

1 **A new spatial model for points above a threshold**

2 March 30, 2015

3 **1 Introduction**

4 In most climatological applications, researchers are interested in learning about the average behavior of
5 different climate variables (e.g. ozone, temperature, rainfall). However, averages do not help regulators
6 prepare for the unusual events that only happen once every 100 years. For example, it is important to have
7 an idea of how much rain will come in a 100-year floor in order to construct strong enough river levees to
8 protect lands from flooding.

9 Unlike multivariate normal distributions, it is challenging to model multivariate extreme value distri-
10 butions (e.g. generalized extreme value and generalized Pareto distribution) because few closed-form ex-
11 pressions exist for the density in more than two-dimensions (Coles and Tawn, 1991). Given this limitation,
12 pairwise composite likelihoods have been used when modeling dependent extremes (Padoan et al., 2010;
13 Blanchet and Davison, 2011; Huser, 2013).

14 One way around the multi-dimensional limitation of multivariate extreme value distributions is to use
15 skew elliptical distributions to model dependent extreme values (Genton, 2004; Zhang and El-Shaarawi,
16 2010; Padoan, 2011). Due to their flexibility, the skew-normal and skew- t distribution offer a flexible way
17 to handle non-symmetric data within a framework of multivariate normal and multivariate t-distributions. As
18 with the spatial Gaussian process, the skew-normal distribution is also asymptotically independent; however,
19 the skew- t does demonstrate asymptotic dependence (Padoan, 2011). Although asymptotic dependence is
20 desirable between sites that are near one another, one drawback to the skew- t is that sites remain asymptot-
21 ically dependent even at far distances.

22 In this paper, we present a model that has marginal distributions with flexible tails, demonstrates asymp-

23 totic dependence for observations at sites that are near to one another, and has computation on the order of
24 Gaussian models for large space-time datasets. Specifically, our contribution is to incorporate thresholding
25 and random spatial partitions using a multivariate skew- t distribution. The advantage of using a thresholded
26 model as opposed to a non-thresholded model is that it allows for the tails of the distribution to inform the
27 predictions in the tails (DuMouchel, 1983). The random spatial partition alleviates the long-range spatial
28 dependence seen by the skew- t .

29 The paper is organized as follows. Section 2.1 is a brief review of the spatial skew- t process. In section
30 3.3, we build upon the traditional skew- t by incorporating censoring to focus on tails, partitioning to remove
31 long-range asymptotic dependence, and extending the model to space-time data. The computing is described
32 in section 4. In section 5, we present a simulation study that examines the predictive capabilities of this
33 model compared with a naïve Gaussian method. We then compare our method to Gaussian and max-stable
34 methods with a data analysis of ozone measurements from the eastern US in section 6. The final section
35 provides brief discussion and direction for future research.

36 **2 Spatial skew processes**

37 Many types of data demonstrate some level of skewness and therefore should be modeled with distributions
38 that allow for asymmetry. The skew-elliptical family of distributions provides models that are mathemati-
39 cally tractable while introducing a slant parameter to account for asymmetric data (Genton, 2004). A brief
40 review of the additive process by which a skew- t process is created is given here.

⁴¹ **2.1 Skew-*t* process**

⁴² Let $Y(\mathbf{s})$ be the observation at spatial location $\mathbf{s} = (s_1, s_2)$. The spatial skew-*t* process can be written

$$Y(\mathbf{s}) = \mathbf{X}(\mathbf{s})^T \boldsymbol{\beta} + \lambda \sigma |z| + \sigma v(\mathbf{s}) \quad (1)$$

⁴³ where $\mathbf{X}(\mathbf{s})$ is a set of spatial covariates at site \mathbf{s} , $\boldsymbol{\beta}$ is a set of regression parameters, $\lambda \in \mathcal{R}$ is a parameter controlling skew, $z \sim N(0, 1)$, $\sigma^2 \sim \text{IG}(a, b)$ is an inverse gamma random variable, and $v(\mathbf{s})$ is a spatial Gaussian process with mean zero and variance one. A common spatial correlation function is the ⁴⁵ Matérn with

$$\text{cor}(v(\mathbf{s}), v(\mathbf{t})) = \gamma I(\mathbf{s} = \mathbf{t}) + (1 - \gamma) \frac{1}{\Gamma(\nu) 2^{\nu-1}} \left(\sqrt{2\nu} \frac{h}{\rho} \right)^\nu K_\nu \left(\sqrt{2\nu} \frac{h}{\rho} \right) \quad (2)$$

⁴⁷ where ρ is the spatial range, ν is the smoothness, γ is the proportion of variance accounted for by the spatial ⁴⁸ variation, K_ν is a modified Bessel function of the second kind, and $h = \|\mathbf{s} - \mathbf{t}\|$.

⁴⁹ Let $\mathbf{Y} = [Y(\mathbf{s}_1), \dots, Y(\mathbf{s}_n)]^T$ be a set of observations at a finite collection of locations $\mathbf{s}_1, \dots, \mathbf{s}_n$. After ⁵⁰ marginalizing over both z and σ ,

$$\mathbf{Y} \sim \text{ST}_n(\mathbf{X}\boldsymbol{\beta}, \boldsymbol{\Omega}, \boldsymbol{\alpha}, 2a), \quad (3)$$

⁵¹ that is, \mathbf{Y} follows an n -dimensional skew-*t* process with location $\mathbf{X}\boldsymbol{\beta}$, correlation matrix $\boldsymbol{\Omega}$, slant parameters ⁵² $\boldsymbol{\alpha}$ and degrees of freedom $2a$, where $\mathbf{X} = [\mathbf{X}(\mathbf{s}_1)^T, \dots, \mathbf{X}(\mathbf{s}_n)^T]$, $\boldsymbol{\Omega} = \boldsymbol{\omega} \bar{\boldsymbol{\Omega}} \boldsymbol{\omega}$, $\boldsymbol{\omega} = \text{diag} \left(\frac{1}{\sqrt{ab}}, \dots, \frac{1}{\sqrt{ab}} \right)$, ⁵³ $\bar{\boldsymbol{\Omega}} = (\boldsymbol{\Sigma} + \lambda^2 \mathbf{1} \mathbf{1}^T)$, $\boldsymbol{\Sigma}$ is a positive definite correlation matrix, $\boldsymbol{\alpha} = \lambda(1 + \lambda^2 \mathbf{1}^T \boldsymbol{\Sigma}^{-1} \mathbf{1})^{-1/2} \mathbf{1}^T \boldsymbol{\Sigma}^{-1}$ is ⁵⁴ a vector of slant parameters. This process is desirable because of its flexible tail that is controlled by the ⁵⁵ skewness parameter λ and degrees of freedom $2a$. Furthermore, the marginal distributions at each location

56 also follow a univariate skew-*t* distribution (Azzalini and Capitanio, 2013).

57 **2.2 Extremal dependence**

58 One measure of extremal dependence is the χ statistic (Padoan, 2011). The χ statistic for the upper tail is
59 given by $\lim_{c \rightarrow \infty} \Pr(Y(\mathbf{s}_1) > c | Y(\mathbf{s}_2) > c)$. For a stationary spatial process, we can write the χ coefficient
60 as

$$\chi(h) = \lim_{c \rightarrow \infty} \Pr[Y(\mathbf{s}) > c | Y(\mathbf{t}) > c]. \quad (4)$$

61 If $\chi(h) = 0$, then observations are asymptotically independent at distance h . For Gaussian processes,
62 $\chi(h) = 0$ regardless of the distance, so they are not suitable for modeling spatially-dependent extremes.
63 Unlike the Gaussian process, the skew-*t* process is asymptotically dependent. However, one problem with
64 the spatial skew-*t* process is that $\lim_{h \rightarrow \infty} \chi(h) > 0$. This occurs because all observations, both near and
65 far, share the same z and σ terms. Therefore, the skew-*t* process is not ideal for spatial analysis of large geo-
66 graphic regions where we expect only local spatial dependence. The explicit expression for $\chi(h)$ (Padoan,
67 2011) and a proof of this are given in Appendix A.4.

68 **3 Spatiotemporal skew-*t* model for extremes**

69 In this section, we propose extensions to the skew-*t* process to model spatial extremes over a large geo-
70 graphic region by introducing censoring to focus on tail behavior and a random partition similar to Kim
71 et al. (2005) to remove long-range asymptotic dependence.

⁷² **3.1 Censoring to focus on the tails**

⁷³ To avoid bias in estimating tail parameters, we model censored data. Let

$$\tilde{Y}(\mathbf{s}) = \begin{cases} Y(\mathbf{s}) & \delta(\mathbf{s}) = 1 \\ T & \delta(\mathbf{s}) = 0 \end{cases} \quad (5)$$

⁷⁴ be the censored observation at site \mathbf{s} where $Y(\mathbf{s})$ is the uncensored observation, $\delta(\mathbf{s}) = I[Y(\mathbf{s}) > T]$, and T
⁷⁵ is a pre-specified threshold value. Then, assuming the uncensored data $Y(\mathbf{s})$ are observations from a skew- t
⁷⁶ process, we update values censored below the threshold using standard Bayesian missing data methods as
⁷⁷ described in Section 4.

