Blending Ensembles of Regional Climate Model Predictions

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The Economist

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It's hard to make predictions - especially about the future.

Yogi Berra

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Regional Climate Models (RCM) produce a "dynamic downscaling" of the output of GCMs. They simulate relatively short-term atmospheric and land-surface processes and the interactions between the two, at a spatial resolution of about 50 km.

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In this talk we focus on the multi-model uncertainty.

Model Assessment

Denote as $F(\boldsymbol{\theta})$ the output from a computer model depending on parameter $\boldsymbol{\theta}$. let Y denote a set of observations corresponding to $F(\boldsymbol{\theta})$.

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The traditional setting for assessment and calibration of a computer model assumes that both, model and observations provide information about a true, unobserved quantity, say ξ. Then

$$Y = \xi + \varepsilon, \quad \text{and} \quad F(\boldsymbol{\theta}) = \xi + \delta$$

where ε is observational error and δ is model discrepancy.

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- Estimation of $\boldsymbol{\theta}$ provides a calibration of the model.
- Estimation of ξ provides information about the property of interest, using both simulations and observations.

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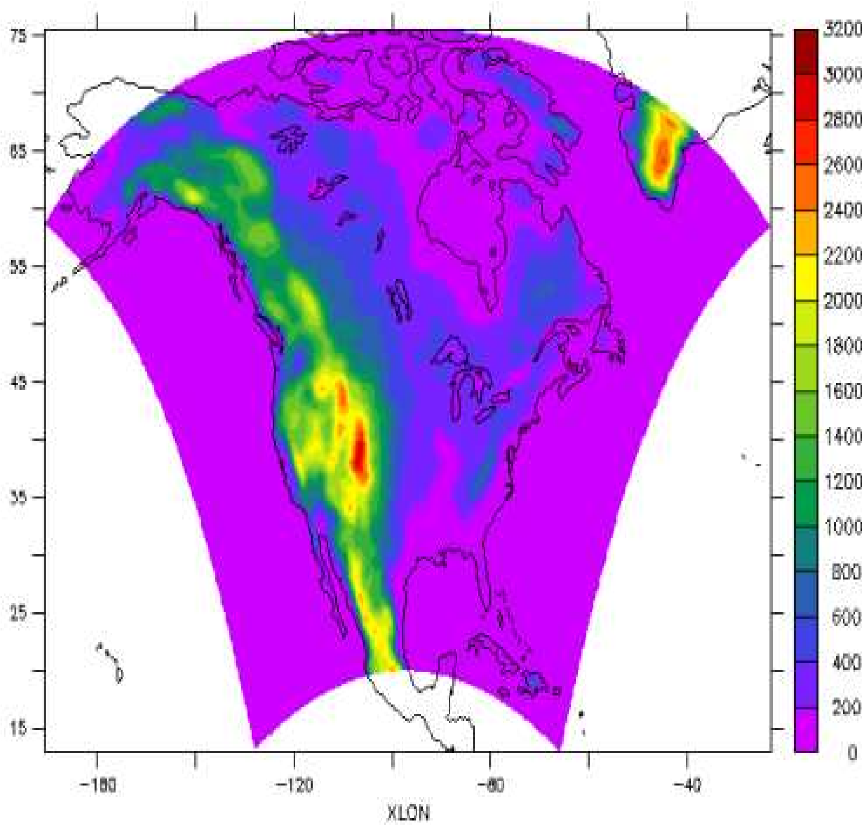
To tackle this issue we can:

- Average over large areas and time spans.
- Consider large scale summaries of the spatial and temporal fields, i.e. trends, cycles, patterns, indexes.
- Use Space-time models for smoothing.

NARCCAP Domain



- NARCCAP is a program to produce high resolution climate change simulations over the US, Canada and Mexico.

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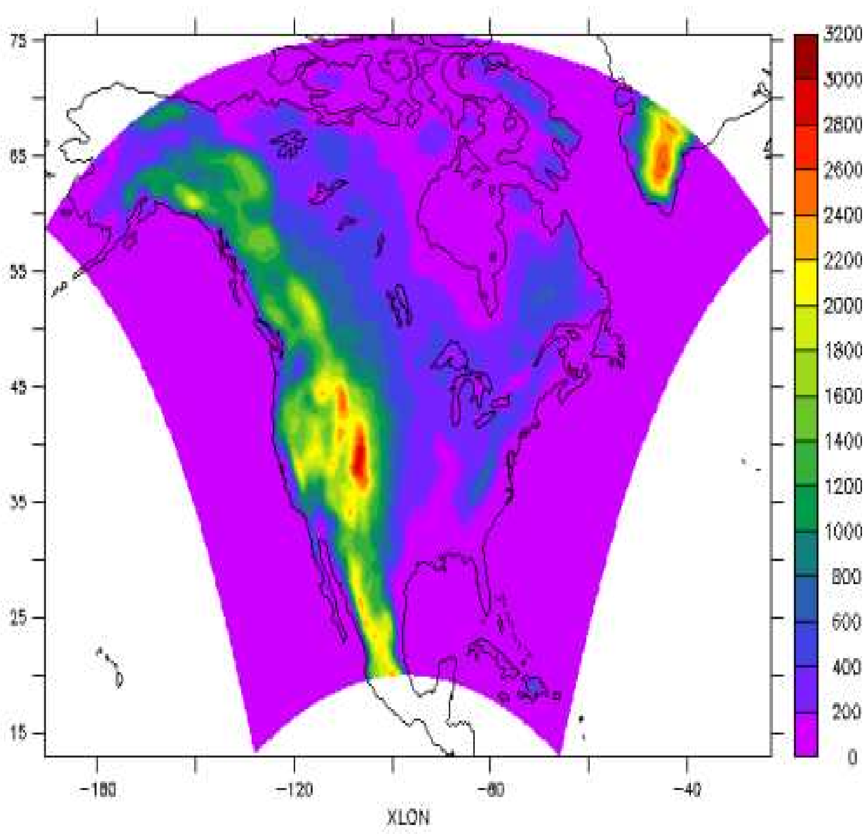

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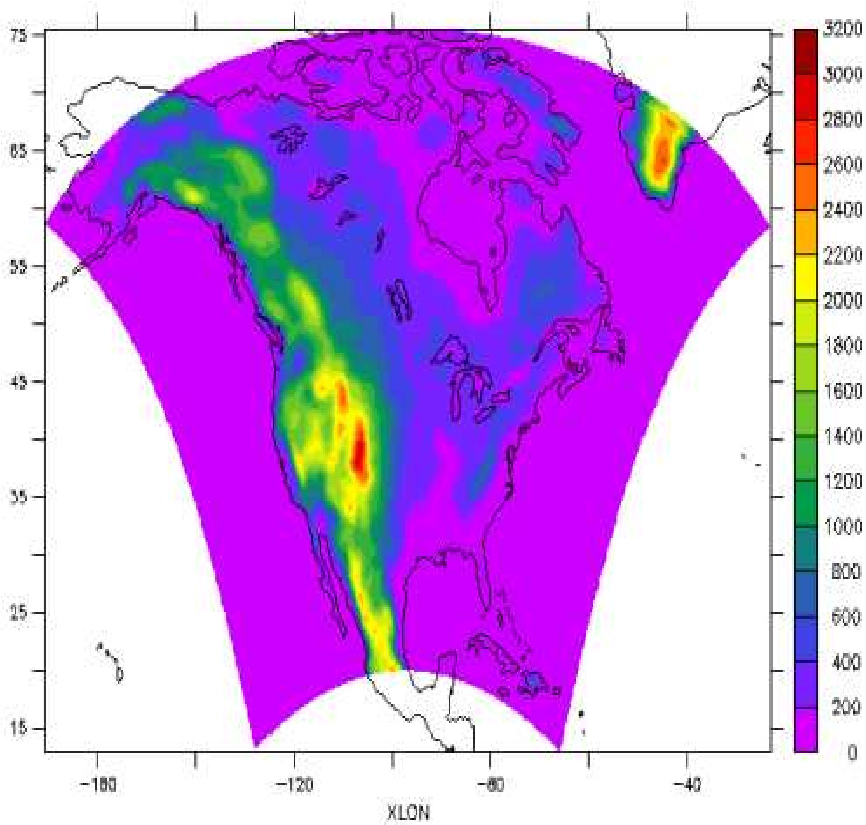

- NARCCAP is a program to produce high resolution climate change simulations over the US, Canada and Mexico.
- The goal is to assess climate variability at a regional level.
- All RCMs use the same 50 km resolution and the same future emission scenario (A2)

- NARCCAP considers six different RCMs, four different AOGCM, NCEP reanalysis and two time slices.

