Appendix C
Climate Change and the Frequency and Intensity of Precipitation Events

Technical Note

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This review has been prepared to address issues raised in the context of the preparation of meteorological data used as input to the SWAT and HSPF watershed models. The data preparation process is summarized as follows: The approach selected for this project is to use the U.S. Environmental Protection Agency's (EPA's) BASINS Climate Assessment Tool (CAT; U.S. EPA, 2009) to modify historical meteorological records to reflect the projected impacts of climate change on important meteorological variables. Temperature and precipitation records from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) stations in and surrounding each pilot watershed have been identified, and hourly data covering the period 1970–2000 is being used in the calibration of models and the simulation of historical patterns of discharge. The projected regional impacts of climate change will be obtained from the North American Regional Climate Change Assessment Program (NARCCAP) dynamically downscaled 50 kilometer Regional Climate Model (RCM) output, primarily at monthly resolution. The original proposal was to use 15 General Circulation Model (GCM)-RCM combinations to simulate a range of future projections, although due to restrictions on the likely availability of NARCCAP downscaled data, a combination of NARCCAP, statistically downscaled CMIP3 projections and direct GCM outputs will likely be used. In each instance, the model-projected changes in temperature and precipitation patterns will be used to modify the historical climate records using CAT. The advantages to this approach include the preservation of short-timescale variability and other aspects of time series behavior, and the preservation of inter-site variability and correlation patterns, none of which are feasible using downscaled GCM outputs directly as model inputs.

CAT permits the sequential modification of weather records to introduce a number of alterations, each reflecting various assumptions concerning the regional manifestations of climate change. Precipitation records can be modified by (1) multiplying all records by an empirical constant reflecting projected climate change to simulate a shift in total precipitation, applied uniformly to all periods and intensity classes, (2) selective application of such a multiplier to specific seasons or months, (3) selective application of the multiplier to a range of months or years within the record, (4) selective application of the multiplier to storm events of a specific size or intensity class; and (5) addition or removal of storm events to simulate changes in the frequency of

precipitation events (U.S. EPA, 2009). Modification (4) can be iteratively applied to more than one event size class. In summary, changes in frequency and intensity as well as changes in overall precipitation accumulation can be represented using CAT and historical records.

Relative changes in the *frequency* and *intensity* of precipitation events associated with climate change may prove to be more influential in determining future patterns of discharge than projected changes in overall (annual, seasonal) precipitation. In particular, the partitioning of precipitation into re-evaporation, runoff and percolation to groundwater is understood to be sensitive to the intensity and timing of precipitation events. Thus, to ensure that model simulations embody the most important dimensions of projected climate change, particular attention should be paid to precipitation intensity-frequency-duration (IFD) relationships. As a general pattern, the warming of the lower atmosphere is projected to lead to a more vigorous hydrologic cycle, characterized by increases in global precipitation, and proportionally larger increases in high-intensity events (Trenberth et al., 2007). This memorandum is intended to provide a summary review of recent literature to address the following questions: (1) How should precipitation change as a consequence of lower atmosphere warming? (2) What is the historical evidence for increases in precipitation intensity over the United States? (3) What do climate models project with respect to precipitation frequency and intensity? (4) What are the important limitations in these projections? and (5) What are the implications for the development of meteorological time series used in the modeling study?

1. How should precipitation change as a consequence of lower atmosphere warming?

Physical arguments predicting increases in precipitation intensity as a consequence of the warming of the lower atmosphere are presented by Trenberth et al. (2003). The basic argument can be summarized as follows: (1) The primary conditions for precipitation to occur include (a) availability of precipitable moisture in the atmosphere and (b) a mechanism for lifting and cooling parcels of air, leading to condensation and precipitation. (2) Progressive warming of the land surface and lower atmosphere (i.e., climate change) will lead to increases in atmospheric (precipitable) moisture through the positive relationship between air temperature and saturation vapor pressure (moisture-holding capacity). The Clausius-Clapeyron equation quantifies this relationship, and can be used to predict an increase in atmospheric water holding capacity of around 7% per °C at current global mean temperatures.[1] (3) Precipitation, when it occurs, often exceeds the extractable fraction (typically below 30%) of available moisture in the immediate zone of precipitation. This reflects the role of low-level convergence in drawing moist air into convective zones from surrounding areas. Trenberth et al. (2003) calculate that as an approximate global average, a zone of precipitation is supported by a larger region – roughly three to five times the radius of the precipitation zone – from which it draws moisture. Assuming no significant change in the efficiency of precipitation generation (i.e., maximum rate of extraction of water from the atmosphere), the intensity of such events should therefore increase as a function of mean temperature at roughly the same rate as atmospheric water-holding capacity (i.e., around 7% per °C). Finally (4), the increased atmospheric moisture supply also provides additional latent heat

