To weight or not to weight: assessing sensitivities of climate model weighting to multiple methods, variables, and domains in the south-central United States

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Abstract. Given the increasing use of climate projections and multi-model ensemble weighting for a diverse array of applications, this project assesses the sensitivities of climate model weighting, and their resulting ensemble means, to multiple components, such as the weighting schemes, climate variables, or spatial domains of interest. The analysis makes use of global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), and their statistically downscaled counterparts created with the Localized Canonical Analogs (LOCA) method. This work focuses on historical and projected future mean precipitation and daily high temperatures of the south-central United States. Results suggest that the model weights and the corresponding weighted model means are highly sensitive to the weighting scheme that is applied. For instance, when estimating model weights based on Louisiana precipitation, the weighted projections show a wetter and cooler south-central domain in the future compared to other weighting schemes. Alternatively, for example, when estimating model weights based on New Mexico temperature, the weighted projections show a drier and warmer south-central domain in the future. However, when considering the entire south-central domain in estimating the model weights, the weighted future projections show a compromise in the precipitation and temperature estimates. As for uncertainty, our matrix of results provided a more certain picture of future climate compared to the spread in the original model ensemble. If future impact assessments utilize weighting schemes, then our findings suggest that how the weighting scheme is derived and applied to the projections may depend on the needs of an impact assessment or adaptation plan. From the results of our analysis, we summarize our recommendations concerning multi-model ensemble weighting as follows:

- That model weighting, if used, be derived using both common (e.g., precipitation) and stakeholder-specific (e.g., streamflow) variables to produce relevant analysis for impact assessments or using multiple climate variables relevant for a national assessment region.
- That weighting is derived for individual sub-regions in addition to what is derived for the continental United States or other nations and that weighting for impact assessment is also derived for a domain relevant to the impact assessment.

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- Weighted ensemble means should be used not only for national and international assessments but also for regional impacts assessments and planning.
- Multiple strategies for model weighting are employed when feasible, to assure that uncertainties from various sources (e.g., weighting strategy used, domain or variable of interest applied, etc.) are considered.
- Future efforts should examine the weighting of impacts model outputs from climate model inputs.

1 Introduction

The simulation output from climate models has been traditionally used for research into characterizing and understanding the climate system across multiple spatial scales. In recent years, ensembles of climate projections are increasingly used for impact and vulnerability assessments (e.g., Allstadt et al. 2015; Basso et al. 2015; Pourmoktharian et al. 2016; Gergel et al. 2017; Massoud et al., 2018, 2019, 2020ab; Wootten et al., 2020ab). These include large-scale assessments, such as the National Climate Assessment (NCA, Wuebbles et al. 2017), and local and regional assessments for individual areas of the United States. Large and local scale assessments can make use of the entire ensemble of climate projections (composed of global climate models [GCMs]) or make use of the unweighted ensemble mean. For these assessments, using the ensemble mean provides a useful and convenient way to assess projected changes in a region. Given the coarse resolution of the GCMs (typically > 100km^2), many of these assessments make use of downscaled climate projections to translate larger-scale changes to local scales.

Alongside the use of climate modeling and downscaling for climate research and increased use for impact and vulnerability assessments, there has also been a transition in the last 20 years toward using weighted multi-model means. Projections based on model weights derived from historical skill have been shown to have greater accuracy than an arithmetic multi-model mean in many cases, provided that there is enough information to determine a weight for each model (Knutti et al. 2010; Weigel et al. 2008; Peña and Van den Dool, 2008; Min and Hense, 2006). More recently, weighting based solely on skill has given way to weighting based upon both skill and independence. This transition has resulted from the recognition that some models can be more skillful for certain variables and regions, but also as common bases of model structure, parameterizations and associated programming code can result in a lack of independence between GCMs (Massoud et al. 2019, 2020a; Sanderson et al. 2015, 2017; Knutti, 2010; Knutti et al. 2017). In acknowledgment of studies indicating that the global climate models are not fully independent, the Fourth National Climate Assessment (NCA4) was the first major climate assessment in the United States to use skill and independence-based model weighting on the ensemble of climate models (Sanderson and Wehner, 2017).

The authors of this paper have extensively investigated the effect of model weighting on the outcome of climate change projections from multi-model ensembles (Massoud et al. 2019, 2020a; Wootten et al. 2020a). For example, in Massoud et al.

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Multiple strategies for model weighting are employed when feasible, to assure that uncertainties from various sources (e.g., weighting strategy used, domain or variable of interest applied, etc.) are considered.¶
That weighting is derived for individual sub-regions (such as the NCA regions) in addition to what is derived for the continental United States.¶
That domain-specific weighting be derived using both common (e.g. precipitation) and stakeholder-specific (e.g. streamflow) variables to produce relevant analysis for impact assessments and planning.¶

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(2019), the authors utilized information from various model averaging approaches to evaluate 21 global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), and they based their weighting strategies on model independence as well as performance skill of the models to simulate atmospheric rivers globally. In Massoud et al. (2020a), the authors used Bayesian model averaging (BMA) as a framework to constrain the spread of uncertainty in climate projections of precipitation over the contiguous United States (CONUS). In Wootten et al. (2020a), the authors applied various ensemble-weighting schemes to constrain precipitation projections in the south-central United States and applied these strategies to both the 26-model ensemble from the CMIP5 archive and the downscaled version of the models. The latter study is distinct from prior research, because it compared the interactions of ensemble-weighting schemes with GCMs and statistical downscaling to produce multi-model ensemble means.

Some studies have applied model weighting to a certain variable or to multiple variables and went on to investigate climate change impacts for other variables (e.g., temperature or streamflow) (c.f. Knutti et al., 2017; Massoud et al., 2018). The National Climate Assessment had previously considered weighting based only on commonly used climate variables (e.g., precipitation and temperature, Wuebbles et al., 2017), but discussions to use additional variables are currently ongoing. Other studies have calculated weights based on metrics in one domain (e.g. globally) and then applied them to projections for another domain (e.g. North America or Europe) (Massoud et al., 2019). However, these studies are rare, as are studies providing comparisons of various weighting schemes (e.g. Shin et al. 2020; Brunner et al., 2020a; Kolosu et al. 2021), and no previous study offers a comprehensive cross-comparison of the effects on the ensemble means from the choices of the domain, variable, weighting scheme, and ensemble.

Taking these points into consideration, we assess the choice of model weighting strategy by developing and investigating a multi-dimensional sensitivity matrix for applying model averaging for the south-central region of the US - as defined by the NCA. To this end, we look at mean precipitation and high temperatures as our climate variables of interest. Furthermore, we use two sub-domains, the states of Louisiana and New Mexico, alongside the south-central U.S. study region. Overall, we created and apply various sets of model weights based on several choices: a) the choice of the ensemble (CMIP5 or downscaled), b) the choice of model weighting scheme, c) the choice of climate variable of interest (precipitation vs temperature), and d) the choice of the domain used to derive weighting (entire south-central region vs smaller sub-domain). Therefore, one example of a strategy that we apply to estimate a set of weights uses the BMA weighting method on the CMIP5 ensemble projections of the precipitation variable for the Louisiana domain. To our knowledge, there has not been a model weighting study that included as many dimensions in the experimental matrix as this study, again these are model ensemble, domain, variable, and importantly, the weighting scheme itself.

Weighted multi-model means have primarily been focused on GCMs and continental scales (Brunner et al. 2019; Pickler and Mölg, 2021; Sperna Weiland et al. 2021). However, the use of climate projections has extended to regional, state, local, and

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tribal uses for climate impact assessments and adaptation planning. In these regional to local efforts, the raw projection data has been used but also provided to impact models (such as hydrology or crop models). Currently, impact assessments outside the traditional venues of climate modeling tend not to use weighted multi-model means but tend to use unweighted means created using downscaled GCM ensembles. Whether to use model weighting or not is currently a hot topic in the climate modeling community, and the current study aims to provide answers to this debate by focusing on the following questions:

1. Should model weights be developed separately when investigating different climate variables?
2. Should model weights be estimated separately when investigating different domains?
3. Should impact assessments and national / international climate assessments make use of weighted multi-model means?
4. If yes to Question 3, then a fourth question is, should multiple weighting schemes and ensemble means be used?
5. Should a sensitivity analysis with multi-model weighting strategies be repeated using impact model results?

All such questions could be considered in terms of climate modeling or broader impact assessments and applications. Our analysis results in a wide array of possible future outcomes, which comes with high uncertainties on what to expect in the future in this domain. The main question we are after is whether or not some variables or domains have projected climate change signals that have high certainty, and alternatively, we would like to find out whether or not there are climate variables in any of the regions that have highly uncertain climate change projections, and if the use of model weighting can provide a better sense of this uncertainty. We aim to address these uncertainties by applying the multi-dimensional experimental matrix of model weighting strategies and hope to inform the scientific community of these sensitivities for the benefit of future stakeholders, including climate modelers and boundary organizations providing climate services.

2 Methods and Data

2.1 Study Domain and Variables

The south-central United States (from about 26°N 108.5°W to 40°N 91°W) has a varied topography with a sharp gradient in mean annual precipitation from the east (humid) to the west (arid), and a generally warm climate. The Mississippi River Valley and the Ozark Mountains in the eastern portion of the region (elevations of 200–800 m), the Rocky Mountains in the west (1500–4400 m), and the Gulf of Mexico in the southeast (near sea level). Average annual precipitation in the southeast portion of the domain can be eight times higher than drier western locations and average daily high temperatures can reach 40°C (Figure 1).

2.2 Climate Projection Datasets

We use one member each from 26 GCMs in the CMIP5 archive to form the GCM multi-model ensemble. To form the downscaled ensemble, the same 26 GCMs are used from the downscaled projections created with the Localized Constructed

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Weighted multi-model means have primarily been focused on GCMs and continental scales. However, the use of climate projections has extended to regional, state, local, and tribal uses for climate impact assessments and adaptation planning. In these regional to local efforts, the raw projection data has been used but also provided to impact models (such as hydrology or crop models). Currently, impact assessments outside the traditional venues of climate modeling tend not to use weighted multi-model means but tend to use unweighted means created using downscaled GCM ensembles. From this study, several questions arise. First, should impact assessments make use of weighted multi-model means? If yes, then a second question is, should multiple weighting schemes and ensemble means be used? Third, for situations where projections are provided to impact models, does this type of study need to be repeated using impact model results? These three questions are also related to the questions mentioned earlier. Should model weights be developed separately when investigating different climate variables? Should model weights be estimated separately when investigating different domains? All such questions could … [1]
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Analogs (LOCA) method (Pierce et al. 2014). The LOCA-downscaled projections have been used in other studies, including the NCA4 (USGCRP, 2017) and Wootten et al. (2020a). CMIP5 GCMs are used in this study because LOCA downscaling with CMIP6 was not available at the time of this writing. Table S1 lists the GCMs used for both the GCM ensemble (hereafter CMIP5 ensemble) and downscaled ensemble (hereafter LOCA ensemble). See Wootten et al. (2020a) for more details on the climate projection datasets.

To facilitate analysis, the data for each ensemble member and the gridded observations are interpolated from their native resolution to a common 10 km grid using a bi-linear interpolation similar to that described in Wootten et al. (2020b). We examine projected daily precipitation (pr) and daily high temperature (tmax) changes from 1981–2005 to 2070–2099 under the RCP 8.5 scenario, which ramps the anthropogenic radiative forcing to 8.5 W/m^2 by 2100. We chose RCP 8.5 to maximize the change signals and allow us to analyze greater differences between weight schemes and downscaling techniques. The historical period (1981–2005) is used for both the historical simulations and observations to facilitate comparisons with other studies (Wootten et al. 2020b) and because the historical period of the CMIP5 archive ends in 2005 (Taylor et al. 2012).

2.3 Observation Data

Many publicly available downscaled projections (including LOCA) are created using gridded observation-based data for training. Gridded observations are based largely on station data that are adjusted and interpolated to a grid in a manner that attempts to account for biases, temporal/spatial incoherence, and missing station data (Behnke et al. 2016; Wootten et al. 2020b; Karl et al. 1986; Abatzoglou, 2013). In this study, we use Livneh version 1.2 (hereafter Livneh [Livneh et al. 2013]), interpolated to the same 10 km grid using bilinear interpolation, as the gridded observation data used for comparison to the ensembles. Livneh is used in part to facilitate any comparisons between this study and the results of Wootten et al. (2020a). The LOCA ensemble used the Livneh data as the training data, so it is expected that LOCA will be more accurate than the CMIP ensemble when compared to the Livneh dataset. While we recognize that different gridded observations and downscaling techniques influence projections of precipitation variables (e.g., number of days with rain, heavy rain events), the effect is minimal on the mean annual precipitation (Wootten et al. 2020b). Therefore, we find it is appropriate to make use of only one statistical downscaling method and one gridded observation dataset.

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2.4 Weighting Schemes

In this analysis, we make use of model weighting schemes detailed in Wootten et al. (2020a) and similar to the weighting schemes applied in Massoud et al. (2020a). The resulting weighting schemes are applied multiple times to complete an experimental matrix allowing for in-depth comparisons of the sensitivity of the ensemble mean to various approaches to deriving and applying the multi-model weights. These weighting methods include the unweighted model mean, the historical skill weighting (hereafter Skill), the historical skill and historical independence weighting (SI-h), the historical skill and

future independence weighting (SI-c), and the Bayesian Model Averaging (BMA) method. All of the methods are calculated in the same manner as in Wootten et al (2020a). In essence, the unweighted strategy takes the simple mean of the entire ensemble. The Skill strategy utilizes each model's skill in representing the historical observations via the root mean square error (RMSE) of the model against the historical observations. The SI-h strategy is the same weighting scheme as shown in Sanderson et al. (2017), creating an independence and skill weight using the historical simulations of each model in an ensemble. To briefly summarize the SI-h (Sanderson et al. 2017) approach, an intermodel distance matrix is calculated using the area-weighted RMSE of each model with the other models and with observations. This distance matrix is used to calculate independence and skill weights, where the distances between one model and every other model are used to calculate the independence weight and the distance between one model and the observations are used to calculate the skill weight. The overall weight given to each model is the product of the skill and independence weights normalized such that all the overall weights for each model sums to one. The SI-c strategy is unique to Wootten et al. (2020a) and modifies the Sanderson et al. (2017) approach to use historical skill to derive the skill component of the weighting and the climate change signal (i.e., the future projections) to derive the independence component of the weighting. To achieve this, the SI-c uses two distance matrices, the first distance matrix (used to calculate the skill weight) is the same as the SI-h, while the second distance matrix (used to calculate the independence weight) is the area-weighted RMSE of the change signals between the models. The overall weights are then calculated in the same way as the overall weights from SI-c. The BMA strategy employs a probabilistic search algorithm to find an optimal set of model weights that produce a model average that has high skill and low uncertainty when compared to the observation and its uncertainty. BMA is an approach that produces a multi-model average created from optimized model weights, which correspond to a distribution of weights for each model, such that the BMA-weighted model ensemble average for the historical simulation closely matches the observational reference constraint. In essence, the close fit to observations is a consequence of applying higher weights on more skillful models. Furthermore, since the BMA method estimates a distribution of model weights, various model combinations become possible, which explicitly takes care of the model dependence issue. The equations for all the weighting schemes used in this study are provided in the supplemental material, and readers are referred to Wootten et al. (2020a) and Massoud et al. (2019, 2020a) for more details on each method.