NARCCAP Combinations

	AOGCMs			
RCMs	GFDL	HADCM3	CGCM3	CCSM
RegCM3	X		X	
ECPC	X	X		
PRECIS	X	X		
CRCM			X	X
WRF			X	X
MM5		X		X

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- Not every combination of the RCMs and the AOGCM are considered, so the experiment resulted in a fractional factorial design.
- All models consider present day conditions from 1971 to 2000 and future simulations 2041 to 2070.

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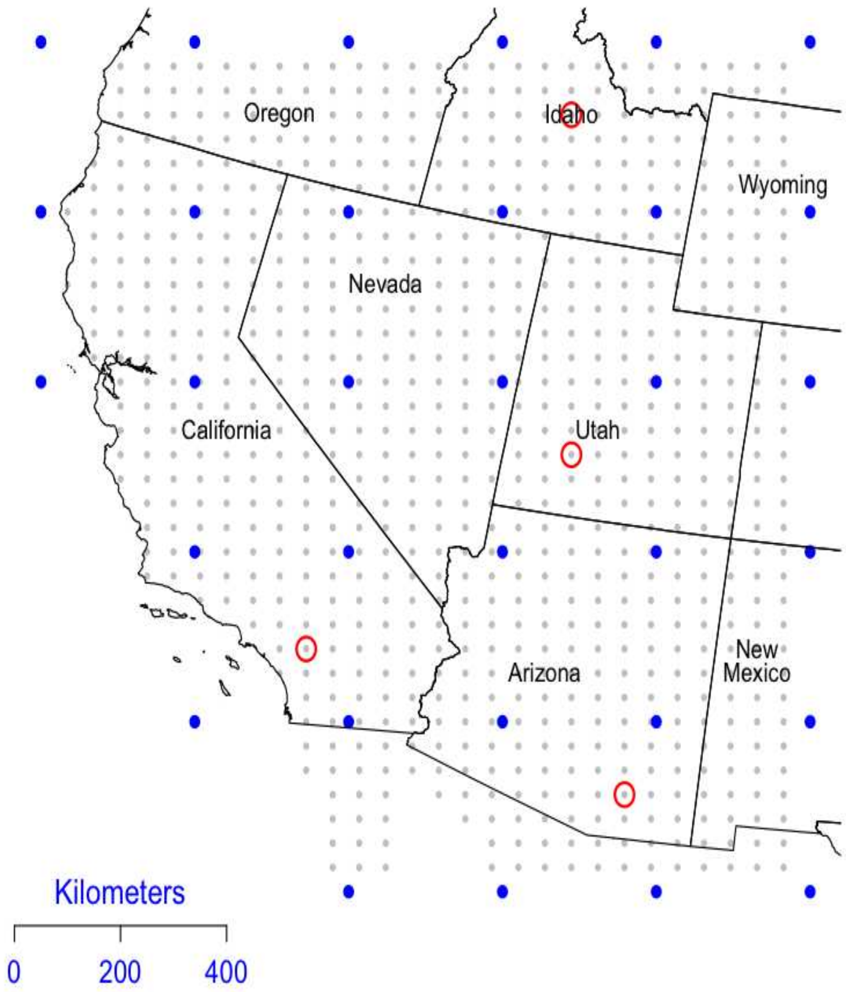
The Domain of our Analysis



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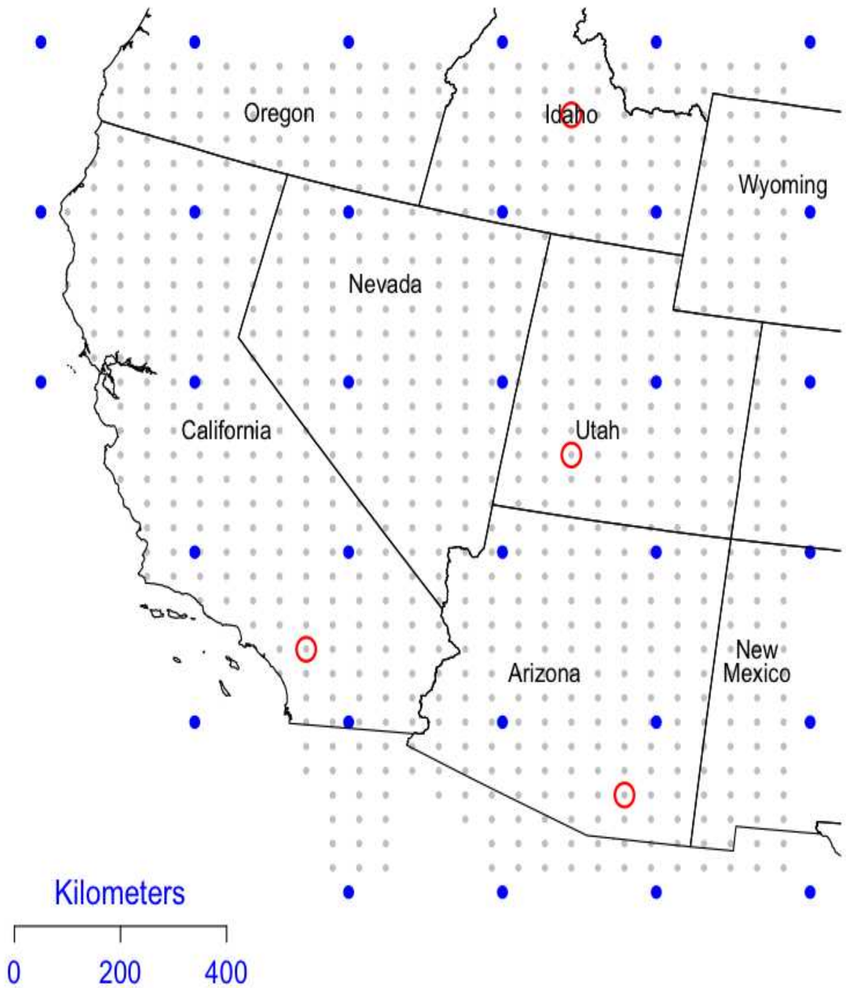

