Federal Highway Administration

The Use of Climate Information in Vulnerability Assessments

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Prepared for

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INTRODUCTION

This memorandum focuses on the use of climate information when performing a vulnerability assessment, a topic that was discussed at the Newark Pilot Peer Exchange Workshop on May 4-5, 2011. The memorandum describes several sources of climate information,[1] and provides some recommendations on how this information can be used by the pilots (or other transportation planners) as they consider their climate-related risks.

The memorandum is organized into three sections:

- Information about Historical Climate
- Information about Future Climate
- Sources of Technical Assistance

The memorandum also has an Appendix which outlines some of the methods being employed by pilots to estimate the impacts of sea-level rise.

HISTORICAL CLIMATE

VALUE OF EXAMINING HISTORICAL CLIMATE

Analysis of historical climate allows decision makers to better understand and communicate the projected changes in climate and their associated impacts. The following sections discuss three specific types of benefits that can emerge from the analysis of historical climate:

- Information on the extent and magnitude of a transportation system's **sensitivity**, which can be used to consider the response of the system to climate change;
- Variability in temperature and precipitation conditions, which provides **context** for judging the magnitude of future climate changes; and
- Case studies of weather events that matter to the community. These examples can be valuable **communication tools** to raise awareness of climate risks to a variety of audiences.

Sensitivity

In many locations, the temperature and precipitation patterns of the 21st century are likely to be considerably different than those experienced in the 20th century. However, the ability to anticipate the consequences of climate change on transportation services and assets will draw heavily on agencies' experiences regarding their performance in the past climate, especially during extreme conditions (e.g., heat waves, heavy rainfall events). Understanding how transportation systems have performed during periods of high temperature, heavy precipitation and flooding, or prolonged lack of precipitation can provide qualitative, and in some cases, quantitative information that can be extrapolated to future climate conditions.

[1] In this memorandum, discussion of "climate" will remain focused on temperature and precipitation. This is consistent with the discussion of climate information that took place during the Breakout Session at the Newark Pilot Peer Exchange workshop, May 4-5, 2011. As such, other aspects of climate (e.g., atmospheric circulation patterns, ocean currents, streamflow, snowpack) will not be discussed at length in this memorandum. Although some of these other aspects of climate may affect transportation infrastructure, the applicability, reliability, and availability of data will be highly variable from location to location; temperature and precipitation, on the other hand, will likely need to be considered in any vulnerability assessment.

The following questions are examples of the way in which past climate information can be employed to identify this type of sensitivity information:

- Which types of services or assets are currently affected by weather extremes?
- Have heat waves, floods, or droughts recently caused service disruptions or damage to assets?
- Are there service disruptions or damage to assets associated with more subtle or longer-term weather and climate events, such as a warmer-than-normal summer or a wetter-than-normal winter?
- What is the nature of the service disruption or asset damage? Examples of types of impacts include reduced service reliability, lower quality of service for travelers, and increased repair or construction costs.
- Are there particular locations within the transportation system that frequently suffer impacts tied to storms or other weather events, or suffer the most significant impacts?
- Are there thresholds (e.g., a specific high temperature, an amount of precipitation within a day or over several days) at which the system begins to experience impacts?

Performing a sensitivity analysis can provide a foundation from which to identify future vulnerabilities. In addition, it helps to identify the particular climate variables that should be extracted from future climate projections (see discussion below) as part of the vulnerability analysis. For example, if heat waves pose problems for a transportation service, then the model projections for temperature during the spring, summer, and fall months should be investigated closely (increases in winter temperatures are unlikely to result in "heat waves" for most locations). Also, if heat waves are an issue, some attention should be paid to the daily-scale temperature variability associated with model projections (see the **Projection of daily-scale extremes**),[2] in addition to the monthly and seasonal statistics.

Historical variability and the context for future changes

Examination of past climate allows future projections to be put into context. To illustrate the importance of understanding historical variability, records of annual precipitation and average annual temperature for a weather station in Pasadena, California are shown in Figures 1 and 2. These graphs and the accompanying discussion show that a comparison between historical variability and projected changes can be an important part of the assessment of local-scale impacts.

[2] Climate models' ability to simulate the daily-scale statistics of climate in a particular region is limited. Quantitative information derived from daily-scale statistics should be scrutinized and used with care (as discussed further in the "Translating to Impacts" section). For example, changes in daily-scale extremes can span a wide range – projections for California exhibit increases in the frequency of intense heat waves ranging from a doubling or tripling to increases by a factor of 20 (Cayan et al., 2009). Although all models and scenarios project a warmer future, including an increase in the frequency and intensity of heat waves, there is significant uncertainty as to how this warming translates into daily-scale changes in weather in particular locations across California.