⁷⁸ **3.2 Partitioning to remove long-range asymptotic dependence**

⁷⁹ We handle the problem of long-range asymptotic dependence with a random partition model. As discussed in
⁸⁰ Section 2, the source of long-range dependence is the shared z and σ . Therefore, to alleviate this dependence,
⁸¹ we allow z and σ to vary by site. Then, the model becomes

$$Y(\mathbf{s}) = \mathbf{X}(\mathbf{s})^T \boldsymbol{\beta} + \lambda\sigma(\mathbf{s})|z(\mathbf{s})| + \sigma(\mathbf{s})v(\mathbf{s}). \quad (6)$$

⁸² Let $\mathbf{w} = (w_1, w_2)$ be the location of a spatial knot. To model spatial variation, consider a set of spatial knots
⁸³ $\mathbf{w}_1, \dots, \mathbf{w}_K$ from a homogeneous Poisson process with intensity μ over spatial domain $\mathcal{D} \in \mathbb{R}^2$. The knots
⁸⁴ define a random daily partition of \mathcal{D} by subregions P_1, \dots, P_K defined as

$$P_k = \{\mathbf{s} : k = \arg \min_\ell \|\mathbf{s} - \mathbf{w}_\ell\|\}. \quad (7)$$

85 All $z(\mathbf{s})$ and $\sigma(\mathbf{s})$ for sites in subregion k are assigned common values

$$z(\mathbf{s}) = z_k \quad (8)$$

$$\sigma(\mathbf{s}) = \sigma_k, \quad (9)$$

86 and the z_k and σ_k^2 are distributed as $z_k \stackrel{iid}{\sim} N(0, 1)$ and $\sigma^2 \stackrel{iid}{\sim} \text{IG}(a, b)$. So, within each partition, $Y(\mathbf{s})$
87 follows the spatial skew- t process defined in Section 2. Across partitions, the $Y(\mathbf{s})$ remain correlated via the
88 correlation function for $v(\mathbf{s})$ because it spans the partitions.

89 When incorporating the random daily partition, conditional on knots $\mathbf{w}_1, \dots, \mathbf{w}_K$, the χ statistic for two
90 sites \mathbf{s} and \mathbf{t} in partitions k_s and k_t respectively is

$$\begin{aligned} \chi(h) &= I(k_s = k_t)\chi_{\text{skew-}t}(h) + I(k_s \neq k_t)\chi_{\text{Gaus}}(h) \\ &= I(k_s = k_t)\chi_{\text{skew-}t}(h) \end{aligned} \quad (10)$$

91 where $\chi_{\text{skew-}t}(h)$ is the χ statistic for a skew- t process, $\chi_{\text{Gaus}}(h)$ is the χ statistic for a Gaussian process,
92 and $h = ||\mathbf{s} - \mathbf{t}||$. Therefore, sites in different subregions are asymptotically independent. Marginally, over
93 the knots $\mathbf{w}_1, \dots, \mathbf{w}_K$, $\chi(h) = \pi(h)\chi_{\text{skew-}t}(h)$, where $\pi(h) = \Pr(k_s = k_t)$ is the probability that two sites
94 separated by distance h are in the same partition. So, to show that $\lim_{h \rightarrow \infty} \chi(h) = 0$, we need only know
95 that $\lim_{h \rightarrow \infty} \pi(h) = 0$. A proof of this is given in Appendix A.3. Figure 1 shows how partitioning reduces
96 the extremal dependence.

97 3.3 Extension to space-time data

98 When using daily measurements, the assumption of temporal independence is inappropriate. There are
99 several places where temporal dependence could be incorporated in the model, including the residual $v_t(\mathbf{s})$.

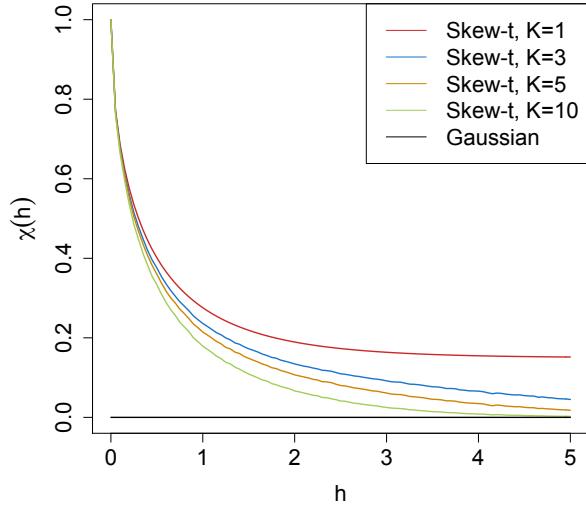


Figure 1: $\chi(h)$ for $K = 1, 3, 5$, and 10 knots as a function of distance.

100 However, we choose to allow for temporal dependence in the \mathbf{w} , z , and σ terms because these terms dictate
 101 the tail behavior which is our primary focus. In this section, we extend (6) to the spatiotemporal setting. Let

$$Y_t(\mathbf{s}) = \mathbf{X}_t(\mathbf{s})^T \boldsymbol{\beta} + \lambda \sigma_t(\mathbf{s}) |z_t(\mathbf{s})| + \sigma_t(\mathbf{s}) v_t(\mathbf{s}), \quad (11)$$

102 where $t \in \{1, \dots, T\}$ denotes the day of each observation. Let $\mathbf{w}_{tk} = (w_{tk1}, w_{tk2})$ be a spatial knot on day
 103 t , and let w_{t1}, \dots, w_{tK} be a collection of spatial knots on day t . As in section 3.2, these knots define a daily
 104 partition P_{t1}, \dots, P_{tK} , and for $\mathbf{s} \in P_{tk}$,

$$z_t(\mathbf{s}) = z_{tk} \quad (12)$$

$$\sigma_t(\mathbf{s}) = \sigma_{tk}. \quad (13)$$

105 We use an AR(1) time series model for w_{tk} , z_{tk} , and σ_{tk} . The time series model must be specified after
 106 a transformation to preserve the skew- t process at each time point. We first transform the spatial knots from

¹⁰⁷ \mathcal{D} to \mathcal{R}^2 as follows. Let

$$w_{tki}^* = \Phi^{-1} \left[\frac{(w_{tki} - \min(\mathbf{s}_i))}{\text{range}(\mathbf{s}_i)} \right], \quad i = 1, 2 \quad (14)$$

¹⁰⁸ where Φ is a univariate standard normal density function, and $\mathbf{s}_i = [s_{1i}, \dots, s_{ni}]$. Then $\mathbf{w}_{tk}^* \in \mathcal{R}^2$. We use
¹⁰⁹ a copula on $\sigma_t^2(\mathbf{s})$ to ensure that the marginal distributions of $\sigma_t^2(\mathbf{s})$ are inverse gamma. Let

$$\sigma_t^{2*}(\mathbf{s}) = \Phi^{-1} \{ \text{IG}[\sigma_t^2(\mathbf{s})] \} \quad (15)$$

¹¹⁰ where IG is the distribution function for an $\text{IG}(a, b)$ random variable. We also use a copula on $z_t(\mathbf{s})$ to
¹¹¹ ensure that the marginal distributions of $z_t(\mathbf{s})$ are half-normal. Let

$$z_t^*(\mathbf{s}) = \Phi^{-1} \{ \text{HN}[\sigma_t^2(\mathbf{s})] \} \quad (16)$$

¹¹² The AR(1) process for each tail parameter is $\mathbf{w}_{1k}^* \sim N_w(0, 1)$, $z_{1k}^* \sim N(0, \sigma_{1k}^2)$, $\sigma_{1k}^{2*} \sim N(0, 1)$, and for
¹¹³ $t > 1$ the time series is modeled as

$$\mathbf{w}_{tk}^* | \mathbf{w}_{t-1,k}^* \sim N_2 [\phi_w \mathbf{w}_{t-1,k}^*, (1 - \phi_w^2)] \quad (17)$$

$$z_{tk}^* | z_{t-1,k}^* \sim N [\phi_z z_{t-1,k}^*, \sigma_{tk}^2 (1 - \phi_z^2)] \quad (18)$$

$$\sigma_{tk}^{2*} | \sigma_{t-1,k}^{2*} \sim N [\phi_\sigma \sigma_{t-1,k}^{2*}, (1 - \phi_\sigma^2)] \quad (19)$$

¹¹⁴ where $|\phi_w|, |\phi_z|, |\phi_\sigma| < 1$. These are stationary time series models with marginal distributions $\mathbf{w}_k^* \sim$
¹¹⁵ $N_2(0, 1)$, $z_k^* \sim N(0, \sigma_k^2)$, $\sigma_k^{2*} \sim N(0, 1)$. After transformation back to the original space, $\mathbf{w}_{tk} \sim \text{Unif}(\mathcal{D})$,
¹¹⁶ $z_{tk} \sim HN(0, \sigma_{tk}^2)$, $\sigma_{tk}^2 \sim \text{IG}(a, b)$. For each day, the model is identical to the spatial-only model in (6) by

¹¹⁷ construction.