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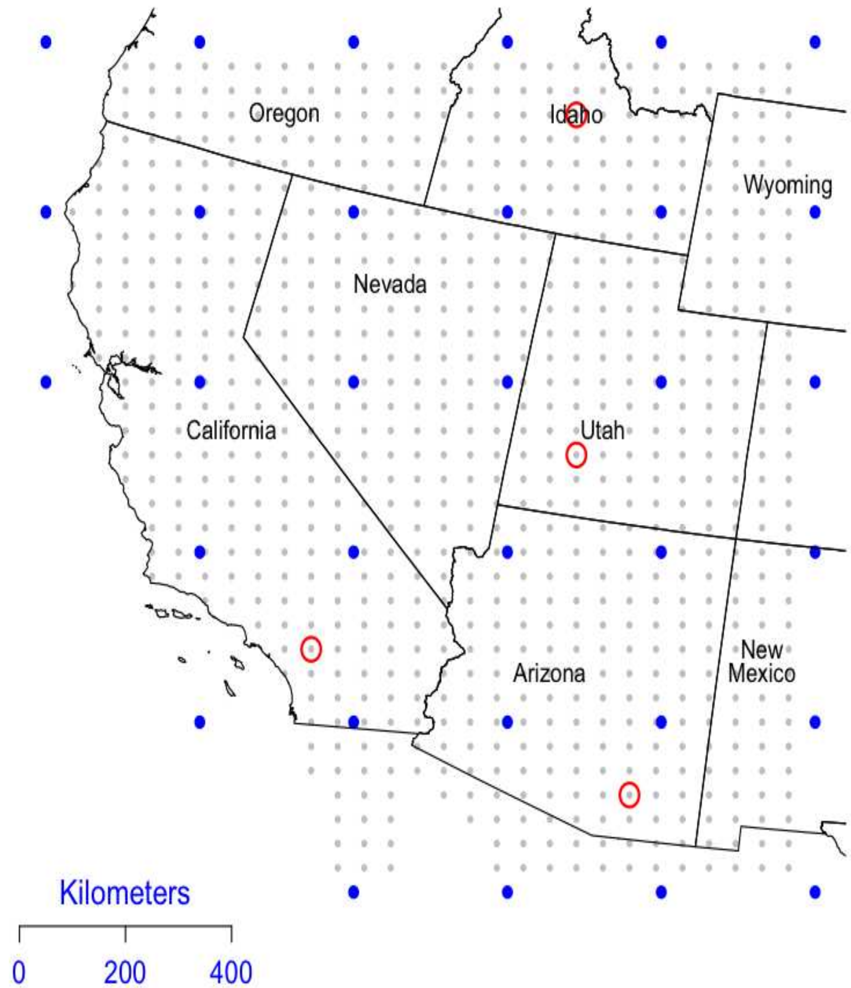

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- We consider the simulations obtained using RegCM3 under NCEP, GFDL and CGCM3 forcings.
- We study the variability of yearly mean summer temperature at each of the 802 locations.

Data Description and Processing

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- We did a simple kriging of the residuals and then averaged of all the 3 hourly values.

- Validate the RCM simulations with respect to the observational records.

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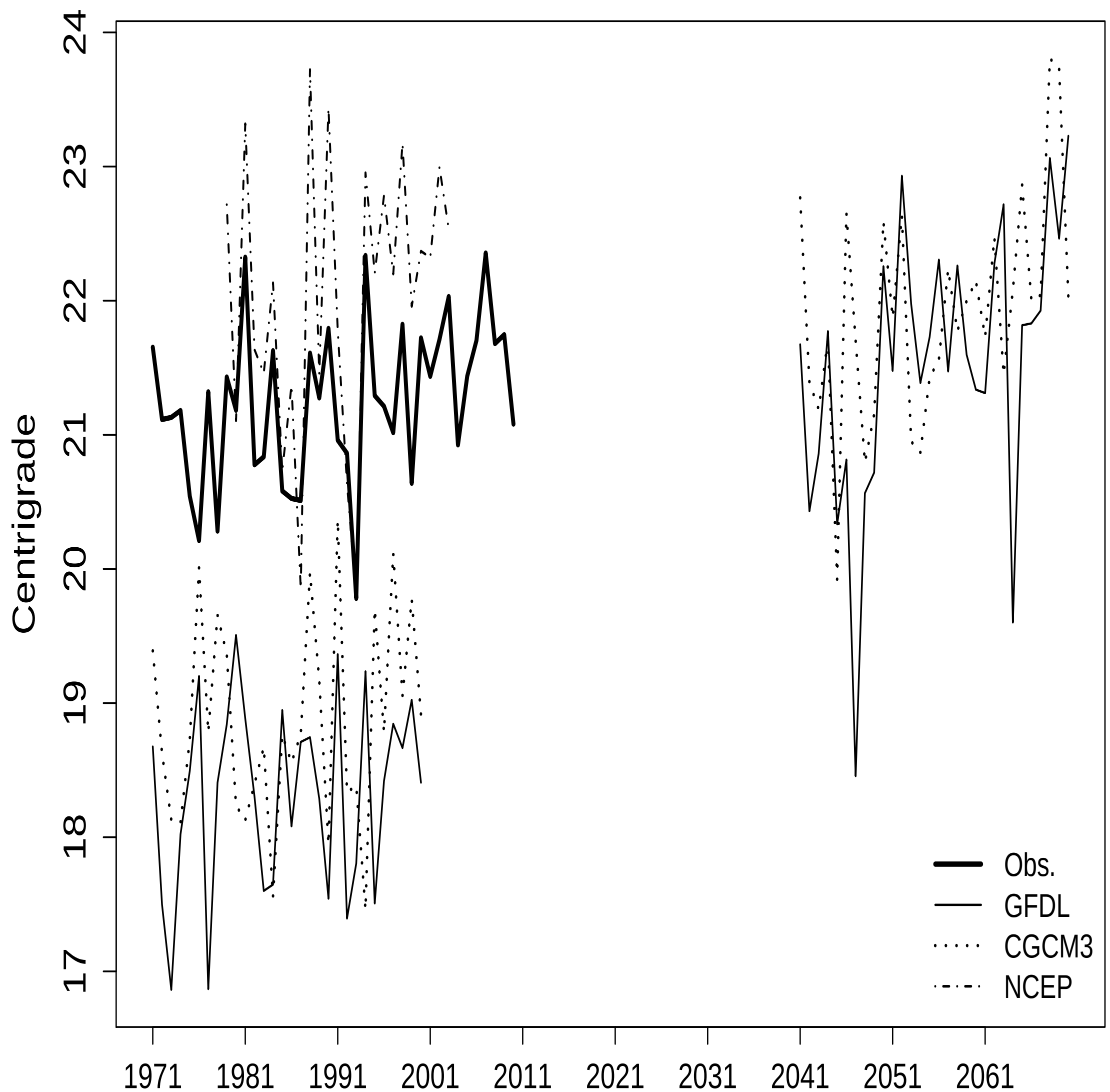
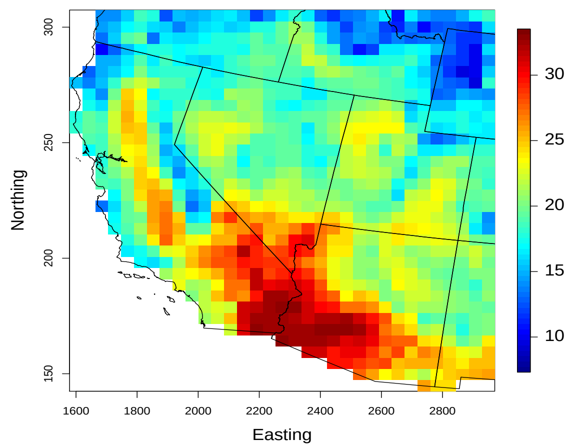
- Compare the RCM simulations temporally and spatially. A one way spatio-temporal ANOVA.
- Explore trends of spatial and temporal variability that are common for the four sources of information.
- Merge the four data sources to obtain blended reconstructions and forecasts, including probabilistic measures of uncertainty.