[1] The slope of the saturation vapor pressure curve is around 6% at 300 K and 7.4% at 270 K.

to drive the convective process, further enhancing low-level convergence. Thus, increases in atmospheric temperature lead to proportional increases in precipitation intensity when other conditions required for initiating convective precipitation are present. Trenberth et al. (2003) note that the GCMs supporting the Intergovernmental Panel on Climate Change (IPCC) assessment simulate increases in precipitation of around 1% to 2% per °C.[2] This suggests (assuming these GCMs accurately simulate the atmospheric water balance) that the increase in precipitation intensity predicted by Clausius-Clapeyron (7% per °C) for intense convective events must be compensated for by reductions in the frequency and/or intensity of light to moderate intensity events. The latter hypothesis assumes that the durations of intense precipitation events do not also change significantly as a function of temperature.

2. Historical evidence of increases in precipitation intensity over the United States

If the proposed relationship between increasing air temperatures and precipitation intensity is theoretically sound, then the predicted changes should already be evident due to observed increases in global and U.S. air temperatures. Analysis of instrumental records from 1850–2005 indicates that globally-averaged temperatures have increased by 0.76°C (+/- 0.19°C) over this period, with the most rapid warming occurring in the last 50 years and the steepest increase in global temperatures, equivalent to changes of +0.177°C per decade, occurring over the last 25 years (Trenberth et al., 2007). Within the United States, temperature increases have also been observed at rates exceeding the global average. Present (1993–2008) U.S. temperatures are on average over 1.1°C warmer than during the 1961–1979 period (Karl et al., 2009). Corresponding, increasing trends in evaporation, atmospheric moisture and precipitation, particularly high-intensity precipitation, should thus be in evidence. However, it is not necessarily the case that all of these increases (if observed) should be of the magnitude predicted by Clausius-Clapeyron (7% per °C) since globally, evaporation is controlled by the availability of surface moisture (over land) and by the availability of energy at the earth's surface to drive evaporation and transpiration (Allen and Ingram, 2002).

Evaporation: Among the predicted impacts of a warming lower atmosphere, increases in actual evaporation and transpiration (evapo-transpiration, or ET) have been the most difficult to demonstrate, largely due to the relative absence of long-term records of direct ET measurements (Lettenmaier et al., 2008). Physical theory (the Clausius-Clapeyron equation) predicts an increase in *potential* ET, since a supply of moisture available for ET cannot be assumed. A relatively small number of recent land-based studies in the United States, India, China and Australia that make use of long-term evaporation pan data conclude that actual evaporation rates

2. Trenberth et al. (2003) refer to the GCMs supporting the Third IPCC Assessment (2001).

have *decreased*. One proposed explanation for this paradox is a reduction in incoming solar radiation due to increases in aerosols associated with air pollution (Trenberth et al., 2007). Alternatively, Brutsaert and Parlange (1998) conjecture that as humidity supplied by the surrounding landscape increases, pan evaporation will decrease (a reverse of the "oasis effect"). A synthesis of water balance studies of several major North American watersheds (Walter et al., 2004), in which ET was estimated as the residual of precipitation and discharge, concludes that actual ET has increased over the last 50 years. More direct evidence of a temperature-induced increase in actual evaporation is provided by Yu and Weller (2007). These authors utilized satellite remote sensing and atmospheric model re-analysis to estimate trends in evaporation over the ocean surface, where moisture supply is not limited. They estimate that globally averaged ocean latent heat flux (evaporation) has increased by approximately 10% over the 25-year period 1981–2005. This reflects increases in both atmospheric moisture capacity (Clausius-Clapeyron) and sea surface temperature (SST).