¹¹⁸ 3.4 Hierarchical model

¹¹⁹ Conditioned on $z_{tk}(\mathbf{s})$, $\sigma_{tk}^2(\mathbf{s})$, and P_{tk} , the marginal distributions are Gaussian and the joint distribution
¹²⁰ multivariate Gaussian. However, we do not fix the partitions, they are treated as unknown and updated in the
¹²¹ MCMC. We model this with a Bayesian hierarchical model as follows. Let $\mathbf{w}_{t1}, \dots, \mathbf{w}_{tK}$ be a set of daily
¹²² spatial knots in a spatial domain of interest, \mathcal{D} , and P_{tk} as defined in (7).

¹²³ Then

$$Y_t(\mathbf{s}) \mid z_t(\mathbf{s}), \sigma_t^2(\mathbf{s}), P_{tk}, \alpha, \beta, \Theta = \mathbf{X}_t(\mathbf{s})^T \beta + \lambda |z_t(\mathbf{s})| + \sigma_t(\mathbf{s}) v_t(\mathbf{s}) \quad (20)$$

$$z_t(\mathbf{s}) = z_{tk} \text{ if } \mathbf{s} \in P_{tk} \quad (21)$$

$$\sigma_t^2(\mathbf{s}) = \sigma_{tk}^2 \text{ if } \mathbf{s} \in P_{tk} \quad (22)$$

$$\lambda = \lambda_1 \lambda_2 \quad (23)$$

$$\lambda_1 = \begin{cases} +1 & \text{w.p.0.5} \\ -1 & \text{w.p.0.5} \end{cases} \quad (24)$$

$$\lambda_2^2 \sim IG(a, b) \quad (25)$$

$$v_t(\mathbf{s}) \mid \Theta \sim \text{Matérn}(0, \Sigma) \quad (26)$$

$$z_{tk}^* \mid z_{t-1,k}^*, \sigma_{tk}^2 \sim N(\phi_z z_{t-1,k}^*, \sigma_{tk}^2(1 - \phi_z^2)) \quad (27)$$

$$\sigma_{tk}^{2*} \mid \sigma_{t-1,k}^{2*} \sim N(\phi_\sigma \sigma_{t-1,k}^{2*}, (1 - \phi_\sigma^2)) \quad (28)$$

$$\mathbf{w}_{tk}^* \mid \mathbf{w}_{t-1,k}^* \sim N_2(\phi_w \mathbf{w}_{t-1,k}^*, (1 - \phi_w^2)) \quad (29)$$

¹²⁴ where $\Theta = \{\rho, \nu, \gamma\}$, and Σ is a Matérn covariance matrix as described in Section 2.1. We parameterize
¹²⁵ $\lambda = \lambda_1 \lambda_2$ to help with convergence in the MCMC.

126 **4 Computation**

127 First, we impute values below the threshold. Then, we update Θ using Metropolis Hastings or Gibbs sam-
128 pling when appropriate. Finally, we make spatial predictions using conditional multivariate normal results
129 and the fact that the distribution of $Y_t(\mathbf{s}) \mid \Theta, z(\mathbf{s})$ is the usual multivariate normal distribution with a
130 Matérn spatial covariance structure.

131 We can use Gibbs sampling to update $Y_t(\mathbf{s})$ for censored observations that are below the threshold T .
132 After conditioning on $\lambda, z_t(\mathbf{s})$ and non-censored observations, $Y_t(\mathbf{s})$ has truncated normal full conditionals.
133 So we sample $Y_t(\mathbf{s}) \sim N_{(-\infty, T)}(\mathbf{X}\boldsymbol{\beta}, \boldsymbol{\Sigma})$. After imputing the censored observations, we update the model
134 parameters. To update the model parameters, we use standard Gibbs updates for parameters when possible.
135 In the case Gibbs sampling is not possible, parameters are updated using a random-walk Metropolis Hastings
136 algorithm. See Appendices A.1 and A.2 for details regarding the MCMC. The final step of the computation
137 is to use Bayesian Kriging to generate a predictive distribution for $Y_t(\mathbf{s}^*)$ at prediction location \mathbf{s}^* . This
138 step is similar to the imputation for censored observations except that the full conditionals are no longer
139 truncated at T .

140 **5 Simulation study**

141 In this section, we conduct a simulation study to investigate how the number of partitions and the level of
142 thresholding impact the accuracy of predictions made by the model.

143 **5.1 Design**

144 For all simulation designs, we generate data from the model in Section 3.2 using $n_s = 144$ sites and
145 $n_t = 50$ independent days. The sites are generated $\text{Uniform}([0, 10] \times [0, 10])$. We generate data from 7
146 different simulation designs:

- 147 1. Gaussian marginal, $K = 1$ knot
 148 2. Symmetric- t marginal, $K = 1$ knot
 149 3. Symmetric- t marginal, $K = 5$ knots
 150 4. Skew- t marginal, $K = 1$ knots
 151 5. Skew- t marginal, $K = 5$ knots
 152 6. Max-stable
 153 7. Transformation below $T = q(0.80)$

154 In the first five designs, the $v_t(\mathbf{s})$ terms are generated using a Matérn covariance with smoothness parameter
 155 $\nu = 0.5$ and spatial range $\rho = 1$. For the covariance matrices in designs 1 – 5, the proportion of the variance
 156 accounted for by the spatial variation is $\gamma = 0.9$ while the proportion of the variance accounted for by the
 157 nugget effect is 0.1. In the first design, $\sigma^2 = 2$ is used for all days. For designs 2 – 4, $\sigma_{tk}^2 \stackrel{iid}{\sim} \text{IG}(3, 8)$
 158 For designs 1 – 3, we set $\lambda = 0$. For designs four and five, $\lambda = 3$ was used, and the z_t are generated as
 159 described in (8). In the sixth design, we generate from a spatial max-stable distribution (Reich and Shaby,
 160 2012). In this design, data have marginal distributions that follow a generalized extreme value distribution
 161 with parameters $\mu = 1, \sigma = 1, \xi = 0.2$. In this model, a random effect is used to induce spatial dependence
 162 using 144 spatial knots on a regular lattice in the square $[1, 9] \times [1, 9]$. For this setting, we set $\gamma = 0.5$. In
 163 the final design, we generate \tilde{y} using the setting from design 4, and then consider the data

$$y = \begin{cases} \tilde{y}, & \tilde{y} > T \\ T \exp\{\tilde{y} - T\}, & \tilde{y} \leq T \end{cases} \quad (30)$$

164 where $T = q(0.80)$ is the 80th sample quantile of the data. In all seven designs, the mean $\mathbf{X}\beta = 10$ is
 165 assumed to be constant across space.

166 $M = 50$ data sets are generated for each design. For each data set we fit the data using

- 167 1. Gaussian marginal, $K = 1$ knots
 168 2. Skew- t marginal, $K = 1$ knots, $T = -\infty$
 169 3. Symmetric- t marginal, $K = 1$ knots, $T = q(0.80)$
 170 4. Skew- t marginal, $K = 5$ knots, $T = -\infty$
 171 5. Symmetric- t marginal, $K = 5$ knots, $T = q(0.80)$

172 where $q(0.80)$ is the 80th sample quantile of the data. The design matrix \mathbf{X} includes an the intercept with a
 173 prior of $\beta \sim N(0, 10)$. The spatial covariance parameters have priors $\log(\nu) \sim N(-1.2, 1)$, $\gamma \sim Unif(0, 1)$,
 174 $\rho \sim Unif(15)$. The skewness parameter has prior $\lambda \sim N(0, 2)$. The residual variance terms have priors
 175 $\sigma_t^2(\mathbf{s}) \sim IG(0.1, 0.1)$. The knots have priors $\mathbf{w} \sim Unif(\mathcal{D})$. We do not fit the data using the max-stable
 176 methods from Reich and Shaby (2012) because of the time it takes.

177 **5.2 Cross validation**

178 Models were compared using cross validation with 100 sites used as training sites and 44 sites withheld for
 179 testing. The model was fit using the training set, and predictions were generated at the testing site locations.
 180 Because one of the primary goals of this model is to predict extreme events, we use Brier scores to select
 181 the model that best fits the data (Gneiting and Raftery, 2007). The Brier score for predicting exceedance of
 182 a threshold c is given by $[e(c) - P(c)]^2$ where $e(c) = I[y > c]$ is an indicator function indicating that a test
 183 set value, y , has exceeded the threshold, c , and $P(c)$ is the predicted probability of exceeding c . We average
 184 the Brier scores over all test sites and days. For the Brier score, a lower score indicates a better fit.

185 **5.3 Results**

186 We compared the Brier scores for exceeding 4 different thresholds for each dataset. The thresholds used for
 187 the Brier scores are extreme quantiles from the simulated data for $q(0.90)$, $q(0.95)$, $q(0.98)$, and $q(0.99)$.