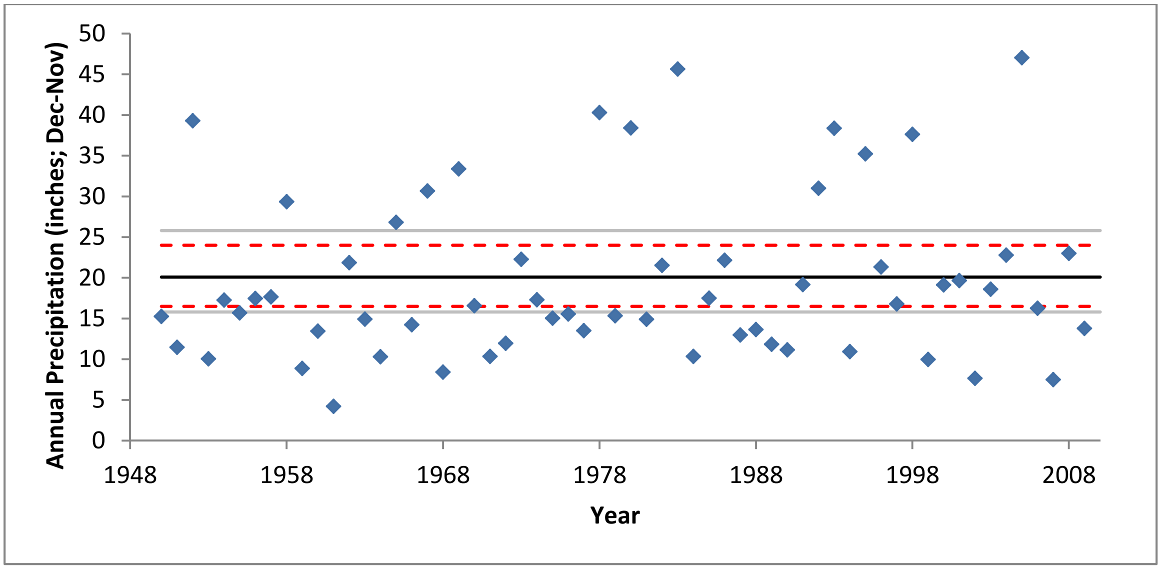

Figure 1: Historical precipitation in Pasadena, California

Total annual precipitation (December –November) is shown for the period 1950-2009. The black line shows the average rainfall (~20 inches per year). The gray lines show the averages for El Niño years (top gray line; wettest of the three averages) and La Niña years (bottom gray line; driest of the three averages). The red dashed lines correspond to hypothetical future increases and decreases in annual precipitation by 20%. The graph demonstrates that the year-to-year variability of precipitation is very large relative to the average precipitation. Future changes in precipitation (+/- 4 inches) are relatively small compared to the historical range, and the difference between the average of El Niño years and La Niña years. Data taken from the NCDC/NOAA U.S. Historical Climate Network.

Note: total precipitation is calculated from December through November to prevent splitting winter months that experience the same signal from El Niño-Southern Oscillation, as would be done by using the calendar years.

The precipitation graph demonstrates that the year-to-year variability of precipitation is very large relative to the average precipitation (middle black line on the graph). Although such variability is not representative of most stations across the country, many locations in Southern California exhibit this level of variability. For Southern California (and much of the U.S. West Coast), the El Niño-Southern Oscillation has a significant impact on precipitation falling during the winter, which in turn has a significant impact on annual precipitation. For Pasadena, the average precipitation falling during El Niño years is 10 inches greater than the average for the La Niña years.[3]

Understanding this variability can help to put future changes in context. Although climate model projections vary regarding the direction of future precipitation changes in Southern California, many models show increases or decreases that are around 20% or less of average precipitation by the 21st century. These changes (both increases and decreases) have been shown in the graph above as red, dashed lines. Although these changes are not negligible, they clearly fall within the range of historical variability. The projected changes are much smaller (by more than a factor of 2) than the difference between the averages for El Niño and La Niña years.

[3] The relationship between El Niño-Southern Oscillation and precipitation in Southern California is particularly strong. Many locations in the United States, especially away from the West Coast, will not exhibit such a strong connection.

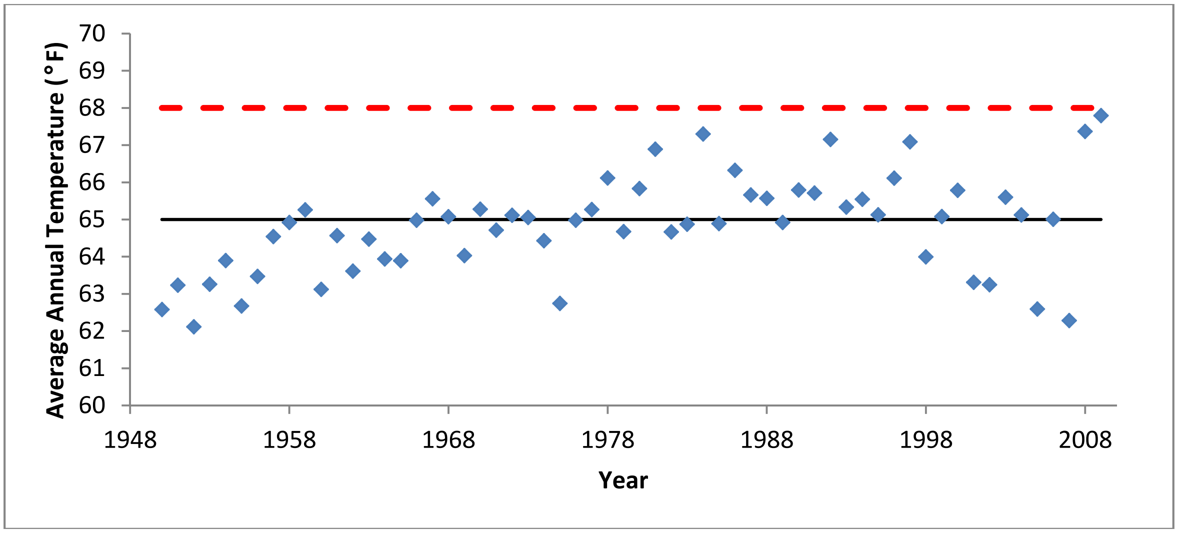

Figure 2: Historical temperature in Pasadena, California

Average annual temperature is shown for the period 1950-2009. The black line shows the average for the period 1961-1990. The red dashed line corresponds to a hypothetical increase in average annual temperature by 3°F. In comparison to the precipitation graph, the hypothetical change in temperature, which is at the low end of projections for the end of the 21st century, is large compared to the historical variability. Data taken from the NCDC/NOAA U.S. Historical Climate Network.

Note: The black line only represents an average of a 30-year portion of the record. This was chosen because 1) the time series as a whole has a linear trend toward warming, and 2) the late 20th century is often used as a baseline from which warming is estimated from the output of climate models.

By comparison, the projection for future average temperature for Southern California (as shown by the red, dashed line in Figure 2) is outside the range of historical conditions. The hypothetical warming shown in Figure 2 is 3°F, which is at the low end of projections for the end of the 21st century. Some models and scenarios project warming of 8°F.

The purpose of the Pasadena example is to demonstrate that consideration of historical variability is an important component of an impacts assessment. Clearly, the increases anticipated for temperature in Southern California represent a fundamental change in the regional climate by the end of the 21st century. The projections for precipitation are both more uncertain (i.e., increases or decreases could occur) and fall within the range of historical conditions. This is not to say that the changes will be insignificant or negligible, but simply that the future average conditions are likely to resemble a significant portion of the historical record. In addition, the analysis shows that some of the year-to-year changes in precipitation may be worth considering as part of the impacts assessment, or in the development of adaptation options (i.e., a system that is resilient to some of the relatively large swings in historical year-to-year rainfall is also likely to be resilient to longer term changes in precipitation).