2.5 Experimental Matrix

Each weighting scheme (Skill, SI-h, SI-c, and BMA) is applied to both ensembles (CMIP5 and LOCA) and three domains (south-central U.S., Louisiana, New Mexico) to fill out an experimental matrix of weights, representing a collection of weighting strategies. As a result, for each weighting scheme (skill, SI-h, SI-c, and BMA) and ensemble (CMIP5 and LOCA), there are six sets of weights produced (i.e., 3 regions and 2 variables). One example of a weighting strategy would be the BMA weighting scheme used on the CMIP5 ensemble trained on tmax for the entire domain. Another weighting strategy example would be a skill-based weighting scheme used on the LOCA ensemble trained on precipitation in Louisiana. There are a total of 48 such model weighting strategies (ensemble choice x variable choice x weighting scheme choice x domain

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choice = 2 x 2 x 3 x 4 = 48). In addition to the set of 48 weighting strategies, an unweighted ensemble mean is also used. The unweighted strategy effectively has equal weights for all models regardless of variable, domain, or ensemble. As such, including an unweighted ensemble mean represents only one additional modeling strategy, which brings the total to 49 model averaging strategies in our experimental matrix.

The various model weights from each scheme are calculated, and the derived sets of weights are then applied to create ensemble means for the three domains and two variables. In other words, a certain set of weights can be used to determine projected changes in either tmax or pr and can be used for any of the domains, the full domain, Louisiana, or New Mexico. There are a total of 288 such maps that can be created to investigate future climate change. These are 48 model averaging choices described above, applied to 2 different variables in 3 different domains, or 48 x 2 x 3 = 288 combinations of maps. This collection of 288 is in addition to the results from unweighted means of temperature and precipitation. Including these unweighted means, there are 290 combinations of maps from this project. This explains the highly dimensional experimental matrix applied in this study, which provides the total uncertainty that is estimated with our future change projections. See Figure 2 for a schematic describing the various choices made to create each model weighting strategy and the choices made to how each of these model weights can be applied. However, we also note that there will be several duplicates in the experiment. For example, when using the same weighting strategy, the resulting ensemble mean in a subdomain will be the same as the resulting ensemble mean in the same portion of the full domain.

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3 Results

This section will first consider the sensitivity of the model weighting schemes to the ensembles, variables, and domains used. This section will then focus on the bias and change signal from the resulting combinations of ensemble means.

3.1 Ensemble weights – results from various model weighting strategies

The resulting sets of model weights for the CMIP5 ensemble based on the weighting scheme, variable, and domain, are shown in Figure 3. The 24 sets of model weights for the LOCA ensemble based on the weighting scheme, variable, and domain, are shown in Figure 4. Alongside the best-estimated weight from the BMA weighting scheme, the box-whisker plots in the image show the spread of weights from the 100 iterations of BMA for each ensemble, variable, and domain to which BMA was applied. The red dots in these figures depict the outliers from the BMA distributions of weights.

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One observation is that the weighting schemes themselves are all sensitive to the ensemble, variable, and domain for which they are derived in terms of which GCMs are given the highest weight. This is reflected further when one considers which models from each ensemble are given the strongest weights by each model weighting scheme (Table 1). From Table 1, no

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model appears in the top three for all weighting strategies. The model most consistently in the top three is the CanESM2, which is in the top three for 35.4% of the 48 weighting strategies.

Although the weighting schemes are sensitive to ensemble, variable, and domain, the weights produced by Skill, SI-h, and SI-c are similar to each other, while the BMA weighting tends to be different. This is particularly true for precipitation and follows what was shown by Wootten et al. (2020a) and Massoud et al. (2020a). The BMA approach provides a distribution of weights for each model and this distribution of weights overlaps the weights of the Skill, SI-h, and SI-c approaches. This distribution of weights covers a broader region of the model weight space, but the best BMA combination (marked as orange squares in Figures 3 and 4) is noticeably different from the other schemes. The BMA best combination is the single set of model weights from the BMA posterior that creates a weighted model average that has the best fit to the observations. Although all the samples of model weights from the BMA posterior have an improved fit compared to the original ensemble mean and provide a range of model weights as shown in the BMA distributions in Figures 3 and 4, the BMA best combination is considered the best of all these samples.

The pattern of the weights, shown in Figures 3 and 4, changes significantly between weighting strategies, particularly among the BMA weights and in the CMIP ensemble. Among the BMA and CMIP5 ensemble combinations (Figure 3), there are no common patterns to the model weights based on domain or variable. However, while the patterns between Skill, SI-h, and SI-c are similar to each other, their magnitude is consistently smaller than BMA. This indicates that when applying different weighting schemes, different models are given higher weights when applying the CMIP5 ensemble for different domains or variables.

When using the LOCA ensemble (Figure 4), there is more consistency in which models are given higher weights, particularly when weights are derived based on high temperature (tmax). For the LOCA ensemble, the distribution of the BMA weights has a similar pattern across all three domains for the tmax derived weights, and the best-weighted models are also somewhat consistent between domains. Similar to the CMIP5 ensemble in Figure 3, the BMA weights tend to be larger for the highest weighted models in the LOCA ensemble compared to those derived with the Skill, SI-h, and SI-c schemes. We speculate that the reason for this is because the Skill, SI-h, and SI-c strategies involve the 'skill' of each model when estimating weights, and since the LOCA downscaled ensemble is bias corrected, most models have similar skill and therefore similar weights. For weights derived with tmax, the Skill, SI-h, and SI-c have very similar patterns for both the full and New Mexico domains. The Skill and SI-h weighting schemes, which focus entirely on the historical period, created nearly identical weights for the 26 models when weights are derived based on tmax in the full and New Mexico domains. While the weights from Skill and SI-h are not identical when derived using tmax in the Louisiana domain, the weights for the LOCA ensemble in Louisiana generally range from 0.025 to 0.050. The SI-c weights derived using tmax in the LOCA ensemble have a similar pattern between the full and New Mexico domains, but a very different pattern in the Louisiana

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domain (Figure 4). In addition, the SI-c also tends to have a different pattern from the Skill and SI-h weights when tmax and LOCA are used for derivation. There is much more sensitivity to domains when using precipitation and the LOCA ensemble to derive weights, compared to that of tmax. Regardless of the weighting scheme, there is no common pattern in the weights between domains when the LOCA ensemble and precipitation are used to derive weights. Again, the BMA scheme applies much larger weights to the top models for precipitation-based LOCA weighting compared to the Skill, SI-h, and SI-c weighting schemes.

The LOCA statistical downscaling method, like most statistical downscaling methods, incorporates a bias correction approach, which inherently improves the historical skill. In addition, the Skill, SI-h, and SI-c methods focus primarily on the first moment of the ensemble distribution when deriving weights, which limits the ability to penalize for co-dependence between models in an ensemble. Finally, the BMA considers multiple moments of the ensemble distribution using multiple samples via Markov Chain Monte Carlo (MCMC), rewarding skillful models and penalizing co-dependency. Of the weighting combinations used here, the BMA tends to be the most sensitive to the ensemble, variable, and domain used to determine weights. Given that the BMA focuses on multiple moments of the distribution and is most sensitive to the different choices considered here (ensemble, variable, and domain) it is plausible that the BMA approach responds to and captures the changes in skill and co-dependence among the ensemble members resulting from these various choices.

3.2 Size of the experimental matrix of model weights and how to apply them

One can apply the 48 weighting combinations described above in a similar manner to the way the weighting combinations themselves are created. For example, one could apply the weights derived from the CMIP5 ensemble precipitation for the full domain using BMA to create a weighted ensemble mean of CMIP5 precipitation for Louisiana. As shown in Figure 2, each weighting combination is applied to the variables (high temperature and precipitation) and domains (full, Louisiana, and New Mexico) to produce a set of ensemble means. Altogether, the maximum number of weighted ensemble means produced with these 48 weighting combinations is 48x2x3=288. However, this maximum number of ensemble means resulting from the experiment contains several duplicates. For example, when using the same set of weights, the resulting ensemble mean in a subdomain will be the same as the resulting ensemble mean from the same portion of the full domain. As such, the actual number of ensemble means in this experiment is smaller than 288.

3.3 Historical Bias and Future Projected Changes in unweighted model ensembles

The figures shown in later sections focus on the ensemble means from the 48 weighting combinations applied to the full domain. The discussion surrounding bias and projected changes represented by the ensemble means in the following subsection will be compared to the unweighted ensemble means of high temperature and precipitation from the CMIP5 and LOCA ensembles. For this reason, we first show the historical ranges and the ranges of the future projected changes using the unweighted model ensemble (Figure 5) before reporting on the results using the weighted ensembles. The unweighted

CMIP5 ensemble as a whole tends to underestimate high temperatures in the historical period, overestimate precipitation in New Mexico, and underestimate precipitation in Louisiana (top left panel of Figure 5). The LOCA ensemble is much closer to the Livneh observations, which is expected given the bias correction applied in statistical downscaling. Yet, for the unweighted LOCA ensemble, there is a tendency to underestimate precipitation in the whole domain and the New Mexico subdomain and to overestimate temperature in all of the domains (bottom left panel of Figure 5). For the future projected changes in the unweighted CMIP and LOCA ensembles, the projected high temperature changes are consistent between ensembles (bottom right panel of Figure 5), and the projected changes in precipitation are less variable in the LOCA ensemble for the New Mexico domain and more variable for the Louisiana domain (top right panel of Figure 5). Given this baseline information, the following subsections discuss and compare the unweighted and weighted ensemble means for each ensemble (CMIP5 and LOCA).

3.4 Historical Bias and Future Projected Changes using the weighted ensembles

The 48 combinations of model weights are then applied across three domains and two variables to produce 288 ensemble means. The mean projected changes can be sensitive to the weighting scheme, domain, and variable used. The future projected changes from the different ensemble means are summarized in Figure 6, where the boxplots represent the range of the ensemble mean change from the 100 BMA posterior weights. When the weighting is derived using tmax, the resulting CMIP5 mean projected change shows predominantly a decrease in precipitation for all domains (top-left group of panels in Figure 6, top row of figures). For the tmax derived weighting with the LOCA ensemble (top right group of panels in Figure 6, top row of figures), the mean precipitation projections are more variable concerning the domain the weighting is applied.

Using weights derived with precipitation and the CMIP5 ensemble, the mean projected precipitation increases/decreases when Louisiana/New Mexico is used to derive weights across all three applied domains (top-left group of panels in Figure 6, bottom row of figures). Using weights with precipitation in the LOCA ensemble, the mean projected precipitation generally decreases for most weighting schemes (top right group of panels in Figure 6, bottom row of figures), except for the resulting means for Louisiana with the BMA weighting scheme. In contrast to precipitation, the ensemble mean changes for tmax are fairly consistent for both CMIP and LOCA ensembles (bottom groups of panels in Figure 6, all rows of figures), with all model weighting strategies indicating a consistent increase in temperature for all domains.

As for the uncertainty in the results, we find in our matrix of results a reduction in the overall uncertainty compared to the spread in the original ensemble. This can be seen when comparing the results of the unweighted (Figure 5) and weighted ensembles (Figure 6). Although the maps of future change and the results from Figure 6 show that the weighted ensemble means have different results based on the weighting strategy used, the overall uncertainty is still reduced when applying model weighting even when considering the many strategies implemented in this study. This is particularly evident when examining the results for those strategies using the BMA weighting scheme (Figure 6).

Aside from the comparisons of the weighted mean change to the raw ensemble change and unweighted mean change, one can consider the magnitude of these means compared to the internal variability of the climate models and intermodel spread of the projected change. The intermodel spread calculated here is represented by the unweighted standard deviation of the projected change of ensemble members. The internal variability is represented by the ensemble average of the standard deviation of each variable from each ensemble member (per Hawkins and Sutton, 2009; 2011). In the case of tmax, the projected changes from each ensemble mean is greater than the internal variability of the models and the intermodel spread regardless of the weighting scheme, ensemble, domain used to derive the weights, or the variable used to derive the weights (Figure 7). In contrast, the differences between weighting strategies do result in some differences in weighted means for the projected change in precipitation that are comparable to the internal variability and intermodel spread. For example, for the CMIP5 ensemble means weighted for Louisiana precipitation and applied to Louisiana precipitation, the difference between the BMA ensemble mean and the unweighted mean is comparable to the intermodel spread and internal variability. In addition, the difference between the BMA ensemble mean created based on Louisiana precipitation and all the weighted ensemble means created based on full domain precipitation is also comparable to the intermodel spread and internal variability. Overall, results in Figure 7 suggest that, in general, the projected changes in temperature are larger than the ensemble spread and the internal variability of temperature, whereas for precipitation, the projected changes are not as great as the original ensemble spread or the internal variability of precipitation.

The following section and corresponding figures compare the results from the various weighting schemes applied in this study. Figure 8 looks at historical biases and Figure 9 shows the projected future change signals in precipitation for the CMIP5 ensemble of models. Figures 10 and 11 look at historical bias and projected future change signals in high temperature for CMIP5. Figure 12 looks at the projected future change signal in precipitation for the LOCA ensemble, and Figure 13 looks at the projected future change signal in high temperature for the LOCA ensemble. For an in-depth analysis of how the model weighting strategies impact the resulting historical bias and climate change signals shown in Figures 8-13, readers are referred to the supplementary section, with a discussion on the main findings reported in the next section. For additional results that complete the analysis, readers are referred to the supplementary section (Figures S1-S6), which includes bias maps from the LOCA ensemble (S1-S2) as well as error distributions from the historical simulations of both ensembles (S3-S6).