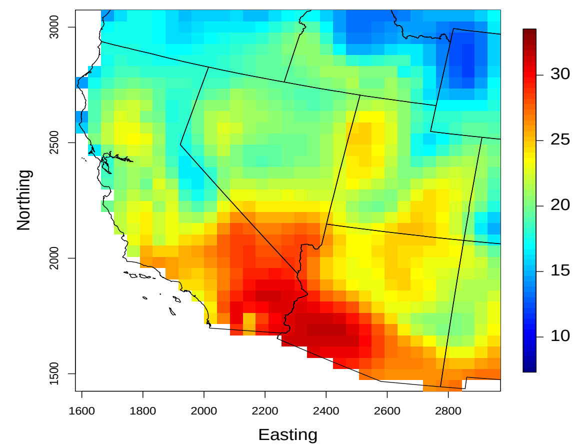


Note the gap in the first part of the 21st Cent., and the discrepancy between obs. and simul. during the 20th Cent. for CGCM3 and GFDL.

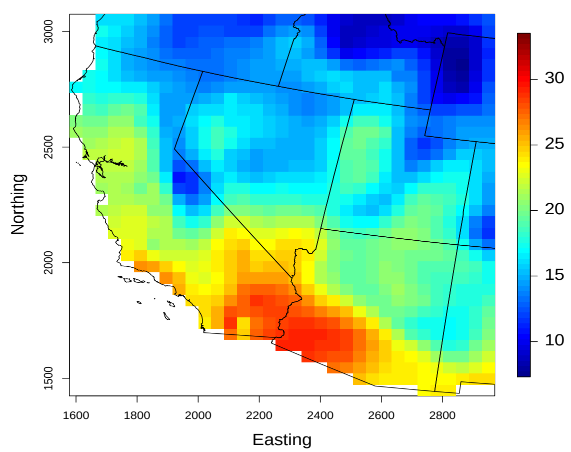
Observations



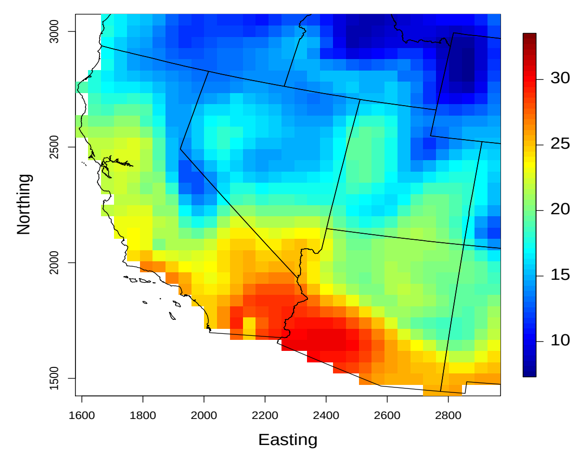
NCEP



GFDL



CGCM3



Our Model

We use a small number of components to explain the temporal and spatial variability. This provides computational advantages as well as estimation of the modes of main spatial variability.

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All four data sources correspond to a common space-time process. RCMs deviations from that process are time and space varying.

$$
\begin{aligned}
y_t(\boldsymbol{s}) &= \boldsymbol{x}_t^T(\boldsymbol{s})\eta + \xi(t-t_0) + \omega_t(\boldsymbol{s}) + \qquad\qquad + \epsilon_t(\boldsymbol{s}) \\
y_{jt}^{CM}(\boldsymbol{s}) &= \underbrace{\boldsymbol{x}_t^T(s)\eta}_{\text{covariates}} + \underbrace{\xi(t-t_0)}_{\text{trend}} + \underbrace{\omega_t(\boldsymbol{s})}_{\text{baseline}} + \underbrace{d_{jt}(\boldsymbol{s})}_{\text{discrepancy}} + \epsilon_{jt}(\boldsymbol{s})
\end{aligned}
$$

$\epsilon_t(\boldsymbol{s})$ and $\epsilon_{jt}(\boldsymbol{s})$ are observational errors.

The dimensionality of $\omega_t(\boldsymbol{s})$ is reduced with a predictive Gaussian process approach:

$$\omega_t(\boldsymbol{s}) = \sum_{m=1}^{M} B_m(\boldsymbol{s})\gamma_{m,t} + \tilde{\varepsilon}_t(\boldsymbol{s}) = \boldsymbol{B}(\boldsymbol{s})^T \boldsymbol{\gamma}_t + \tilde{\varepsilon}_t(\boldsymbol{s})$$

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$B_m(\boldsymbol{s}) = [\boldsymbol{v}(\boldsymbol{s})^T\boldsymbol{H}^{-1}]_m$, $\boldsymbol{\gamma}_t \sim N(\varphi\boldsymbol{\gamma}_{t-1}, \boldsymbol{H})$ and $\tilde{\varepsilon}_t(\boldsymbol{s}) \sim N(0, \tau^2 - \boldsymbol{v}(\boldsymbol{s})^T\boldsymbol{H}^{-1}\boldsymbol{v}(\boldsymbol{s}))$.

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$\boldsymbol{v}(\boldsymbol{s}) = \tau^2(\rho(\boldsymbol{s}, \boldsymbol{s}_1^*; \boldsymbol{\phi}), \ldots, \rho(\boldsymbol{s}, \boldsymbol{s}_M^*; \boldsymbol{\phi}))$ and $H_{lk} = \tau^2\rho(\boldsymbol{s}_l^*, \boldsymbol{s}_k^*; \boldsymbol{\phi})$.

$\boldsymbol{\gamma}_t$ is a Gaussian process on the set of points $\{\boldsymbol{s}_1^*, \ldots, \boldsymbol{s}_M^*\}$. Its correlation function ρ is the Matèrn with parameters $\boldsymbol{\phi} = (\phi_1, \phi_2)$.

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$\omega_t(\boldsymbol{s})$ is the predictive expectation of $\gamma_t(\boldsymbol{s}^*)$ at location $\boldsymbol{s}$.

Dimension Reduction

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In our application $M = 32$ and the sites $\boldsymbol{s}_m^*$ are located on a regular grid with a resolution of 290 km.

Consider the spectral decomposition $\boldsymbol{H} = \boldsymbol{P}\boldsymbol{\Lambda}\boldsymbol{P}^T$, $\boldsymbol{P}$ orthogonal and $\boldsymbol{\Lambda}$ diagonal. Let $\boldsymbol{\gamma}_t = \boldsymbol{P}\boldsymbol{\alpha}_t$, $\forall t$, then

$$\omega_t(\boldsymbol{s}) = \boldsymbol{B}(\boldsymbol{s})^T\boldsymbol{P}\boldsymbol{\alpha}_t = \boldsymbol{\psi}(\boldsymbol{s})^T\boldsymbol{\alpha}_t \;\text{ and }\; \boldsymbol{\alpha}_t \sim N(\varphi\boldsymbol{\alpha}_{t-1}, \boldsymbol{\Lambda}).$$

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A similar representation for d_{jt} yields