188 Figure 2 gives the Brier score relative to the Brier score for the Gaussian method calculated as

$$BS_{\text{rel}} = \frac{BS_{\text{method}}}{BS_{\text{Gaussian}}}. \quad (31)$$

189 We analyzed the results for the simulation study using a Friedman test at $\alpha = 0.05$. If the Friedman test
190 came back with a significant results, we conducted a Wilcoxon-Nemenyi-McDonald-Thompson test to see
191 which methods had different results. The full results for the Wilcoxon-Nemenyi-McDonald-Thompson tests
192 are given in Appendix A.5. Generally, the results of the study show that when the data come from a Gaussian
193 process, our methods at least perform comparably to the Gaussian method. The results also show that our
194 method performs better when the number of knots is the same as used in the data generation.

195 In the Gaussian setting, the performance of the single-partition skew- t method is comparable to the
196 Gaussian method. Looking at Brier scores for more extreme quantiles, either skew- t methods have results
197 that are comparable to the Gaussian method. For data settings with symmetric- t and skew- t marginals
198 (settings 2 – 5), we find significant improvement over the Gaussian method. Furthermore in these data
199 settings, we find the best performance occurs when the number of knots used in the method matches the
200 number of knots used for data generation. The non-thresholded methods tend to outperform the thresholded
201 methods, but this is not surprising given that the data are generated directly from the model used in the
202 method. In setting 6, we see that for low-extreme quantiles, the Gaussian method performs better, for more
203 extreme quantiles, the single-partition method, both thresholded and non-thresholded, perform significantly
204 better. Finally, for setting 7, although the thresholded version of the single-partition model tends to perform
205 the best across all of the extreme quantiles, the difference between the thresholded and non-thresholded
206 methods is no longer significant in the more extreme quantiles.

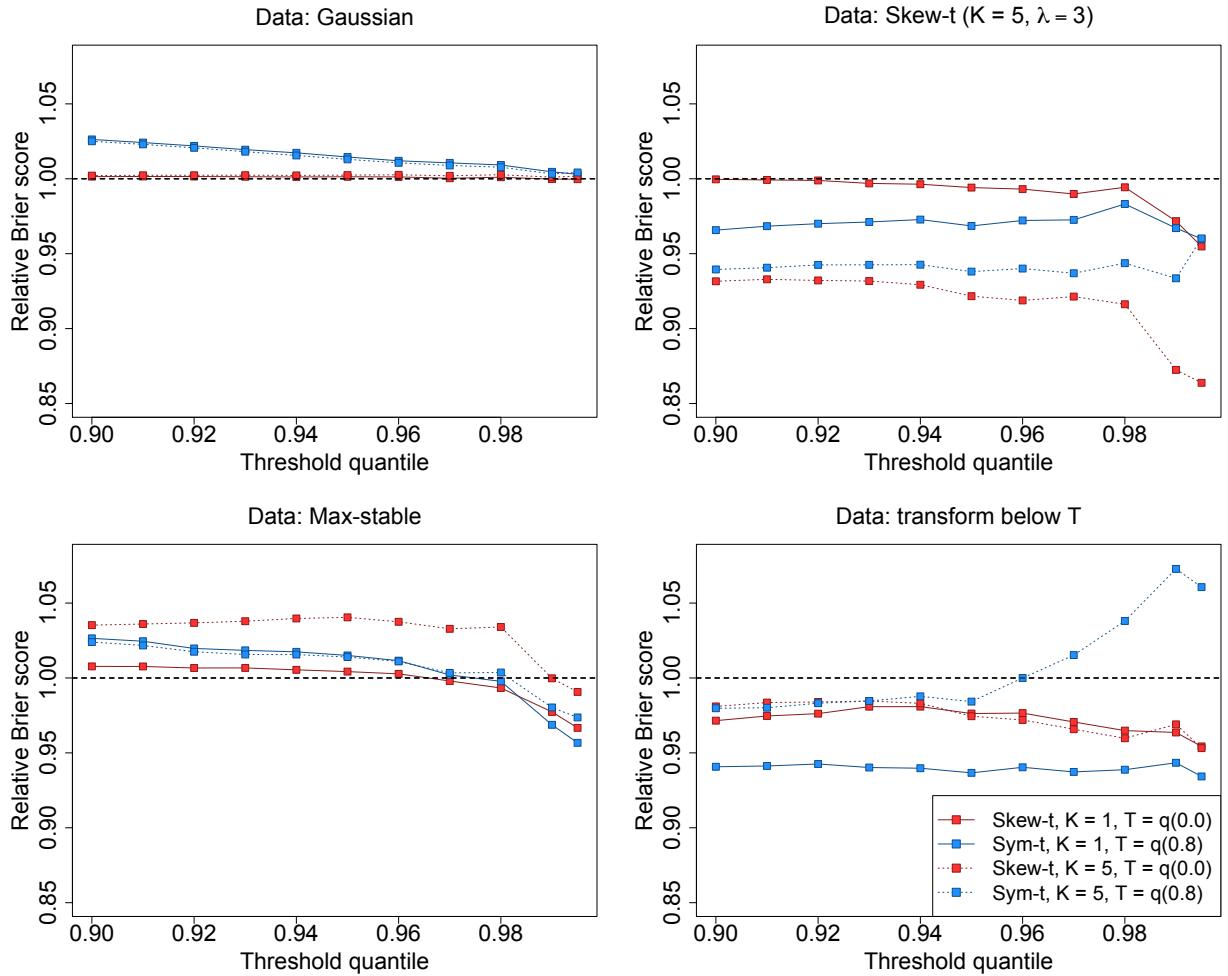


Figure 2: Brier scores relative to the Gaussian method for simulation study results. A ratio lower than 1 indicates that the method outperforms relative to the Gaussian method.

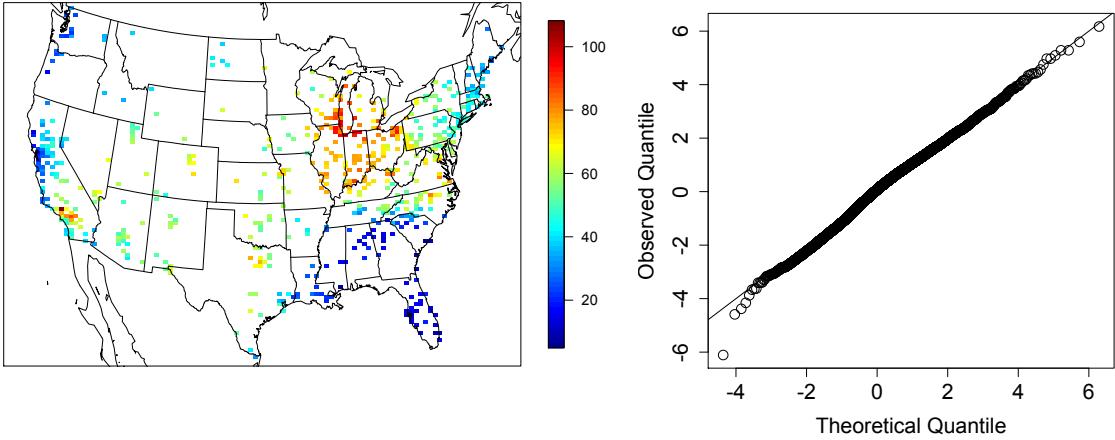


Figure 3: Ozone values on 10 July 2005 (left) Q-Q plot of the residuals (right)

207 6 Data analysis

208 To illustrate this method, we consider the daily maximum 8-hour ozone measurements for July 2005 at 735
 209 Air Quality System (AQS) monitoring sites in the eastern United States as the response (see Figure 3). For
 210 each site, we also have covariate information containing the estimated ozone from the Community Multi-
 211 scale Air Quality (CMAQ) modeling system. Initially, we fit a linear regression assuming a mean function
 212 of

$$\mathbf{X}\boldsymbol{\beta} = \beta_0 + \beta_1 \cdot \text{CMAQ}_t(\mathbf{s}). \quad (32)$$

213 The data from July 10 are shown in Figure 3 along with a Q-Q plot of the residuals compared to a skew-*t*
 214 distribution with 10 d.f. and $\alpha = 1$.