It is important to emphasize that the variability represented in the Pasadena record is not necessarily representative of other locations. In other places, the variability of precipitation is likely to be smaller, such that a 20% change in precipitation could represent a more significant difference from historical conditions. Similarly, other locations could exhibit greater temperature variability, in which a warming of 3°F may appear less drastic. The diversity in climate conditions across the country underscores the need to assess future climate projections in light of historical regional climate variability.

Communication tool

Past weather events (e.g., strong storms, heat waves) or climate events (e.g,, droughts, warmer-than-normal summers, wetter-than-normal years) that have negatively affected the transportation system can be used as examples to facilitate discussion with staff within a transportation agency or with other groups external to the agency (e.g., political representatives, commuters, transit riders). These examples can be important ways to raise awareness among these groups. Benefits include:

Drawing on shared experience: Past weather and climate events represent a shared experience. Within transportation agencies, this shared experience can be a valuable way to acquire information on sensitivity. More broadly, these events can be a way to invite participation from desired audiences, making the issue of climate change and climate impacts more personal and less technical.

Identification of potential adaptive responses: Especially for internal staff audiences, the experience of dealing with past weather and climate events can provide valuable information about what does and does not work when attempting to minimize damage or maximize opportunities associated with impacts. Past experience provides "lessons learned" that can help spark and guide discussion about adaptation options.

Justification for action: Past examples can provide the answer to "why are you performing a vulnerability assessment?" Discussion of the examples can help make the case that the vulnerability assessment can help to reduce the risks associated with similar, repeat occurrences of the examples.

Education regarding weather and climate: Aspects of the examples can help to educate staff or the broader community about climate variability, climate change, and local-scale impacts. Making the connection between weather and climate, in and of itself, is an important step toward educating people about climate.

Alternative framing of climate-related initiatives: Among some audiences, the terms "climate" and "climate change" are laden with significant political connotations. These connotations are likely unrelated to, or at best are tangential to, the task of increasing the resilience of the transportation system to extreme weather and climate impacts. Framing the vulnerability assessment in terms of past weather and climate events can help to avoid some of these political issues.

Limits of making extrapolations based on historical data

As outlined above, examination of historical climate data and observed impacts from weather and climate events can be useful for both analysis of vulnerability and communication. However, it is important to recognize a fundamental issue in considering climate change: the prevailing or typical historical climate conditions are unlikely to be representative of the future climate conditions. Although analysis of the past can yield useful "analogs" for certain types of weather events, provide insights into the types of impacts that might occur (or might occur more frequently), or serve as efficient communication tools, the climate is changing, and some future climate impacts may go beyond the range of impacts that have occurred historically.

On a related note, care should also be taken when examining and making inferences from trends in historical climate data. Although these trends can be informative when considering the types of changes that may occur (e.g., warming over the last 30 years has accompanied a greater frequency of heat waves), or in identifying sensitive infrastructure (e.g., the lifetimes of equipment or infrastructure have been shrinking as a result of more frequent recent high temperatures), it is unlikely that the trends of past decades will persist *unchanged* into the future. In most cases, extending past trend lines into the future would represent a poor model of future conditions, especially on longer timescales (greater than 30 to 40 years). For example, for all parts of the U.S., the rates of warming for the 21st century are expected to be greater than the rate of warming between 1900 and 2000. Moreover, for many scenarios of warming, the latter half of the 21st century is likely to exhibit more rapid warming than the first half of the 21st century.

DATA SOURCES

Historical climate information can be found in a variety of data products that are maintained by the National Oceanic and Atmospheric Administration (NOAA). These products fall into two general categories:

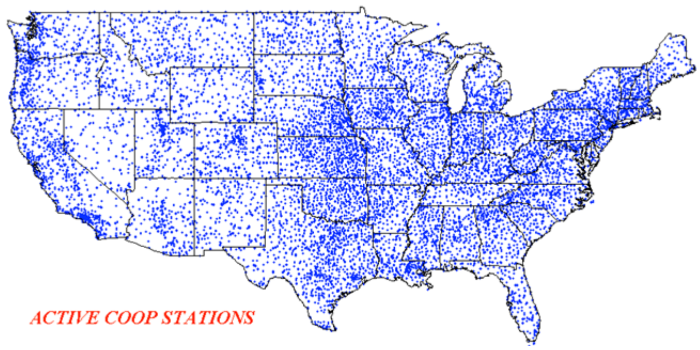

Figure 3: Locations of active COOP weather and climate stations

Station Data – these records correspond to a specific location. NOAA's National Weather Service, in conjunction with significant volunteer contributions, maintains the Cooperative Station Network (COOP), which represents a large set of stations across the country (Figure 3), some of which have relatively long periods of record (greater than 100 years). These stations have observations for daily temperature, precipitation, and some provide measures of snowfall. A subset of these stations, the U.S. Historical Climate Network has been quality controlled for use in climatological research, and has over 1200 stations across the country (http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html).

Figure 4: Locations of NCDC climate divisions

Station data portrays the daily and monthly variability that has been witnessed at a particular location, including any extreme events that may have occurred there. Such a record can be particularly useful if it is nearby transportation assets that are included in the vulnerability assessment. However, such a station's record may not be representative of larger regions. Topography, differences in land cover, the presence of water bodies, and features of the average larger-scale circulation can affect the extent to which a station might be considered representative of a larger area.

Climate Division Data

The National Climate Data Center (also a part of NOAA) maintains a climate division data set. In these data, individual stations that fall in a region with a similar climate are averaged together. A map of the 344 climate divisions is shown in Figure 4.

These data have better quality from 1931 to the present than earlier periods (data from 1895-1930 were sometimes based on state averages, rather than actual station observations). These data can be useful for examining trends and variability over larger geographic areas, and avoid any issues of data quality that might arise from looking at an individual station. However, only monthly and annual data for temperature and precipitation are available.

Other Sources

There are many other sources of historical climate information for variables such as streamflow (data from U.S. Geological Survey (USGS)), snowpack measurements (the National Resource Conservation Service (NRCS), which is part of the U.S. Department of Agriculture), and gridded "reanalysis" products for more complex meteorological variables (National Centers for Environmental Prediction, which is part of NOAA).[4] These data sets can be useful for assessing some types of impacts, especially hydrological impacts such as droughts and floods. However, we have restricted our discussion to those products that are most closely related to temperature and precipitation at the surface, and to those products that would be easy to download and use.