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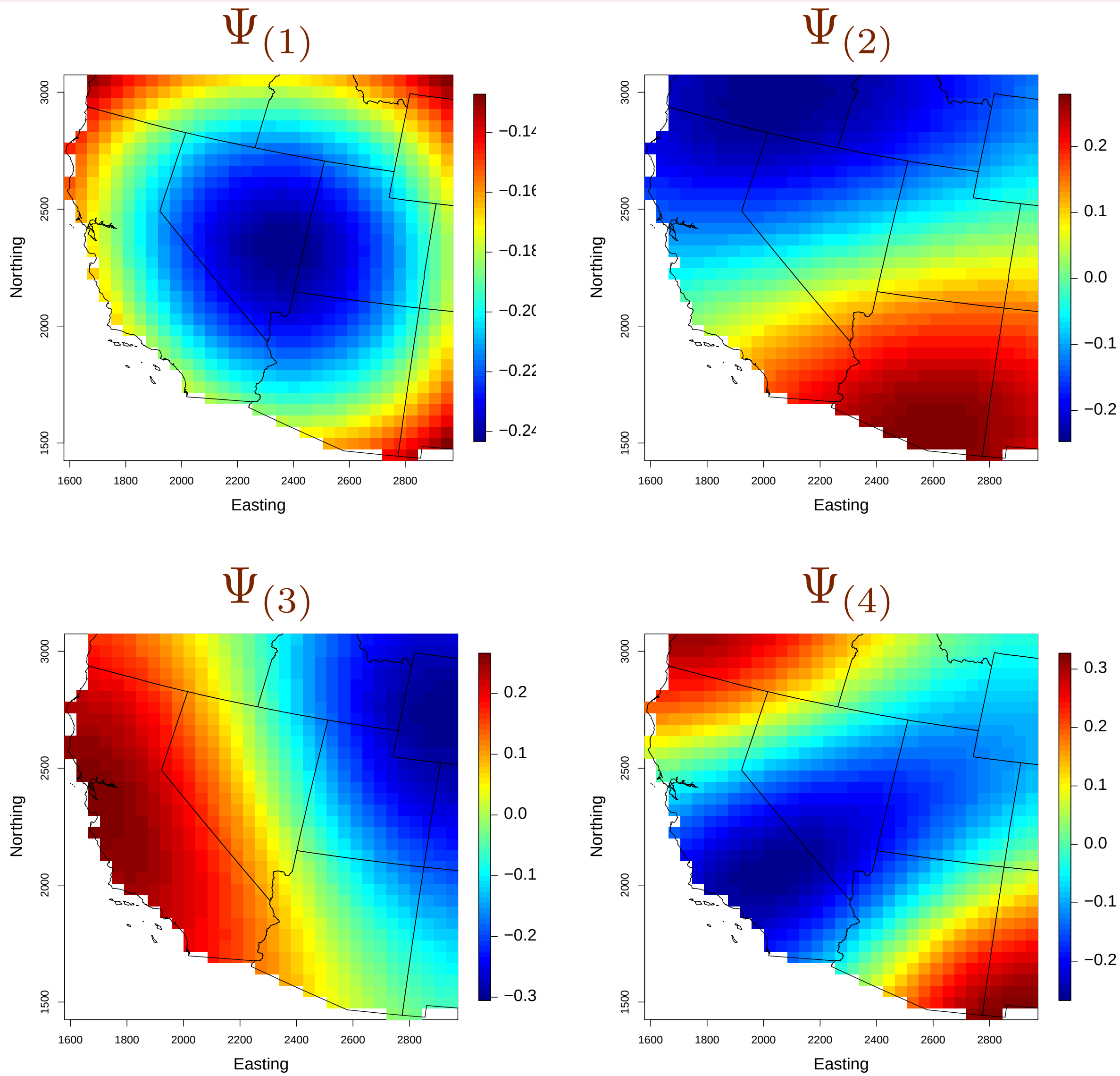
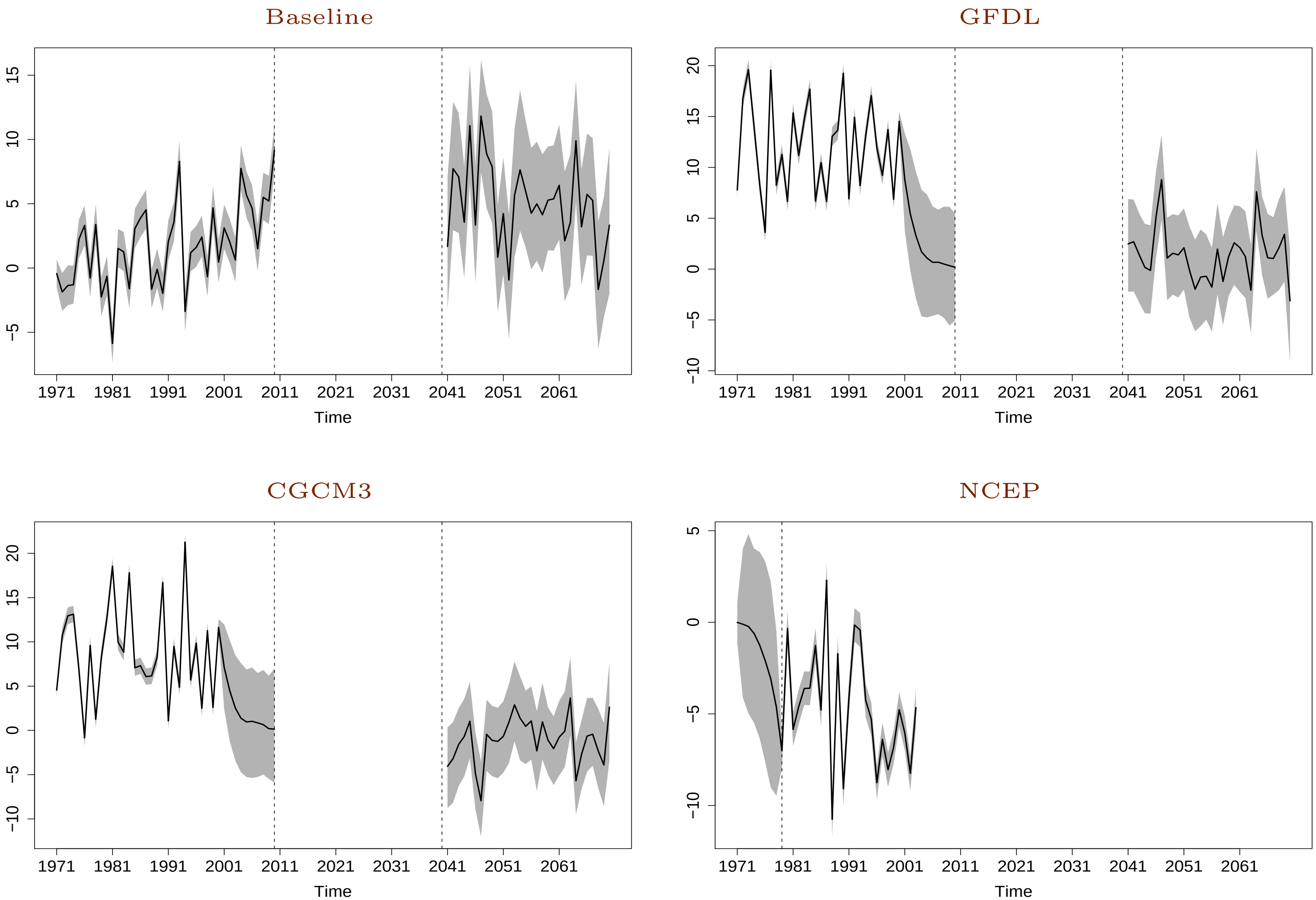
$$\boldsymbol{\alpha}_{jt} \sim N(\varphi_j \boldsymbol{\alpha}_{j,t-1}, \boldsymbol{\Lambda}_j).$$