215 We explore spatial and temporal extremal dependence by considering $\chi_c = \Pr[Y(\mathbf{s}) > c | Y(\mathbf{t}) > c]$. To
 216 examine spatial dependence in high quantiles, we consider observations at all pairs of sites \mathbf{s} and \mathbf{t} that are
 217 distance h apart where h is separated into bins of size 0.25 km. Then conditioned on $Y(\mathbf{t}) > c$, we take

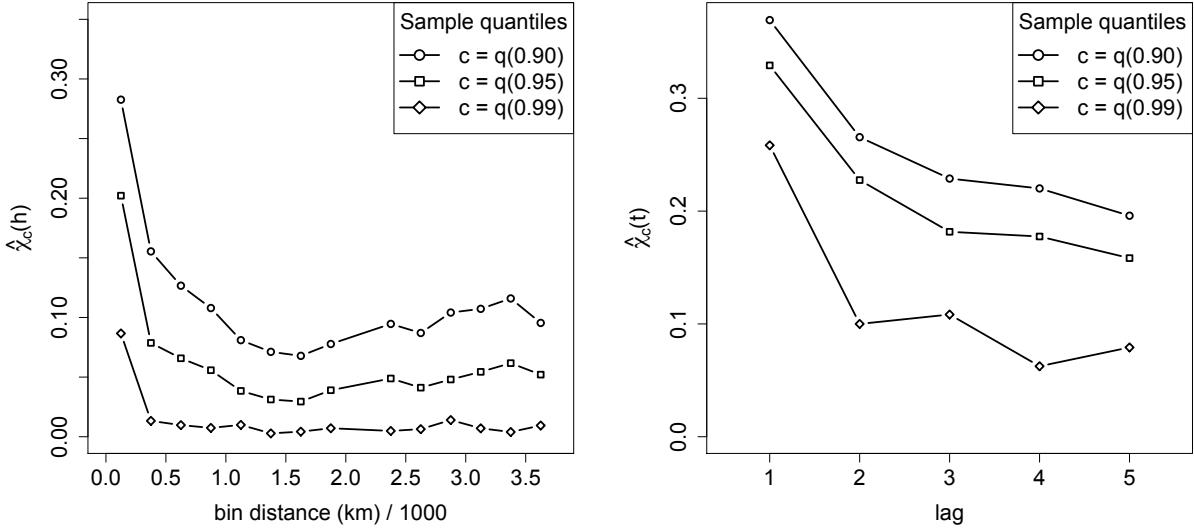


Figure 4: $\hat{\chi}_c(h)$ plot for the residuals (left). $\hat{\chi}_c(t)$ plot for the residuals (right).

the sample proportion of $Y(\mathbf{s}) > c$. Finally, $\hat{\chi}_c(h)$ is averaged over all days at each of the three threshold quantiles. To examine temporal dependence in high quantiles, we consider observations at a single site that are taken lag- t days apart. Then conditioned on $Y_n(\mathbf{s}) > c$, we take the sample proportion of $Y_{n+t}(\mathbf{s}) > c$. Finally, $\hat{\chi}(t)$ is averaged over all sites at each of the three threshold quantiles. The $\hat{\chi}_c(h)$ and $\hat{\chi}_c(t)$ plots in Figure 4 show the estimated spatial and temporal dependence of the residuals for the ozone data at three quantile levels $q(0.90)$, $q(0.95)$, and $q(0.99)$. Both plots indicate that there is dependence in the high quantile levels beyond what we expect if the residuals were independent.

6.1 Model comparisons

We fit the model using Gaussian and skew- t marginal distributions with $K = 1, 5, 6, 7, 8, 9, 10, 15$ partitions. We choose to censor $Y(\mathbf{s})$ at $T = 0$, $\hat{q}(0.42) = 50$, $\hat{q}(0.92) = 75$ ppb in order to compare results from no, moderate, and high censoring. We also compare models with no time series to models that include the time series. Finally, as a comparison to max-stable methods, we fit the model using the hierarchical max-stable

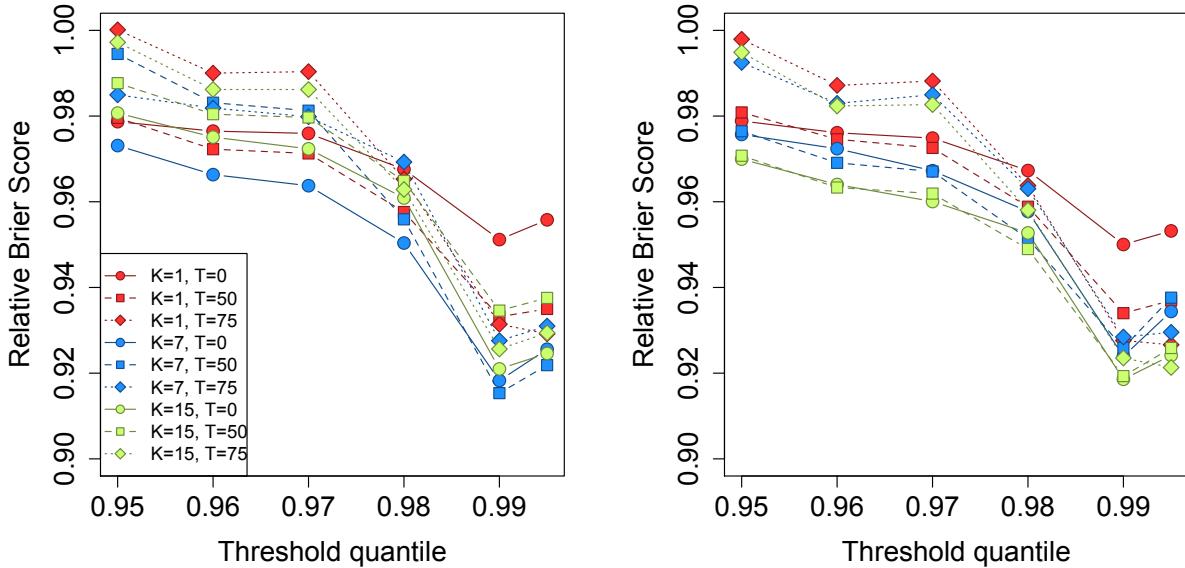


Figure 5: Relative Brier scores for time-series models (left) and non-time-series models (right). Relative brier score for the max-stable model is between 1.07 and 1.15

model of Reich and Shaby (2012). All methods assume the mean function given in (32). For each model, Brier scores were averaged over all sites and days to obtain a single Brier score for each dataset. At a particular threshold or quantile level, the model that fits the best is the one with the lowest score. We then compute the relative Brier scores to compare each model.

6.2 Results

The plots in Figure 5 shows the relative Brier scores (see Section 5.3) for time-series and non-time-series models, using $K = 1, 7$, and 15 knots at thresholds $T = 0, 50$, and 75 ppb. Both plots have similar features suggesting that most settings do reasonably well. In particular, for all extreme quantiles, selecting a moderate number of knots (e.g. $K = 5, \dots, 10$) tends to give the best results. Table 1 shows the best two models for selected extreme quantiles. The results demonstrate the importance of accounting for the temporal dependence when making extreme predictions. They also show the importance of thresholding for predictions

Table 1: Top two performing models for ozone analysis at extreme quantiles with Relative Brier score

	1st				2nd			
$q(0.90)$	No time series	$K = 7$	$T = 0$	BS: 0.980	No time series	$K = 9$	$T = 0$	BS: 0.980
$q(0.95)$	No time series	$K = 15$	$T = 50$	BS: 0.970	No time series	$K = 9$	$T = 50$	BS: 0.970
$q(0.98)$	No time series	$K = 5$	$T = 50$	BS: 0.945	No time series	$K = 10$	$T = 50$	BS: 0.946
$q(0.99)$	Time series	$K = 10$	$T = 75$	BS: 0.912	Time series	$K = 6$	$T = 75$	BS: 0.913
$q(0.995)$	Time series	$K = 6$	$T = 75$	BS: 0.917	Time series	$K = 10$	$T = 75$	BS: 0.918

241 further out in the tails of the data. This is further illustrated by the plots in Figure 6.

242 7 Discussion

243 In this paper we propose a new approach for spatiotemporal modeling of extreme values. The proposed
 244 model gives flexible tail behavior, demonstrates asymptotic dependence for observations at sites that are
 245 near to one another, and has computation on the order of Gaussian models for large space-time datasets –

246 Do I need to add anything about the computation in the paper?. In the simulation study, we demonstrate
 247 that this model shows statistically significant improvements over a naïve Gaussian approach. In both the
 248 simulation study, and the application to ozone data, we find that incorporating a partition in the model
 249 improves extreme prediction. Furthermore the results from the data analysis suggest that thresholding can
 250 improve performance when predicting in the extreme tails of the data.

251 This model presents new avenues for future research. One possibility is the implementation of a different
 252 partition structure. We choose to define the random effects for a site by using an indicator function based on
 253 closeness to a knot. However, this indicator function could be replaced by kernel function that would allow
 254 for multiple knots to impact each site, with the weight of each knot to be determined by some characteristic
 255 such as distance. Another area that should be explored is the temporal dependence in the model. Instead of
 256 implementing a time series on the random effects, a three-dimensional covariance structure on the residuals
 257 could be implemented to address temporal dependence. Finally, we acknowledge that by specifying the
 258 number of knots, we may be underestimating the uncertainty in the model. This could be incorporated by

