximum temperature greater than 5°C above the 1961-1990 average maximum temperature for that day of the year.



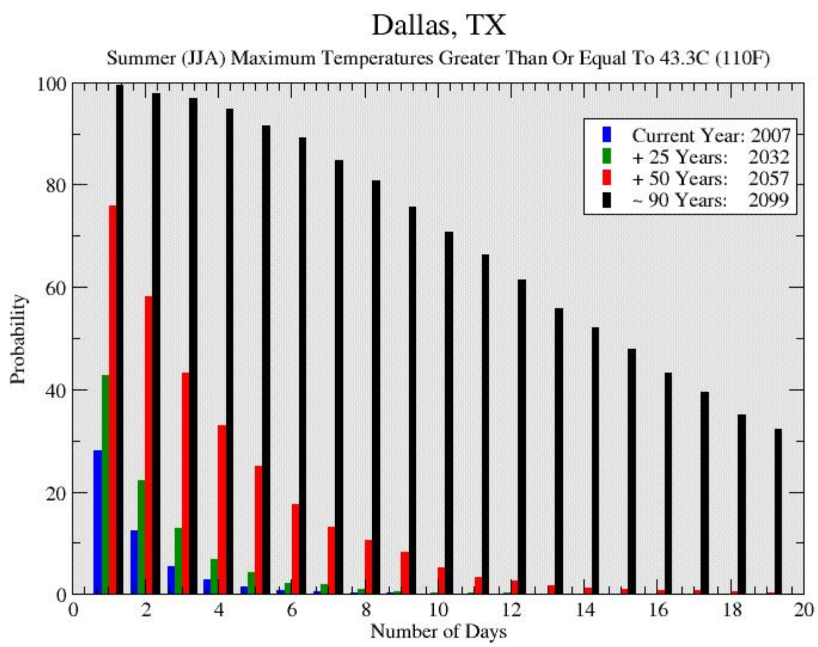
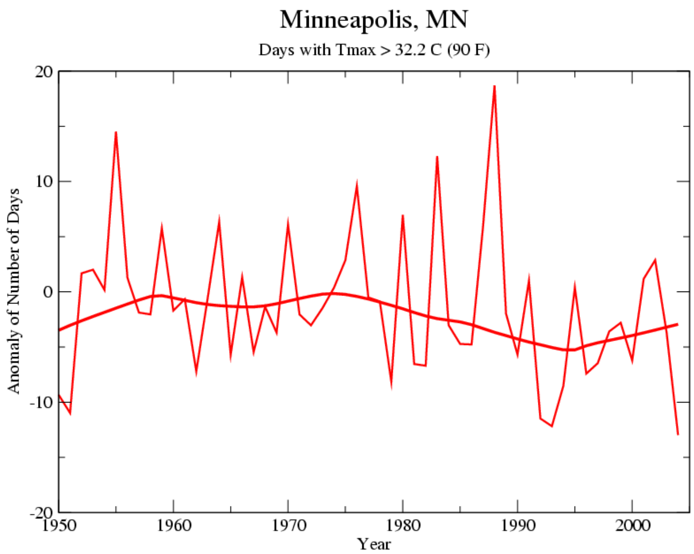


Figure 10. Top: historical time series from stations within 500 km of the Dallas, TX showing anomalies of the number of days above 37.7°C (100°F). Bottom: the current and future probability of having one to twenty days during the summer at or above 43.3°C (110°F) at Dallas, TX.



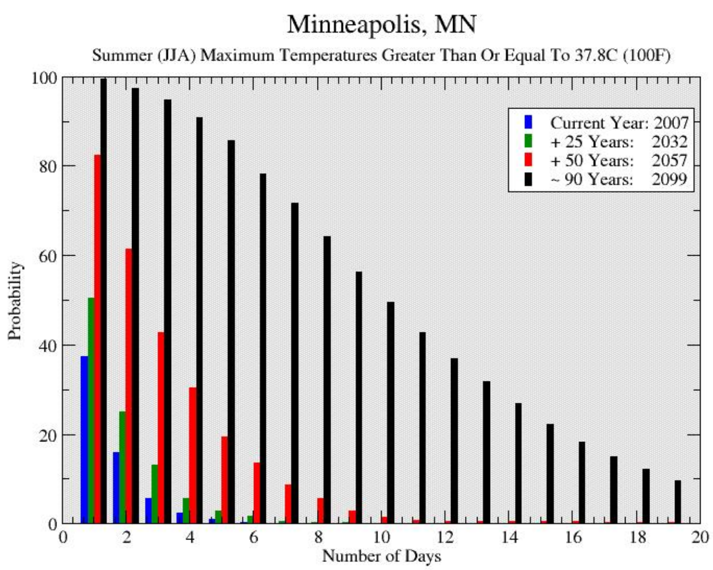
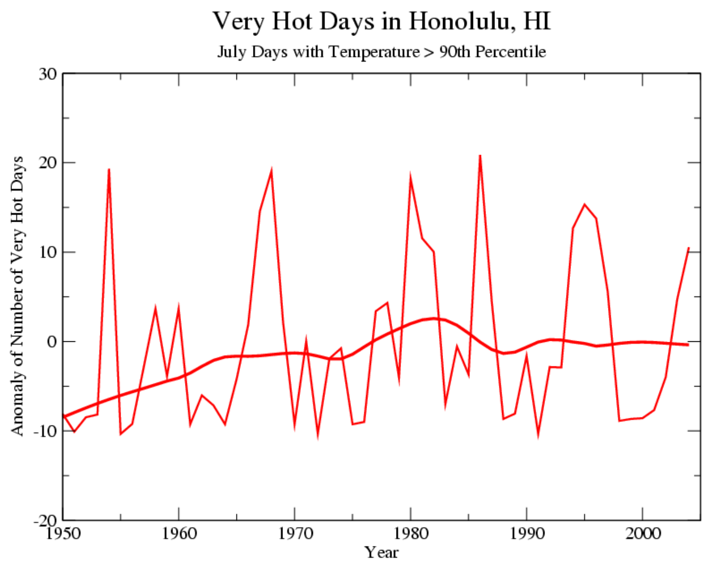


Figure 11. Top panel shows the historic anomaly time series for the area within 500 km of Minneapolis, MN of the number of days above 32.2°C (90°F). Bottom: the current and future probability of having one to twenty days during the summer at or above 37.8°C (100°F) at Minneapolis, MN.



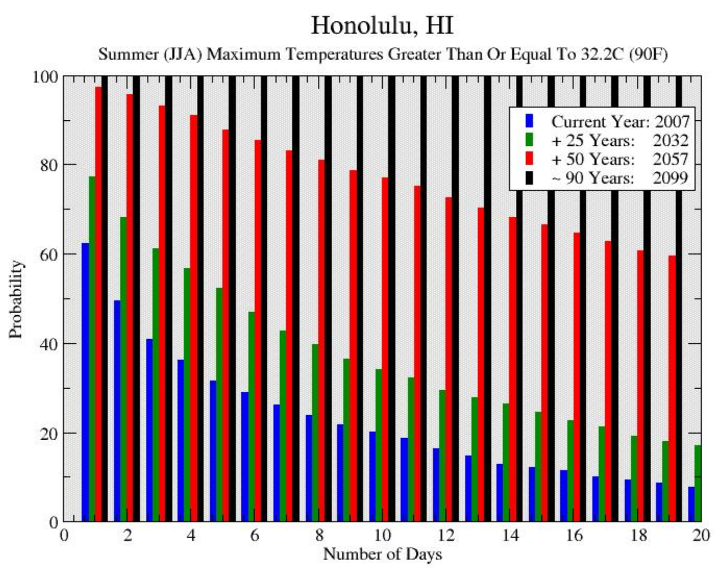


Figure 12. Top: historical time series from stations within 500 km of the Honolulu, HI showing anomalies of July days above the 90th percentile of maximum temperature. Bottom: the current and future probability of having one to twenty days during the summer at or above 32.2°C (90°F) at Honolulu, HI.

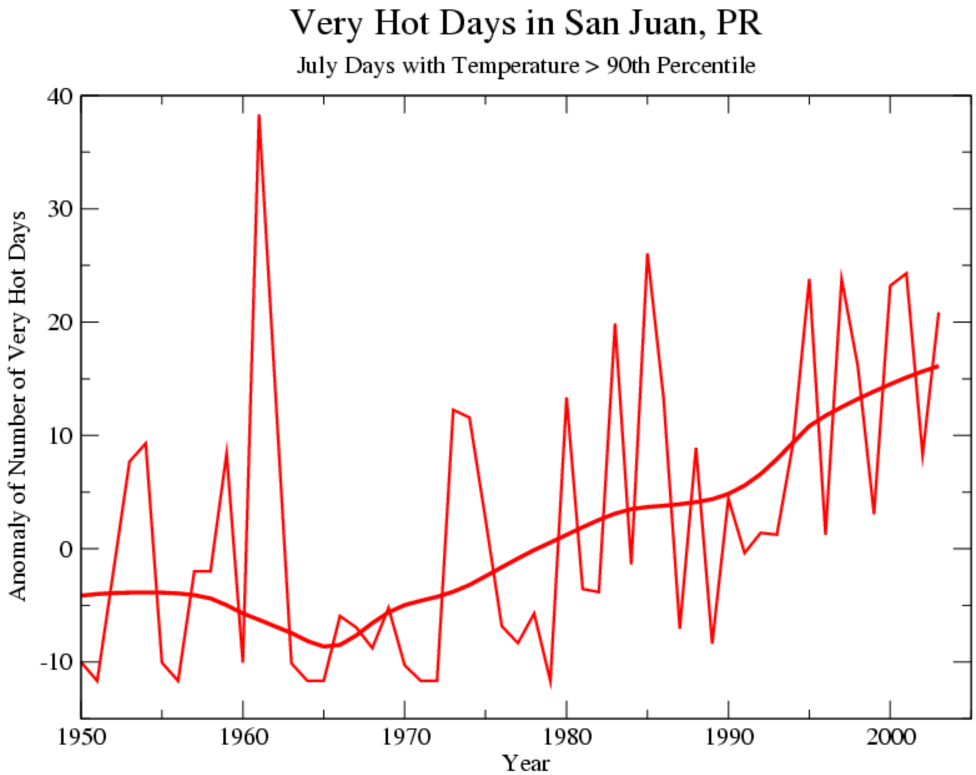


Figure 13. Top: historical time series from stations within 500 km of the San Juan, PR showing anomalies of July days above the 90th percentile of maximum temperature.

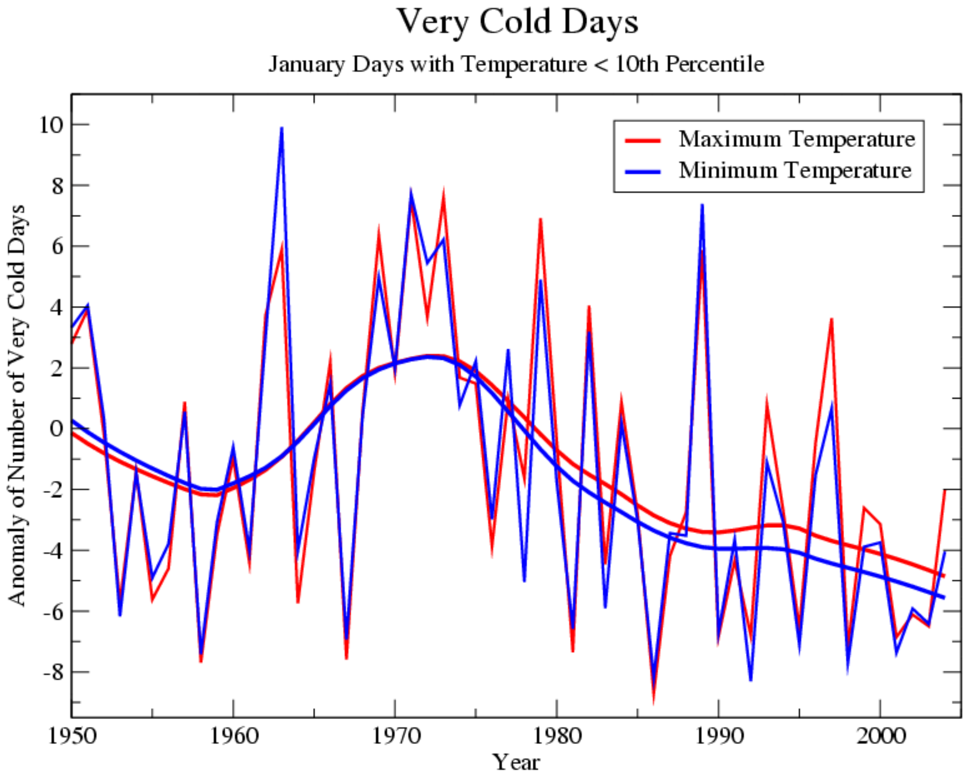
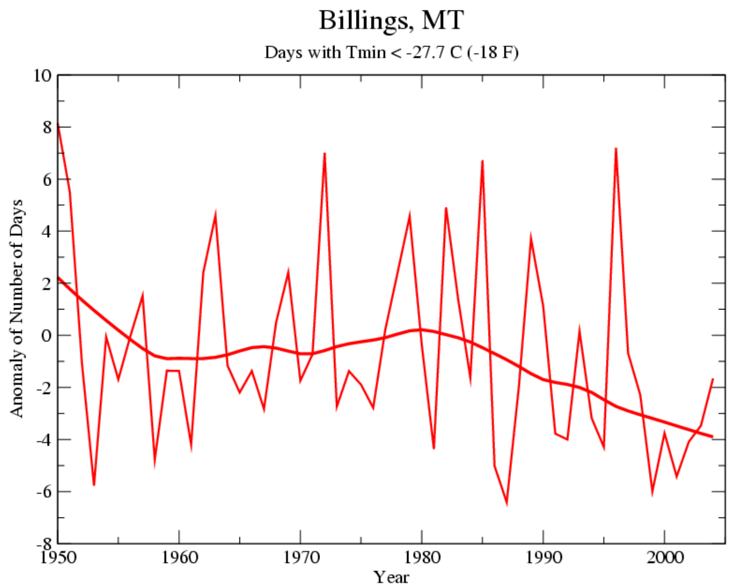


Figure 14. U.S. nationally averaged anomaly of the number of days at or below the coldest 10% of January maximum and minimum temperature at each stations.