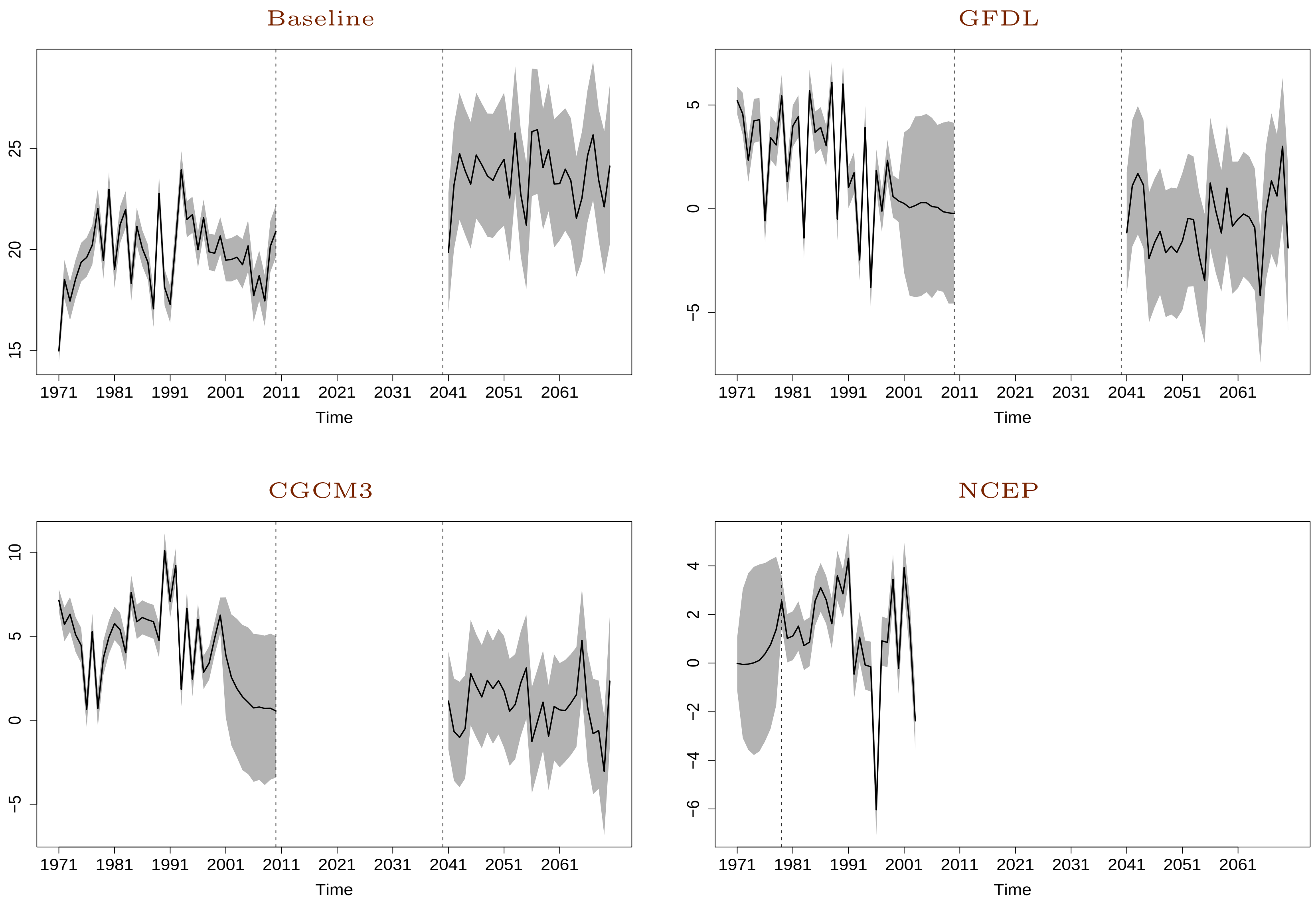
The fields $\psi_m(\boldsymbol{s})$ are not orthogonal, but the corresponding coefficients are independent with decreasing variance.


$\Psi_{(1)}$
$\Psi_{(2)}$
$\Psi_{(3)}$
$\Psi_{(4)}$
Northing
Easting
1500
2000
2500
3000
1600
1800
2000
2200
2400
2600
2800
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3