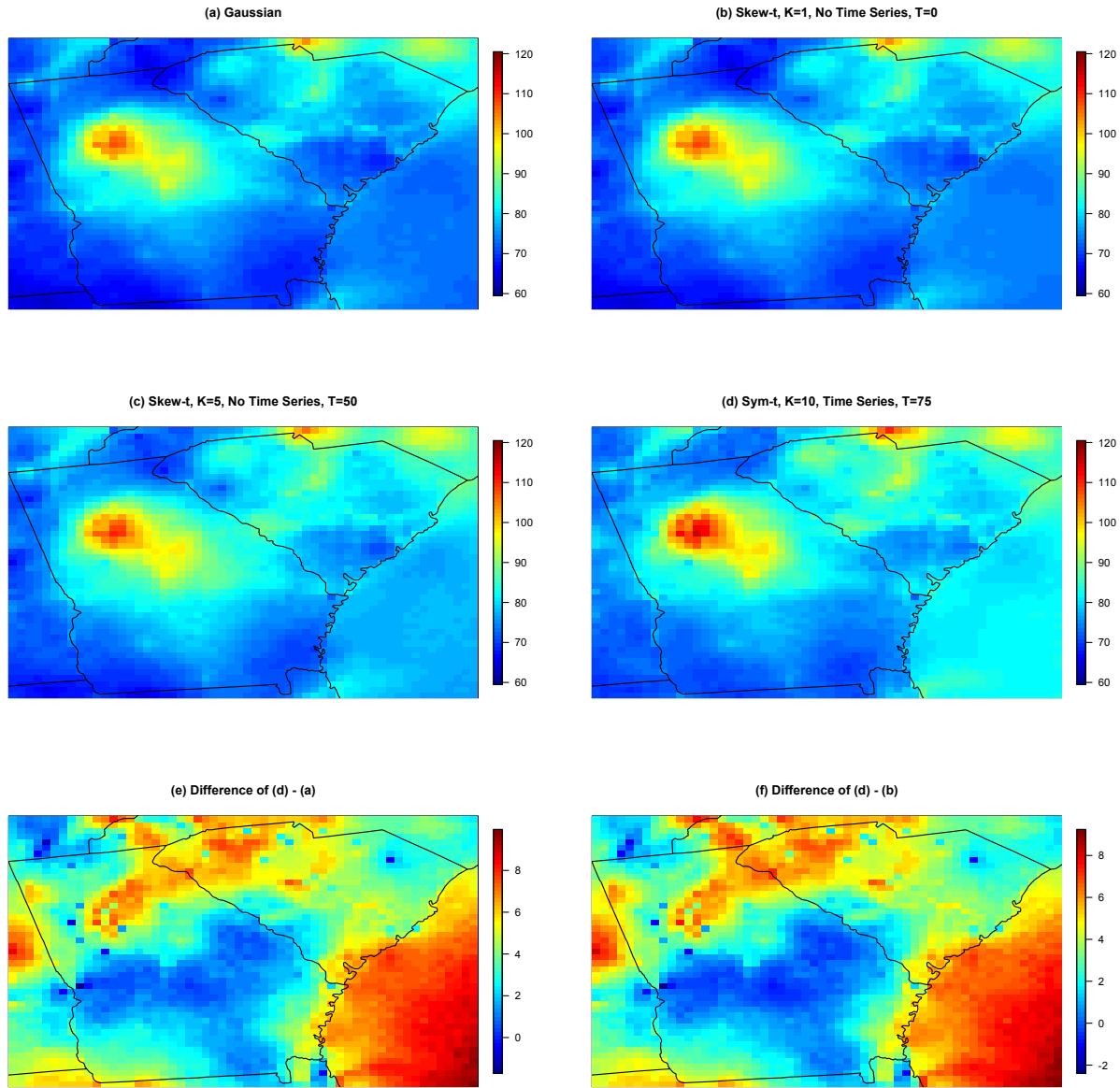


Figure 6: (a) – (d) give the posterior predictive $\hat{q}(0.99)$ for the month of July under four different models, (e) gives the difference between $\hat{q}(0.99)$ in plots (d) and (a), (f) gives the difference between $\hat{q}(0.99)$ in plots (d) and (b).

259 treating the number of knots as a model parameter instead of fixing it to be a specific value.

260 **Acknowledgments**

261 **A Appendices**

262 **A.1 MCMC details**

263 The MCMC sampling for the model 3.4 is done using R (<http://www.r-project.org>). Whenever possible,
264 we select conjugate priors (see Appendix A.2); however, for some of the parameters, no conjugate prior
265 distributions exist. When no conjugate prior distribution exists, we use a random walk Metropolis Hastings
266 update step. In each Metropolis Hastings update, we tune the algorithm to give acceptance rates near 0.40.

267 **Spatial knot locations**

268 For each day, we update the spatial knot locations, $\mathbf{w}_1, \dots, \mathbf{w}_K$, using a Metropolis Hastings block up-
269 date. Because the spatial domain is bounded, we generate candidate knots using the transformed knots
270 $\mathbf{w}_1^*, \dots, \mathbf{w}_K^*$ (see section 3.3) and a random walk bivariate Gaussian candidate distribution

$$\mathbf{w}_k^{*(c)} \sim N(\mathbf{w}_k^{*(r-1)}, s^2 I_2)$$

271 where $\mathbf{w}_k^{*(r-1)}$ is the location for the transformed knot at MCMC iteration $r - 1$, s is a tuning parameter,
272 and I_2 is an identity matrix. After candidates have been generated for all K knots, the acceptance ratio is

$$R = \left\{ \frac{l[Y_t(\mathbf{s}|\mathbf{w}_1^{(c)}, \dots, \mathbf{w}_K^{(c)}, \dots)]}{l[Y_t(\mathbf{s}|\mathbf{w}_1^{(r-1)}, \dots, \mathbf{w}_K^{(r-1)}, \dots)]} \right\} \times \left\{ \frac{\prod_{k=1}^K \phi(\mathbf{w}_k^{(c)})}{\prod_{k=1}^K \phi(\mathbf{w}_k^{(r-1)})} \right\} \times \left\{ \frac{\prod_{k=1}^K p(\mathbf{w}_k^{*(c)})}{\prod_{k=1}^K p(\mathbf{w}_k^{*(r-1)})} \right\}$$

273 where l is the likelihood given in (20), and $p(\cdot)$ is the prior either taken from the time series given in (3.3)
 274 or assumed to be uniform over \mathcal{D} . The candidate knots are accepted with probability $\min\{R, 1\}$.

275 **Spatial random effects**

276 If there is no temporal dependence amongst the observations, we use a Gibbs update for z_{tk} , and the posterior
 277 distribution is given in A.2. If there is temporal dependence amongst the observations, then we update z_{tk}
 278 using a Metropolis Hastings update. Because this model uses $|z_{tk}|$, we generate candidate random effects
 279 using the z_{tk}^* (see Section 3.3) and a random walk Gaussian candidate distribution

$$z_{tk}^{*(c)} \sim N(z_{tk}^{*(r-1)}, s^2)$$

280 where $z_{tk}^{*(r-1)}$ is the value at MCMC iteration $r - 1$, and s is a tuning parameter. The acceptance ratio is

$$R = \left\{ \frac{l[Y_t(\mathbf{s})|z_{tk}^{(c)}, \dots]}{l[Y_t(\mathbf{s})|z_{tk}^{(r-1)}]} \right\} \times \left\{ \frac{p[z_{tk}^{(c)}]}{p[z_{tk}^{(r-1)}]} \right\}$$

281 where $p[\cdot]$ is the prior taken from the time series given in Section 3.3. The candidate is accepted with
 282 probability $\min\{R, 1\}$.

283 **Variance terms**

284 When there is more than one site in a partition, then we update σ_{tk}^2 using a Metropolis Hastings update.
 285 First, we generate a candidate for σ_{tk}^2 using an $IG(a^*/s, b^*/s)$ candidate distribution in an independence
 286 Metropolis Hastings update where $a^* = (n_{tk} + 1)/2 + a$, $b^* = [Y_{tk}^T \Sigma_{tk}^{-1} Y_{tk} + z_{tk}^2]/2 + b$, n_{tk} is the number
 287 of sites in partition k on day t , and Y_{tk} and Σ_{tk}^{-1} are the observations and precision matrix for partition k on

288 day t . The acceptance ratio is

$$R = \left\{ \frac{l[Y_t(\mathbf{s}) | \sigma_{tk}^{(c)}, \dots]}{l[Y_t(\mathbf{s}) | \sigma_{tk}^{(r-1)}]} \right\} \times \left\{ \frac{l[z_{tk} | \sigma_{tk}^{(c)}, \dots]}{l[z_{tk} | \sigma_{tk}^{(r-1)}, \dots]} \right\} \times \left\{ \frac{p[\sigma_{tk}^{(c)}]}{p[\sigma_{tk}^{(r-1)}]} \right\} \times \left\{ \frac{c[\sigma_{tk}^{(r-1)}]}{c[\sigma_{tk}^{(c)}]} \right\}$$

289 where $p[\cdot]$ is the prior either taken from the time series given in Section 3.3 or assumed to be $\text{IG}(a, b)$, and

290 $c[\cdot]$ is the candidate distribution. The candidate is accepted with probability $\min\{R, 1\}$.