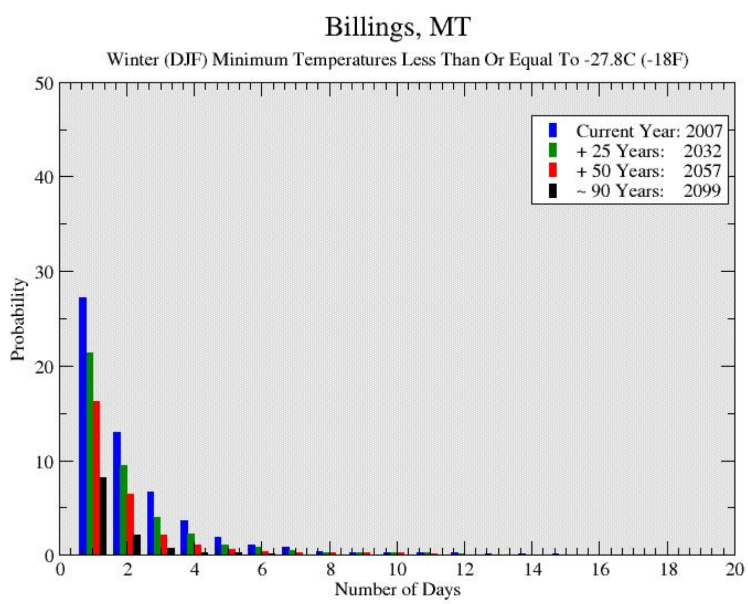
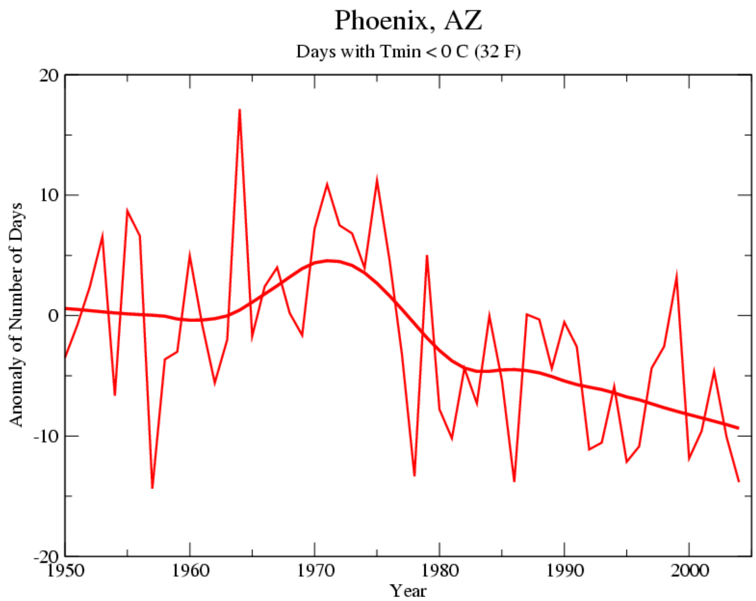


Figure 15. Top: anomalies of the number of days with minimum temperature at or below -27.7°C (-18°F) for stations within 500 km of Billings, MT. Bottom: the current and future probability of having one to 20 days where minimum temperature is at or below -27.7°C in Billings, MT during the winter.



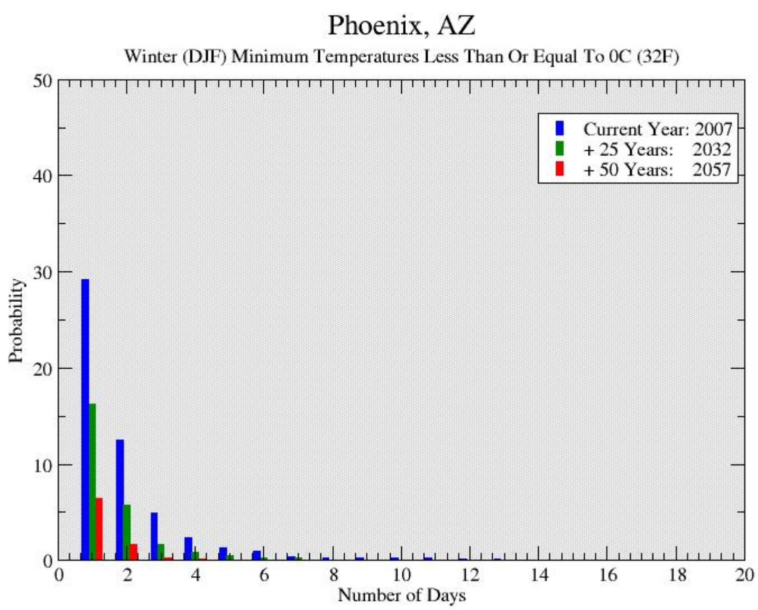


Figure16. Top: Anomaly of the number of days per year with minimum temperature equal to or less than 0°C (32°F) based on analysis of stations within 500 km of Phoenix. Bottom: The current and future probability of have one to twenty days with minimum temperature at or below freezing during the winter. No analysis is presented for the year 2099 because the projected change in temperature was greater than the software that generated the probabilities was able to handle.

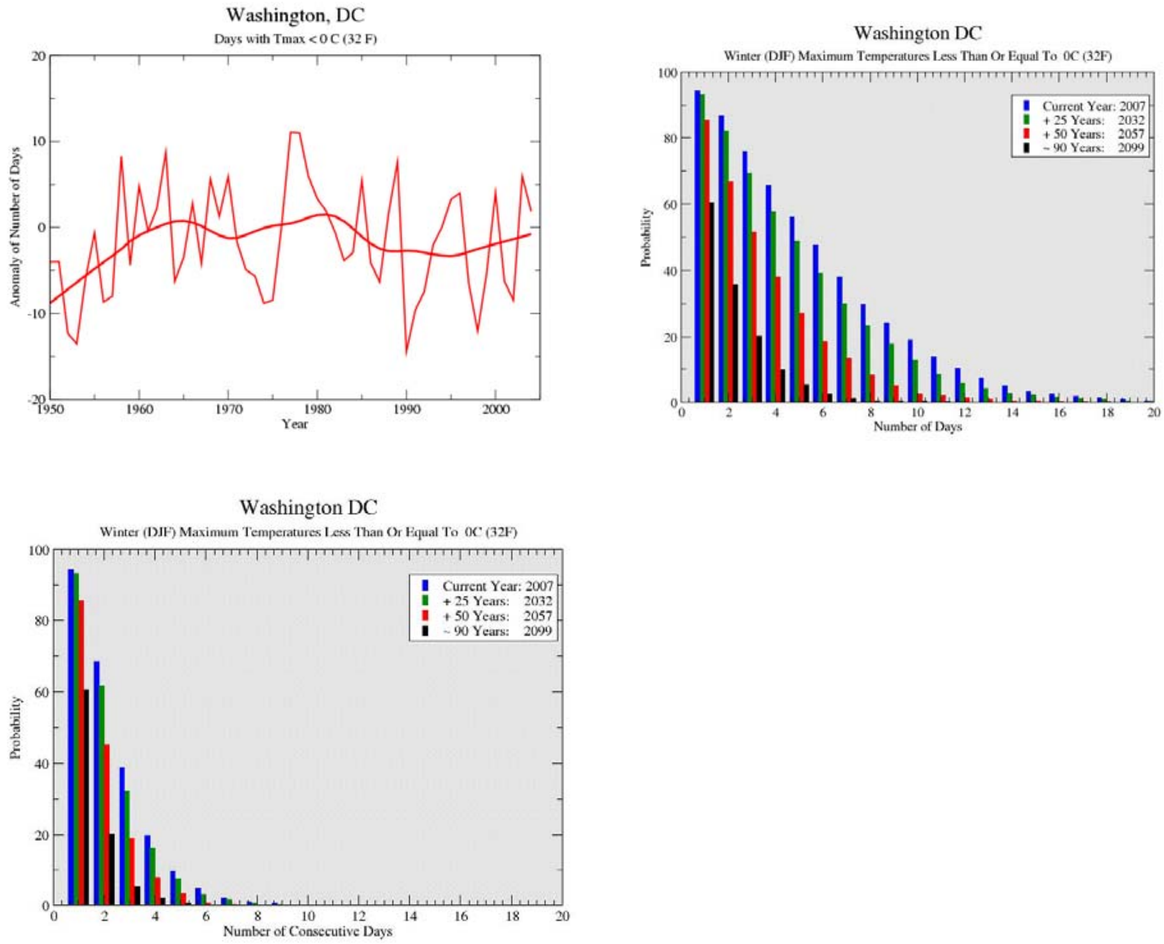


Figure 17. Top: anomaly of the number of days with maximum temperature at or above 0°C (32°F) from stations within 500 km of Washington DC. Middle: current and future probability of having one to 20 days with maximum temperature at or below 0°C at Washington, DC. during winter. Bottom: current and future probability of having one to 20 days in a row with with maximum temperature at or below 0°C at Washington, DC. during winter.

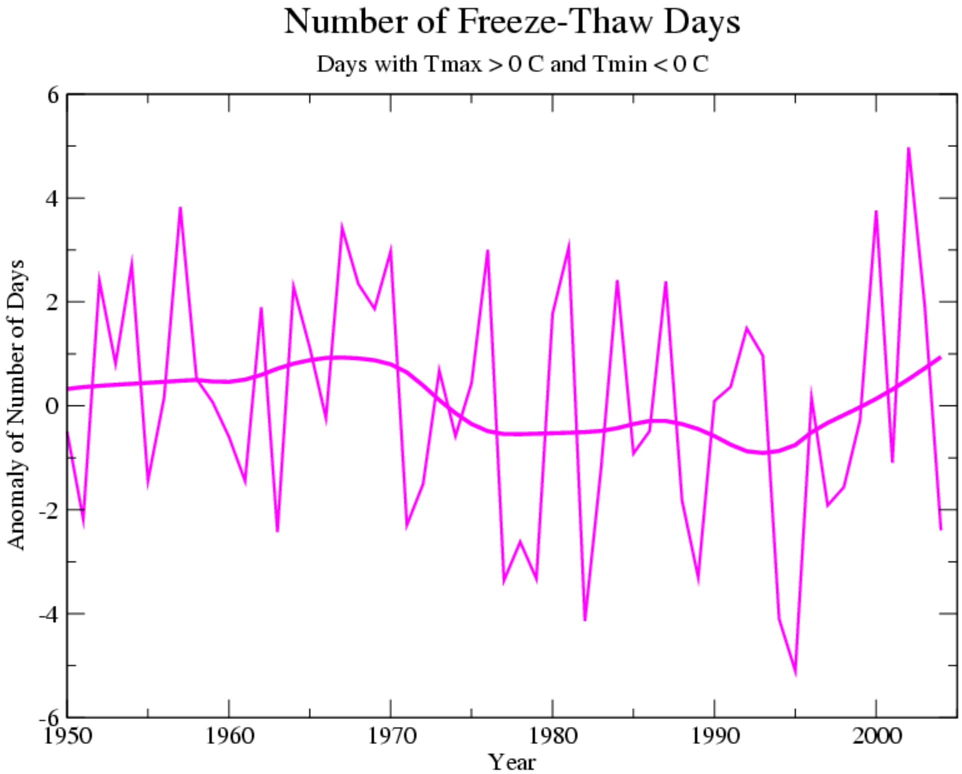


Figure 18. Nationally averaged anomaly in the number of days with a station's maximum temperature being above freezing and the station's minimum temperature below freezing.