4 Discussion

Among climate scientists and the climate modeling community, there is a debate regarding the weighting of multi-model ensembles and, if one does apply weighting, how to do so. This debate includes scientists involved in the development of climate projections for the United States' Fifth National Climate Assessment (US 5th NCA report), as well as other national

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and international assessments. The authors of this study are involved in the development of climate projections for the US 5th NCA report via group discussions on climate modeling, downscaling, and model weighting, and these discussions include the same questions of interest in this study. The debate over climate model weighing, particularly as connected with the NCA, is a main reason that this study investigates an extensive and comprehensive research matrix. Previous studies, such as those of Sanderson et al (2015 and 2017) and Knutti (2017) have focused on the evaluation and application of singular weighting strategies, while other studies have begun to consider the added components of bias correction (Shin et al. 2020), additional approaches to weighting (Brunner et al. 2020b), and the sensitivities of multi-model ensemble weighting in small regions (Kolusu et al. 2021).

This is the first study, to the authors' knowledge, to comprehensively assess the sensitivities of the model weights and resulting ensemble means to the combinations of variables, domains, ensemble types (raw or downscaled), and weighting schemes used for a large and complex region of the United States. The specific weighting schemes used include the Sanderson et al. (2017) approach and the Bayesian Model Averaging (BMA; Massoud et al. 2019, 2020a; Wootten et al. 2020a). The former approach is a prominent weighting scheme used in the Fourth National Climate Assessment, while the BMA is an increasingly prominent technique that will be used to create the projections in the Fifth National Climate Assessment (NCA). The remaining two weighting schemes used are a variation of the Sanderson et al. (2017) method proposed by Wootten et al (2020a) and a common skill weighting approach. These weighting schemes are compared alongside the resulting values from an unweighted ensemble mean, which is the most commonly used from of multi-model ensemble averaging in the literature. Therefore, this study quantifies multiple weighting sensitivities to inform the larger discussion on multi-model ensemble weighting.

4.1 Sensitivities of the Results to the Experimental Design

The results from individual weighting schemes are sensitive to the choice of domain and variable of interest, regardless of whether the ensemble is downscaled or not. However, one can also note that the BMA weighting scheme tends to be more sensitive than the others. As noted by Wootten et al. (2020a) and Massoud et al. (2019, 2020a), the Skill, SI-h, and SI-c weighting schemes focus on the first moment of the distribution of a variable, while the BMA approach focuses on multiple moments of the distribution of weights. The BMA weighting can therefore produce weights that are significantly different from the other schemes. In addition, the BMA will also be more sensitive to the differences between domains and variables that are provided to derive model weighting. This is particularly the case with regards to the CMIP5 ensemble results for both variables but also is evident in the LOCA ensemble results for precipitation. The ensemble weights are most sensitive to the variable and domain using the CMIP5 ensemble and the weights created with the LOCA ensemble are less sensitive. A statistical downscaling procedure reduces the bias of the ensemble members compared to the raw CMIP5 ensemble, which likely results in there being less sensitivity when the LOCA ensemble is used. This is particularly likely for high temperatures, which is traditionally much less challenging for both global models and downscaling techniques to capture.

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We find that, for precipitation, the ensemble mean projected change from a multi-model ensemble is sensitive to the various choices associated with the derivation of model weighting. In contrast, for high temperature, the ensemble mean projected change is less sensitive. The larger domain of the south-central region contains multiple climatic regions. The western portion of the domain includes the arid and mountainous New Mexico and Southern Colorado. The eastern portion of the domain is the much wetter and less mountainous area of Louisiana, Arkansas, and southern Missouri. The complexity of the region presents a challenge to GCM representation of precipitation and temperature. Deriving ensemble weights based on Louisiana precipitation favors models which are wetter while deriving ensemble weights based on New Mexico precipitation favors those models which are drier. This effect translates into the projected changes for precipitation in the CMIP5 ensemble that can reverse the change signal in the domain (Figure 9). The sensitivity for precipitation is evident when precipitation is the focus for deriving model weights, but also present to a lesser degree when high temperature is the focus for deriving model weights. The high temperature changes are also sensitive to the domain when precipitation weighting is used because precipitation-based weighting favors wetter or drier models (Figure 11). In contrast, the high temperature change from the CMIP5 ensemble is much less sensitive when calculated with weights derived from high temperatures. The sensitivity present using the CMIP5 ensemble is less apparent for the projected changes with the LOCA ensemble. LOCA ensemble means derived using the BMA weighting are more sensitive to the variable and domain used to derive weights. The LOCA downscaling, like most statistical downscaling methods, corrects the bias of the CMIP5 ensemble, pushing all models to have similar historical skill. It follows that the BMA weighting is more sensitive to the different choices considered here (ensemble, variable, and domain) and that the BMA weighting responds to and captures changes in skill and co-dependence resulting from the different options of ensemble, variable, and domain. One caveat in this study is that the sub-domains of New Mexico and Louisiana are quite small compared to the resolution of the GCMs in CMIP5. This suggests that natural variability may have had some effect on the results. In future work, the authors will repeat this analysis using the larger regions of the United States used in the National Climate Assessment.

4.2 Consideration of weighting scheme, variables of interest, and domain choice

The questions (Questions 1 and 2) regarding the use of multiple weighting schemes and deriving such schemes with a specific focus on domains or variables of interest are interrelated given the sensitivities of the various weighting schemes to variable and domain. The use of multiple weighting schemes would allow for the sensitivities associated with model weighting to be captured and considered. However, it is important to note that the added value of using multiple weighting schemes may well depend on the domain and variables of interest. Mean projections of temperature are much less sensitive to the weighting scheme used, while mean projections of precipitation are more sensitive, particularly if the domain is very wet or very arid.

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Weighting for a specific variable is a more difficult question. In an impact assessment, one might justifiably argue that one should weigh the ensemble on the specific variable or variables of interest for that assessment. Likewise, for national-level assessments and climate modeling, weighting on specific variables could be used to address the large biases and co-dependencies with respect to that variable among the models and produce ensemble means that reflect the appropriate confidence with regards to that variable. However, temperature, precipitation, and multiple other variables have strong physical relationships and thus are not fully independent themselves. As such, creating separate weights for variables independently may break the physical relationships in resulting ensemble means. Nevertheless, the weighting schemes used in this study have the capacity for multivariate ensemble weighting. As such, in response to Question 1, we have two separate recommendations. For national assessments, we recommend the use of multiple weighting schemes with multiple variables to assess the sensitivity and ultimately reduce the uncertainty for projected mean changes. For individual impact assessments, the focus on individual variables is likely context dependent as individual planning decisions and impact assessments are strongly dependent on the region of interest and local climatic changes. A local/regional assessment often focuses on variables uncommon to climate model evaluations that are (or can be) derived from common variables in climate model evaluations. As such, a stakeholder-specific variable (such as growing season length) has a strong relationship with a common climate variable (such as temperature). With this in mind, weighting used in impact assessments should likely be derived using multiple variables incorporating both common and stakeholder-specific variables to produce relevant analysis for impact assessments and planning. Future work by the authors will explore multivariate ensemble weighting, in part to assess if multivariate weighting results in robust weighting for the variables used while retaining the physical relationships between the variables of interest.

Climate model evaluations and national and international assessments typically focus global or continental areas. However, the individual National Climate Assessment (NCA) regions are climatically very different from each other. The individual GCMs in the CMIP ensemble likely do not have the same performance across all regions and an individual downscaling technique can be evaluated in one of these regions but applied to the entire continental United States or North America. In addition, the regions of Alaska, the U.S. Pacific Islands, and the U.S. Caribbean Islands have vastly different climates to the continental United States. The model weighting for each of these regions will likely be vastly different than the weighting for the continental United States as a whole. Given the different climates across regions, and the sensitivity to that observed in this study, it is recommended that weighting is derived for the NCA regions in addition to what is derived for the continental United States (Question 2). This will allow for larger-scale assessments to account for the ability of the ensemble to reflect the unique climate of these regions while considering the ability of the ensemble to reflect the larger scale patterns which influence the climate in the different subregions. With respect to impact assessments, we have two recommendations with regards to Question 2 because an impact assessment or adaptation planning effort can span a range of spatial scales. Given the observed sensitivities in the weighted means with regard to domain noted by this study, we recommend that impact assessments over larger states or regions using weighted means use a domain focused weighting to capture the needs of the

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planners or stakeholders involved and to capture the climate in the area of interest. However, for smaller states or local municipalities, we do not recommend deriving model weighting based on these small regions. At small scales, the internal variability of a climate model may result in a model having the local climate correct, but the larger climatic patterns represented incorrectly. As such, for impact assessments involving smaller areas, we recommend that model weighting be derived using the larger region that the smaller domain is situated in to avoid the confounding factor of internal variability in model weighting.

4.3 To weigh or not to weigh?

At the time of writing, discussion surrounding the use of weighted multi-model ensembles has been traditionally limited to climate model developers and the production of national or international climate assessments, but is beginning to be used in impact assessments. Among climate model developers, Knutti et al. (2017) argue that model weighting is a necessity in part to account for situations where the model spread in the present-day climatology is massive resulting in some models having biases so large that using an unweighted mean is difficult to justify. In other situations, model interdependence becomes increasingly relevant with the increased use of common code bases across institutions causing unweighted means to be overconfident (Brunner et al., 2020b). This concern was also shared by Wootten et al. (2020a) with respect to the common modeling code base applied in the statistical downscaling process. Based on expert discussions surrounding downscaling and model weighting, the NCA is now considering weighting based on model climate sensitivity as opposed to traditional model weighting approaches.

The results from this study demonstrate that the weights and resulting ensemble means are sensitive to the ensemble (CMIP or LOCA), variable, and domain used. However, the concerns of Knutti et al. (2017) and Wootten et al. (2020a) still stand. An unweighted mean will allow models with large biases and co-dependencies regardless of the domain or variable of interest larger influence in either climate models or impact assessments. For this reason, in response to Question 3, we recommend the use of weighted ensemble means not only for national and international assessments but also for regional impacts assessments and planning. Additionally, given the sensitivities presented in this study (Figures 5-13, sections 4.1 and 4.2), in response to Question 4, we recommend not only that model weighting is applied, but that multiple strategies for model weighting are employed when feasible, to assure that uncertainties from various sources (e.g., weighting strategy used, domain or variable of interest applied, etc.) are considered as there is no 'single answer' for an appropriate weighting strategy. However, we do find that all weighting strategies reduce the uncertainty of the ensemble for projections of precipitation and temperature (Figures 5-6).

4.4 Challenges and Future Work

In this study, we have observed that the weighting schemes and the resulting weighted ensemble means are sensitive to the domain and variable used. From this analysis, our general experience, and previous studies, we have made several

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Weighted multi-model means have primarily been focused on GCMs and continental scales. However, the use of climate projections has extended to regional, state, local, and tribal uses for climate impact assessments and adaptation planning. In these regional to local efforts, the raw projection data has been used but also provided to impact models (such as hydrology or crop models). Currently, impact assessments outside the traditional venues of climate modeling tend not to use weighted multi-model means but tend to use unweighted means created using downscaled GCM ensembles. From this study, several questions arise. First, should impact assessments make use of weighted multi-model means? If yes, then a second question is, should multiple weighting schemes and ensemble means be used? Third, for situations where projections are provided to impact models, does this type of study need to be repeated using impact model results? These three questions are also related to the questions mentioned earlier. Should model weights be developed separately when investigating different climate variables? Should model weights be estimated separately when investigating different domains? All such questions could be considered in terms of climate modeling or broader impact assessments and applications.¶

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The questions regarding the use of multiple weighting schemes and deriving such schemes with a specific focus on domains or variables of interest are interrelated given the sensitivities of the various weighting schemes to variable and domain. The use of multiple weighting schemes would allow for the sensitivities associated with model weighting to be captured and considered. However, it is important to note that the added value of using multiple weighting schemes may well depend on the domain and variables of interest. Mean projections of temperature are much less sensitive to the

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recommendations for both the climate modeling community and the users and stakeholders using climate projections in regional impact assessments to answer our questions in Section 1. These recommendations are briefly summarized in the order of the research questions. First, that model weighting, if used, be derived using both common (e.g., precipitation) and stakeholder-specific (e.g., streamflow) variables to produce relevant analysis for impact assessments or using multiple climate variables relevant for a national assessment region (Question 1). Second, that weighting is derived for individual sub-regions in addition to what is derived for the continental United States or other nations and that weighting for impact assessment is also derived for a domain relevant to the impact assessment (Question 2). Third, that weighted ensemble means should be used not only for national and international assessments, but also for regional impact assessments and planning (Question 3). Fourth, that multiple strategies for model weighting are employed when feasible to ensure that uncertainties from various sources (e.g. weighting strategy used, domain or variable of interest applied, etc.) are considered (Question 4).

The authors recognize that the above recommendations are similar between the community of climate model developers invested in evaluation and assessment generally and the users and stakeholders now using climate projections for local and regional impact assessments. The authors also recognize that implementing such recommendations is more feasible for the former community than the latter. The latter community, users and stakeholders invested in impact assessments and adaptation planning, faces the added challenge that some impact assessments or planning efforts require using climate model projections (or downscaled climate projections) as inputs to additional modeling efforts such as hydrology modeling or crop modeling. While most impact assessments have not incorporated model weighting directly, some are beginning to do so (e.g., Skahill et al., 2021; Amos et al. 2020; Sperna Weiland et al. 2021). Knowing this and the sensitivities that this study demonstrates and the non-linear relationships between climate and impacts models, it is recommended for future efforts to examine the weighting of impacts model outputs from climate model inputs (Question 5). Would weighting based on climate model inputs produce the same result as weighting based on, for example, streamflow output using an ensemble of climate projections as inputs? Given the sensitivities for weighting schemes, variables, domains, and ensembles, we suspect that the weighting would not be the same and that the translation of error and co-dependencies from climate model projections to impacts models (such as a hydrology model) may result in a higher degree of sensitivity with respect to the resulting ensemble mean of stakeholder specific variables (such as streamflow). While there is less capacity among the users of climate projections to address such questions, the boundary organizations in the United States and internationally are developing the capacity to provide or derive ensemble weights with emphasis on the need of stakeholders. Therefore, the questions of sensitivity of weighting schemes and ensemble means bear increasing relevance as the number of users of climate projection output continues to increase.