FUTURE CLIMATE

Our knowledge of future climate conditions is based on experiments performed with **climate models** (also known as atmosphere-ocean general circulation models). This section describes how to judge and utilize the output from climate models in regional-scale vulnerability assessments, and where to access climate model information.

TRANSLATING TO IMPACTS

Climate model output can be an integral component to a vulnerability assessment (and the subsequent adaptation decisions). Outputs can provide information regarding how much or how fast the climate could change. However, it is important to establish what types of information climate models ***DO*** and ***DO NOT*** provide. This section will discuss emerging issues regarding scenario selection, downscaling, and uncertainty in the context of regional-scale vulnerability assessments.

What is a climate model?

A climate model is a mathematical representation of the climate system:

> …*climate models* are used to simulate how…changes in GHG [greenhouse gas] emissions and other climate forcing agents will translate into changes in the

[4] Much of this data is available online. USGS Streamstats (http://water.usgs.gov/osw/streamstats/) has historical streamflow data and statistics for various locations across the country Federal Emergency Management Agency allows users to access maps of floodplains (referred to as Flood Insurance Rate Maps, or FIRMs; http://www.fema.gov/hazard/map/firm.shtm), which have been developed using historical data; NRCS has snowpack and soil moisture data across much of the western United States (http://ftp.wcc.nrcs.usda.gov/).

climate system. Climate models are computer-based representations of the atmosphere, oceans, cryosphere [ice and snow], land surface, and other components of the climate system. All climate models are fundamentally based on the laws of physics and chemistry that govern the motion and composition of the atmosphere and oceans. (National Research Council, 2010; bracketed phrases have been inserted)

The models' simulations for the 21st century are called **projections**. These projections are designed to help us understand how the addition of greenhouse gases to the atmosphere might change our climate. Models are intended to be heuristic tools, illuminating how many processes (e.g., the way in which oceans transport heat around the planet; the strength and location of the jet streams) might respond to the addition of these greenhouse gases, and the subsequent warming that occurs. Climate models are not intended to be "prediction machines" that reveal the precise future conditions in a particular location.

It is also important to note that climate models, by themselves, do not yield information about the impacts of climate change. They simply provide simulations for future temperature and precipitation, which can be converted into statistics (e.g., average seasonal temperatures, annual return-frequency for days with temperatures above 100°F) that can be compared to similar statistics representing the current climate.[5] It is essential that users understand the types of climate information that are most important to the performance of their respective transportation networks. Performing a sensitivity analysis (see "Value of Examining Historical Climate" section above) is a way to identify the types of climate information (i.e., which measures of temperature and precipitation, and on what time scale) that correspond to the quality and reliability of service, or to damage and repair of assets.

Scenarios

Whenever a climate model is "run" into the future, a set of assumptions regarding the future trajectory of the planet's greenhouse gas emissions and other climate-forcing agents (e.g., aerosols) is used as inputs to the model. These assumptions chart a path forward for the world's population growth, economic growth, and rates of technological development and transfer of technology. These assumptions, taken together, constitute an **emissions scenario**.[6]

The Intergovernmental Panel on Climate Change (IPCC) has developed a set of standard emissions scenarios that are used in climate models. These scenarios are typically designated by a set of letters and numbers (e.g., "A1B", "B2") that communicate information about the various assumptions regarding future population, economic growth, and technological development that relate

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[5] Technically speaking, the model projections should be compared to the model simulations for the 20th century, and then the *projected change* should be compared to the observed statistics (e.g., those taken from station data). For any model, especially at the regional-scale, the simulated 20th-century climate is likely to differ slightly from the observed 20th-century climate –this is often referred to as *bias*. Focusing on the projected change avoids incorporating the model's bias into any interpretation of expected regional-scale climate changes.

[6] Notably, scenarios do not include any assumptions about policies designed to explicitly discourage emissions of greenhouse gases.

to the scenarios' respective emissions trajectories.[7]

It is important to note that the likelihood of occurrence of any scenario has not been assessed – there are no probabilities assigned to the individual scenarios. The scenarios simply represent possible future pathways. They do not necessarily "bracket" what future conditions could look like, nor do they constitute what is most likely to occur.

Downscaling

Climate models render the Earth in a series of "pixels" or grid boxes (Figure 5) that are several degrees of longitude each side (roughly 60-200 miles, depending on the geographic location and the particular model). Within each grid box, calculations for meteorological variables are performed, and the flows of mass and energy between grid boxes are tracked.

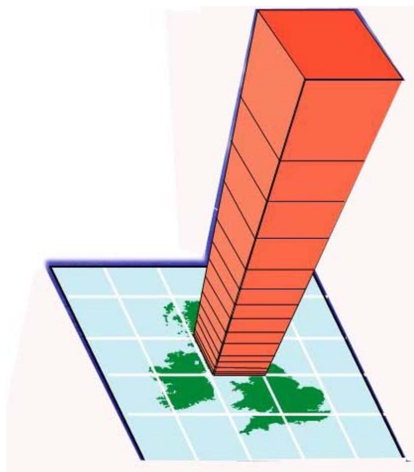

Figure 5: Illustration of a climate model's grid boxes. (Source: climateprediction.net)

The resolution of current climate models provides a coarse view of the land surface. For example, details of coastlines and mountain ranges that are smaller than the size of the grid boxes are not directly incorporated into the model's calculations. Similarly, aspects of meteorology and climate that occur on these relatively small spatial scales (e.g., structure of weather fronts, the evolution and properties of clouds) are not always represented well.[8]

Downscaling techniques have emerged as a way to transform the output from climate models to smaller spatial scales, often to grid boxes that are a quarter or an eighth of a degree of latitude and longitude on each side (between about 10-20 miles on a side). There are two general methods of downscaling:

Statistical downscaling: Empirically-observed relationships between observed climate (at high resolution) and modeled climate (at a coarse scale) are applied to future projections. These relationships act as a "transfer function" that allow small-scale information to be added to the patterns generated from the coarse-scale global climate model. Statistical downscaling techniques are based on the assumption that historically observed relationships between larger-scale climate patterns and the smaller-scale patterns (colloquially, these small-scale patterns are sometimes referred to as microclimates) will not change as a result of climate change.