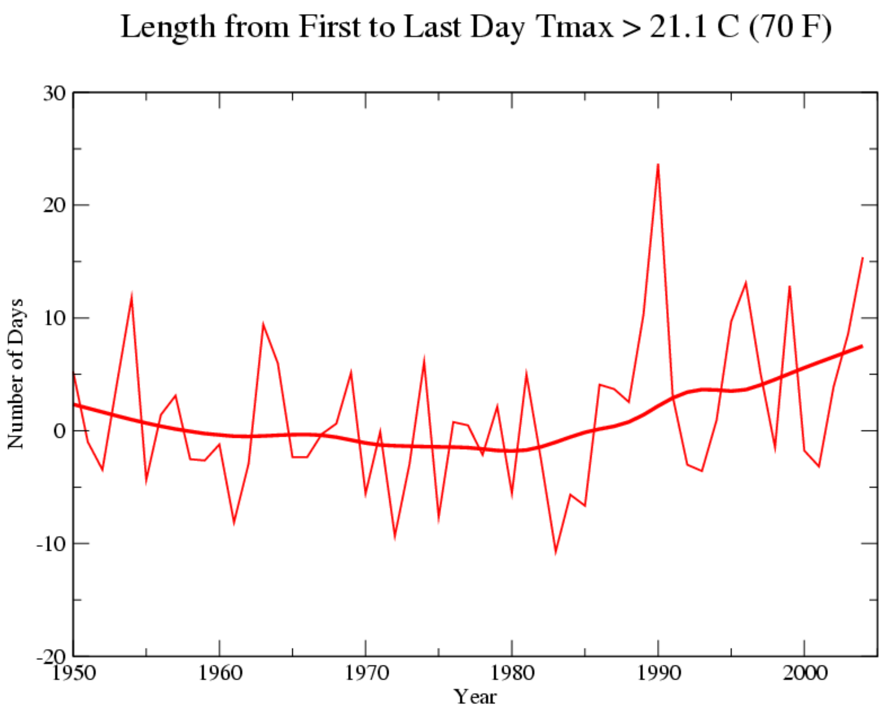
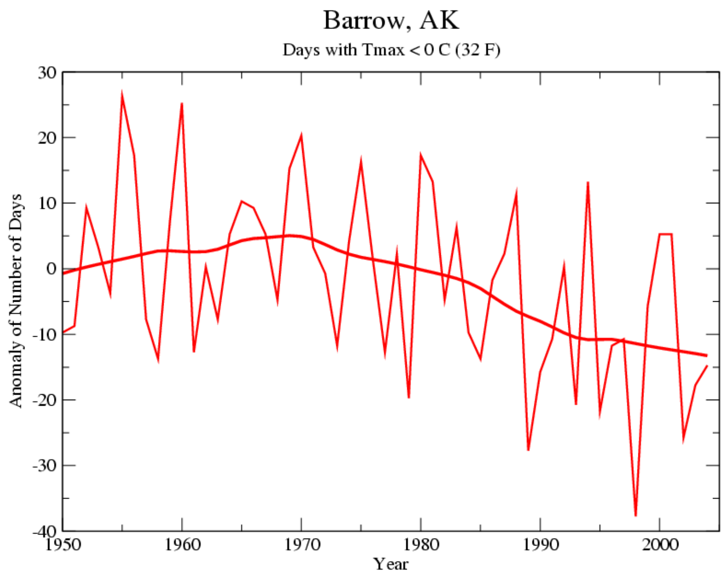


Figure 19. U.S. area-averaged anomaly of the length of time between the first day above 21.1°C (70°F) in the spring and the last day above 21.1°C in the fall.



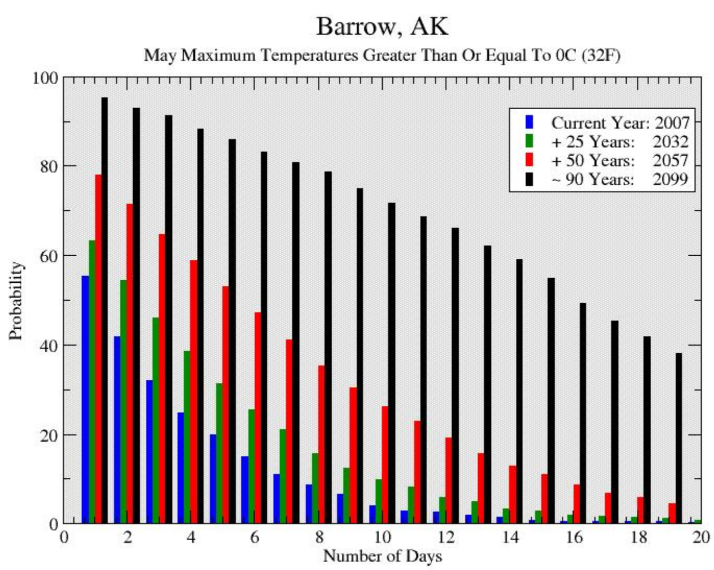
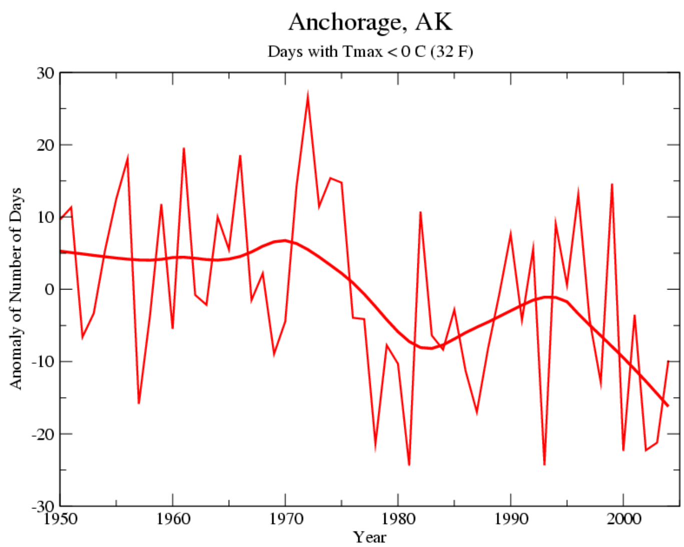


Figure 20. Top: Anomaly of the number of days per year with maximum temperature equal to or less than 0°C (32°F) based on analysis of stations within 500 km of Barrow, AK. Bottom: The current and future probability of have one to twenty days with maximum temperature greater or equal to freezing during the month of May.



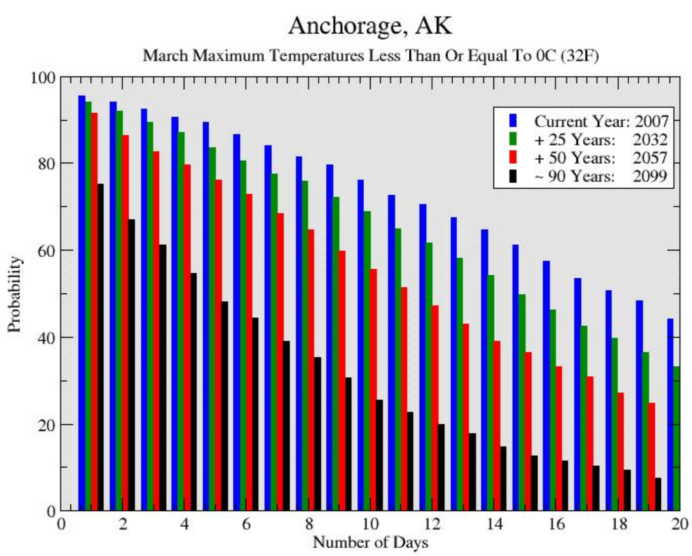


Figure 21. Top: Anomaly of the number of days per year with maximum temperature equal to or less than 0°C (32°F) based on analysis of stations within 500 km of Anchorage, AK. Bottom: The current and future probability of have one to twenty days with maximum temperature less than or equal to freezing during the month of March.

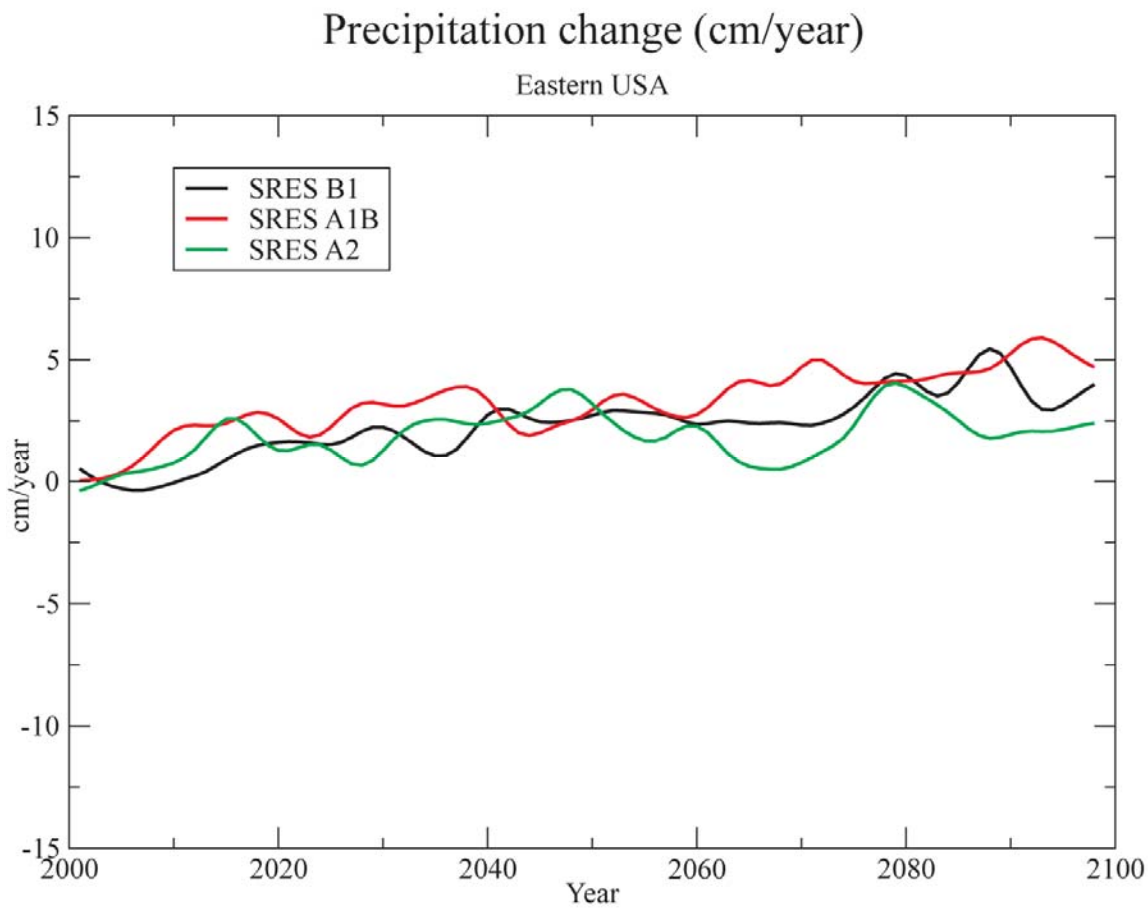


Figure 22. Smoothed median precipitation from the AR4 model runs for the Eastern United States from the three different scenarios.