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5 Conclusions

This study examines the sensitivity of the multi-model ensemble weighting process and resulting ensemble means to the choices of variable, domain, ensemble, and weighting scheme for the south-central region of the US. In general, we see that weighting for Louisiana makes the future wetter and less hot, weighting for New Mexico makes the future drier and hotter, and accounting for the whole domain provides a compromise between the two. In addition, we see that ensemble mean projections for precipitation are more sensitive to the various aspects tested in this study, while ensemble mean projections for high temperature are less sensitive. As such, some domains/variables have uncertain outcomes, regardless of the weighting method. But for other domains/variables, the uncertainty is dramatically reduced, which can be helpful for the assessment of climate models and climate adaptation planning. The sensitivity of precipitation and temperature projections is reduced when LOCA is used, which is likely the result of the bias correction associated with the LOCA downscaling method. In addition, the BMA weighting scheme is more sensitive than the other weighting schemes. BMA's sensitivity is the result of the BMA approach focusing on multiple moments of the distribution to account for model biases and co-dependencies.

Although there is sensitivity associated with the model weighting, efforts using a multi-model ensemble of climate projections should incorporate model weighting. Model weighting still accounts for issues of bias and co-dependence that preclude a model democracy approach to crafting multi-model ensemble means. Incorporating multiple weighting schemes allows for assessing and capturing the sensitivity associated with model weighting to the benefit of both climate modeling efforts and climate adaptation efforts. Given the sensitivity associated with weighting for different variables and domains, one may also consider crafting weighting schemes with a focus on the domains or variables of interest to an application. In addition, since some impact assessments or adaptation planning efforts make use of climate projections as inputs to impacts models (such as hydrology or crop models) there is a need to consider similar research to this study with regards to the direct outputs of impacts models using climate projections.

From the results of our analysis, we summarize our recommendations concerning weighting as follows:

- That model weighting, if used, be derived using both common (e.g., precipitation) and stakeholder-specific (e.g., streamflow) variables to produce relevant analysis for impact assessments or using multiple climate variables relevant for a national assessment region (Question 1).
- That weighting is derived for individual sub-regions in addition to what is derived for the continental United States or other nations and that weighting for impact assessment is also derived for a domain relevant to the impact assessment (Question 2).
- Weighted ensemble means should be used not only for national and international assessments but also for regional impacts assessments and planning (Question 3).

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- Multiple strategies for model weighting are employed when feasible, to assure that uncertainties from various sources (e.g., weighting strategy used, domain or variable of interest applied, etc.) are considered (Question 4).
- Future efforts should examine the weighting of impacts model outputs from climate model inputs (Question 5).

There are a couple of caveats and suggested future research. First, this study makes use of domains that are fairly small where the spatially aggregated internal climate variability is larger than that of a large domain. Second, this study focused on the south-central United States. Future efforts should consider this analysis using larger regions, such as the continental United States and the NCA sub-regions. Future efforts should also consider examining multivariate weighting to account for the physical relationships between variables. Third, this study does assume stationarity in the multi-model ensemble weights and resulting weighted means. Future research will examine the accuracy and sensitivity using a perfect model exercise (such as what is described by Dixon et al. 2016) to test the stationarity assumption associated with ensemble weighting. Finally, in the case of impacts models using climate projections, the weighting of the raw ensemble is likely different from weighting that may be applied using the output from impacts models using the ensemble as input. Given the increasing use of climate model ensembles in impacts models, future efforts should consider a similar investigation to this study using an impacts model. Such future efforts will answer multiple questions regarding the appropriate model weighting schemes, but also provide potential guidance to boundary organizations building capacity to assist in regional and local climate adaptation planning and impact assessments.

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6 Code Availability

R Code to calculate weights associated with the Skill, SI-h, and SI-c weighting and produce all analysis in this study are available from Dr. Wootten on request. Programming code for BMA calculations is available from Dr. Massoud on request.

7 Data Availability

CMIP5 GCM output are available through the Earth System Grid Federation Portal at Lawrence Livermore National Laboratory (https://esgf-node.llnl.gov/search/cmip5/). The LOCA downscaled climate projections for CMIP5 GCMs are available through numerous portals included the USGS Center for Integrated Data Analytics GeoData Portal (cida.usgs.gov/gdp). The Livneh gridded observations are available from the National Centers for Environmental Information (https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.nodc:0129374;view=html).

8 Author Contribution

Dr. Wootten and Dr. Massoud – Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft preparation, Writing – review and editing, Visualization, Validation. Dr. Wootten – Data Curation. Dr. Waliser and Dr. Lee – Supervision, Writing – review and editing.

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9 Competing Interest

The authors declare that they have no conflict of interest.

10 Acknowledgements

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Figures

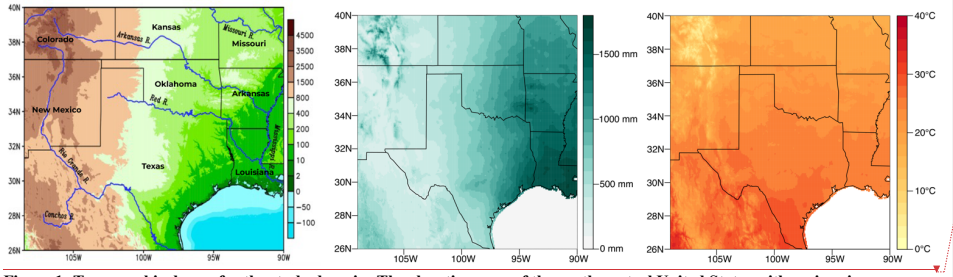

Figure 1: Topographical map for the study domain: The elevation map of the south-central United States with major rivers overlaid on it. Brown/green shading denotes elevation (in units of m), while the rivers are outlined in blue. Topography, bathymetry, and shoreline data are obtained from the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center's ETOPO1 Global Relief Model (Amante and Eakins, 2009). This is a 1 arc-minute model of the Earth's surface developed from diverse global and regional digital datasets and then shifted to a common horizontal and vertical datum. River shapefiles are obtained from the Global Runoff Data Centre's Major River Basins of the World (GRDC 2020). Center — Study domain overlaid with annual average precipitation (mm) from Livneh v. 1.2 (Livneh et al. 2013). Right— Study domain overlaid with annual high temperatures (°C) from Livneh v. 1.2 (Livneh et al. 2013).

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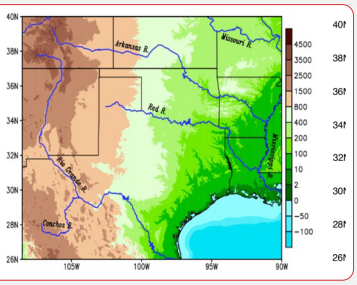

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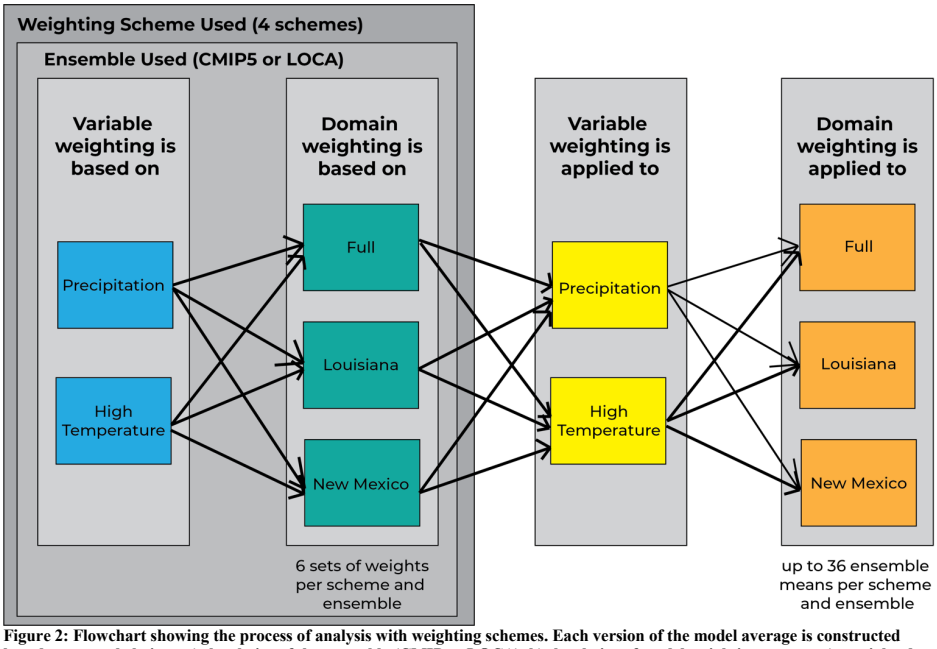

Figure 2: Flowchart showing the process of analysis with weighting schemes. Each version of the model average is constructed based on several choices: a) the choice of the ensemble (CMIP vs LOCA), b) the choice of model weighting strategy (unweighted, Skill, SI-h, SI-c, or BMA), c) the choice of climate variable of interest (precipitation or temperature), and d) the choice of the domain used for the ensemble averaging (entire south-central region, Louisiana, or New Mexico). These various choices give up to 48, plus the unweighted version, so 49 overall choices of model weighting strategies. Then, once the model average is constructed and trained, there is a choice to be made on which variable and which domain to apply this model average to. Therefore, this results in 48 x 2 x 3 = 288 possible future outcomes in our experimental matrix plus 2 unweighted outcomes, for a total of 290 combinations.

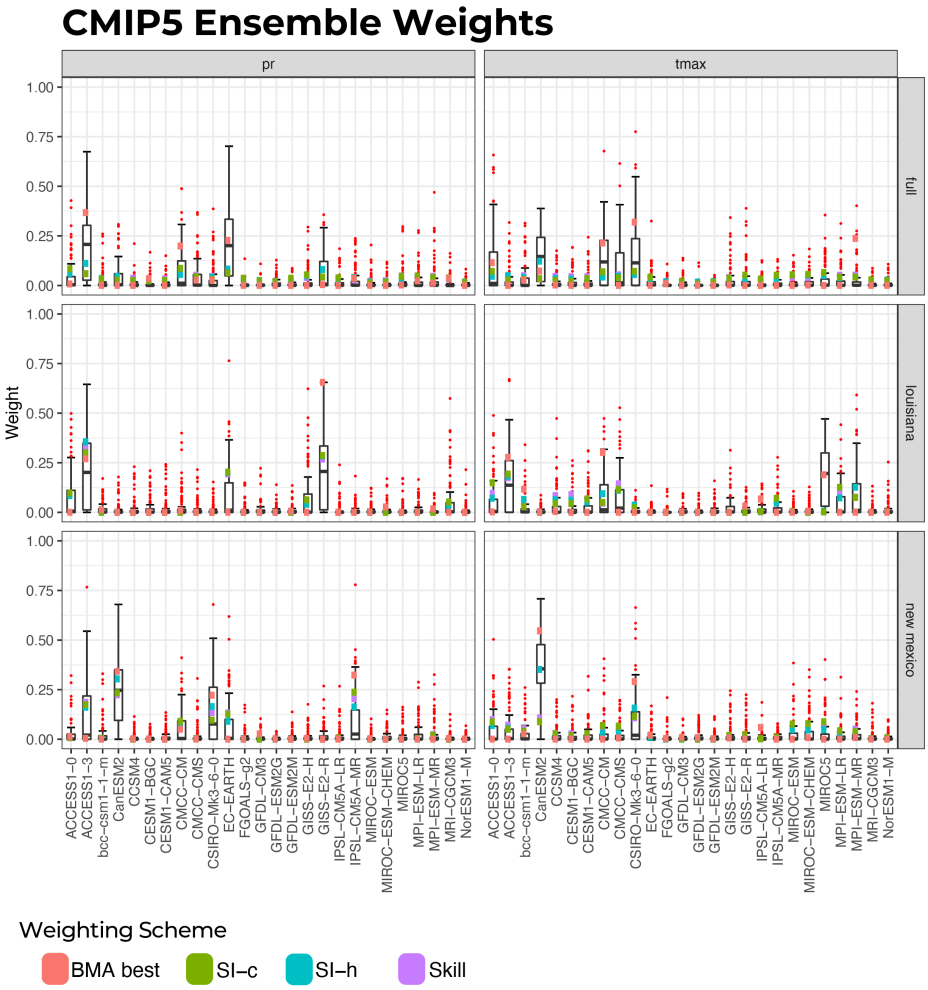

Figure 3: Model Weights for each of the 4 weighting schemes using the CMIP5 ensemble. The left column is weights based on precipitation (pr) alone and the right column is weights based on high temperature (tmax) alone. The top row is weights based on the full domain, the middle row is weights based on Louisiana alone, the bottom row is weights based on New Mexico alone. The boxplots are the spread of weights from the 100 iterations of the BMA weighting scheme. The red dots in these figures depict the outliers from the BMA distributions of weights.

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Figure 4: Same a Figure 3, but for the LOCA ensemble.

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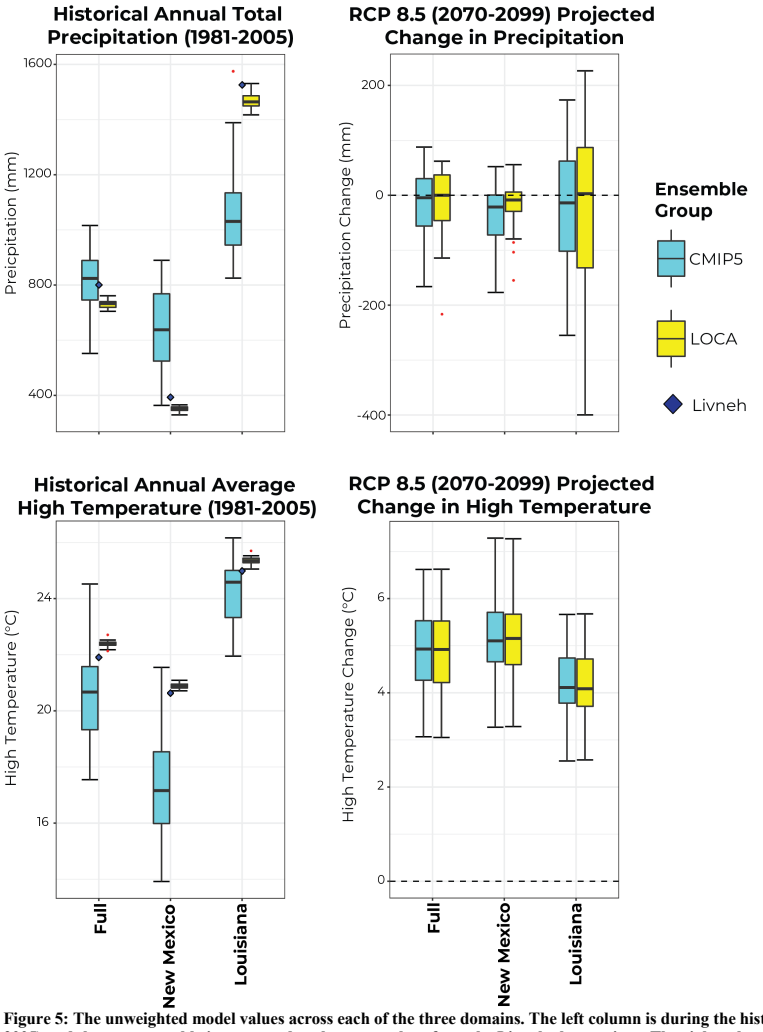

Figure 5: The unweighted model values across each of the three domains. The left column is during the historical period (1981-2005) and the raw ensemble is compared to the same values from the Livneh observations. The right column is the 2070-2099 projected changes under RCP 8.5 from both ensembles. The top row is for precipitation, the bottom row is for high temperature.