[7] For the next round of IPCC model simulations (the Fifth Assessment, or AR5), new scenarios are being developed. These scenarios, or Representative Concentration Pathways (RCPs), will often involve similar assumptions about future population growth and changing socio-economic conditions as the scenarios used in previous Assessments. However, the RCPs have been developed with greater emphasis on greenhouse gas concentrations, rather than emissions. Concentrations can be used more efficiently as inputs to integrated assessment models that examine impacts. Also, the RCPs will include information about possible mitigation policies, which was also lacking from the previous scenarios. For more information, see the recent issue of Climatic Change, which is devoted to discussing various aspects of the RCPs (http://www.springerlink.com/content/f296645337804p75/).

[8] Sub-grid scale processes are represented using *parameters* that are based on empirically-derived relationships, rather than direct calculations that are emerge from physical or chemical first principles.

Dynamic downscaling: The outputs from a coarse-scale, global climate model are used as inputs for a climate model that operates in a smaller spatial domain (typically sub-continental). This smaller-scale model works much like a global climate model – equations describing the physics and chemistry of the atmosphere are solved in each of the grid boxes on the smaller domain, with the solutions forced to be roughly consistent with the large-scale characteristics of climate that have been simulated in the global model.

Statistical downscaling techniques are computationally less intensive than dynamic methods. Although there are many algorithms for applying statistical downscaling, some of the more popular methods (e.g., bias correction statistical downscaling, constructed analogs) often yield results that are similar to one another.

The use of dynamic methods is an active area of research and the types of information that can be gained by dynamic downscaling are still being established and debated. Given the computational requirements, experiments using many combinations of global models and regional models are time-consuming and expensive; hence, these investigations are likely to continue for the coming years.

It is important to note that downscaling rarely improves the information about climate change that is derived from the coarse-scale, global models. Although downscaling may reveal small-scale patterns of interest (e.g., larger amounts of rainfall on windward slopes of mountains, relative to nearby flatter terrain), the difference in the *changes* for the future may be less significant (e.g., the change in precipitation for the mountainous areas and the flatter areas may be quite similar). Similarly, downscaling the output from a suite of coarse-scale models will not necessarily result in a tighter range of projections for a particular area.

Which models, scenarios, and spatial scales are right for you?

Unfortunately, the answer to this question in not simple or straightforward. A few important points to keep in mind:

- *All models have some biases;*
- *Scenarios outline potential futures, as opposed to likely or probable futures;* and,
- *Downscaled model output is not necessarily more accurate or precise than the information from the coarse-scale model.*

Although there may not be a well established set of "best practices" for selecting models, scenarios, and the spatial scale of future climate information, knowledge of the sensitivity of the transportation system can be used to narrow some of these choices.

- Since all models involve some bias, it is judicious to use a range of models. Ideally, studies have been performed in your region to identify which models perform the best when simulating features of the historical climate.
- Typically, model differences have a larger impact than the scenarios on projected climate changes through 2050. For 2100, the scenario differences are larger than the model differences. Thus, if decisions between now and 2050 are of highest priority, it is less important to examine a wide range of scenarios. If it is important to sample from a wide range of temperature and precipitation changes, then a wide range of models should be used. Conversely, for decisions with long time frames (greater than 40-50 years), examining a range of scenarios is likely more important than a range of models.
- Downscaled data can be extremely valuable as inputs to high-resolution models (e.g., hydrologic models) for aspects of the environment (e.g., river dynamics, coastal

processes) that affect transportation networks. However, the types of information that they will “add” to the analysis should be established prior to expending significant time or cost in performing the downscaling.

Projection of daily-scale extremes

Some of the most important impacts of weather and climate on transportation assets and services occur during relatively short-lived events, including severe storms, floods, and heat waves. However, model abilities to simulate the daily-scale statistics of climate in a particular region are limited. Quantitative information derived from daily-scale statistics should be scrutinized and used with care. For example, changes in the number of extremely hot days occurring in future decades can span a wide range – projections for the end of the 21st century in parts of California exhibit increases in the frequency of intense hot days occurring in a year ranging from a doubling to increases by a factor of 8 or more. For heat waves lasting 5 days or more, the increases in frequency cover an even wider range, with several models projecting 20- and 30-fold increases (Cayan et al., 2009). Although all models and scenarios project a warmer future and an increase in the frequency and intensity of heat waves across California, there is significant uncertainty as to how this warming translates into daily-scale changes in weather at specific locations. Similarly, for changes in precipitation, many models project a future with heavier downpours for many regions in the U.S.; however, the magnitude of the changes can vary widely both across scenarios, and even across models using the same scenario.[9]

Although there is no way to “eliminate” the uncertainty associated with projections of daily-scale extremes, the mere fact that the model results involve uncertainty about the future does not need to be a barrier to making useful conclusions about daily-scale extremes. Two potential techniques include:

1) If it’s available, use data from many models and scenarios. For variables and regions where many models agree about the direction and magnitude of change, more confident conclusions can be made about the projected changes.

2) Identify impact thresholds from historical data, then apply the results of climate models qualitatively. In other words, rather than trying to identify the quantitative change in the frequency or intensity of heat waves or heavy precipitation at some future date, the goal of the analysis can be altered to focus on more binary issues (i.e., yes/no issues; is the event becoming more/less frequent?). Using heat waves as an example, if the impacts from an historical heat wave of a certain magnitude or duration can be characterized, then models could be used to conclude with high confidence that such events are likely to become more frequent. If output from multiple models is available, conclusions can go farther and involve some quantitative qualifiers such as “at least” (in reference to projections from the most conservative/coldest models) or “in the range of.”

[9] To clarify, this section is specific to understanding the statistics of daily-scale events as derived from climate models. For seasonal and annual timescales, all model and scenario combinations project increased temperatures for the United States and the globe (i.e. this is a robust finding of the models). For seasonal and annual precipitation, some models and some scenarios project increases in precipitation, while others project decreases. The results, and the consensus (or lack of a consensus) among models, are dependent on the geographic region.

DATA SOURCES

A variety of research institutions across the world conduct model experiments, using high-end computing resources. The output of these experiments are made available online (see Text Box on Online Resources) for download.