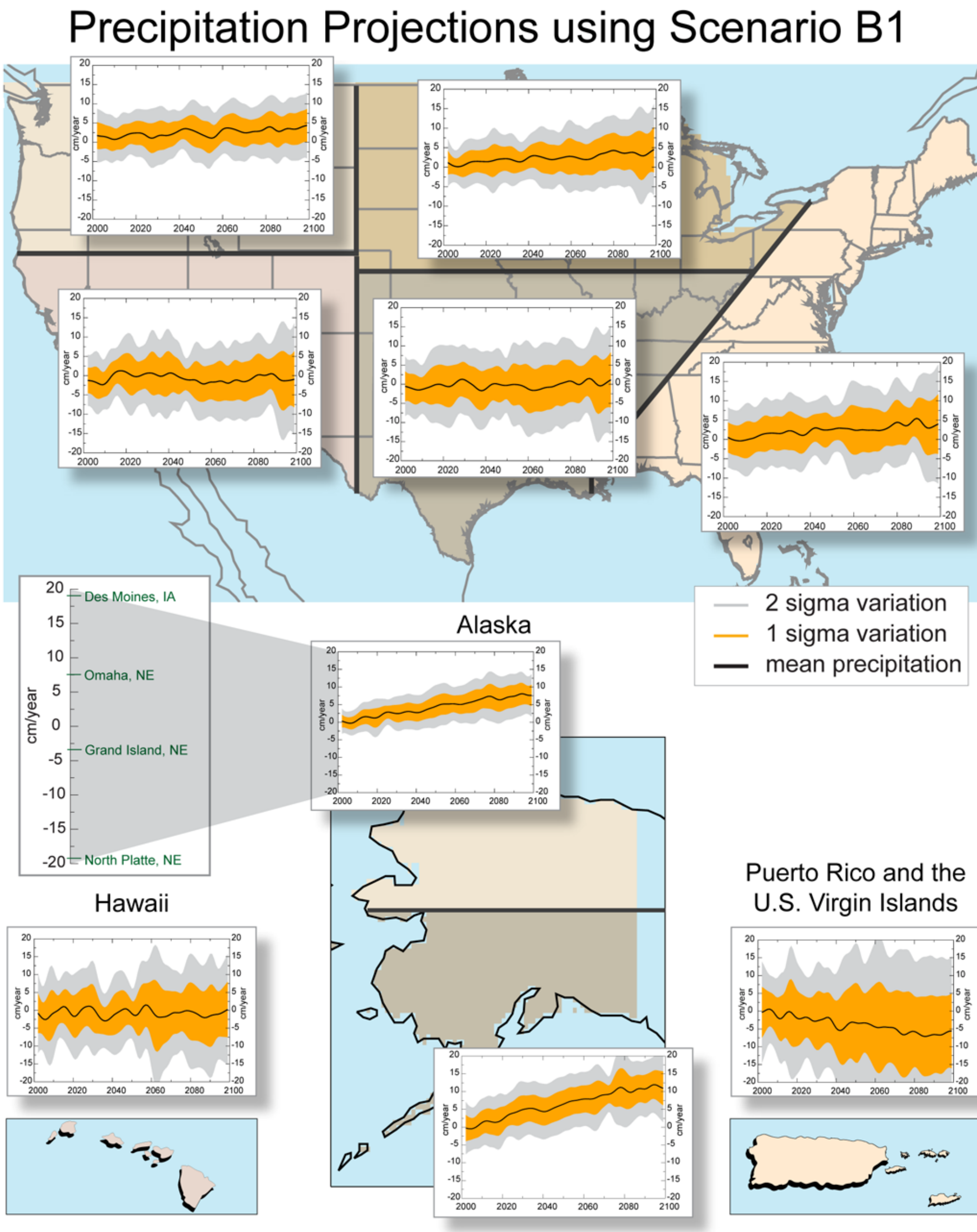

Precipitation Projections using Scenario B1
Des Moines, IA
Omaha, NE
Grand Island, NE
North Platte, NE
cm/year
Alaska
Hawaii
Puerto Rico and the U.S. Virgin Islands
2 sigma variation
1 sigma variation
mean precipitation

Figure 23a.

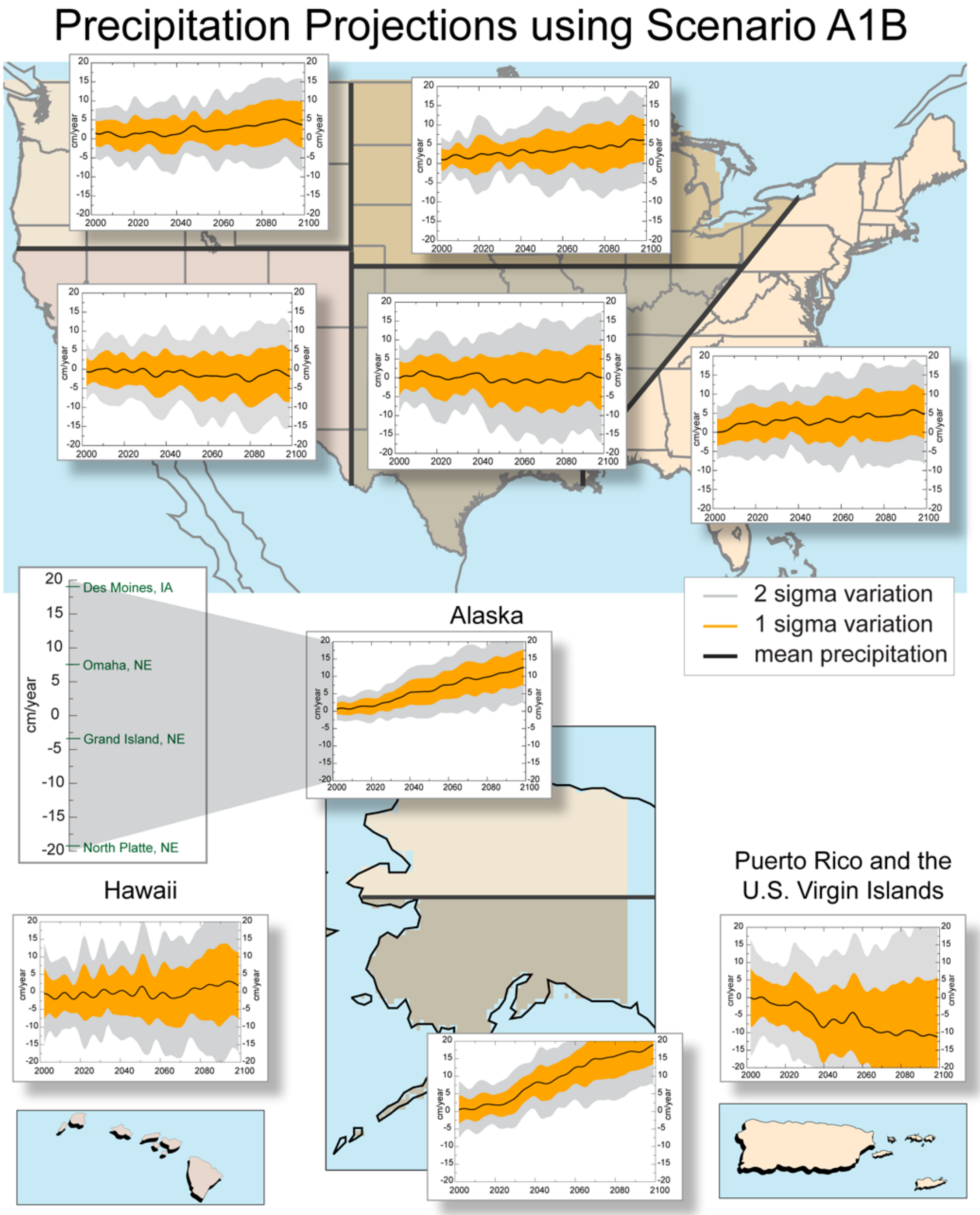

Precipitation Projections using Scenario A1B
Alaska
Hawaii
Puerto Rico and the U.S. Virgin Islands
2 sigma variation
1 sigma variation
mean precipitation
Des Moines, IA
Omaha, NE
Grand Island, NE
North Platte, NE
cm/year

Figure 23b.

Precipitation Projections using Scenario A2

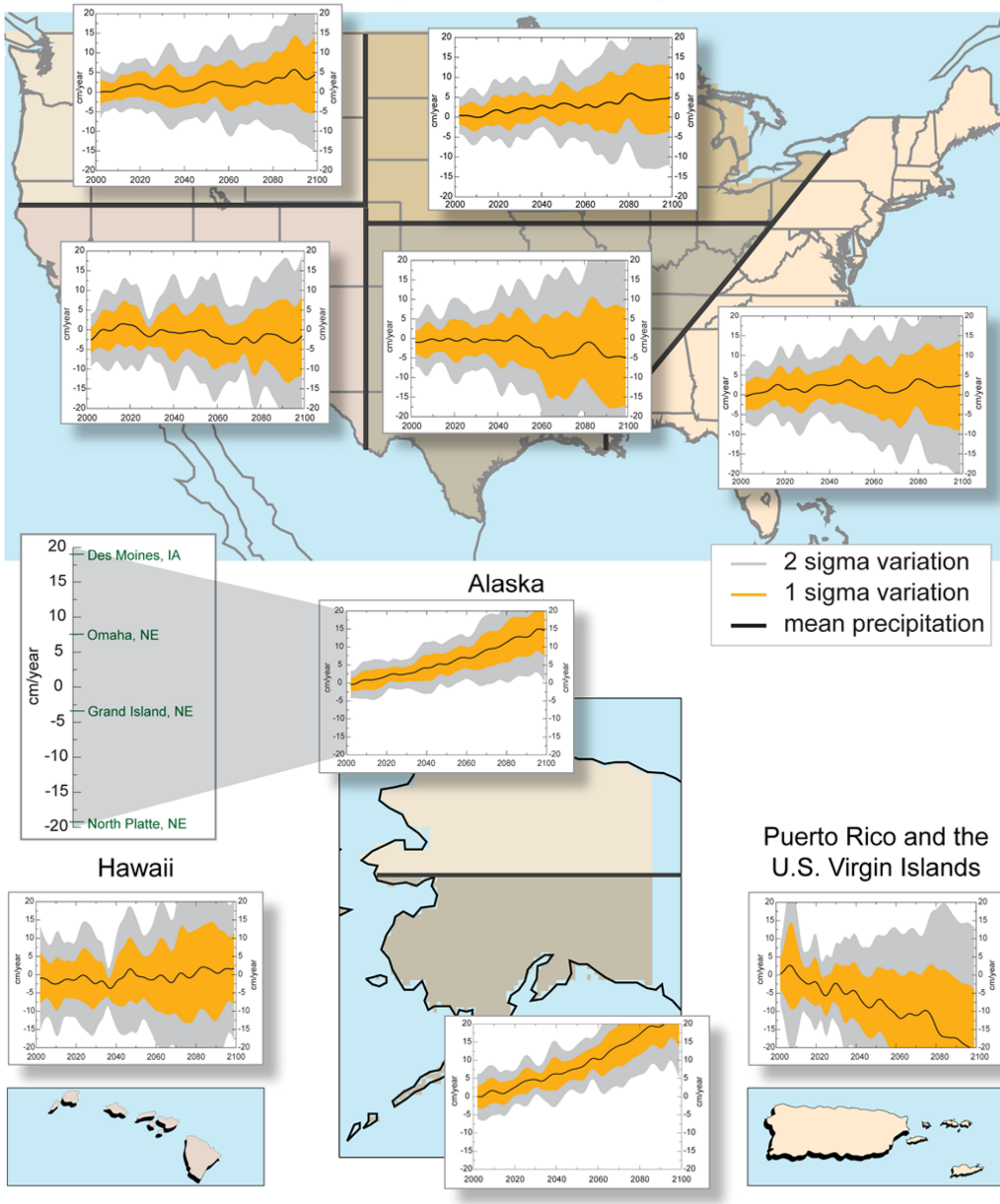


Figure 23c.