291 **Spatial covariance parameters**

292 We update the three spatial covariance parameters, $\log(\rho)$, $\log(\nu)$, γ , using a Metropolis Hastings block

293 update step. First, we generate a candidate using a random walk Gaussian candidate distribution

$$\log(\rho)^{(c)} \sim N(\log(\rho)^{(r-1)}, s^2)$$

294 where $\log(\rho)^{(r-1)}$ is the value at MCMC iteration $r - 1$, and s is a tuning parameter. Candidates are

295 generated for $\log(\nu)$ and γ in a similar fashion. The acceptance ratio is

$$R = \left\{ \frac{\prod_{t=1}^T l[Y_t(\mathbf{s}) | \rho^{(c)}, \nu^{(c)}, \gamma^{(c)}, \dots]}{\prod_{t=1}^T l[Y_t(\mathbf{s}) | \rho^{(r-1)}, \nu^{(r-1)}, \gamma^{(r-1)}, \dots]} \right\} \times \left\{ \frac{p[\rho^{(c)}]}{p[\rho^{(r-1)}]} \right\} \times \left\{ \frac{p[\nu^{(c)}]}{p[\nu^{(r-1)}]} \right\} \times \left\{ \frac{p[\gamma^{(c)}]}{p[\gamma^{(r-1)}]} \right\}.$$

296 All three candidates are accepted with probability $\min\{R, 1\}$.

²⁹⁷ **A.2 Posterior distributions**

²⁹⁸ **Conditional posterior of $z_{tk} | \dots$**

²⁹⁹ If knots are independent over days, then the conditional posterior distribution of $|z_{tk}|$ is conjugate. For
³⁰⁰ simplicity, drop the subscript t , let $\tilde{z}_{tk} = |z_{tk}|$, and define

$$R(\mathbf{s}) = \begin{cases} Y(\mathbf{s}) - X(\mathbf{s})\beta & s \in P_l \\ Y(\mathbf{s}) - X(\mathbf{s})\beta - \lambda \tilde{z}(\mathbf{s}) & s \notin P_l \end{cases}$$

³⁰¹ Let

$R_1 = \text{the vector of } R(\mathbf{s}) \text{ for } s \in P_l$

$R_2 = \text{the vector of } R(\mathbf{s}) \text{ for } s \notin P_l$

$$\Omega = \Sigma^{-1}.$$

³⁰² Then

$$\begin{aligned} \pi(z_l | \dots) &\propto \exp \left\{ -\frac{1}{2} \left[\begin{pmatrix} R_1 - \lambda \tilde{z}_l \mathbf{1} \\ R_2 \end{pmatrix}^T \begin{pmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{pmatrix} \begin{pmatrix} R_1 - \lambda \tilde{z}_l \mathbf{1} \\ R_2 \end{pmatrix} + \frac{\tilde{z}_l^2}{\sigma_l^2} \right] \right\} I(z_l > 0) \\ &\propto \exp \left\{ -\frac{1}{2} [\Lambda_l \tilde{z}_l^2 - 2\mu_l \tilde{z}_l] \right\} \end{aligned}$$

³⁰³ where

$$\mu_l = \lambda(R_1^T \Omega_{11} + R_2^T \Omega_{21})\mathbf{1}$$

$$\Lambda_l = \lambda^2 \mathbf{1}^T \Omega_{11} \mathbf{1} + \frac{1}{\sigma_l^2}.$$

³⁰⁴ Then $\tilde{Z}_l | \dots \sim N_{(0,\infty)}(\Lambda_l^{-1} \mu_l, \Lambda_l^{-1})$

³⁰⁵ **Conditional posterior of β | ...**

³⁰⁶ Let $\beta \sim N_p(0, \Lambda_0)$ where Λ_0 is a precision matrix. Then

$$\begin{aligned} \pi(\beta | \dots) &\propto \exp \left\{ -\frac{1}{2} \beta^T \Lambda_0 \beta - \frac{1}{2} \sum_{t=1}^T [\mathbf{Y}_t - X_t \beta - \lambda |z_t|]^T \Omega [\mathbf{Y}_t - X_t \beta - \lambda |z_t|] \right\} \\ &\propto \exp \left\{ -\frac{1}{2} \left[\beta^T \Lambda_\beta \beta - 2 \sum_{t=1}^T [\beta^T X_t^T \Omega (\mathbf{Y}_t - \lambda |z_t|)] \right] \right\} \\ &\propto N(\Lambda_\beta^{-1} \mu_\beta, \Lambda_\beta^{-1}) \end{aligned}$$

³⁰⁷ where

$$\begin{aligned} \mu_\beta &= \sum_{t=1}^T [X_t^T \Omega (\mathbf{Y}_t - \lambda |z_t|)] \\ \Lambda_\beta &= \Lambda_0 + \sum_{t=1}^T X_t^T \Omega X_t. \end{aligned}$$

³⁰⁸ **Conditional posterior of $\sigma^2 | \dots$**

³⁰⁹ In the case where $L = 1$ and temporal dependence is negligible, then σ^2 has a conjugate posterior distribution. Let $\sigma_t^2 \stackrel{iid}{\sim} \text{IG}(\alpha_0, \beta_0)$. For simplicity, drop the subscript t . Then

$$\begin{aligned}\pi(\sigma^2 | \dots) &\propto (\sigma^2)^{-\alpha_0 - 1/2 - n/2 - 1} \exp \left\{ -\frac{\beta_0}{\sigma^2} - \frac{|z|^2}{2\sigma^2} - \frac{(\mathbf{Y} - \boldsymbol{\mu})^T \Sigma^{-1} (\mathbf{Y} - \boldsymbol{\mu})}{2\sigma^2} \right\} \\ &\propto (\sigma^2)^{-\alpha_0 - 1/2 - n/2 - 1} \exp \left\{ -\frac{1}{\sigma^2} \left[\beta_0 + \frac{|z|^2}{2} + \frac{1}{2} (\mathbf{Y} - \boldsymbol{\mu})^T \Sigma^{-1} (\mathbf{Y} - \boldsymbol{\mu}) \right] \right\} \\ &\propto \text{IG}(\alpha^*, \beta^*)\end{aligned}$$

³¹¹ where

$$\begin{aligned}\alpha^* &= \alpha_0 + \frac{1}{2} + \frac{n}{2} \\ \beta^* &= \beta_0 + \frac{|z|^2}{2} + \frac{1}{2} (\mathbf{Y} - \boldsymbol{\mu})^T \Sigma^{-1} (\mathbf{Y} - \boldsymbol{\mu}).\end{aligned}$$

³¹² In the case that $L > 1$, a random walk Metropolis Hastings step will be used to update σ_{lt}^2 .

³¹³ **Conditional posterior of $\lambda | \dots$**

³¹⁴ For convergence purposes we model $\lambda = \lambda_1 \lambda_2$ where

$$\lambda_1 = \begin{cases} +1 & \text{w.p.0.5} \\ -1 & \text{w.p.0.5} \end{cases} \quad (33)$$

$$\lambda_2^2 \sim IG(\alpha_\lambda, \beta_\lambda). \quad (34)$$

$$(35)$$

315 Then

$$\begin{aligned}\pi(\lambda_2 | \dots) &\propto \lambda_2^{2(-\alpha_\lambda - 1)} \exp\left\{-\frac{\beta_\lambda}{\lambda_2^2}\right\} \prod_{t=1}^T \prod_{k=1}^K \frac{1}{\lambda_2} \exp\left\{-\frac{z_{tk}^2}{2\lambda_2^2 \sigma_{tk}^2}\right\} \\ &\propto \lambda_2^{2(-\alpha_\lambda - kt - 1)} \exp\left\{-\frac{1}{\lambda_2^2} \left[\beta_\lambda + \frac{z^2}{2\sigma_{tk}^2}\right]\right\}\end{aligned}$$

316 Then $\lambda_2 | \dots \sim IG(\alpha_\lambda + kt, \beta_\lambda + \frac{z^2}{2\sigma_{tk}^2})$

317 **A.3 Proof that** $\lim_{h \rightarrow \infty} \pi(h) = 0$

318 Let $N(A)$ be the number of knots in A , the area between sites s_1 and s_2 . Consider a spatial Poisson process

319 with intensity $\mu(A)$. So,

$$P[N(A) = k] = \frac{\mu(A)^k \exp\{-\mu(A)\}}{k!}.$$

320 Then for any finite k , $\lim_{h \rightarrow \infty} P[N(A) = k] = 0$ because $\lim_{h \rightarrow \infty} \mu(A) = \infty$. With each additional knot

321 in A , the chance that s_1 and s_2 will be in the same partition will decrease, because partition membership

322 is defined by the closest knot to a site. Therefore, $\lim_{h \rightarrow \infty} \pi(h) = 0$.

323 **A.4 Skew-t distribution**

324 **Univariate extended skew-t distribution**

325 We say that Y follow a univariate extended skew-t distribution with location $\xi \in \mathcal{R}$, scale $\omega > 0$, skew

326 parameter $\alpha \in \mathcal{R}$, extended parameter $\tau \in \mathcal{R}$, and degrees of freedom ν if has distribution function

$$f_{EST}(y) = \omega^{-1} \frac{f_T(z; \nu)}{F_T(\tau/\sqrt{1+\alpha^2}; \nu)} F_T \left[(\alpha z + \tau) \sqrt{\frac{\nu+1}{\nu+z^2}}; 0, 1, \nu+1 \right] \quad (36)$$

³²⁷ where $f_T(t; \nu)$ is a univariate Student's t with ν degrees of freedom, $F_T(t; \nu) = P(T < t)$, and $z = (y - \xi)/\omega$.

³²⁸ In the case that $\tau = 0$, then Y follows a univariate skew- t distribution.