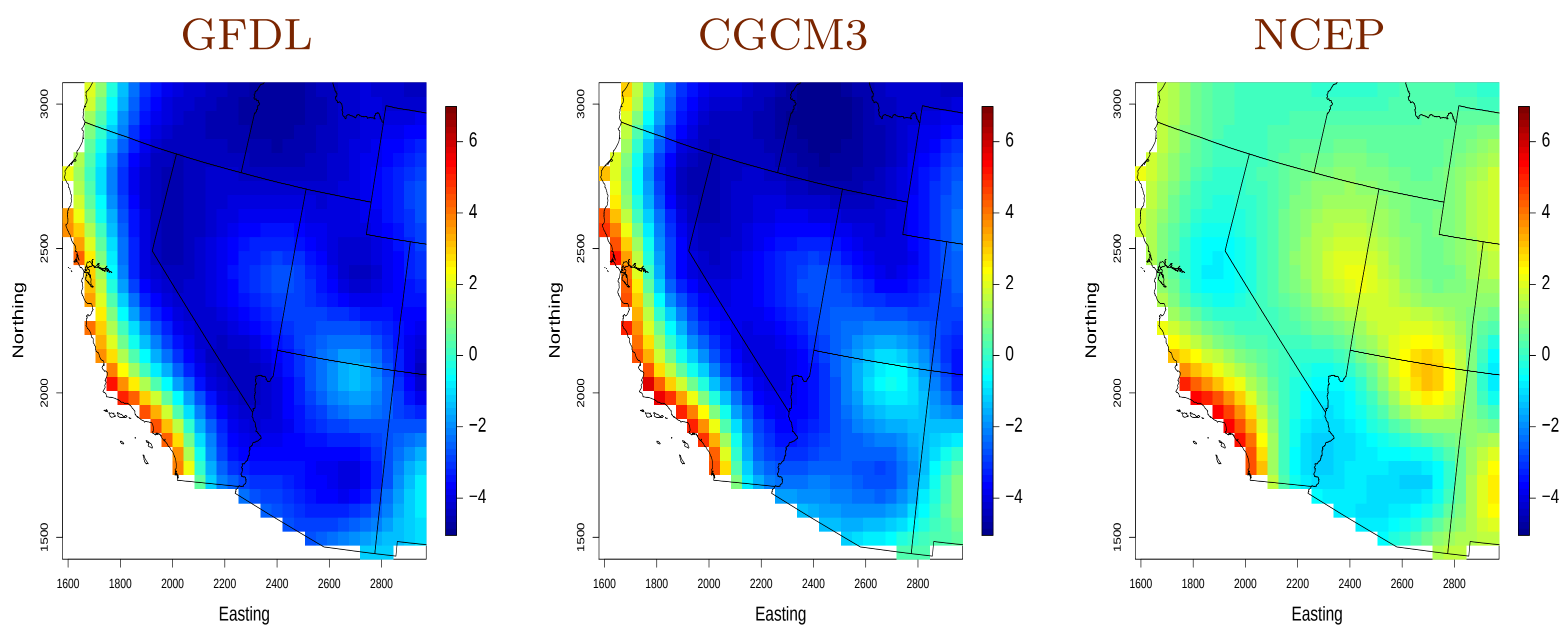
First Factor Coefficients



Second Factor Coefficients



Constant Discrepancy Model



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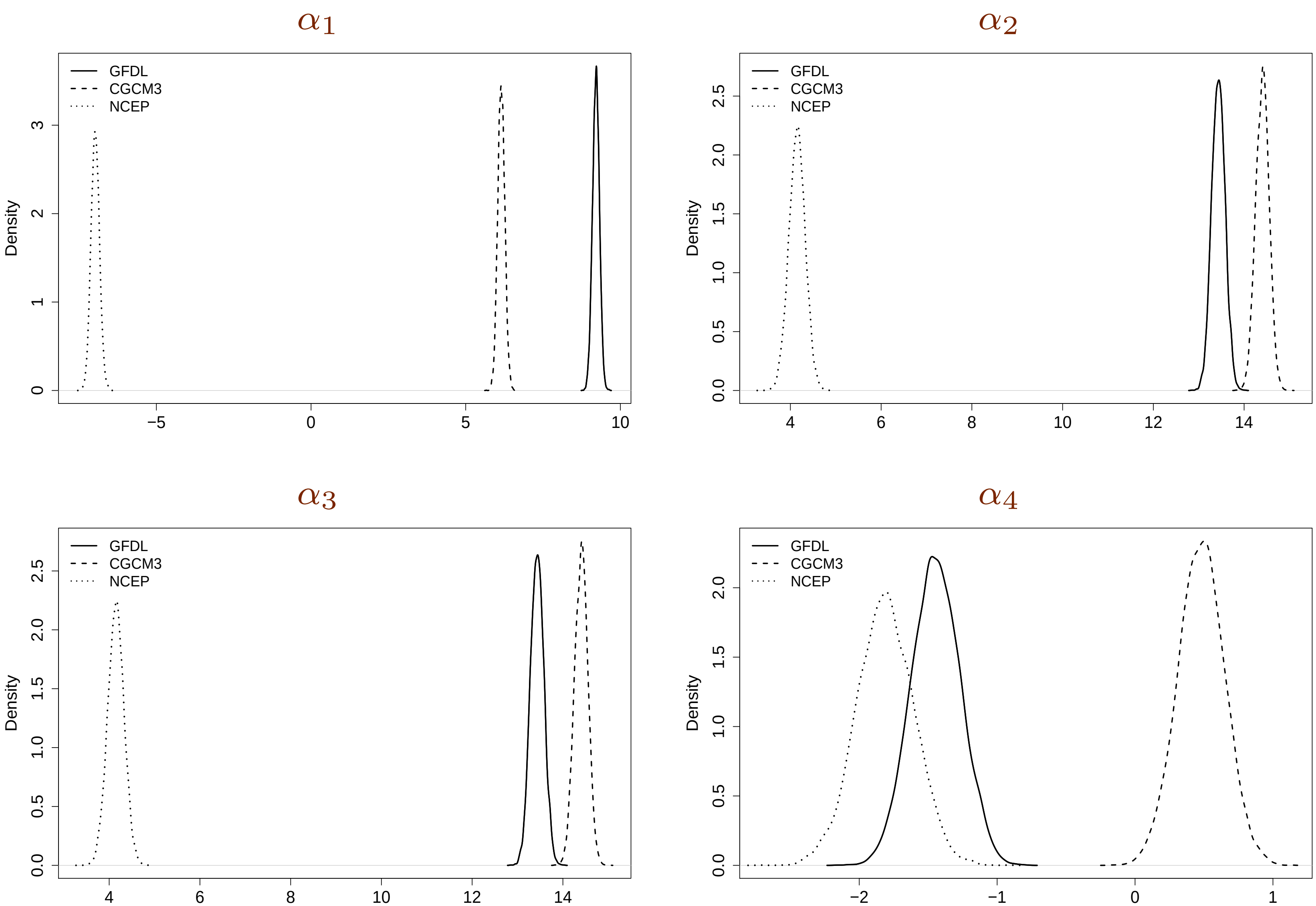

Model Assessment

We assess our future predictions by taking a training set (1971–1990) and a test set (1991–2000). We consider:

- Continuous rank probability scores.
- Energy scores
- Root mean square error
- Mean absolute error

Model Assessment

Forecast	CRPS	ES	RMSE	MAE
CGCM3	2.91	108.80	3.98	3.38
GFDL	3.20	115.50	4.17	3.67
Merged	3.01	110.40	4.06	3.51
Observations	0.59	20.15	1.03	0.79
Model 1 (32 knots)	2.19	74.20	3.53	2.95
Model 2 (32 knots)	**1.20**	**42.94**	**2.14**	**1.69**
Model 2 (68 knots)	1.22	43.72	2.17	1.70