One of the most commonly used sets of model experiments is the Coupled Model Intercomparison Project (CMIP). The CMIP models act as a benchmark for climate research, and form the core of the assessment of future climate in the IPCC reports. These models that are part of CMIP meet a certain set of requirements regarding their technical specifications, their performance, and the types of experiments to which they've been subjected.

Although it is possible to access the data from any of these climate models, manipulating the data can be a challenge. The data formats (often Network Common Data Format, NetCDF) are not easily read-able by typical desktop software (e.g., Excel) or Geographic Information System (GIS) software packages. In addition, these data files are often extremely large and contain information on a wide range of variables (e.g., temperature, wind speed and direction, heights of pressure surfaces) for the entire globe. However, many of these variables would likely be extraneous when conducting a vulnerability assessment for transportation assets in a specific location.

Online Resources for Climate Model Output

Direct Access to Climate Model Output

CMIP 3 (the model projections used in the IPCC Fourth Assessment Report (AR4))
http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

CMIP 5 (the models projections that will be used in the upcoming IPCC Fifth Assessment Report (AR5))
http://pcmdi-cmip.llnl.gov/cmip5/index.html

National Center for Atmospheric Research – Earth System Grid (a portal for many output from a variety of models, both those used by the IPCC and those under development)
http://www.earthsystemgrid.org/home.htm

Evaluation of Models

IPCC AR4, Chapter 8: *Climate Models and their Evaluation* (a high-level, technical discussion of the state of climate modeling and an evaluation of the models used by the IPCC)
http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-es.html

Examples of Processed or Downscaled Model Output

North American Regional Climate Assessment Program (a portal for dynamically-downscaled climate model output; output can be requested in various formats (ASCII, GIS))
http://www.narccap.ucar.edu/

North American Climate and Hydrology Projections (downscaled output from CMIP3 models and scenarios; output can be requested in NetCDF or ASCII formats; climate projections are valid for the continental U.S.; hydrologic data are available for the western U.S.)
http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html

Cal-Adapt (a web-based climate adaptation planning tool for the state of California. Contains statistically-downscaled data for the state, which can be downloaded or manipulated in an embedded Google maps viewer.) http://cal-adapt.org/

TECHNICAL ASSISTANCE

For assistance in acquiring historical climate data, performing a sensitivity analysis, and acquiring or making decisions about future climate information, there are many groups that can offer potential assistance.

Some research institutions and non-profit organizations have begun to make downscaled climate information available in more easy-to-use formats. Examples include the North American Regional Climate Assessment Program and the Cal-Adapt project (see Text Box on Technical Assistance). As these efforts become more widespread, and more examples of the use of these data become available, the utility of these data portals is likely to grow.

Technical Assistance Resources Regarding Climate Information

NOAA Regional Climate Centers – focus more heavily on historical observations of climate http://www.ncdc.noaa.gov/oa/climate/regionalclimatecenters.html

Department of Interior Regional Climate Centers – focus on issues related to ecology and public lands http://nccwsc.usgs.gov/csc.shtml

NOAA's Regionally Integrated Sciences and Assessments Centers (RISAs) – each center pursues themes related to environmental issues in its respective region; however, climate has emerged as an important issue among many RISAs http://www.cpo.noaa.gov/cpo_pa/risa/

State climatologists – Many states have a climatologist that serves as a resource for acquiring and interpreting regional historical climate data, and in some cases, future projected data. It should be noted, that for a few states, the state climatologist position (which is often an unpaid position) may be occupied by an individual without advanced training in climatology. http://www.stateclimate.org/

Local university researchers – many universities have or are the process of forming groups or institutes to address regional issues related to climate change

Consulting firms – several private and non-profit firms exist that have expertise in applying climate information to transportation planning

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APPENDIX

PILOT METHODOLOGIES FOR ESTIMATING THE IMPACTS OF SEA-LEVEL RISE

Since each of the FHWA pilot study areas included coastal areas, all of the pilots considered vulnerability to sea-level rise to be a key climate change risk. Each of the pilots assessed this vulnerability differently, but they experienced common challenges and faced similar types of decisions. The purpose of this Appendix is to describe the pilots' approaches and to detail the relevant data sources, methodologies, challenges and barriers involved in conducting local-scale vulnerability assessments of the impacts of sea-level rise.

BACKGROUND: ESTIMATING IMPACTS OF SEA-LEVEL RISE

INUNDATION MAPPING

Spatial analysis is a key part of assessing the vulnerability of assets to sea-level rise. Without information on location and elevation, it is impossible to determine which assets will be exposed to sea level rise, or for that matter storm surge and wave impacts associated with tropical storms or other coastal storms. In order to characterize exposure, most studies of sea-level rise risk rely on inundation mapping. This method uses a Geographic Information System (GIS) to map inundated areas by analyzing areas of land that fall below increased water levels under different scenarios of sea-level rise (also called the "bathtub model").

As described in NOAA (2009), inundation mapping involves the following key steps:

- Obtain and prepare elevation data and elevation surfaces for coastal land areas (includes calibrating elevation to local tidal elevations);[10]
- Determine projected sea-level rise and/or storm surge scenarios;
- Use GIS to overlay the water surfaces onto the digital elevation map in order to identify inundation areas; [11]
- Add other features of interest, produce final inundation maps.

CHALLENGES FOR LOCAL ANALYSES

The utility and accuracy of a sea-level rise assessment depends on the resolution of the underlying elevation data. One standard source of elevation data, the USGS National Elevation Dataset, supplies elevation data with a horizontal resolution of 30m and 10m for the entire United States, which may be considered relatively coarse where coastlines are highly developed.

[10] Calibration often involves the choice of a vertical *datum*. As defined by NOAA (2011), "A datum is a base elevation used as a reference from which to reckon heights or depths. A tidal datum is a standard elevation defined by a certain phase of the tide. Tidal datums are used as references to measure local water levels." Example tidal datums include mean higher high water and mean high water.

[11] The sea-level rise projection must be chosen to account for the vertical accuracy of the elevation data for the land (and vice versa). An accurate map requires the root mean square error of the elevation data to be smaller than the projected change in sea-level rise (NOAA 2009). For more in-depth discussion of land elevation data resolution and accuracy, see Chapter 2 of CCSP (2009).