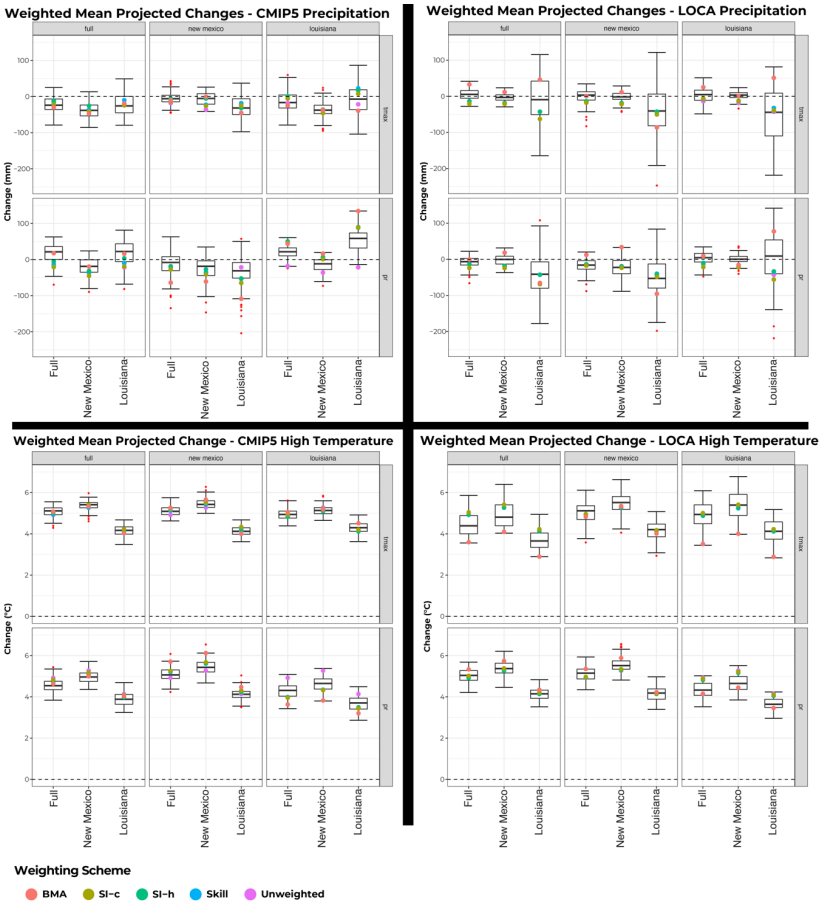

Figure 6: Mean projected changes in temperature and precipitation using all 48 weighting schemes, applied to all three domains and both variables (tmax and pr). The top group focuses on pr, the bottom row focuses on tmax, the left group focuses on the CMIP5 ensemble, and the right group focuses on the LOCA ensemble. In an individual group, the top row is the results from weighting schemes derived with tmax, and the bottom row is the results from weighting schemes derived with pr. In addition, within an individual group, the left column is the results for weighting derived using the full domain, the middle column is the results for weighting derived using the New Mexico domain, and the right column is the results for weighting derived using the Louisiana domain. Within a given domain and variable, the results are shown from left to right for the domain the weights are applied to. The boxplots are the results from the 100 BMA posterior weights.

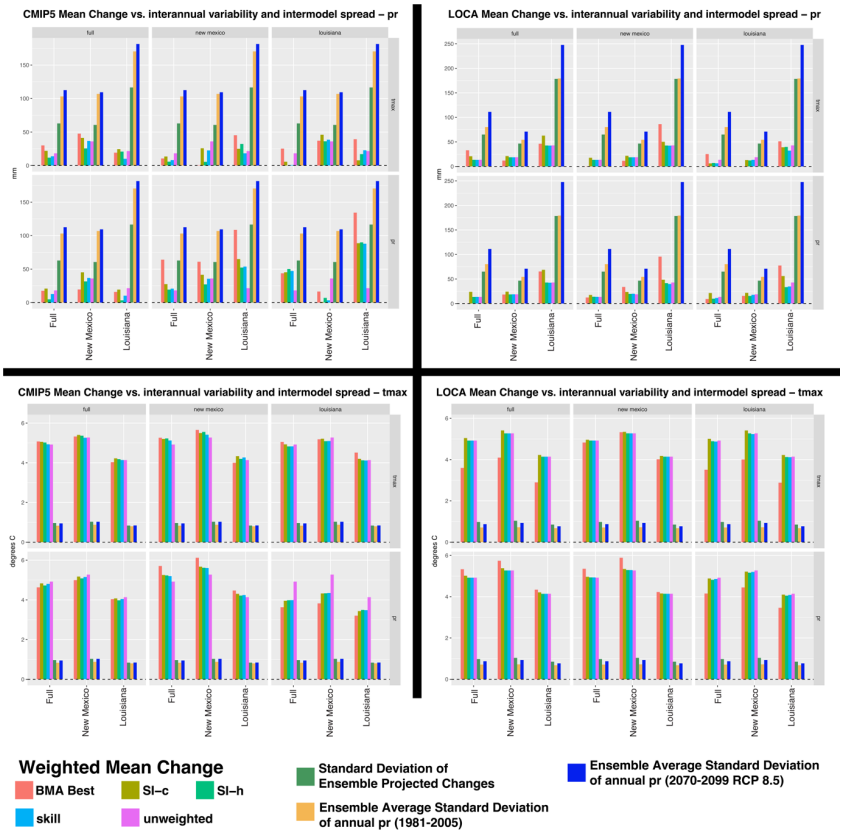

Figure 7: Absolute value of mean projected changes in temperature and precipitation using all 48 weighting schemes, applied to all three domains and both variables (tmax and pr), the standard deviation of the projected changes from the CMIP5 and LOCA ensembles for both variables, and ensemble average standard deviation of annual precipitation and temperature for both the historical and future periods (no weighting is used to calculate any standard deviations). The top group focuses on pr, the bottom row focuses on tmax, the left group focuses on the CMIP5 ensemble, and the right group focuses on the LOCA ensemble. In an individual group, the top row is the results from weighting schemes derived with tmax, and the bottom row is the results from weighting schemes derived with pr. In addition, within an individual group, the left column is the results for weighting derived using the full domain, the middle column is the results for weighting derived using the New Mexico domain, and the right column is the results for weighting derived using the Louisiana domain. Within a given domain and variable, the results are shown from left to right for the domain the weights are applied to.

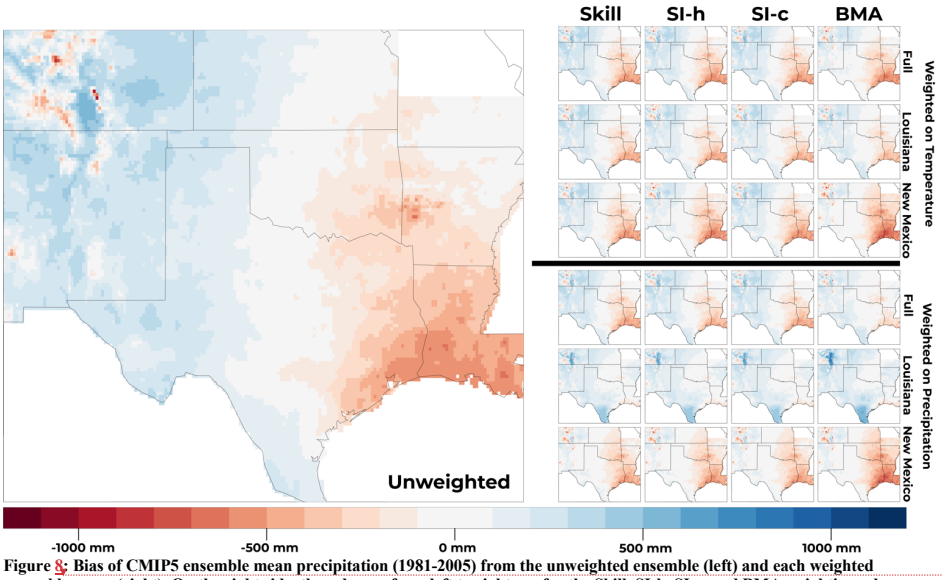

Figure 8: Bias of CMIP5 ensemble mean precipitation (1981-2005) from the unweighted ensemble (left) and each weighted ensemble mean (right). On the right side, the columns from left to right are for the Skill, SI-h, SI-c, and BMA weighting schemes respectively. On the right side, the top group of twelve plots are the results for weights derived using temperature (tmax) and the bottom group of twelve plots are the results for weights derived using precipitation (pr). Within a group of twelve on the right-hand side, the top row is for weights deriving using the full domain, the middle row is for weights derived using the Louisiana domain, and the bottom row is for weights derived using the New Mexico domain.

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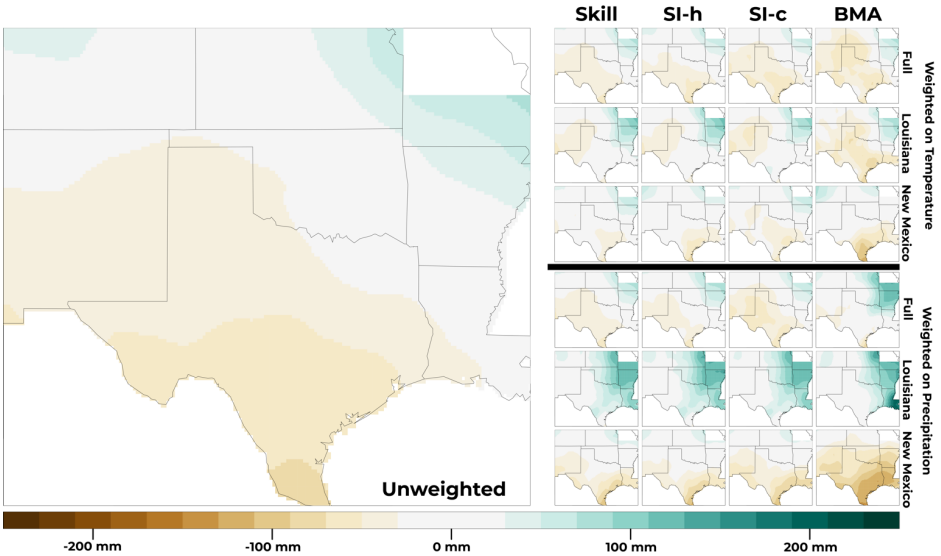

Figure 9: CMIP5 ensemble mean projected precipitation change (2070-2099, RCP 8.5) from the unweighted ensemble (left) and each weighted ensemble mean (right). On the right side, the columns from left to right are for the Skill, SI-h, SI-c, and BMA weighting schemes respectively. On the right side, the top group of twelve plots are the results for weights derived using temperature (tmax) and the bottom group of twelve plots are the results for weights derived using precipitation (pr). Within a group of twelve on the right-hand side, the top row is for weights deriving using the full domain, the middle row is for weights derived using the Louisiana domain, and the bottom row is for weights derived using the New Mexico domain.

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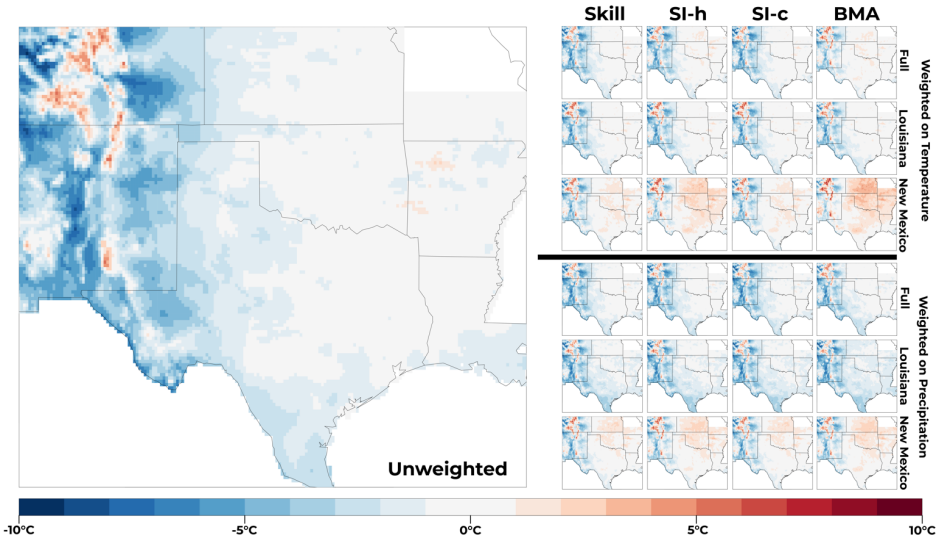

Figure 10: Same as Figure 8, but for the bias of high temperature of the CMIP5 ensemble.