Atmospheric moisture: Clausius-Clapeyron predicts an increase in absolute or specific humidity (q) with increasing temperature, as distinct from relative humidity (RH). Climate model simulations tend to indicate that temperature-related changes in RH are small (Trenberth et al., 2003). Balloon-borne radiosonde has been used to estimate altitude-integrated RH, although time series analysis based on radiosonde is subject to a number of constraints. Specifically, the density of radiosonde observations is low, observations are unavailable over the open ocean and radiosonde sensors have changed over time, confounding efforts to measure decadal-scale changes in atmospheric water content (Dai, 2006b), effectively limiting analysis to the mid-1970s and onward. Nevertheless, Ross and Elliott (1996; 2001) used radiosonde time series records to estimate changes in RH and precipitable water (up to 500 mb) over North America in recent decades. They found that precipitable water has increased by 3% to 7% per decade between 1973 and 1995 over the area ranging from the Caribbean to 45°N, with greater increases in the south and smaller increases in the north. Above 45°N, changes were either uncertain or negative over this period. Ross and Elliott (2001) note also that these changes appear greater and more uniform over North America than over Eurasia.

Dai (2006b) evaluated changes in surface specific q and RH using a much wider range of sensors, located both over land and over ocean. Near-surface measurements do not provide altitude-integrated estimates of q and RH, although the spatial sampling is greatly improved relative to Ross and Elliott (1996; 2001) due to the large number of records (over 15,000 surface and ocean weather stations), and the sensor technology is more consistent over the period of record. Dai (2006b) found that globally averaged specific humidity (q) increased by around 0.06 g kg^{-1} per decade over the 1976–2004 period. This corresponds to roughly 4.9% per degree (°C) of warming over that period, globally averaged. The response of q to temperature increases over water (i.e., not source-limited) was found to be around 5.7% per °C of warming, reasonably consistent with the predictions of Clausius-Clapeyron (7% per °C) at constant RH. By contrast, the response over land is around 4.3% per °C of warming, presumably reflecting spatio-temporal

limitations in water available for evaporation. Finally, column-integrated estimates of atmospheric water vapor have been available since 1988 from the special sensor microwave imager (SSM/I). On the basis of SSM/I, Trenberth et al. (2005) estimate that over the period 1988–2003, altitude-integrated atmospheric precipitable water over oceans has increased by around 0.40 mm per decade (1.3%). Variability over the period of analysis was found to reflect variations in SST. Assuming relatively constant RH, the observed trend is reasonably close to the 7% per °C predicted by Clausius-Clapeyron.

Precipitation: Increases in the frequency and intensity of heavy precipitation events over the last several decades are among the most clearly documented changes in recent U.S. climate (Kunkel, 2008). The following studies are representative of several recent studies examining trends in precipitation in the United States and globally. Karl and Knight (1998) found that precipitation over the U.S. increased by around 10% between the 1910s and the 1980s. These authors examined the respective contributions of changes in both frequency and intensity of precipitation to changes in total precipitation. Precipitation events were disaggregated into 20 intensity classes, each encompassing 5% of observed events; and extreme intensity events, defined as precipitation exceeding 2 inches (50.4) mm per day, were also examined. Among their conclusions, Karl and Knight (1998) found that observed increases reflect both increased frequency and intensity of rainfall events. While the frequency of events increased for all intensity (percentile) classes, intensity increased for heavy and extreme precipitation days only, and the proportion of total annual precipitation attributable to these heavy and extreme events has increased relative to more moderate events. Specifically, over half (53%) of the observed increase was due to increases in the upper 10% of events. Karl and Knight (1998) also found that the percentage of total area within the U.S. experiencing extreme precipitation events (> 50.4 mm/day) had increased by roughly 20% between 1910 and the mid-1990s. Kunkel et al. (1999) found statistically significant increasing trends in 1-year and 5-year return period 7-day precipitation events in the United States. However, subsequent work (Kunkel et al., 2003) extended the period of record back to 1895, and the frequency of extreme events in the late 19th-early 20th century was found to be similar to the late 20th Century, suggesting that natural variability cannot be ruled out as an additional factor contributing to the observed late 20th century increases in intensity.