Vertical resolution can vary, based on the source of the elevation data utilized by NED, but the stated accuracy of available data from the NED is around +/-2.4m. However, since global projected sea-level rise changes only reach 2m by the end of the 21st century (if at all), maps based on the NED will generally not provide accurate predictions of exposure of specific assets. In order to obtain more useful elevation information, local assessments will likely need to rely on digital elevation models derived from high resolution LiDAR (Light Detection and Ranging) data. These data are not available in all locations. In addition, projects must ensure that the LiDAR data have been properly processed, including adjustments to the vertical datum[12] before use.

In addition to the horizontal and vertical resolution requirements for elevation data, there are other challenges for analyzing sea-level rise vulnerability at a local scale. As described in CCSP (2009), inundation mapping can be misleading because elevation is not the only determinant of coastal vulnerability. Mapping may not take into account the uplift or subsidence of the land surface. In areas where land is sinking, the apparent rate of sea-level rise (often referred to as the "local" or "relative" rate of sea-level rise) will be greater than the rate associated with changes in the global mean sea level.

Sea-level rise will likely occur slowly over a period of time and will manifest differently in different areas due to ongoing coastal processes, such as changes in tidal flow and sediment volume. In some places, land will become permanently flooded, while in other areas it will erode. Barrier islands and wetlands may migrate or disappear, and storms, waves, and currents will continually modify the landscape as the sea-level rises. Although the simple bath tub approach may indicate the relative risk among areas, it may not serve as a "prediction" for how the future landscape will appear. Typically, such limitations are not critical for identifying areas at risk at broad spatial scales (e.g., regionally or nationally) or communicating these risks to the general public. However, they may be important to keep in mind when such maps are used for local land use planning.

[12] Adjustments to the vertical datum are a necessary part of mapping inundation. The land elevation data are usually referenced to a vertical datum called the North American Vertical Datum of 1988 (NAVD88). This datum is not tidal, meaning that a value of 0 does not equate to any particular local tide value. Correcting this issue requires converting the elevation data from NAVD88 to a tidal datum, such as mean high tide (NOAA, 2011).

Resources for Assessing Sea-Level Rise

Useful Guidance on Analyzing Exposure to Sea-Level Rise

Army Corps of Engineers (2009). Water Resources Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs. http://www.dbw.ca.gov/csmw/pdf/EC_Sea_Level_Change.pdf

CCSP (2009). *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. http://www.climatescience.gov/Library/sap/sap4-1/final-report/

NOAA, Coastal Services Center (2009). Coastal Inundation Mapping Guidebook. Charleston, South Carolina. www.csc.noaa.gov/digitalcoast/inundation/_pdf/guidebook.pdf

NOAA (2010). Technical Considerations for Use of Geospatial Data in Sea Level Change Mapping and Assessment. http://www.csc.noaa.gov/digitalcoast/inundation/_pdf/SLC_Technical_Considerations_Document.pdf

Useful Data Sources and Models for Inundation Mapping or Sea-Level Rise Risk Assessment

NOAA. SLOSH (Sea, Lake, and Overland Surges from Hurricanes; http://slosh.nws.noaa.gov/sloshPub/) Model www.nhc.noaa.gov/HAW2/english/surge/slosh.shtml

Thieler, R., J. Williams, and E. Hammar-Klose. National Assessment of Coastal Vulnerability to Sea-Level Rise. Woods Hole Field Center, Woods Hole, MA. USGS. http://woodshole.er.usgs.gov/project-pages/cvi/

Examples of Regional or Local Inundation Mapping

Keim, B.D., T.W. Doyle, V.R. Burkett, I. Van Heerden, S.A. Binselam, M.F. Wehner, C. Tebaldi, T.G. Houston, and D.M. Beagan (2008). How is the Gulf Coast Climate Changing? In: *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. http://www.climatescience.gov/Library/sap/sap4-7/final-report/

DETAILS OF PILOT APPROACHES

Each of the FHWA pilot studies accounted for sea-level rise vulnerability differently. The following sections attempt to outline some of the key aspects of their respective technical choices regarding data sets and methods, as well as the goals and partnerships involved in their assessments.

Specifically, we've tried to capture the following decisions made by the pilots:

- *How will sea-level rise vulnerability information be used (e.g. for public education, internal communication, community planning, project level planning)?*
  The intended purpose of the map should shape the inundation mapping approach. For

example, a map intended to inform community or project planning purposes will likely require elevation data at a higher resolution than a map intended to educate the public or communicate overall sea-level rise risk to the region.

- *What estimates of sea-level rise are used? Why or how were these chosen?* Many of the studies relied on estimates adopted by state or regional planning organizations, or those appearing in published literature.
- *What was the source of the elevation data?* The source of the data is typically related to both the purpose of the project and the availability of data sets for a particular region or locality.
- *To what extent should other factors, such as land subsidence or shore protection, be taken into consideration?* Similar to the elevation data, these considerations are often tied to the purpose of the project and the availability of appropriate data sets.

NEW JERSEY

Since sea-level rise is a very important impact to the New Jersey coastal study area, the pilot conducted its own inundation mapping.

- *Elevation data*: The pilot was able to obtain very high resolution LiDAR data that had not yet been publically released by USGS. They then processed these LiDAR points into digital elevation models.
- *Sea-level rise scenarios*: One of the partners in the New Jersey pilot was the Department of Environmental Protection (DEP). The pilot worked closely with the DEP to ensure that all sea-level rise scenarios and projects matched the assumptions of the DEP. Since the DEP had already decided to use 0.5m, 1.0m, and 1.5m 2100 projections for global sea-level rise, the New Jersey pilot began with these estimates.
- *Adjustment to local sea-level rise*: The pilot calibrated these global sea-level rise projections to the study area by adjusting based on local subsidence data. To localize the data further, New Jersey also took salinity, temperature, and other factors into consideration.
- *Storm surge modeling*: The New Jersey pilot chose to use the SLOSH (Sea, Lake, and Overland Surges from Hurricanes; http://slosh.nws.noaa.gov/sloshPub/) model in order to consider the impacts of storm surge.[13] The pilot felt it would be advantageous to examine a range of potential storm paths, which SLOSH does well.[14]

[13] SLOSH (Sea, Lake and Overland Surges from Hurricanes) is a computerized model run by the National Hurricane Center (NHC) to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes. (http://www.nhc.noaa.gov/HAW2/english/surge/slosh.shtml)

[14] This memorandum was originally written prior to Hurricane Irene (August 20-29, 2011). Some of the impacts of Irene are discussed in the New Jersey team's final report.