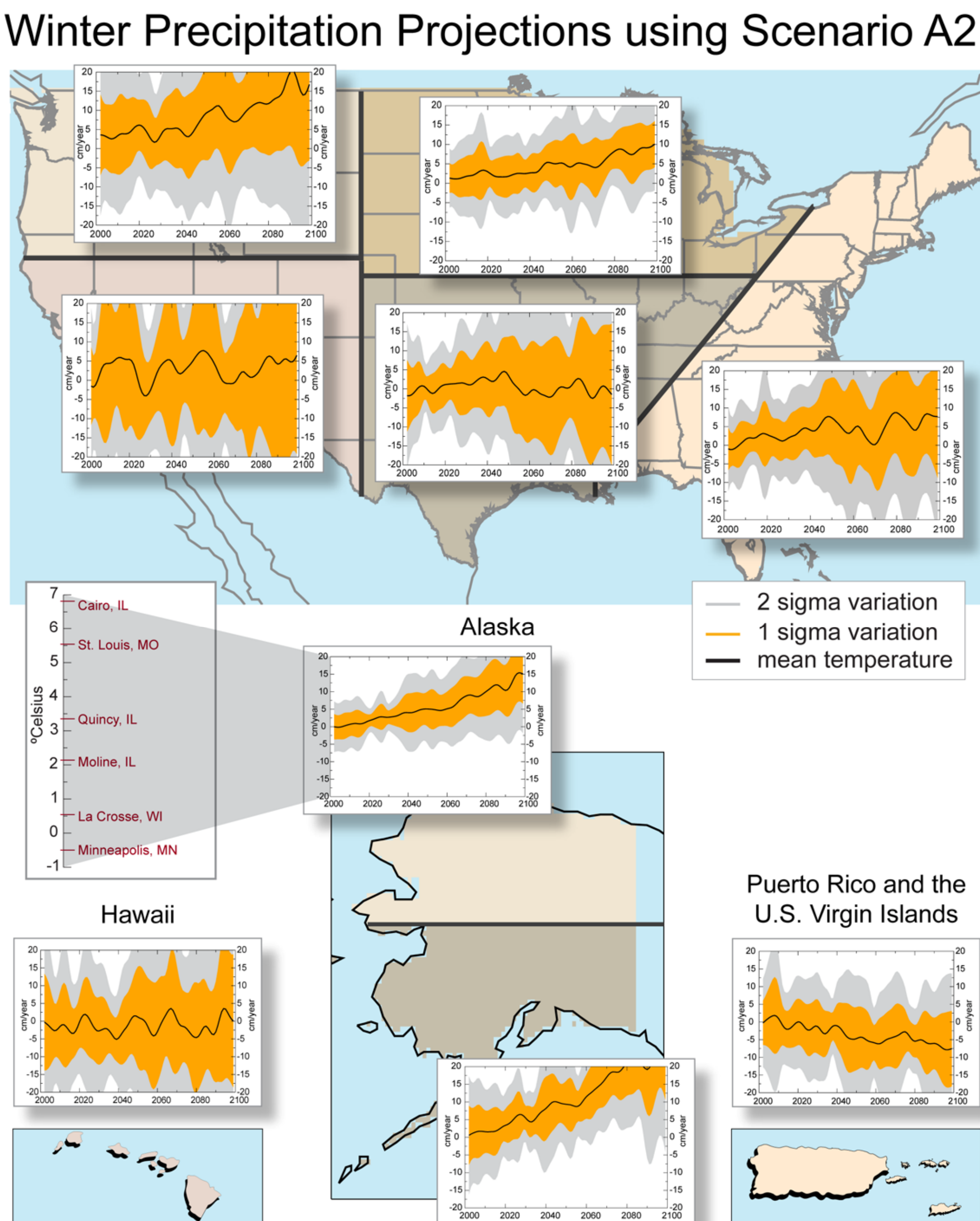

Winter Precipitation Projections using Scenario A2
Alaska
Hawaii
Puerto Rico and the U.S. Virgin Islands
2 sigma variation
1 sigma variation
mean temperature
°Celsius
Cairo, IL
St. Louis, MO
Quincy, IL
Moline, IL
La Crosse, WI
Minneapolis, MN
cm/year

Figure 23d.

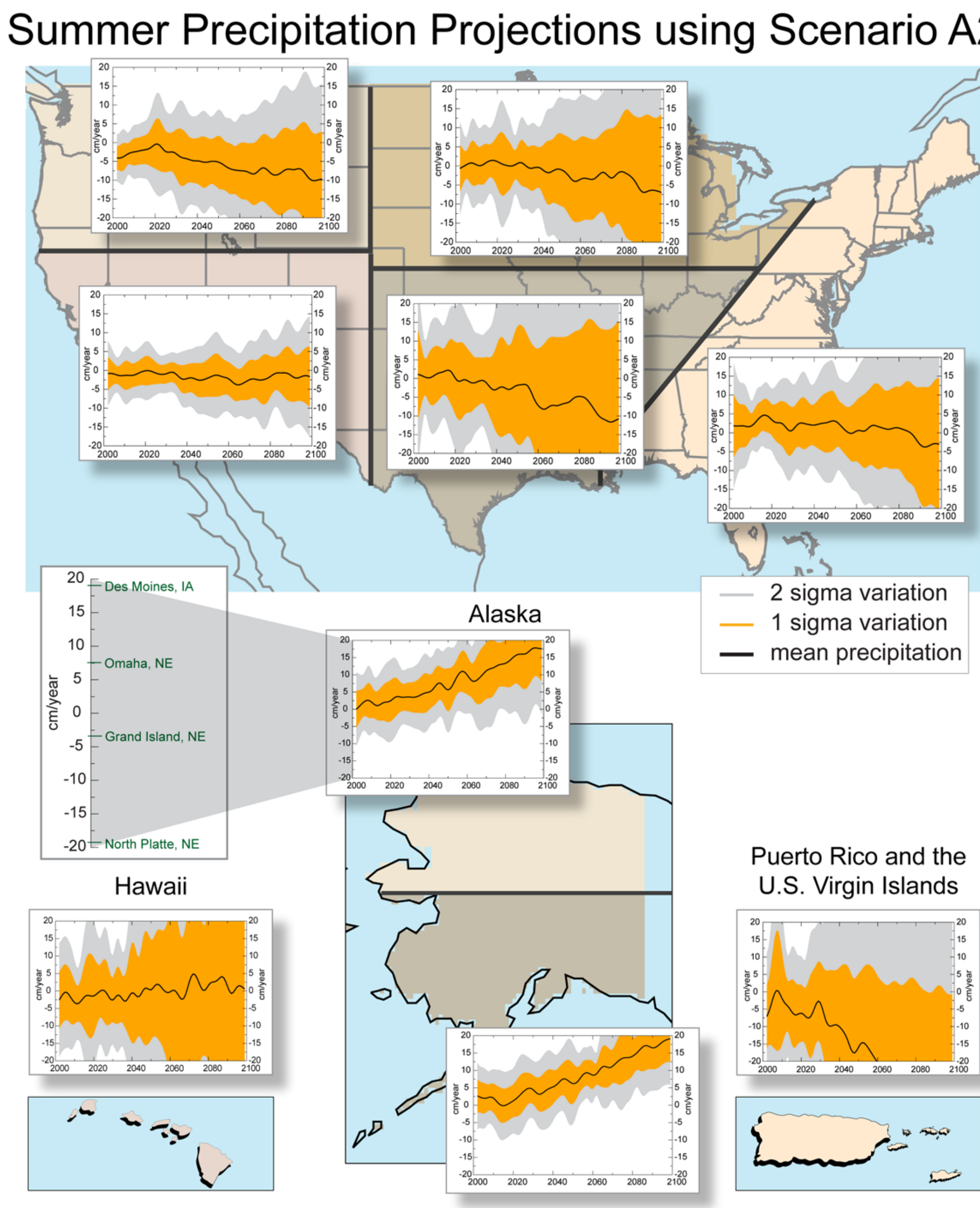


Figure 23e.
Figure 23. Model precipitation projections, smoothed with a 13-year filter, and their one and two σ ranges. To help put the projected changes into perspective, the relative differences in total annual precipitation for four cities have been plotted on the same scale. (a) Scenario B1, (b) scenario A1B, (c) scenario A2, (d) scenario A2 for winter, (e) scenario A2 for summer.

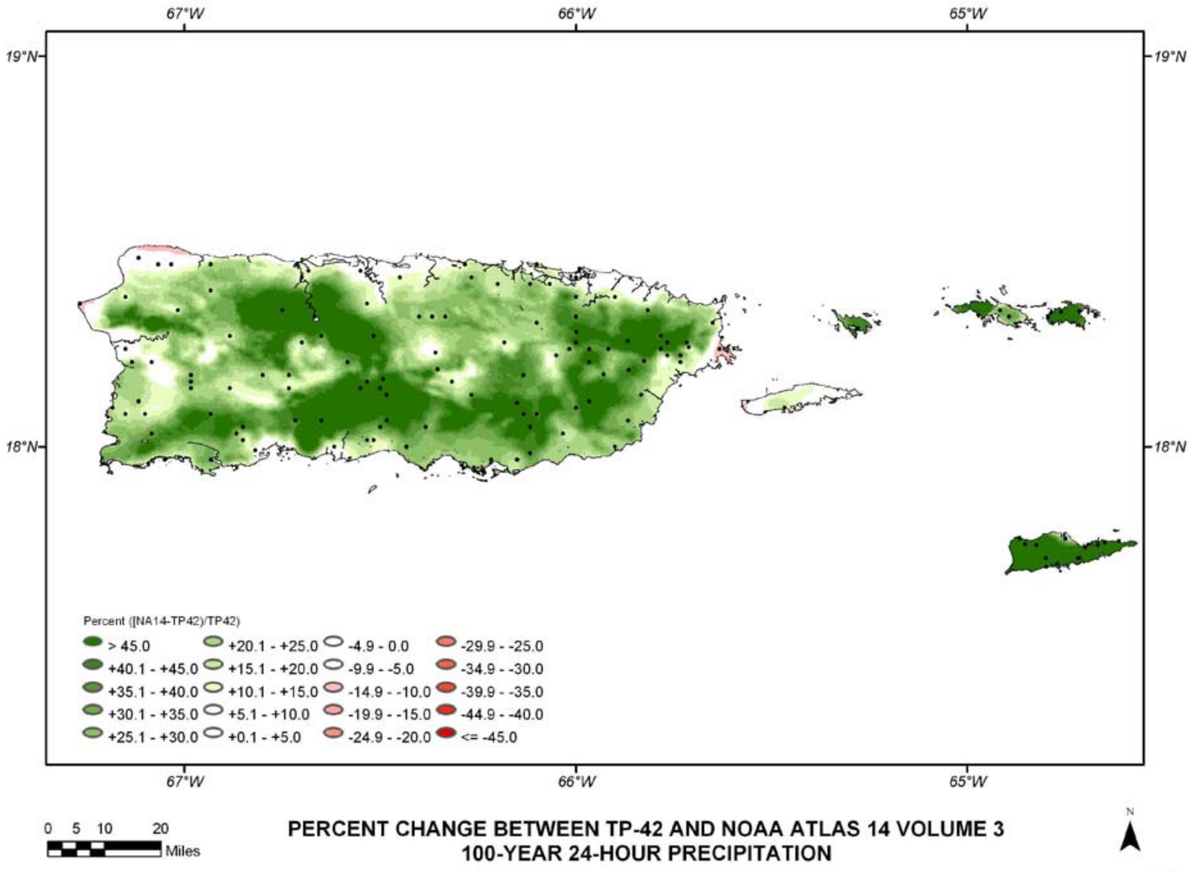


Figure 24. Differences between NOAA Atlas 14 Volume 3 and Technical Paper 42 100-year 24-hour precipitation in Puerto Rico and the U.S. Virgin Islands (Bonnin et al., 2003).