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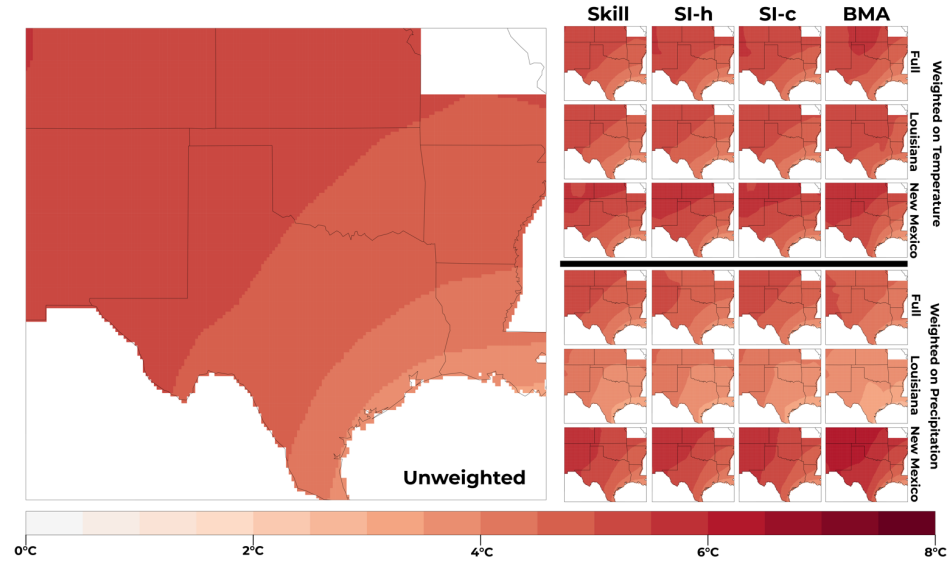

Figure 11: Same as Figure 9, but for the mean projected change of high temperature from the CMIP5 ensemble.

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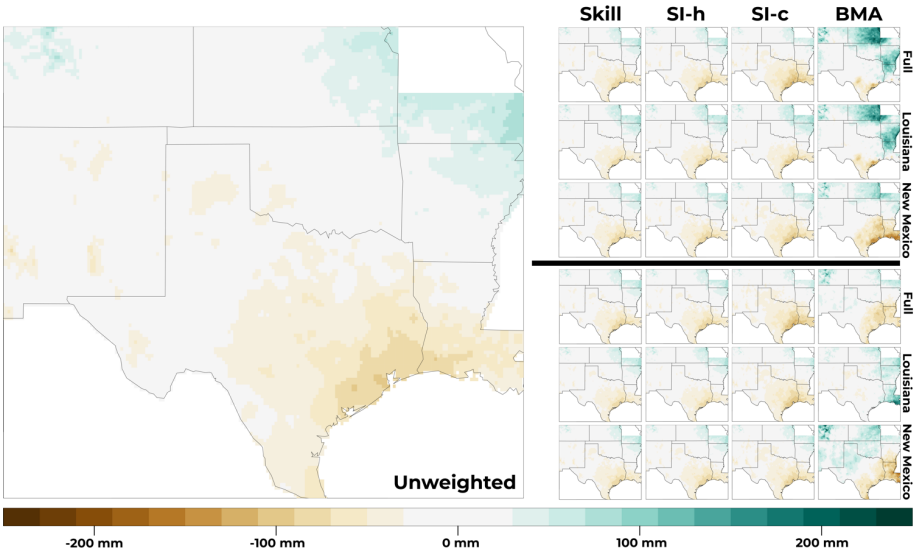

Figure 12: Same as Figure 9, but for the mean projected change of precipitation from the LOCA ensemble.

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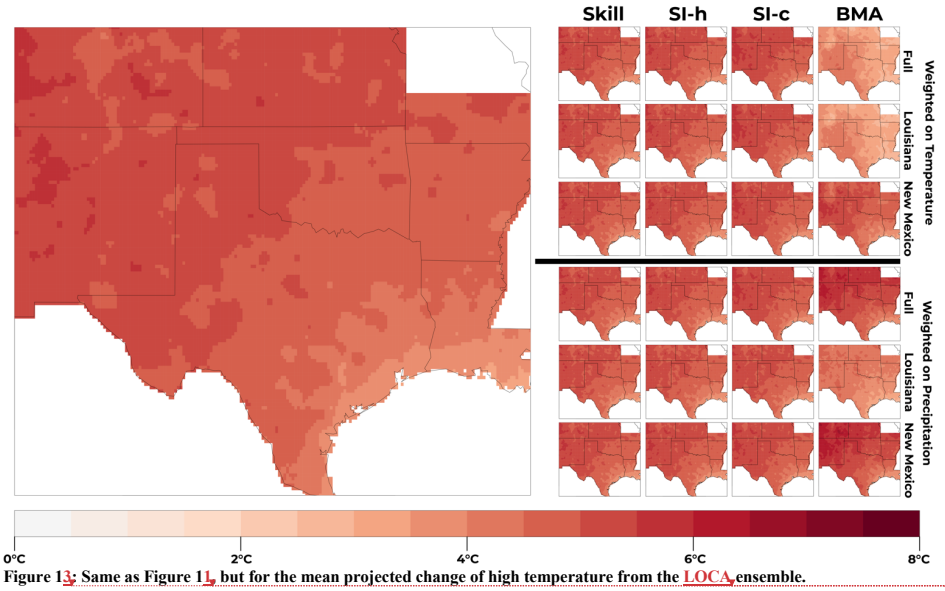

Figure 13: Same as Figure 11, but for the mean projected change of high temperature from the LOCA ensemble.

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Table 1: Top three highest weighted models from each of the 48 weighting combinations.

Domain Weighting is Based On	Variable Weighting is Based On	Ensemble	Skill	SI-h	SI-c	BMA
Full	tmax	CMIP5	ACCESS1-0	CanESM2	CSIRO-Mk3-6-0	CSIRO-Mk3-6-0
			CSIRO-Mk3-6-0	CSIRO-Mk3-6-0	ACCESS1-0	MPI-ESM-MR
			CMCC-CMS	MIROC-ESM	CMCC-CM	CMCC-CM
		LOCA	MRI-CGCM3	MRI-CGCM3	MRI-CGCM3	MRI-CGCM3
			MIROC-ESM	MIROC-ESM	GISS-E2-R	CanESM2
			CESM1-BGC	CESM1-BGC	IPSL-CM5A-MR	FGOALS-g2
	pr	CMIP5	EC-EARTH	ACCESS1-3	CMCC-CM	ACCESS1-3
			CMCC-CM	EC-EARTH	ACCESS1-0	EC-EARTH
			ACCESS1-0	GISS-E2-R	EC-EARTH	CMCC-CM
		LOCA	CESM1-BGC	CanESM2	IPSL-CM5A-MR	MIROC-ESM
			CanESM2	MIROC-ESM	ACCESS1-0	CanESM2
			MIROC-ESM	CESM1-BGC	CMCC-CM	CESM1-BGC
Louisiana	tmax	CMIP5	ACCESS1-3	ACCESS1-3	ACCESS1-3	CMCC-CM
			CMCC-CMS	MPI-ESM-MR	ACCESS1-0	ACCESS1-3
			MPI-ESM-LR	CMCC-CMS	MPI-ESM-LR	MIROC5
		LOCA	MRI-CGCM3	MIROC-ESM	MIROC-ESM-CHEM	MRI-CGCM3
			MIROC-ESM	MRI-CGCM3	MRI-CGCM3	GISS-E2-H
			ACCESS1-3	ACCESS1-3	GFDL-CM3	GFDL-ESM2M
	pr	CMIP5	ACCESS1-3	ACCESS1-3	ACCESS1-3	GISS-E2-R
			GISS-E2-R	GISS-E2-R	GISS-E2-R	ACCESS1-3
			EC-EARTH	EC-EARTH	EC-EARTH	MIROC-ESM-CHEM
		LOCA	CCSM4	GISS-E2-R	GISS-E2-R	CCSM4
			GISS-E2-R	CanESM2	IPSL-CM5A-MR	GISS-E2-R
			GFDL-ESM2M	CCSM4	FGOALS-g2	EC-EARTH
New Mexico	tmax	CMIP5	CanESM2	CanESM2	CSIRO-Mk3-6-0	CanESM2

			CSIRO-Mk3-6-0	CSIRO-Mk3-6-0	ACCESS1-0	CSIRO-Mk3-6-0
			ACCESS1-0	ACCESS1-0	CanESM2	IPSL-CM5A-LR
		LOCA	MRI-CGCM3	MIROC-ESM	MRI-CGCM3	MRI-CGCM3
			MIROC-ESM	MRI-CGCM3	MIROC-ESM	MIROC-ESM
			GISS-E2-H	CanESM2	GFDL-CM3	FGOALS-g2
	pr	CMIP5	CanESM2	CanESM2	IPSL-CM5A-MR	CanESM2
			IPSL-CM5A-MR	CSIRO-Mk3-6-0	CanESM2	IPSL-CM5A-MR
			ACCESS1-3	IPSL-CM5A-MR	ACCESS1-3	CSIRO-Mk3-6-0
		LOCA	MPI-ESM-LR	MPI-ESM-LR	CanESM2	CanESM2
			CanESM2	CanESM2	MPI-ESM-LR	MIROC-ESM
			MIROC-ESM	MIROC-ESM	CMCC-CM	EC-EARTH

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Supplemental Material: To weight or not to weight: assessing sensitivities of climate model weighting to multiple methods, variables, and domains

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S.1 Equations for Weighting Schemes

This section contains the equations for each of the four weighting schemes used in this study. Many of these weighting schemes are drawn from prior literature. As such, they are summarized in the manuscript text, Section 2.4, but the details of the equations are included here. We refer the authors to the prior literature where appropriate for some of the weighting schemes and equations.

S.1.1. Historical Skill and Historical Independence Weighting (SI-h)

The Historical Skill and Historical Independence Weighting (SI-h here and in the main text) is described in full by Sanderson et al. (2017). For full details we refer the reader to Sanderson et al. (2017) and the process and weighting is described here in brief. The SI-h uses a normalized area-weighted root mean square error (RMSE) matrix. This matrix compares the RMSE of each model against the observations (representing the skill) and each model against all other models (representing the independence). Sanderson et al. (2017) uses a normalized matrix for each variable to linearly combine and produce one set of weights. Since this study focused on singular variables independently, and not on a multivariate weighting, we used a single normalized RMSE matrix calculated separately for pr (annual total precipitation) and tasmax (annual average of daily high temperature). As described in Section 2, the weights for each variable are calculated separately.

The normalized area weighted RMSE matrix over the domain is used to calculate separate weights for skill and independence. The independence weights are calculated by first computing a similarity score from the RMSE matrix:

$$S(\delta_{ij}) = e^{-\left(\frac{\delta_{ij}}{Du}\right)^2} \quad (S1)$$

Where S is the similarity score, δ_{ij} is the RMSE between models i and j, and D_u is the radius of similarity. The radius of similarity (Sanderson et al. 2015) is a free parameter that determines the distance over which models are considered similar and are downweighted for co-dependence. For simplicity, we retained the same value for D_u used by Sanderson et al. (2017), $D_u = 0.48$. Given the similarity score for a model I, the effective repetition is calculated as:

$$R_u(i) = 1 + \sum_{j \neq i}^{n} S\left(\delta_{ij}\right) \quad (S2)$$

Where $R_u(i)$ is the effective repetition of model i, and n is the total number of models. The independence weight, w_u, for model i is the inverse of its effective repetition:

$$w_u(i) = \left(R_u(i)\right)^{-1} \quad (S3)$$

The skill weights are also calculated based on the normalized RMSE matrix, specifically, the normalized RMSE of each model against the observations. The skill weight, w_q, for model i is calculated as:

$$w_q(i) = e^{-\left(\frac{\delta_{i,obs)}}{D_q}\right)^2} \quad (S4)$$

Where D_q is the radius of model quality, set to 0.8 to match Sanderson et al. (2017). Finally, the overall weight, w, for model i is calculated as:

$$w(i) = A w_u(i) w_q(i) \quad (S5)$$

Where A is a normalization constant such that the overall weights of all models sum to one.

S.1.2. Historical Skill and Future Independence Weighting (SI-c)

One can argue that downscaling nudges every model toward the historical observations during the historical period because of the bias correction in the statistical downscaling process. As such, one would expect the historical skill of a downscaled ensemble to be high and the independence to be low. The Historical Skill and Future Independence Weighting (SI-c here and in the main text) was designed by Wootten et al. (2020) to account for this feature of statistical downscaling. The SI-c follows the same calculations as the SI-h. However, where the SI-h uses the normalized RMSE matrix of each model against all models in the historical period to calculate independence weights, the SI-c uses a normalized RMSE matrix of the projected change

signal of each model against the other. That is, the independence weighting in the *SI-c focuses on the repetition of the change signal* while the *SI-h focuses on the repetition of the historical climatology*. This is a key difference between the SI-h and SI-c, but the equations are themselves identical between both weighting schemes

S.1.3. Historical Skill Weighting (Skill)

Weighting an ensemble for skill is one of the most well-known approaches to multi-model ensemble weighting. This study makes uses of the normalized area-weighted root mean square error (RMSE) between each model and the observations for the skill weighting. The Skill weighting scheme used here is in essence only the skill component of weighting from Sanderson et al. (2015; 2017) also described in Section S.1.1. After calculating the skill weight for each model *i*, the weights are normalized in the following manner:

$$w(i) = \frac{w(i)}{\sum_{i=1}^{n} w(i)} \quad (S6)$$

Where *n* is the number of models.

S.1.4. Bayesian Model Averaging

Bayesian Model Averaging (BMA) is different from other model averaging methods because it explicitly estimates each model's weight and its uncertainty by maximizing a likelihood function that represents the fit to the historical observations. In other words, BMA provides model weights that produce model combinations with the maximum likelihood of matching the observed data compared to other model combinations. In this study, using the optimized weights, BMA constructs the mean and uncertainty distribution of the climate metric of interest.

Since the BMA method estimates a distribution of model weights, various model combinations become possible, which provides a solution to the model dependence issue. In other words, consider that in the BMA framework there is a hypothetical Model A and a Model B that are similar and therefore not independent. Model A may have higher weights in some combinations, and conversely, Model B might have higher weights in other combinations. Consequently, if both models are rewarded in the same set of weights, it is very likely that each model receives a reduced weight since both models are providing information to the model average. See Supplementary Section 2 of Massoud et al., (2020a) for additional details on how dependence is inferred with the BMA method.