Groisman et al. (2004) examined trends in several climatologic and hydrologic variables for the conterminous U.S. potentially influenced by climate change, including total precipitation, precipitation intensity, temperature and streamflow. Heavy precipitation events, defined as the upper 5% of daily events, increased by 14% over the period 1908–2002. Very heavy events (upper 1 %) increased by 20% over this period, and extreme events (upper 0.1 %) by 21%. The most significant increases occurred in the upper and lower Midwest for annual events, the upper Midwest and Great Lakes areas for summer events, and in New England for winter events. Similar results are presented in the global analysis of Groisman et al. (2005) for the period 1910–1999, who found that while total annual precipitation volumes over the United States increased

by 1.2% per decade over the period 1970–1999, the share of annual precipitation associated with extreme events (defined as above) increased by 14% per decade over this period. These authors note that "*…practically the entire nationwide increase in heavy and very heavy precipitation occurred during the last three decades*" (p. 1328). Alexander et al. (2006), examining global precipitation statistics for the period 1951–2003, reached similar conclusions, specifically, that the contribution to total annual precipitation from very wet days, defined as the upper 5% of daily precipitation events, has increased over this period, even in many areas where total precipitation has decreased.

3. Model projections of trends in precipitation intensity

Evaporation and transpiration are in many circumstances controlled by factors other than the moisture-holding capacity of the atmosphere, including availability of moisture supply over land areas and energy available to drive the ET process (e.g., Allen and Ingram, 2002). Thus, GCMs generally predict increases in the global hydrologic cycle that are more modest than the 7% per °C predicted by Clausius-Clapeyron (Trenberth et al., 2003). Sun et al. (2007) have summarized changes in total global precipitation, precipitation frequency, intensity, fraction of precipitation from convective events and other related variables as projected by 17 of the most recent generation of GCMs from the Program for Climate Model Diagnosis and Intercomparison (PCMDI), used in the IPCC AR4 (2007), for emissions [Special Report on Emissions Scenarios SRES] scenarios B1 (low), A1B (medium) and A2 (high). Ensemble results, averaged over models and scenarios, indicate that global mean precipitation is projected to increase by around 1.2% per °C, and latent heat flux (evaporation) by a comparable amount, although global precipitable water is projected to increase by around 9.1% per °C. These results indicate that the atmospheric state variable (atmospheric precipitable water) responds approximately as predicted by Clausius-Clapeyron (consistent with relatively small increases in average RH), while atmospheric water fluxes (ET, precipitation) are constrained by other factors. Sun et al. (2007) report that overall, the frequency of (daily) precipitation events is projected to decrease, and the intensity of events to increase on average, consistent with Trenberth et al. (2003). However, the frequency of *heavy* precipitation events is projected to increase, indicating a more dramatic reduction in the frequency of light precipitation events. Thus, heavy (20–50 mm day^{-1}) and very heavy (> 50 mm day^{-1}) precipitation events are projected to contribute a disproportionately increasing share of total precipitation, through the combined effects of increased frequency and increased magnitude, with frequency effects more influential than intensity effects. These projected impacts are most pronounced under SRES scenario A2 (high emissions). These authors acknowledge that the (simulated) increases in intensity may not be fully captured in an analysis based on daily precipitation totals, since high-intensity events are often of shorter duration.

Tebaldi et al. (2006) have also examined model-simulated changes in extreme events, encompassing both temperature and precipitation events, on the basis of nine GCMs included in the IPCC AR4 (2007). These authors use a set of indicators of precipitation intensity proposed by

Frich et al. (2002) including the following: (1) frequency of days with precipitation exceeding 10 mm, (2) maximum 5-day precipitation total, (3) mean precipitation intensity (total precipitation divided by number of days with precipitation exceeding 1 mm) and (4) fraction of total precipitation due to events exceeding the 95th percentile. Significant increases in each of these four indices were projected by the GCMs evaluated, although not all trends were statistically significant. Significant (increasing) trends were associated with mid- to high latitudes in the Northern Hemisphere as well as some tropical areas within South America and Africa. Tebaldi et al. (2006) conclude that "Models (also) agree with observations over the historical period that there is a trend towards a world characterized by intensified precipitation, with a greater frequency of heavy-precipitation and high-quantile events, although with substantial geographic variability" (p. 206).