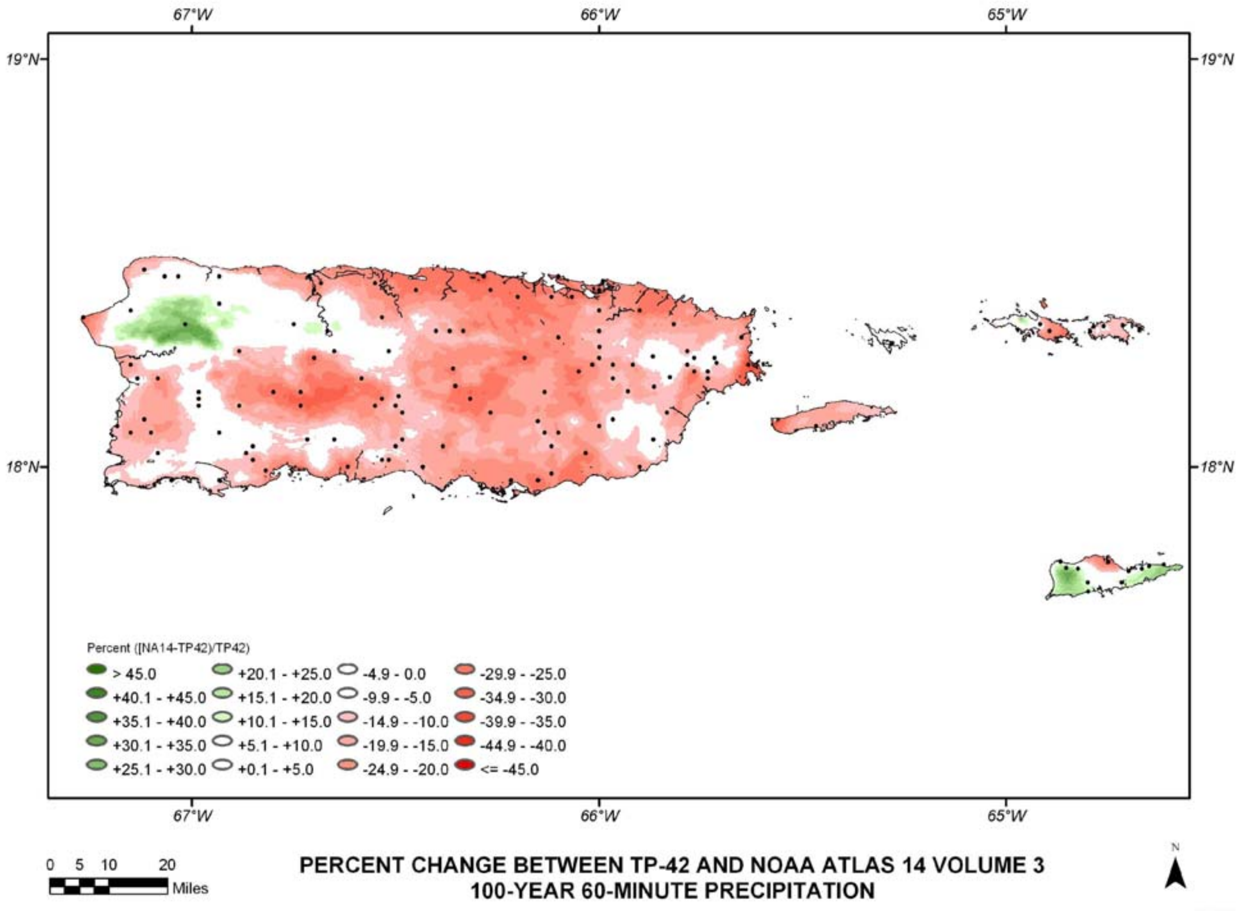


Figure 25. Differences between NOAA Atlas 14 Volume 3 and Technical Paper 42 100-year 60-minute in Puerto Rico and the U.S. Virgin Islands (Bonnin et al., 2003).

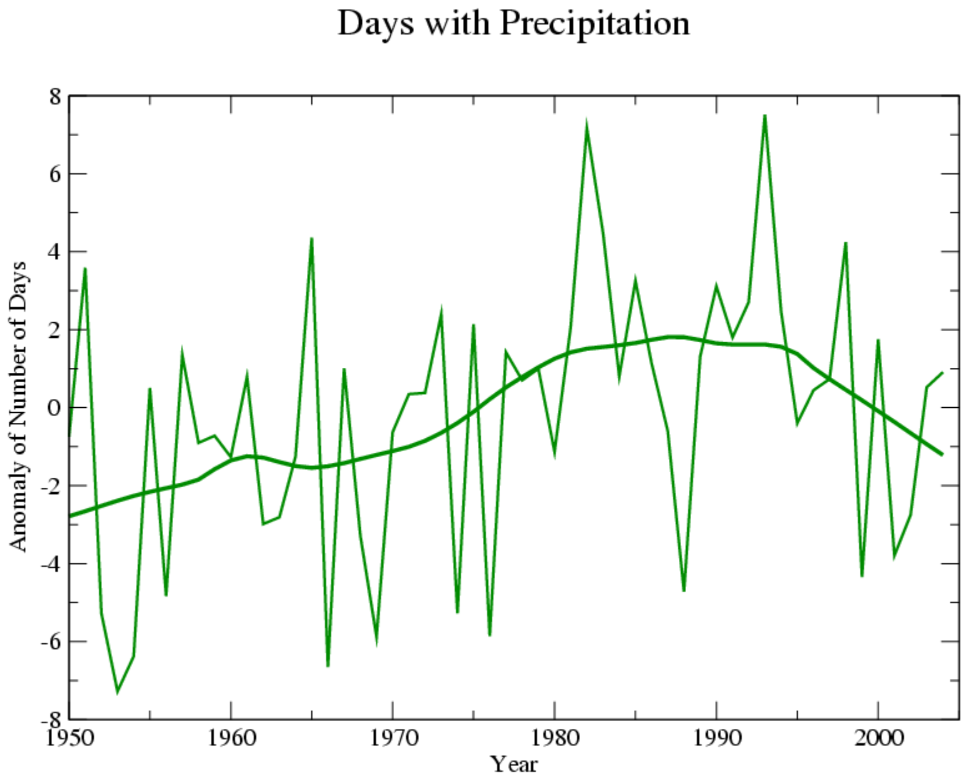


Figure 26. U.S. area-averaged anomaly of the number of days per year with precipitation.

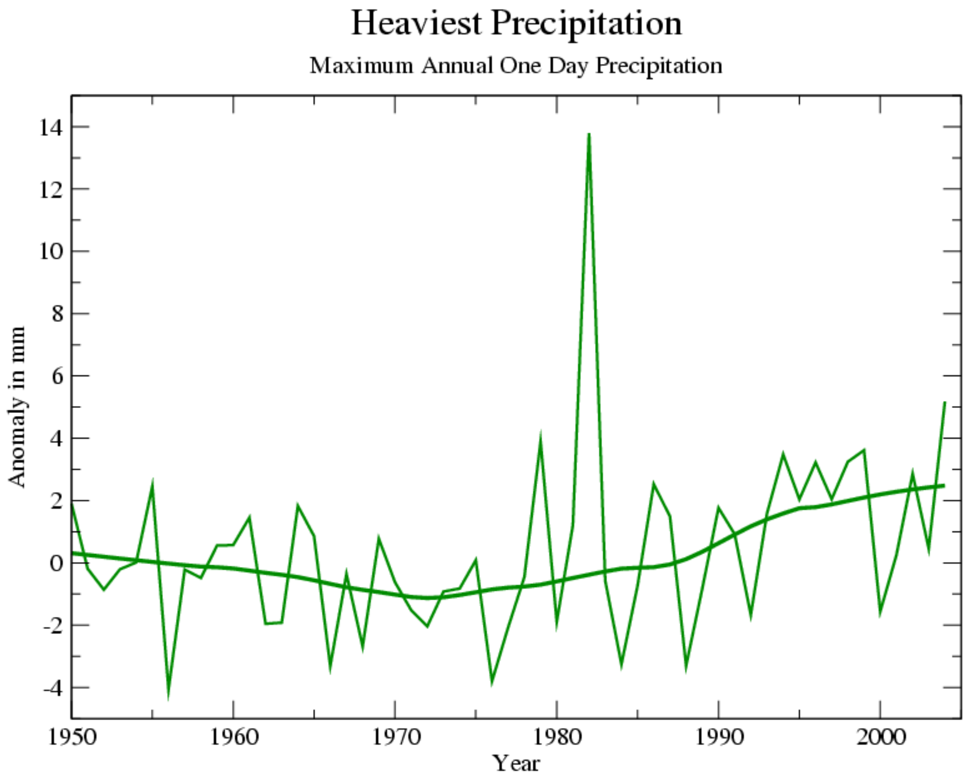
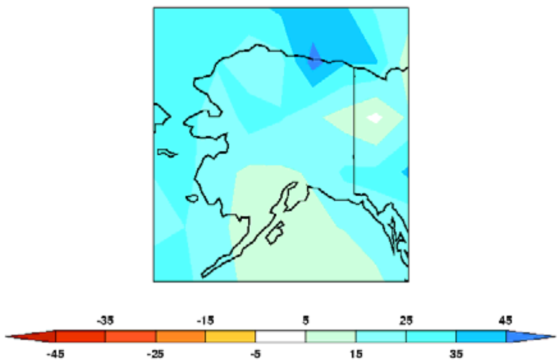

Heaviest Precipitation
Maximum Annual One Day Precipitation
Anomaly in mm
14
12
10
8
6
4
2
0
-2
-4
1950
1960
1970
1980
1990
2000
Year

Figure 27a.



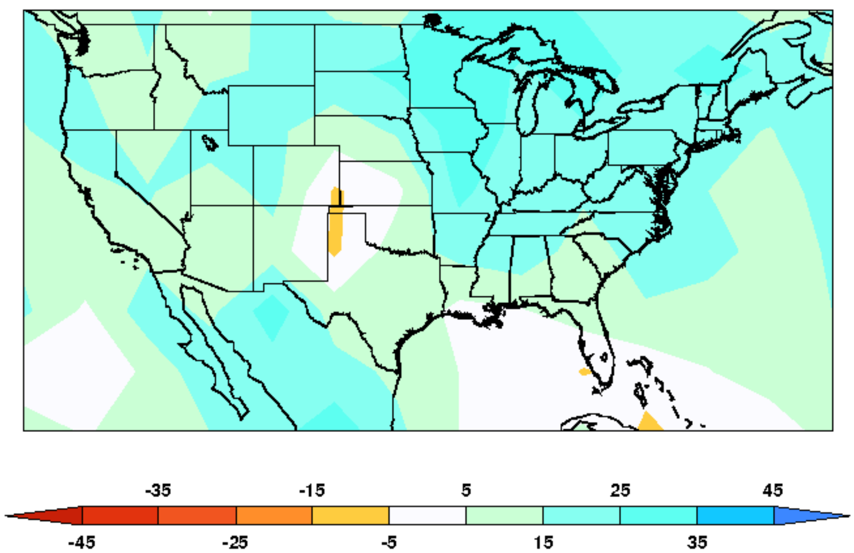


Figure 27b.

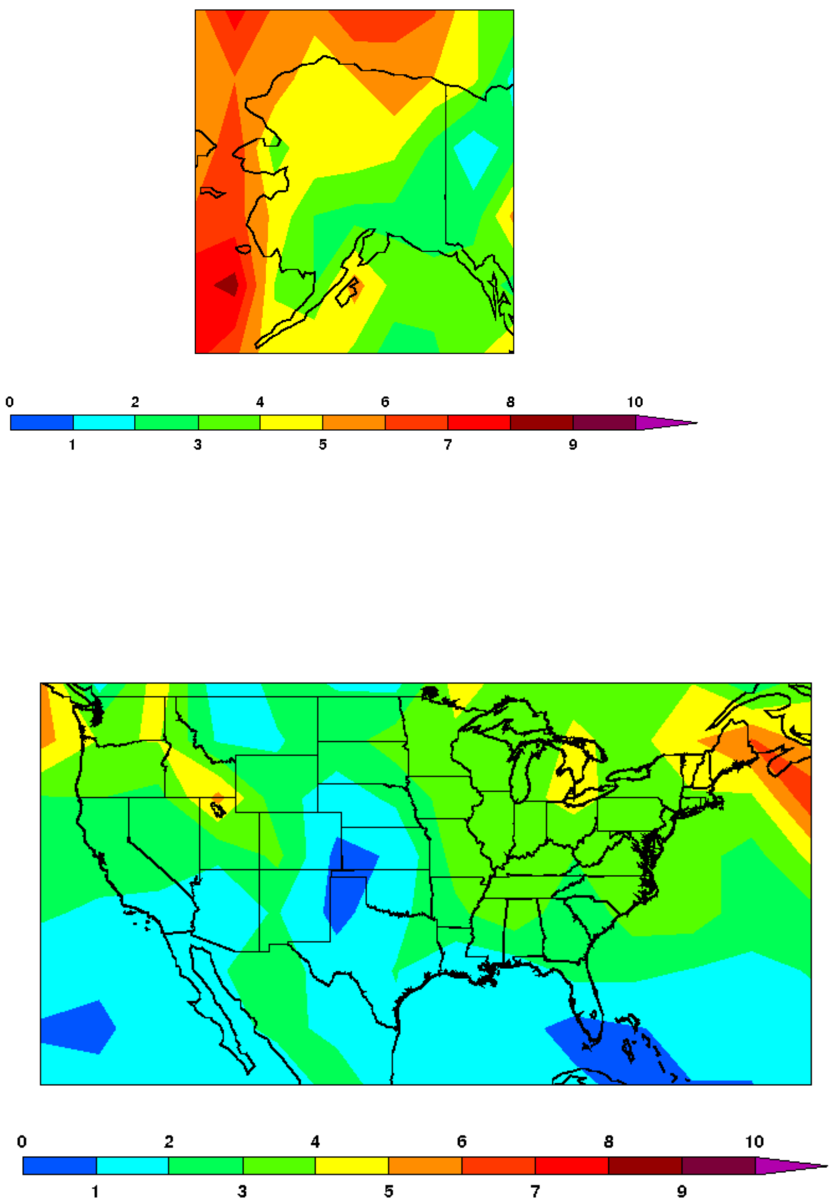


Figure 27c.
Figure 27. (a) U.S. area-averaged anomaly in mm of the yearly maximum one day precipitation. The year 1982 experienced a major El Niño event. (b) The predicted percentage change in the twenty year return value of the annual maximum averaged daily precipitation from the period 1990-1999 to 2090-2099 forcing using scenario A1B. (c) The number of times on average over a twenty year period that the 1990-1999 annual maximum daily averaged precipitation twenty year return value levels would be reached under scenario A1B 2090-2099 forcing.