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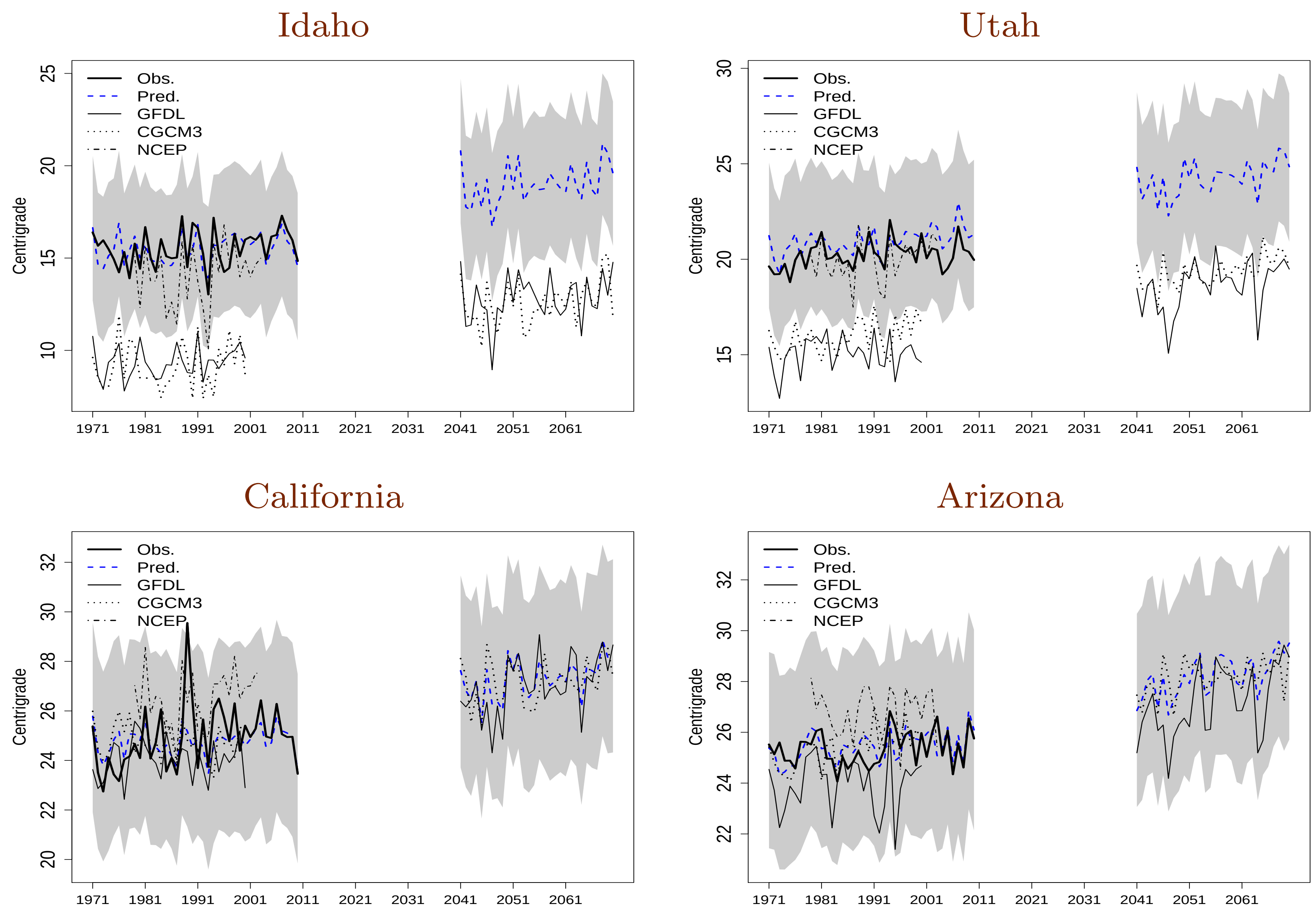
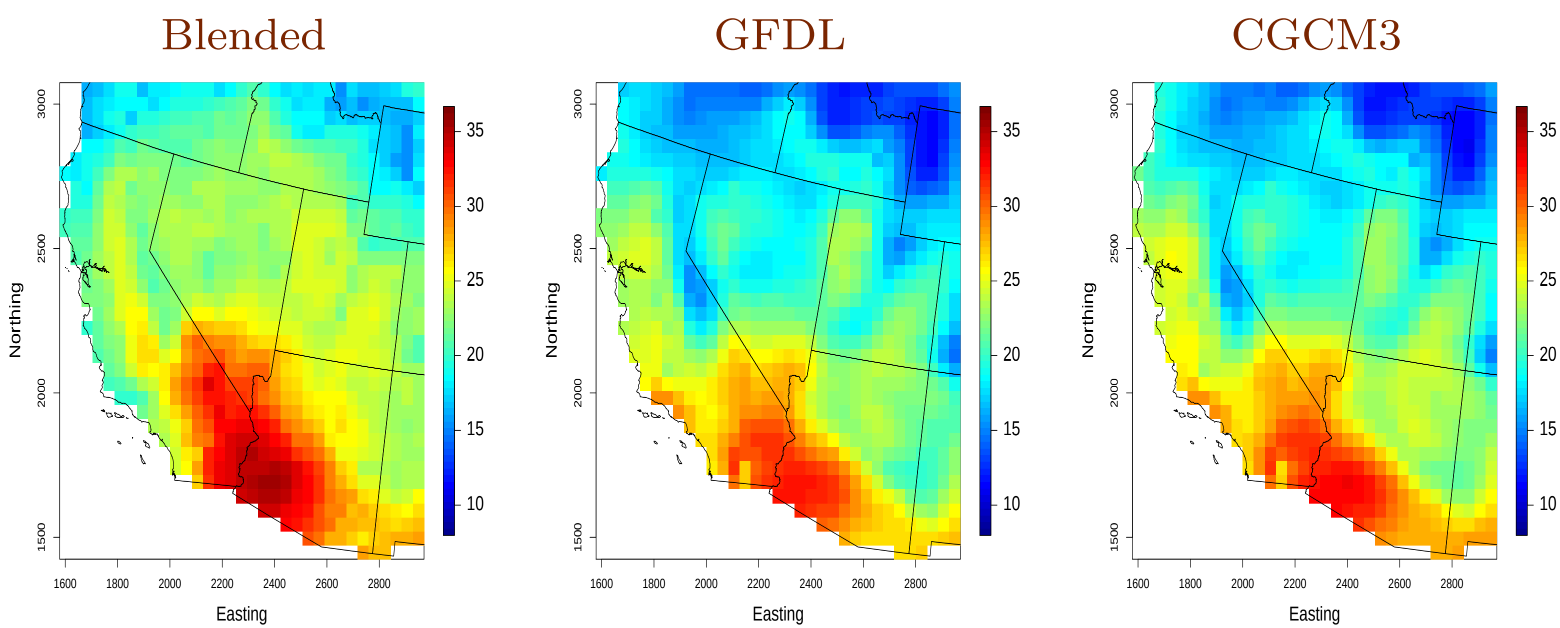
All three statistical procedures improve the predictions of the model runs. The best method is obtained with a coarse grid and constant discrepancies.

Predicted Time Series

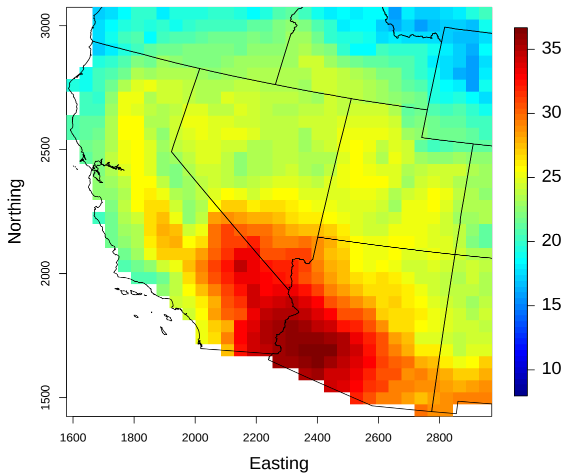


Average Predictions 2041–2070

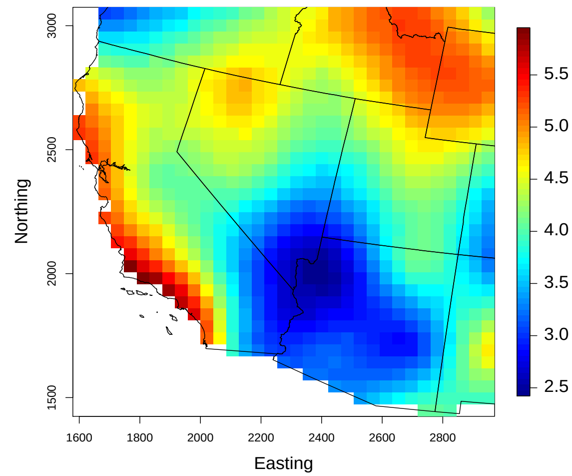


Blended Predictions

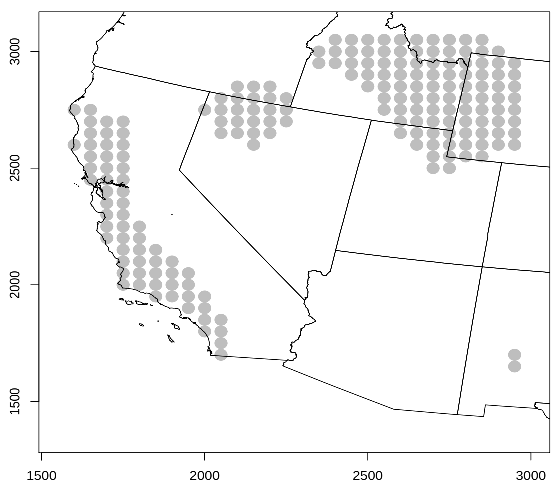
2070



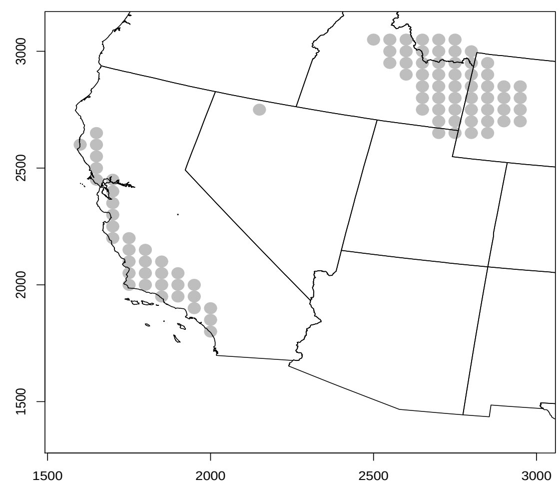
2070 - 2010



Prob(diff>3°)>85%



Prob(diff>3°)>90%



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- Our model provides a quantification of the uncertainties associated with the predictions.

- We use spatial and temporal models to introduce smoothing in time and space.

- Our spatial factor model reduces computations and allows for the description of patterns, cycles and trends that can be used as summaries of the analysis.

REFERENCES

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