The estimated model weights using BMA are as follows:

$$w_{m,BMA} = [w(m_1), w(m_2), \ldots, w(m_k)] \quad (S7)$$

where $w(m_i, i = 1, 2, 3, \ldots, k)$ represents the optimized weights of K models after fitting the observations using the likelihood function. The range of $w(m_i)$ is between 0 and 1, with a weight of 0 for models that do not contribute any information and a weight of 1 for models that fully contribute to the projection. The sum of a given combination of model weights is equal to 1. The final estimates of the BMA model weights, or $w_{m,BMA}$ in Eq. (*S*7), are utilized to constrain the spread of uncertainty in the projected end of century climate.

Our likelihood function is set up here as:

$$L(w_{m,BMA}) = -\frac{1}{2}\sum_{i,j}\left[Y_{ij} - X_{ij}(w_{m,BMA})\right]^2 \quad (S8)$$

where *i, j* refers to the longitudinal and latitudinal indices of grids on the map; $Y(i, j)$ is the observed climate metric at grid *i, j*; and $X(i, j)$ is the BMA-weighted model ensemble average of the climate metric at grid *i, j*. We apply heavy sampling on the possible model weight combination in search of model weights that maximize the likelihood function in Eq. (*S*7), which allows for the estimation of the optimized model weights, or $w_{m,BMA}$ in Eq. (*S*8).

S.2 Maps from the CMIP5 ensembles - precipitation

Among the 288 ensemble means created from this experimental setup, there are numerous times when results are duplicated. For example, applying a given weighting combination created using the full domain to Louisiana would have the same value as the same weighting combination created using the full domain applied to the full domain and examining only the Louisiana area. As such, the results in this and the following sections will focus only on those ensemble means created from the various combinations of weighting schemes applied to the full domain for each ensemble. In this way, one can then examine the effects for the Louisiana and New Mexico domains and other regions of the full domain.

The bias for the CMIP5 ensemble means of precipitation are shown in Figure 8, and they depict the influence of the different weighting schemes. For reference, the precipitation bias of the unweighted ensemble mean shows a tendency to overestimate precipitation in the western portion of the domain and underestimate in the eastern portion of the full domain (Figure 8, larger map on the left). For those ensemble means created with temperature-derived weights (Figure 8, group of maps in the

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top right), the pattern of bias in precipitation remains consistent but changes in magnitude compared to the unweighted scheme. When weighted for the full domain (Figure 8, group of maps in the top right, top row of figures), the bias pattern of precipitation is similar. When weighted for high temperatures in Louisiana (Figure 8, group of maps in the top right, middle row of figures), the magnitude of underestimation of precipitation in the eastern portion of the domain is smaller. In contrast, when weighted for high temperatures in New Mexico (Figure 8, group of maps in the top right, bottom row of figures), precipitation is underestimated by a larger amount in the eastern portion of the domain compared to the full domain temperature weighting. When precipitation is used to derive the weights (Figure 8, group of maps in the bottom right), the resulting ensemble mean of precipitation is sensitive to the domain used for the weighting. When the full domain precipitation is used for weighting (Figure 8, group of maps in the bottom right, top row of figures), the ensemble mean shows a consistent pattern to the bias of the unweighted ensemble mean. Additionally, the magnitudes of the bias in the full domain are decreased using the BMA weighting scheme, which agrees with the results from Wootten et al. (2020a). When weighted for precipitation in Louisiana (Figure 8, group of maps in the bottom right, middle row of figures), the precipitation bias of the ensemble mean is overestimated across much of the larger domain with a lower bias in Louisiana. In contrast, when weighted for precipitation in New Mexico (Figure 8, group of maps in the bottom right, bottom row of figures), the precipitation bias of the ensemble mean is underestimated across much of the larger domain, particularly in the eastern portion of the domain and when using the BMA weighting.

The future projected change maps of precipitation for the CMIP5 ensemble, shown in Figure 9, are also sensitive to the weighting combination used. The unweighted CMIP5 ensemble mean (Figure 9, larger map on the left) projects a decrease in precipitation across much of Texas and New Mexico, with increases in precipitation projected in the northeast portion of the domain. When weighted for high temperature in the full domain (Figure 9, group of maps in the top right, top row of figures), the pattern remains consistent for each ensemble mean, with an expansion of projected decreases into the northern portion of the domain with the BMA weighting. The area of projected decreases shrinks for three out of four weighting schemes (all schemes except the BMA method) when high temperatures in Louisiana are used to derive the weights (Figure 9, group of maps in the top right, middle row of figures). Using BMA and Louisiana high temperatures to derive the ensemble weighting, the ensemble mean has a similar pattern and magnitude to the ensemble mean created with BMA weights derived using high temperatures in the full domain. In contrast, using New Mexico's high temperatures to derive ensemble weights (Figure 9, group of maps in the top right, bottom row of figures) causes the area of projected decreases in the ensemble mean to shrink to a region along the Gulf Coast, with projected increases in the northeast and northwest corners. Using precipitation in the full domain to derive ensemble weights (Figure 9, group of maps in the bottom right, top row of figures), three of the four weighting schemes have a similar pattern to the unweighted mean, while the BMA weighted ensemble mean has a much weaker drying signal and a large increase in precipitation in the northeast corner of the domain. The greatest contrast between the CMIP5 ensemble means exists between the means created with weights based on Louisiana and New Mexico precipitation (Figure 9, group of maps in the bottom right, middle, and bottom row of figures).

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When Louisiana precipitation is used to derive ensemble weights (Figure 9, group of maps in the bottom right, middle row of figures), the ensemble mean shows an increase in precipitation across the eastern portion of the domain. The greatest increase in precipitation is in the northeast corner of the domain for three of four weighting schemes, while the greatest increase in the ensemble mean using the BMA weighting derived with Louisiana precipitation is actually in Louisiana. The ensemble mean created with weights derived from New Mexico precipitation (Figure 9, group of maps in the bottom right, bottom row of figures) projects a decrease in precipitation across New Mexico, much of Texas, and all of Louisiana with three out of four weighting schemes. When BMA weights are derived using New Mexico precipitation, the resulting ensemble mean projects a decrease in precipitation across the entire domain, with the greatest magnitude along the Gulf Coast.

S.3 Maps from CMIP5 ensembles – high temperature

There is more consistency in the historical bias and future projected changes of the weighted CMIP5 ensembles of high temperatures, shown in Figure 10, compared to that of precipitation, and these weighted ensembles are less sensitive to the various weighting combinations. The bias of the unweighted CMIP5 ensemble mean high temperature (Figure 10, larger map on the left) shows a tendency to underestimate high temperatures in the western portion of the domain except for some mountainous regions where the bias is variable. When weights are derived using high temperatures in either the full domain or Louisiana (Figure 10, group of maps in the top right, top, and middle row of figures), the pattern remains similar to the unweighted mean regardless of the weighting scheme used. The ensemble means tend to overestimate temperatures east of the Rocky Mountains when the ensemble weights are derived using New Mexico high temperatures (Figure 10, group of maps in the top right, bottom row of figures). When using precipitation in the full domain to derive the ensemble weights (Figure 10, group of maps in the bottom right, top row of figures), the bias for the resulting ensemble means is similar to the unweighted mean, but the high temperature is broadly underestimated when Louisiana precipitation is used to derive ensemble weights (Figure 10, group of maps in the bottom right, middle row of figures). In contrast, when New Mexico precipitation is used to derive ensemble weights (Figure 10, group of maps in the bottom right, bottom row of figures), high temperatures east of the Rocky Mountains are overestimated, particularly in the northeastern portion of the region. However, the magnitude of the overestimate is not as large as the overestimate of high temperatures when the New Mexico high temperatures are used to derive ensemble weights.

As with the high temperature bias, Figure 11 shows that the future projected changes in high temperature in the resulting ensemble means are less sensitive than projected changes in precipitation with the CMIP5 ensemble (i.e. plots in Figure 9). If the full domain precipitation (Figure 11, group of maps in the bottom right, top row of figures) or high temperature (Figure 11, group of maps in the top right, top row of figures) are used to derive the ensemble weights, the ensemble mean change from three out of four weighting schemes tends to have a similar pattern to the unweighted ensemble mean. The weighting with BMA using the full domain high temperatures results in a similar pattern of projected changes in high temperature but

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concentrates the greatest changes in the northern portion of the domain. Similarly, the weighting with BMA using the full domain precipitation results in a similar pattern of projected changes in high temperature but concentrates the greatest changes on the western edge of the domain. The projected changes in high temperature are larger, particularly in the northwest corner of the domain with BMA, when New Mexico high temperatures (Figure 11, group of maps in the top right, bottom row of figures) or precipitation (Figure 11, group of maps in the bottom right, bottom row of figures) are used to derive ensemble weights. The greatest projected changes in high temperature are in the ensemble mean when created using weights derived with New Mexico precipitation and the BMA weighting scheme. With regards to the Louisiana domain (Figure 11, group of maps in the bottom right, middle row of figures), there is a notable difference in the projected change in high temperature. When the high temperatures in Louisiana are used to derive ensemble weights, the projected high temperature changes follow a similar pattern to the unweighted ensemble mean, however, the projected high temperature changes are less than the unweighted mean and the other ensemble means.

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S.4 Maps from the LOCA ensembles – precipitation and high temperature

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Previous work by Wootten et al. (2020a) has shown that the future projected changes from a resulting ensemble mean can be sensitive to whether or not downscaling was used in the ensemble. In addition, downscaling also reduces the bias of the individual members of a GCM ensemble. The bias reduction resulting from the LOCA downscaling of precipitation projections is demonstrated by the comparison between Figure S1 to Figure 8. The bias reduction resulting from the LOCA downscaling of high temperature projections is demonstrated by the comparison between Figure S2 to Figure 10. For both variables, the use of downscaling demonstrably reduces the bias of the ensemble across all three domains (Figures S3-S6). As such, the results in this section will focus on the projected changes of high temperature and precipitation using the downscaled LOCA ensemble.

The precipitation future projected change from the unweighted mean for the LOCA ensemble is shown in Figure 12 (larger map on the left), and displays a similar pattern to the unweighted CMIP5 ensemble (from Figure 9), with a decrease in precipitation projected along the Gulf Coast and a projected increase in the northeast corner of the domain. When weighting is based on high temperature in all three domains (Figure 12, group of maps in the top right), the projected change in precipitation is similar to the unweighted ensemble mean (with some changes in magnitude) for all of the weighting schemes except for BMA. When weighting is based on the full domain and Louisiana high temperatures with the BMA weighting scheme, the LOCA ensemble mean projects an increase in precipitation across much of the eastern and northern portions of the domain, and any area showing a projected decrease is confined to southern Texas. When weighting is derived using New Mexico high temperatures and the BMA weighting scheme, the same region of southern Texas is projected to see decreases in precipitation as the unweighted version and with a larger magnitude. However, when looking at this scheme, the projected increases in rainfall are primarily in the northern area of the domain with lesser magnitude than other BMA weighted means weighted based on high temperature. When using the full domain precipitation to derive ensemble weights (Figure 12, group

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of maps in the bottom right), the resulting ensemble mean precipitation changes are similar to the unweighted precipitation change, though the BMA weighted version also includes a greater increase in precipitation in the northwest corner of the domain. When weighted on precipitation in New Mexico or Louisiana with the LOCA ensemble (Figure 12, group of maps in the bottom right, middle, and bottom row of figures), the ensemble means for three of the four weighting schemes have a similar projected change to the unweighted ensemble mean. When the ensemble weights are derived using Louisiana precipitation with the BMA weighting scheme, the resulting LOCA ensemble mean projects an increase in precipitation in the eastern portion of the domain, with little to no change in other parts of the domain. The BMA weighted mean of the LOCA ensemble projects a decrease in precipitation along the Gulf Coast and Louisiana and an increase across much of the rest of the domain when New Mexico precipitation is used to derive weights.

The unweighted mean high temperature change for the LOCA ensemble, shown in Figure 13 (larger map on the left) is similar to the CMIP5 ensemble (from Figure 11). For three out of four weighting schemes (all schemes except BMA), the resulting ensemble mean projected change for high temperature tends to be similar to that of the unweighted ensemble mean. However, the resulting LOCA ensemble mean created with the BMA weighting is sensitive to the domain and variable used to derive weights. When the full domain or Louisiana high temperatures are used with BMA to derive model weights (Figure 13, group of maps in the top right), the mean projected high temperature changes are demonstrably cooler across the entire domain, particularly in the northwest corner of the domain. When New Mexico high temperatures are used to derive the BMA weights, the gradient of the projected change remains consistent except for a cool pocket in southern Colorado and northern New Mexico. In contrast, when the full domain or New Mexico precipitation are used with BMA to derive ensemble weights for the LOCA ensemble (Figure 13, group of maps in the bottom right), the projected changes in high temperature are warmer than the unweighted mean, particularly in the northwest corner of the domain. However, when Louisiana precipitation is used to derive ensemble weights with BMA, the mean change from the LOCA ensemble is cooler than the unweighted mean for much of the domain.

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Supplemental Tables and Figures

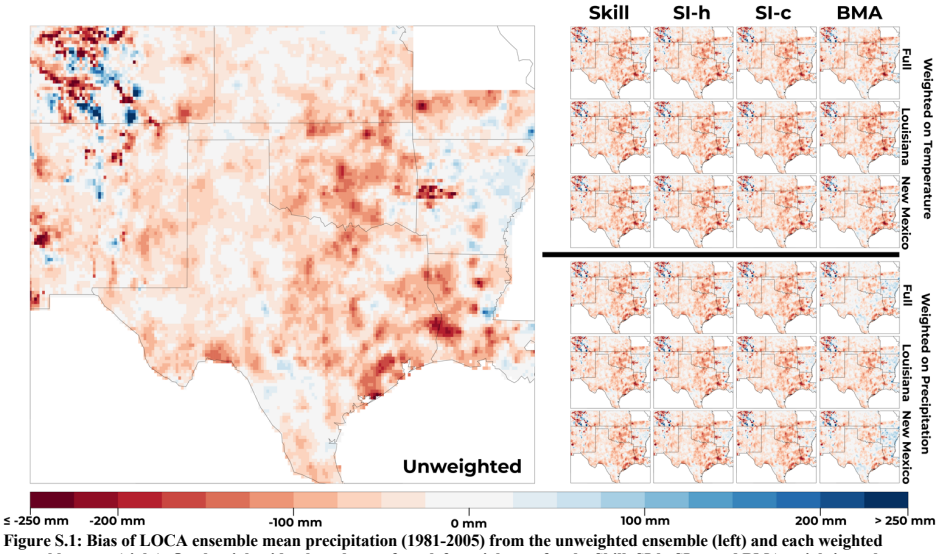

Figure S.1: Bias of LOCA ensemble mean precipitation (1981-2005) from the unweighted ensemble (left) and each weighted ensemble mean (right). On the right side, the columns from left to right are for the Skill, SI-h, SI-c, and BMA weighting schemes respectively. On the right side, the top group of twelve plots are the results for weights derived using temperature (tmax) and the bottom group of twelve plots are the results for weights derived using precipitation (pr). Within a group of twelve on the right-hand side, the top row is for weights deriving using the full domain, the middle row is for weights derived using the Louisiana domain, and the bottom row is for weights derived using the New Mexico domain.