OAHU MPO

The Oahu MPO pilot worked closely with Dr. Chip Fletcher and his lab at the University of Hawaii to develop high resolution inundation maps of the study area.

- *Elevation data*: Dr. Fletcher and his team compared two LiDAR datasets, one from the U.S. Army Corps of Engineers and the other from NOAA. These data were calibrated against the Kahului tide station.
- *Sea-level rise scenarios*: Dr. Fletcher considered two sea-level rise scenarios, 0.75m and 1.9m. These scenarios are for global sea-level rise and are based on Vermeer and Rahmstorf (2009).
- *Mapping inundation*: The pilot used a 'bathtub' approach to identify areas of land which are lower in elevation than each of the sea-level rise scenarios based on the LiDAR digital elevation data.
- *Challenges with the vertical datum*: During the course of this study, Dr. Fletcher and his lab found that there is no established vertical datum for Hawaii. This data gap affects the accuracy of the digital elevation models.
- *Overlays with asset data*: Once he had established the inundation area, Dr. Fletcher analyzed the total land area, length of roads, land and building value, number of Census 2010 blocks, and number of land parcels vulnerable to each sea-level rise scenario.

There are several additional pieces of information that the Oahu MPO would like to explore, including:

- Response of the water table to sea-level rise,
- Improving the understanding of current impacts associated with flooding, wave overwash, erosion, and coastal rock fall, and
- Commuter volumes in vulnerable areas.

Oahu MPO has engaged regional transportation planners and other stakeholders regarding sea-level rise. During the MPO's workshop with stakeholders, the Oahu MPO pilot used "what if" scenarios to help participants think through consequences of climate change, including scenarios of sea-level rise.

SAN FRANCISCO

The purpose of the San Francisco pilot sea-level rise mapping was to inform community and project level planning. Therefore, the pilot's inundation maps are based on very high resolution elevation data and account for local factors such as shoreline protection, inundation depth and extent, wind and wave effects, and hydrologic continuity. The pilot worked closely with Noah Knowles and updated the methodology in Knowles (2009) with new LiDAR data.

- *Elevation data*: The pilot combined five different sources of high resolution elevation data in order to create a digital elevation model (see Knowles 2009 for additional information on data sources).

- *Sea-level rise scenarios*: The pilot assumed 16 inches of global sea-level rise in mid-century and 55 inches at the end of the century. These scenarios are based on the amount of global sea-level rise projected based on CCSM3 global climate model temperature outputs under an A2 greenhouse gas emissions scenario. For each time period, the pilot analyzed both the still water and the 100 year return high tide level with wind and wave effects.
- *Inundation modeling*: In order to quantify the high water levels in the Bay accurately, the pilot used a hydrodynamic model of the San Francisco Bay estuary, based on the methodology described in Knowles (2009).
- *Weak link analysis*: The pilot conducted a weak link analysis to assess inundation depth in order to determine the thresholds at which different share protection barriers would fail.

VIRGINIA DOT/HAMPTON ROADS

The goal of the Virginia DOT/Hampton Roads inundation and storm surge work was to generate realistic scenarios that could be used as inputs into the pilot's multi-criteria decision analysis framework. The Hampton Roads region is highly vulnerable to sea-level rise partially because the area is already subsiding due to geological processes and groundwater withdrawals (HRPDC 2011). One of the main goals of the Virginia pilot was to construct and assess the influence of climate-change scenarios (primarily sea-level rise and storm surge) to the strategic priorities of long-range transportation plans. The pilot relied on sea-level rise and storm surge data from an ongoing Hampton Roads Planning District Commission study.

To get a sense of sea-level rise exposure, HRPDC analyzed historical sea-level rise trends, including subsidence of the land surface, and found that the regional average is 1-2 feet of sea-level rise over the past 100 years. The project assumed that the historical rate of sea-level rise will continue in the future, while recognizing the importance of monitoring trends and adjusting for any acceleration in sea-level rise.

The Hampton Roads Planning District Commission (HRPDC) is currently in its second year of a climate change adaptation project that focuses on sea-level rise and storm surge.

- *Elevation data:* The project used elevation data of varying resolution. While several localities had already developed their own detailed elevation data, the remainder used the USGS topographic data from the National Elevation Dataset (NED).
- *Storm surge modeling:* In order to identify specific areas and assets of Hampton Roads that are at risk from sea-level rise, the project relied on the Virginia Hurricane Evacuation Study, a cooperative effort involving the U.S. Army Corps of Engineers, the Federal Emergency Management Agency, and other state and local agencies. This analysis used the SLOSH model to determine the maximum tide elevations from a set of storms of differing magnitude. Using GIS, the Virginia Hurricane Evacuation Study applied these tide elevations to local elevation data in order to create flood hazard areas.
- *Sea-level rise*: Since not all of the areas had high resolution elevation data, HRPDC is assuming that the storm surge zones are also the areas exposed to sea-level rise (HRPDC

2011). The project is planning future analyses which will further distinguish sea-level rise impacts from storm surge impacts (HRPDC 2011).

WASHINGTON STATE DOT

The Washington State DOT worked closely with the Climate Impacts Group at the University of Washington to develop LiDAR-based inundation maps of the study area. During the pilot's workshops to identify vulnerable assets, workshop participants "ground-truthed" the maps by pointing out missing assets, areas already being impacted, or other factors that should be considered in the vulnerability assessment. The pilot anticipates that these maps will also serve as communication tools to educate influential decisionmakers in Washington State.

- *Elevation data:* The Washington DOT pilot used LiDAR data for the Puget Sound from different sources along with tide gauge data going back at least 70 years.
- *Sea-level rise scenarios*: The pilot adopted the sea-level rise estimates that are used by the Puget Sound Regional Council (2 feet and 4 feet).
- Much of the analysis from the Washington State Climate Assessment (http://cses.washington.edu/cig/res/ia/waccia.shtml) was also incorporated in the sea-level rise considerations.

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