4. How well do GCMs capture the frequency-intensity relationships observed in actual precipitation?

In evaluating the model-generated evidence that precipitation intensity is likely to increase as a consequence of increasing tropospheric temperatures, it is important to recognize that many GCMs display well-documented biases with regard to precipitation frequency and intensity. Specifically, there is a tendency for GCMs to generate too many low-intensity events, and to under-simulate the intensity of heavy events. There are several possible reasons for this (since there are several convective precipitation parameterization schemes in use) although problems associated with the simulation of the diurnal cycle appear to play an important role (Dai, 1999; Trenberth et al., 2003). If conditions for the onset of moist convection in models are biased or poorly specified, convection occurs too early in the diurnal cycle, weaker convection results in less vigorous precipitation, and the removal of atmospheric moisture reduces the likelihood of more intense convective events subsequently (Trenberth et al., 2003).

Sun et al. (2006) compared the performance of 18 coupled Atmosphere-Ocean General Circulation Models (AOGCMs) used in the IPCC AR4 (2007) in simulating precipitation with historic observational data. Most of the models were found to greatly overestimate the frequency of summer (June-August) light precipitation events in the Northern Hemisphere, although the frequency of heavy precipitation events was simulated with greater skill, each subject to regional variations. Sun et al. (2006) summarize their observations as follows: "For *light* precipitation, most of the models greatly *overestimate the frequency* but reproduce the observed patterns of intensity relatively well. For *heavy* precipitation, most of the models roughly reproduce the observed frequency but *underestimate the intensity*" (p. 928, emphasis in original). *Light precipitation* is defined as 1–10 mm day^{-1} and *heavy precipitation* as >10 mm day^{-1}. These authors emphasize the importance of getting precipitation "right for the right reasons" since surface runoff, evaporation and soil moisture are all highly sensitive to precipitation IFD relationships. Dai (2006a) also examines the performance of 18 models from the PCMDI (AR4) ensemble with respect to the characterization of precipitation. Dai's (2006a) study emphasizes

model skill in simulating precipitation via the distinct convective and stratiform mechanisms, noting that (in GCMs) stratiform precipitation is a grid-scale process while convective precipitation is a subgrid-scale process. Model performance is compared to the Tropical Rainfall Measuring Mission (TRMM) observational data. Among other results, Dai (2006a) found that the models examined derived too much of total precipitation (28%–38%) from light precipitation (1–5 mm day^{-1}) relative to TRMM data (19%), and far too little (0–2%) from very heavy precipitation (> 50 mm day^{-1}) (7% for TRMM). Model replication of TRMM results were best for moderate events, defined as 10–20 mm day^{-1}. Dai (2006a) concludes that "…the newest generation of Coupled Ocean-Atmosphere General Circulation Models (CGCMs) still rains too frequently, as in previous generations (…), mostly within the 1–10 mm day^{-1} categories, while heavy precipitation (> 20 mm day^{-1}) occurs too rarely" (p. 4622).

5. Implications for the ORD modeling study

On the basis of literature reviewed here, several observations can be made. First, the importance of getting IFD relationships right cannot be over-emphasized. Analysis of historical data indicates that changes in the distribution of precipitation between light- and heavy-intensity events are quantitatively greater than changes in overall precipitation at annual or seasonal levels in many regions, and projected runoff estimates are likely to be quite sensitive to these IFD relationships. Second, model-generated projections of precipitation are characterized by documented biases with respect to precipitation intensity and frequency. This suggests that the *relative changes* in precipitation IFD relationships should be used as the basis for adjusting historical precipitation records in CAT rather than their absolute levels.

NARCCAP has to date provided summaries of three GCM-RCM downscaled products intended for use in modifying the historical gauge records. These datasets include changes in monthly precipitation accumulation, and changes in the contributions of precipitation by intensity class for 25%, 50%, 70%, and 90% percentile classes. While this data is extremely useful, it is recommended that we obtain a number of representative output series at finer time resolution – down to 3-hourly as output by NARCCAP RCMs. Ideally, we would obtain series that sample from at least three of the climatic zones associated with the pilot watersheds, and including the upper Midwest (Minnesota) in particular, since many of the greatest observed changes in precipitation intensity have occurred in this region. These time series would be processed to obtain estimates of the change in frequency of events, by event size class, to support the appropriate use of CAT. As emphasized above, the "deltas" (changes in projection period relative to base period) would be the basis for CAT transformations rather than the projections themselves, which potentially contain biases, as discussed.

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