³²⁹ Multivariate skew- t distribution

³³⁰ If $\mathbf{Z} \sim \text{ST}_d(0, \bar{\Omega}, \boldsymbol{\alpha}, \eta)$ is a d -dimensional skew- t distribution, and $\mathbf{Y} = \xi + \boldsymbol{\omega}\mathbf{Z}$, where $\boldsymbol{\omega} = \text{diag}(\omega_1, \dots, \omega_d)$,

³³¹ then the density of Y at y is

$$f_y(\mathbf{y}) = \det(\boldsymbol{\omega})^{-1} f_z(\mathbf{z}) \quad (37)$$

³³² where

$$f_z(\mathbf{z}) = 2t_d(\mathbf{z}; \bar{\Omega}, \eta) T \left[\boldsymbol{\alpha}^T \mathbf{z} \sqrt{\frac{\eta + d}{\nu + Q(\mathbf{z})}}; \eta + d \right] \quad (38)$$

$$\mathbf{z} = \boldsymbol{\omega}^{-1}(\mathbf{y} - \xi) \quad (39)$$

³³³ where $t_d(\mathbf{z}; \bar{\Omega}, \eta)$ is a d -dimensional Student's t -distribution with scale matrix $\bar{\Omega}$ and degrees of freedom

³³⁴ η , $Q(z) = \mathbf{z}^T \bar{\Omega}^{-1} \mathbf{z}$ and $T(\cdot; \eta)$ denotes the univariate Student's t distribution function with η degrees of

³³⁵ freedom (Azzalini and Capitanio, 2013).

³³⁶ Extremal dependence

³³⁷ For a bivariate skew- t random variable $\mathbf{Y} = [Y(\mathbf{s}), Y(\mathbf{t})]^T$, the $\chi(h)$ statistic (Padoan, 2011) is given by

$$\chi(h) = \bar{F}_{\text{EST}} \left\{ \frac{[x_1^{1/\eta} - \varrho(h)]\sqrt{\eta+1}}{\sqrt{1-\varrho(h)^2}}; 0, 1, \alpha_1, \tau_1, \eta + 1 \right\} + \bar{F}_{\text{EST}} \left\{ \frac{[x_2^{1/\eta} - \varrho(h)]\sqrt{\eta+1}}{\sqrt{1-\varrho(h)^2}}; 0, 1, \alpha_2, \tau_2, \eta + 1 \right\}, \quad (40)$$

338 where \bar{F}_{EST} is the univariate survival extended skew- t function with zero location and unit scale, $\varrho(h) = \text{cor}(y_1, y_2)$,
 339 $\alpha_j = \alpha_i \sqrt{1 - \varrho^2}$, $\tau_j = \sqrt{\eta + 1}(\alpha_j + \alpha_i \varrho)$, and $x_j = F_T(\bar{\alpha}_i \sqrt{\eta + 1}; 0, 1, \eta) / F_T(\bar{\alpha}_j \sqrt{\eta + 1}; 0, 1, \eta)$ with
 340 $j = 1, 2$ and $i = 2, 1$ and where $\bar{\alpha}_j = (\alpha_j + \alpha_i \varrho) / \sqrt{1 + \alpha_i^2[1 - \varrho(h)^2]}$.

341 **Proof that** $\lim_{h \rightarrow \infty} \chi(h) > 0$

342 Consider the bivariate distribution of $\mathbf{Y} = [Y(\mathbf{s}), Y(\mathbf{t})]^T$, with $\varrho(h)$ given by (2). So, $\lim_{h \rightarrow \infty} \varrho(h) = 0$.

343 Then

$$\lim_{h \rightarrow \infty} \chi(h) = \bar{F}_{\text{EST}} \left\{ \sqrt{\eta + 1}; 0, 1, \alpha_1, \tau_1, \eta + 1 \right\} + \bar{F}_{\text{EST}} \left\{ \sqrt{\eta + 1}; 0, 1, \alpha_2, \tau_2, \eta + 1 \right\}. \quad (41)$$

344 Because the extended skew- t distribution is not bounded above, for all $\bar{F}_{\text{EST}}(x) = 1 - F_{\text{EST}} > 0$ for all
 345 $x < \infty$. Therefore, for a skew- t distribution, $\lim_{h \rightarrow \infty} \chi(h) > 0$.

346 **A.5 Simulation study pairwise difference results**

347 The following tables show the methods that have significantly different Brier scores when using a Wilcoxon-
 348 Nemenyi-McDonald-Thompson test. In each column, different letters signify that the methods have signifi-
 349 cantly different Brier scores. For example, there is significant evidence to suggest that method 1 and method
 350 4 have different Brier scores at $q(0.90)$, whereas there is not significant evidence to suggest that method 1
 351 and method 2 have different Brier scores at $q(0.90)$. In each table group A represents the group with the
 352 lowest Brier scores. Groups are significant with a familywise error rate of $\alpha = 0.05$.

353 **References**

354 Azzalini, A. and Capitanio, A. (2013) *The Skew-Normal and Related Families*. Institute of Mathematical
 355 Statistics Monographs. Cambridge University Press.

Table 2: Setting 1: Gaussian marginal, $K = 1$ knot

	$q(0.90)$	$q(0.95)$	$q(0.98)$	$q(0.99)$
Method 1	A	A	A	A
Method 2	A B	A B	A	A
Method 3	C	C	C	B
Method 4	B	B	B	B
Method 5	C	C	C	B

Table 3: Setting 2: Symmetric- t marginal, $K = 1$ knot

	$q(0.90)$	$q(0.95)$	$q(0.98)$	$q(0.99)$
Method 1	B	D	D	C
Method 2	A	A	A	A
Method 3	B	B	B C	B
Method 4	A	C	B	B
Method 5	B	D	C D	B C

Table 4: Setting 3: Symmetric- t marginal, $K = 5$ knots

	$q(0.90)$	$q(0.95)$	$q(0.98)$	$q(0.99)$
Method 1	B	B	B	B
Method 2	B	B	B	B
Method 3	B	B	B	A B
Method 4	A	A	A	A
Method 5	B	B	A B	A B

Table 5: Setting 4: Skew- t marginal, $K = 1$ knot

	$q(0.90)$	$q(0.95)$	$q(0.98)$	$q(0.99)$
Method 1	B	B	B	B
Method 2	A	A	A	A
Method 3	B	B	B	A B
Method 4	B	B	B	B
Method 5	C	C	C	C

Table 6: Setting 5: Skew- t marginal, $K = 5$ knots

	$q(0.90)$	$q(0.95)$	$q(0.98)$	$q(0.99)$
Method 1	B	B	B	C
Method 2	B	B	B	B C
Method 3	A	A	B	C
Method 4	A	A	A	A B
Method 5	A	A	A	A

Table 7: Setting 6: Max-stable

	$q(0.90)$	$q(0.95)$	$q(0.98)$	$q(0.99)$
Method 1	A	A	A B	C
Method 2	B	A B	A	A B
Method 3	C	B C	A B	A
Method 4	D	D	C	C
Method 5	C D	C	B	B C

Table 8: Setting 7: Transformation below $T = q(0.80)$

	$q(0.90)$	$q(0.95)$	$q(0.98)$	$q(0.99)$
Method 1	C	B	C	C
Method 2	B	B	A B	A B
Method 3	A	A	A	A
Method 4	B C	B	B	B C
Method 5	B C	B	C	C

- 356 Blanchet, J. and Davison, A. C. (2011) Spatial modeling of extreme snow depth. *The Annals of Applied
357 Statistics*, **5**, 1699–1725.
- 358 Coles, S. G. and Tawn, J. A. (1991) Modelling Extreme Multivariate Events. *Journal of the Royal Statistical
359 Society: Series B (Methodological)*, **53**, 377–392.
- 360 DuMouchel, W. H. (1983) Estimating the stable index α in order to measure tail thickness: a critique. *The
361 Annals of Statistics*, **11**, 1019–1031.
- 362 Genton, M. G. (2004) *Skew-Elliptical Distributions and Their Applications: A Journey Beyond Normality*.
363 Statistics (Chapman & Hall/CRC). Taylor & Francis.
- 364 Gneiting, T. and Raftery, A. E. (2007) Strictly Proper Scoring Rules, Prediction, and Estimation. *Journal of
365 the American Statistical Association*, **102**, 359–378.
- 366 Huser, R. (2013) *Statistical Modeling and Inference for Spatio-Temporal Extremes*. Ph.D. thesis.
- 367 Kim, H.-M., Mallick, B. K. and Holmes, C. C. (2005) Analyzing Nonstationary Spatial Data Using Piece-
368 wise Gaussian Processes. *Journal of the American Statistical Association*, **100**, 653–668.

- 369 Padoan, S. A. (2011) Multivariate extreme models based on underlying skew- and skew-normal distribu-
- 370 tions. *Journal of Multivariate Analysis*, **102**, 977–991.
- 371 Padoan, S. A., Ribatet, M. and Sisson, S. A. (2010) Likelihood-Based Inference for Max-Stable Processes.
- 372 *Journal of the American Statistical Association*, **105**, 263–277.
- 373 Reich, B. J. and Shaby, B. A. (2012) A hierarchical max-stable spatial model for extreme precipitation. *The*
- 374 *Annals of Applied Statistics*, **6**, 1430–1451.
- 375 Zhang, H. and El-Shaarawi, A. (2010) On spatial skewGaussian processes and applications. *Environmetrics*,
- 376 **21**, 33–47.