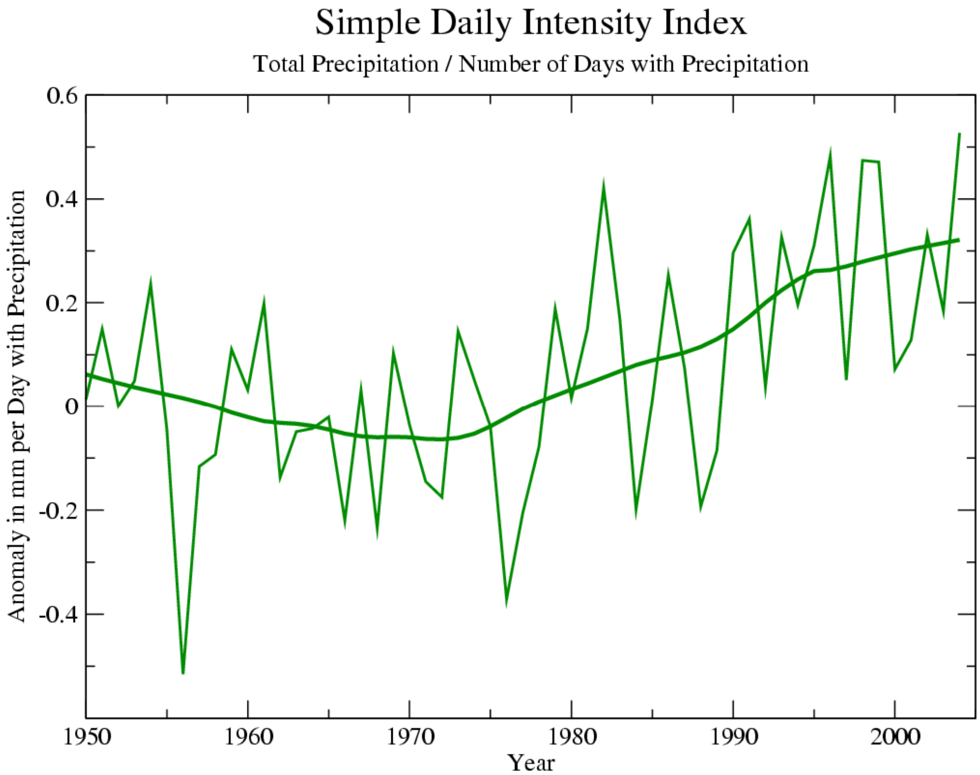

Simple Daily Intensity Index
Total Precipitation / Number of Days with Precipitation
0.6
0.4
0.2
0
-0.2
-0.4
Anomaly in mm per Day with Precipitation
1950
1960
1970
1980
1990
2000
Year

Figure 28a.

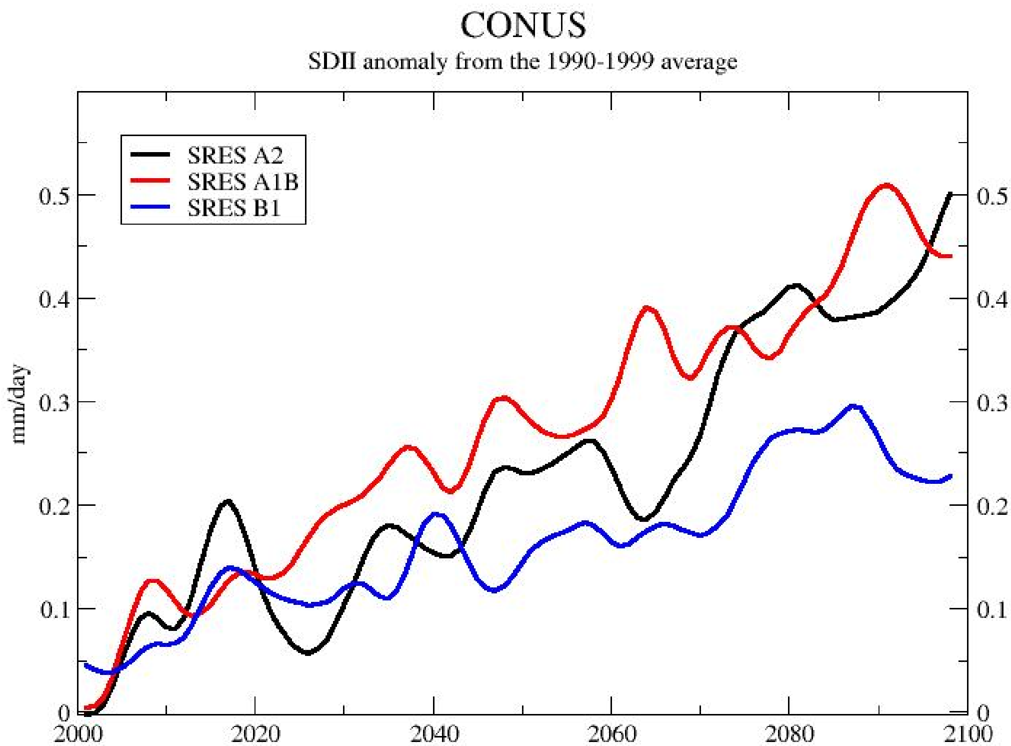
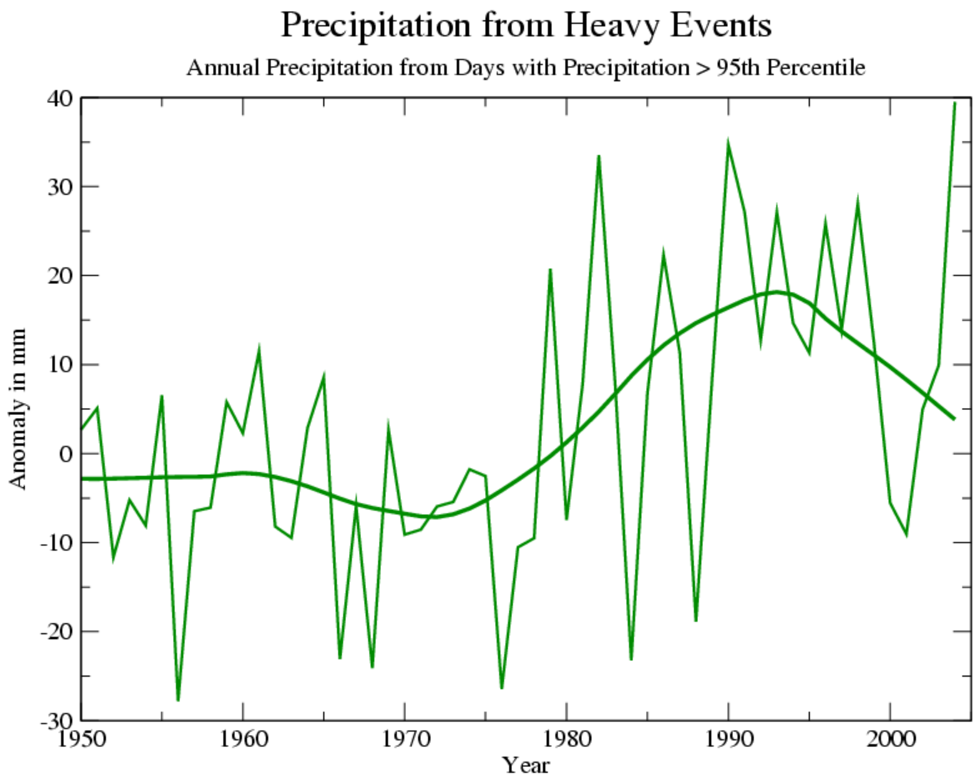


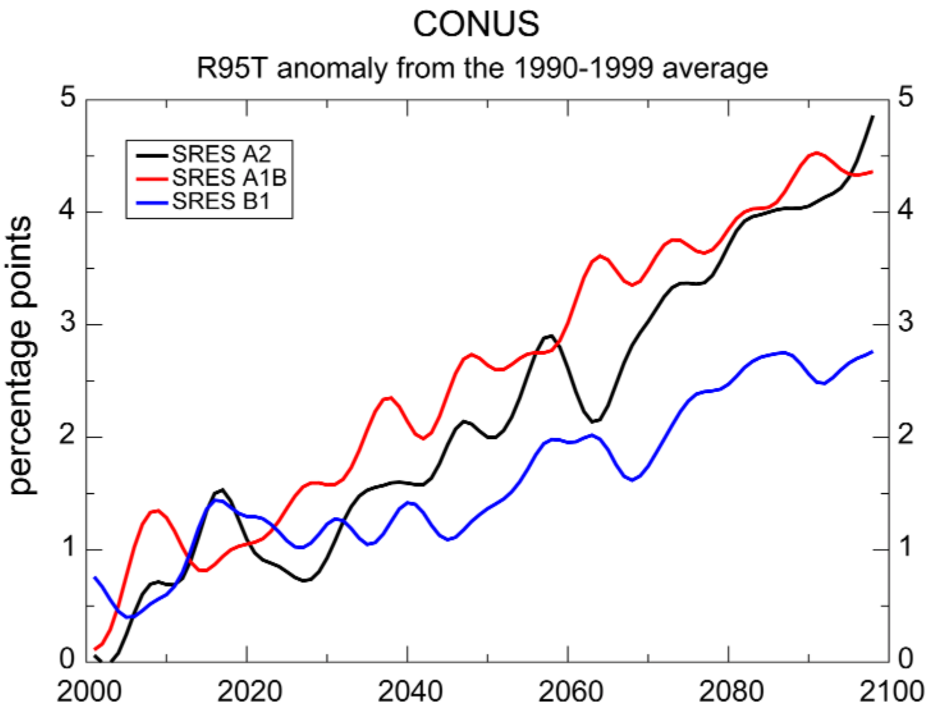
Figure 28b

Figure 28. (a) The upward trend in the Simple Daily Intensity Index, which is simply the total precipitation per year divided by the number of days with precipitation, indicates that, on a U.S. area-averaged basis, when precipitation does occur it tends to be heavier. (b) Median model projected changes in the Simple Daily Intensity Index is projected to continue to increase over the CONUS in the future.



Precipitation from Heavy Events
Annual Precipitation from Days with Precipitation > 95th Percentile
40
30
20
10
0
-10
-20
-30
Anomaly in mm
1950
1960
1970
1980
1990
2000
Year

Figure 29a


CONUS
R95T anomaly from the 1990-1999 average
SRES A2
SRES A1B
SRES B1
percentage points
0
1
2
3
4
5
2000
2020
2040
2060
2080
2100
Figure 29b

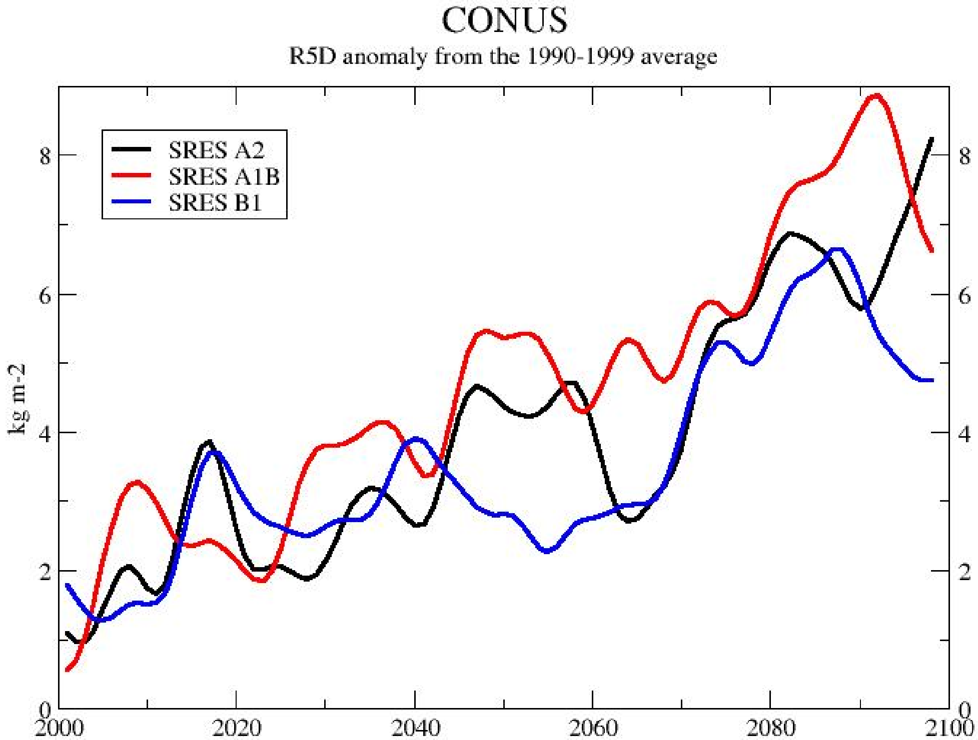


Figure 29c

Figure 29. (a) U.S. area-averaged anomaly in the annual precipitation that is received from days with precipitation greater to or equal to the 95th percentile of precipitation at each station. (b) Median model projected changes from a similar index, the fraction (expressed as a percentage) of annual total precipitation due to events exceeding the 1961-90 95th percentile. (c) According to the median model results, the highest annual five-day precipitation event is projected to increase for the CONUS under all three scenarios evaluated. In this case, the measure of precipitation is kilograms of water per meter squared.