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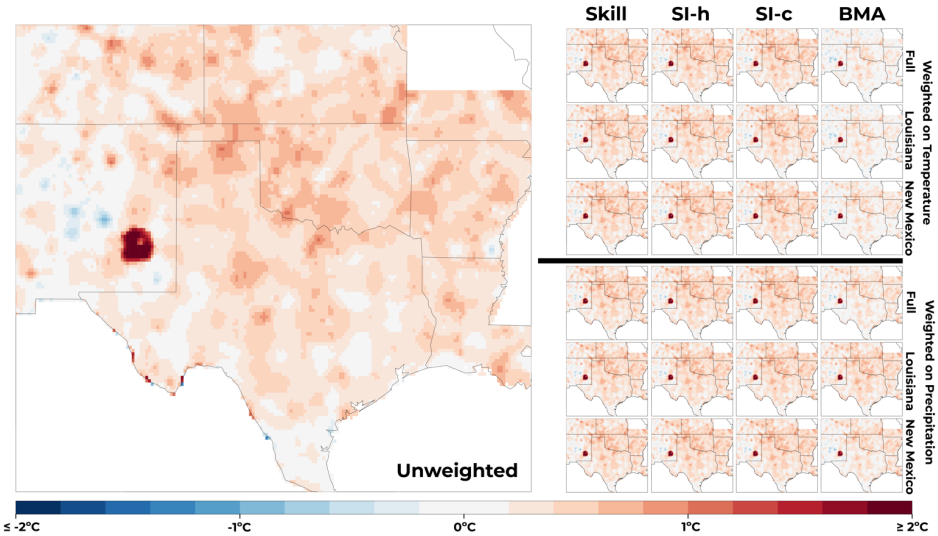

Figure S.2: Same as Figure S1, but for the bias of ensemble mean high temperature of the LOCA ensemble.

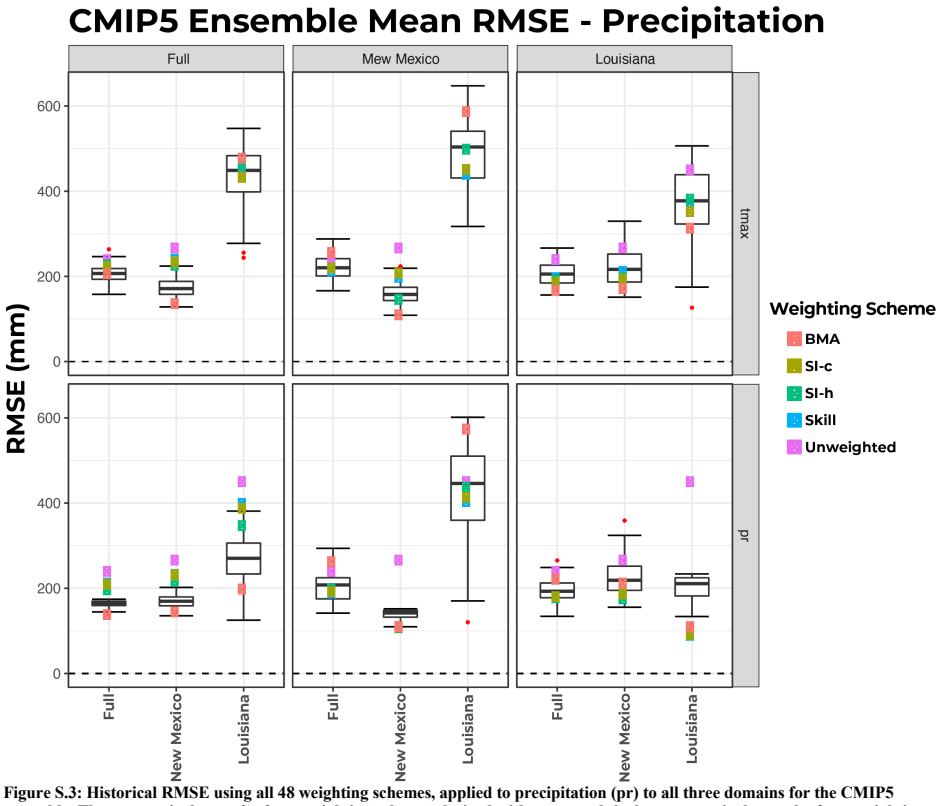

Figure S.3: Historical RMSE using all 48 weighting schemes, applied to precipitation (pr) to all three domains for the CMIP5 ensemble. The top row is the results from weighting schemes derived with tmax, and the bottom row is the results from weighting schemes derived with pr. The left column is the results for weighting derived using the full domain, the middle column is the results for weighting derived using the New Mexico domain, and the right column is the results for weighting derived using the Louisiana. Within a given domain and variable, the results are shown from left to right for the domain the weights are applied to. The boxplots are the results from the 100 BMA posterior weights, with red dots used to represent outliers.

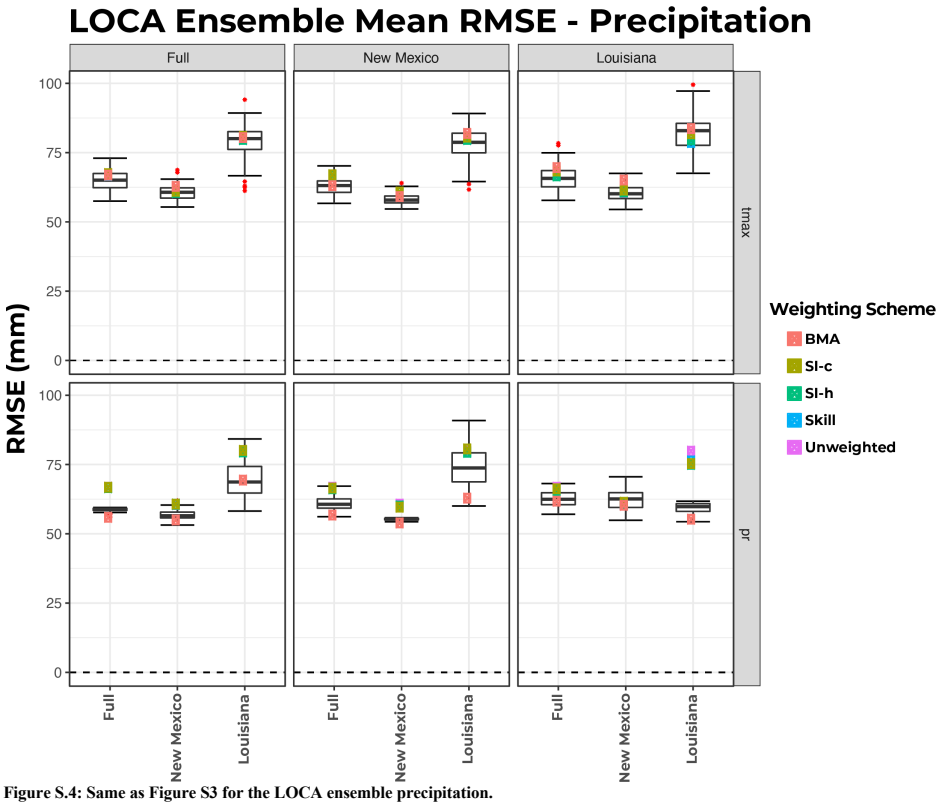

Figure S.4: Same as Figure S3 for the LOCA ensemble precipitation.

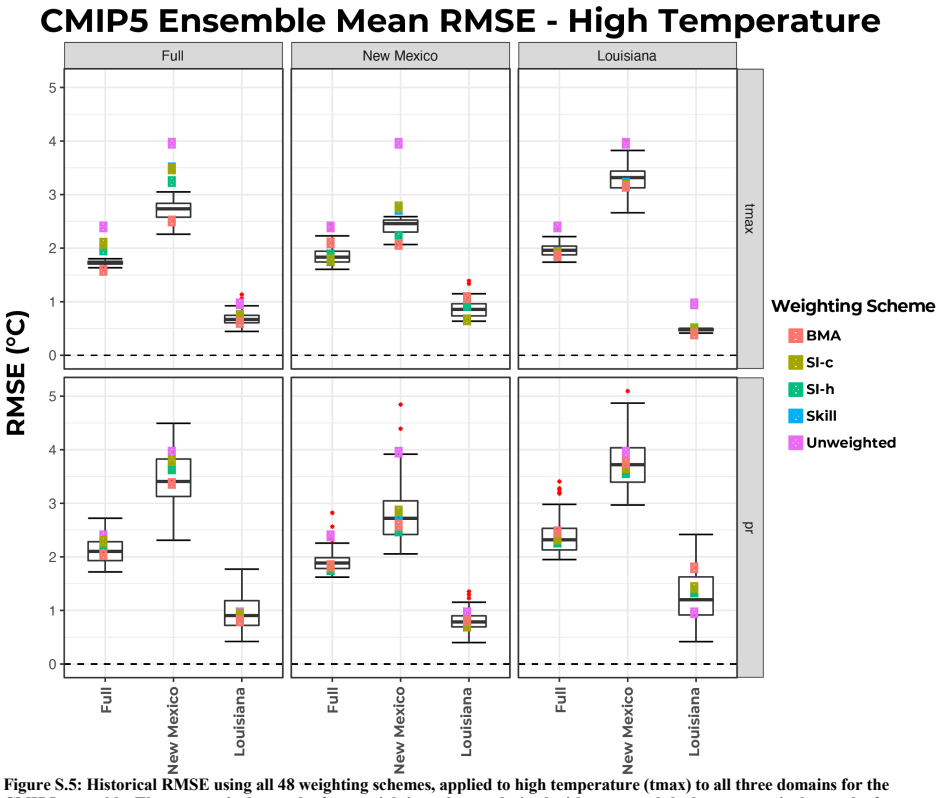

Figure S.5: Historical RMSE using all 48 weighting schemes, applied to high temperature (tmax) to all three domains for the CMIP5 ensemble. The top row is the results from weighting schemes derived with tmax, and the bottom row is the results from weighting schemes derived with pr. The left column is the results for weighting derived using the full domain, the middle column is the results for weighting derived using the New Mexico domain, and the right column is the results for weighting derived using the Louisiana. Within a given domain and variable, the results are shown from left to right for the domain the weights are applied to. The boxplots are the results from the 100 BMA posterior weights, with red dots used to represent outliers.

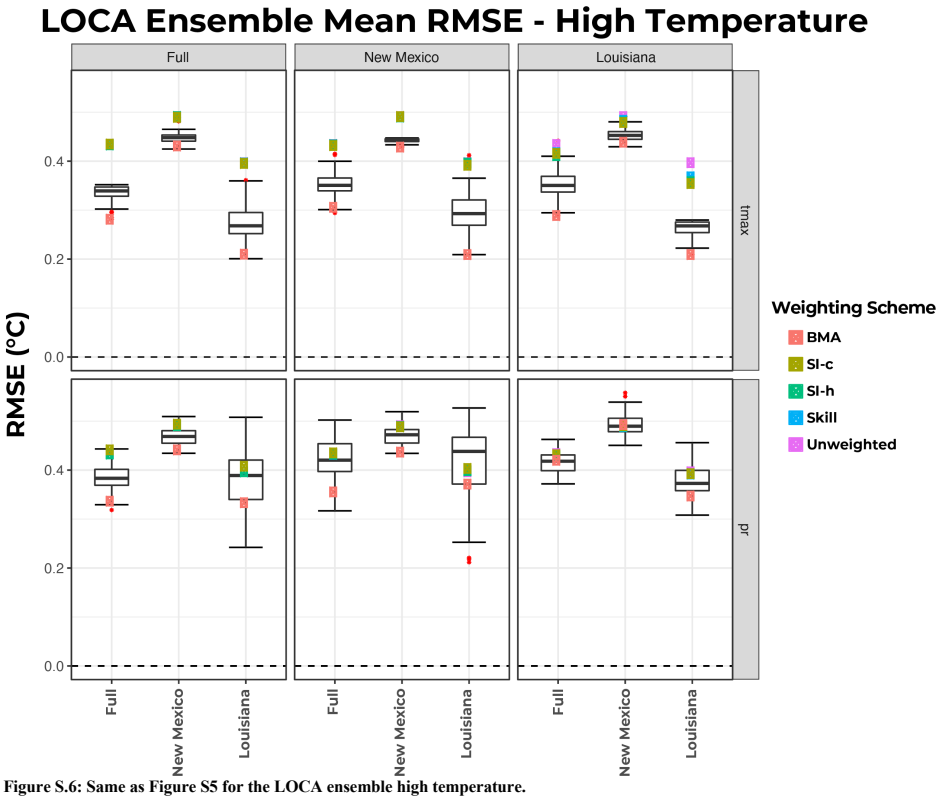

Figure S.6: Same as Figure S5 for the LOCA ensemble high temperature.

Table S1. Global Climate Models used to create both the CMIP5 and LOCA ensembles (adopted from Wootten et al. 2020a).

Modeling Center or Group	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1-0
		ACCESS1-3
Beijing Climate Center, China Meteorological Administration	BCC	bcc-csm1-1-m
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1-BGC
		CESM1-CAM5
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CM
		CMCC-CMS
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3-6-0
EC-EARTH consortium	EC-EARTH	EC-EARTH
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	LASG-CESS	FGOALS-g2
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3
		GFDL-ESM2G
		GFDL-ESM2M
NASA Goddard Institute for Space Studies	NASS GISS	GISS-E2-H
		GISS-E2-R
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR
		IPSL-CM5A-MR
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5

Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM-CHEM
		MIROC-ESM
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-LR
		MPI-ESM-MR
Meteorological Research Institute	MRI	MRI-CGCM3
Norwegian Climate Centre	NCC	NorESM1-M