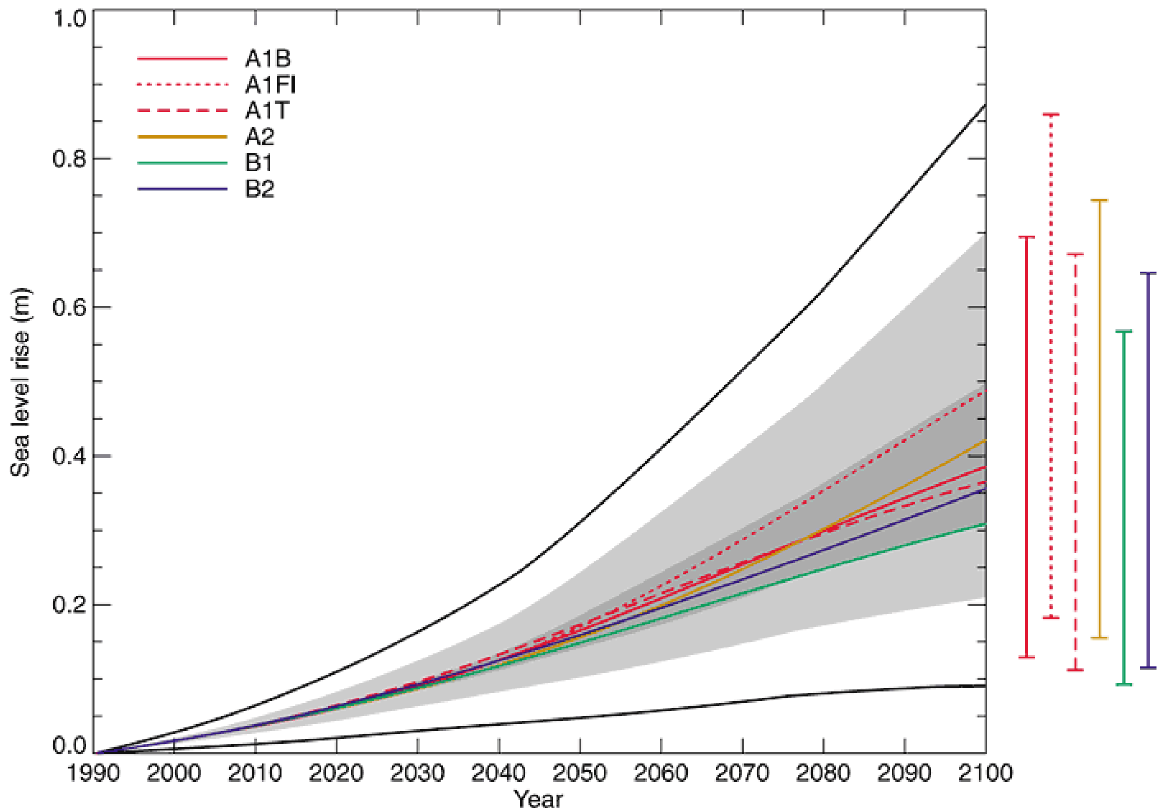


Figure 30. Projected sea level rise from the IPCC TAR (Church et al., 2001).

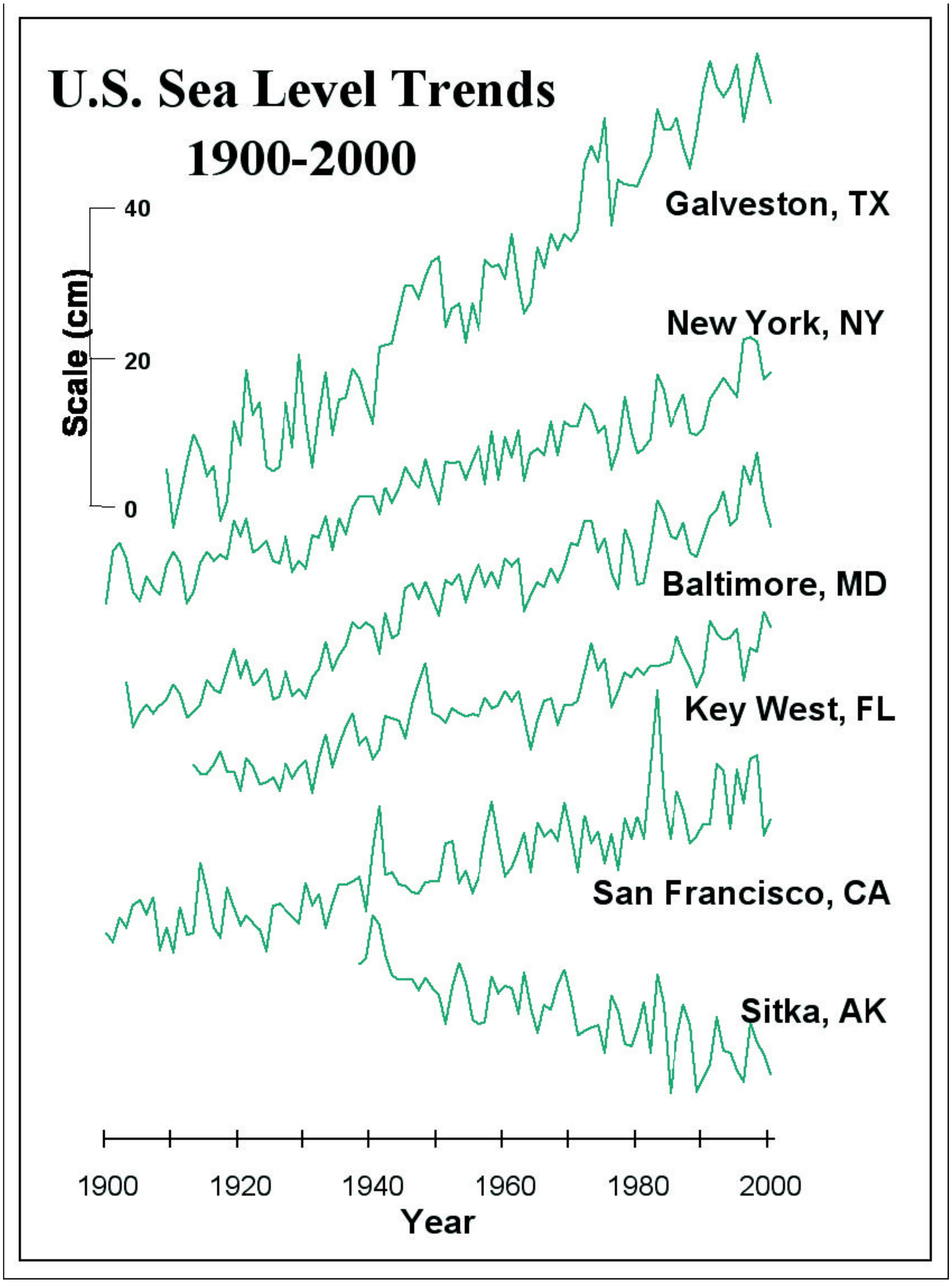


Figure 31. Local sea-level rise depends not only on the rise in sea-level but the uplift or subsidence of the land. This results in individual locations having different rates of sea-level rise or even sea-level fall. From the US National Assessment – Coastal Areas and Marine Resources. Note that southern Alaska is experiencing crustal uplift due to viscoelastic rebound in response to the melting of ancient glaciers, with changes as high as 5.7 m over the last 250 years (Larsen et al., 2005).

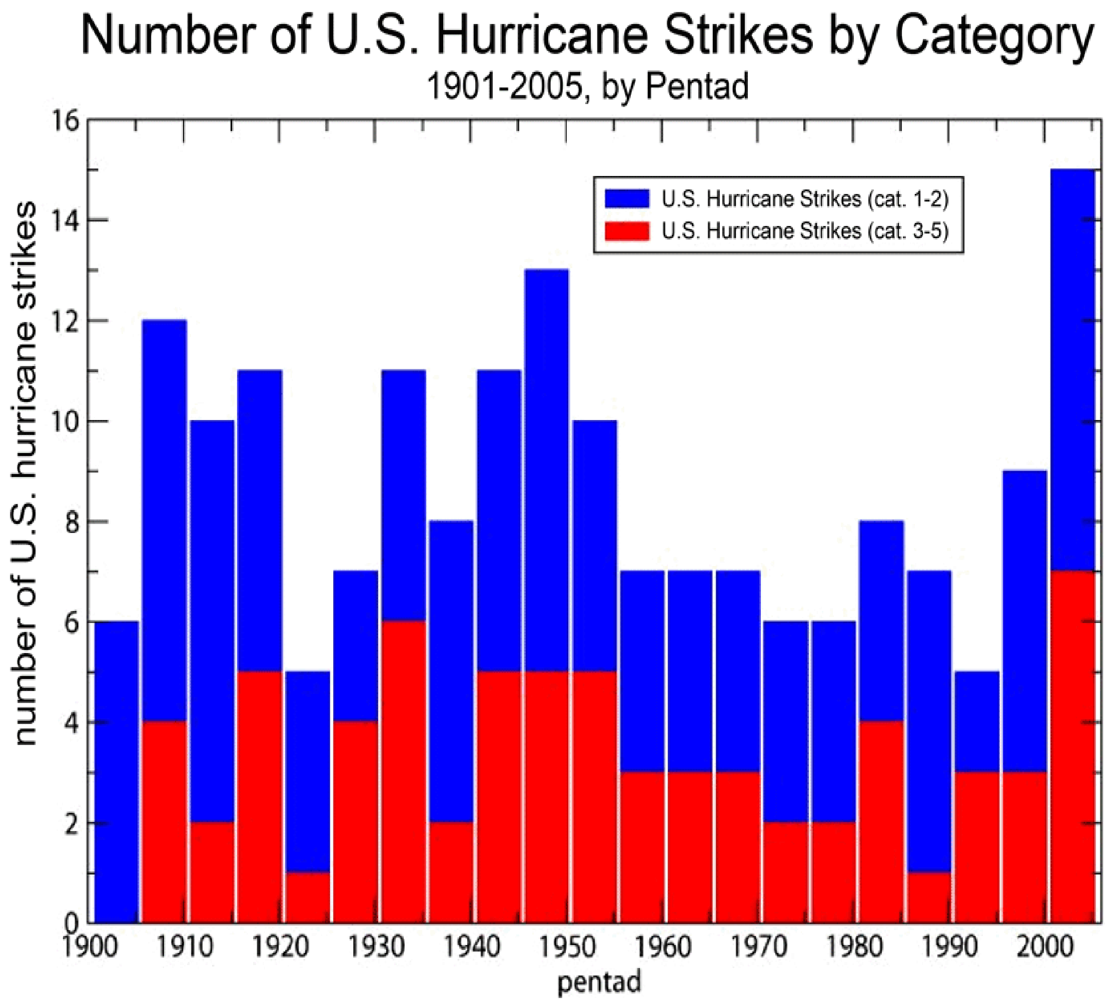


Figure 32. The number of hurricanes striking the U.S. summed by five year periods (e.g. 1901-1905, 1906-1910, etc.). The red bar is the number of major hurricanes (category 3-5) and blue bar is the number of weaker category 1 and 2 hurricanes per five year period (pentad). From NOAA's National Climatic Data Center.