

A Practical Formulation for an Anisotropic and Nonstationary Matérn Class Correlation Operator

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A key component of data assimilation methods is the specification of univariate spatial correlations, which appear in the background-error covariance. For realistic problems in meteorology and oceanography, correlation length scales are nonstationary (variable in space) and anisotropic (variable in each direction). Variational approaches typically use an operator to enforce correlation length scales, and thus the operator must be designed to capture desired levels of nonstationarity and anisotropy. For systems with complex boundaries, such as the ocean, it is natural to use a filtering approach based on the application of an elliptic, Laplacian-like operator. Here we show how an elliptic operator can be formulated to capture a general Matérn-type correlation structure. We show how nonstationarity and anisotropy can be encoded into the operator via a simple change of variables based on user-defined normalization length scales. The change of variables defines a mapping between the computational domain and a space where the analytical Matérn correlation function applies. In addition to the mapping, two other hyperparameters *separately* control the correlation length scale (i.e. range) and shape. As a practical use-case, we apply the operator to a global ocean model. We show that when the normalizing length scales correspond to the local grid scale, the range parameter has an intuitive interpretation as the number of neighboring grid cells at which correlation drops to 0.14. Finally, the correlation model is shown to be computationally efficient in two regards. First, the necessary linear solve can be performed with a high tolerance

($\sim 10^{-3}$) while still achieving the correct statistics, requiring few iterations to converge. Secondly, the operator's exponent, which controls the correlation shape, is linearly related to the diagonal elements of its matrix representation. As a result, using an exponent greater than one can improve convergence properties. Thus, the framework provides flexibility in controlling correlation shape.

KEYWORDS

correlation operators, covariance modelling, background error, ocean data assimilation, variational assimilation, stochastic PDEs

1 | INTRODUCTION

High dimensional geophysical inverse problems, such as numerical weather prediction and oceanographic state estimation, are typically ill-posed due to the sparsity of data relative to the size of the control vector. A classical method for handling this ill-posedness is to prescribe some type of regularization in order to “spread” information to the uninformed regions and variables in the control vector (e.g., Wunsch, 2006). In the Bayesian interpretation of the inverse problem, this regularization is defined so that it represents the prior uncertainty or background-state error (e.g., Bui-Thanh et al., 2013). Ideally, this uncertainty captures the true error in the background state, but for all practical applications the background error must be approximated. Moreover, to make the problem computationally tractable, it is often assumed that the background error is governed by Gaussian statistics, such that the uncertainty is fully described by a covariance matrix.

For realistic data assimilation (DA) problems in meteorology and oceanography, a well formed background error will contain covariance relationships between different variables (e.g., between temperature and velocity components), it will have spatially dependent length scales of covariation (i.e. nonstationarity or inhomogeneity), and it will respect the system's anisotropy, such that length scales of covariance differ appropriately in each direction (e.g., Bannister, 2008a). Within variational DA systems, the background error covariance is usually represented as an operator so that it can be applied efficiently during an iterative optimization algorithm. Thus, for an operator-based covariance model to be useful in this context, it must be able to respect multivariate, nonstationary, and anisotropic features that are necessary for the given problem setting.

Typically, the background state error covariance is decomposed into two operators following Derber and Bouttier (1999). The first, “balance” operator captures multivariate (i.e. cross-variable) covariance information while the second captures “unbalanced” (i.e. univariate) covariance information. Our focus is on the latter operator, but we note the review by Bannister (2008b) which outlines balance operators used in atmospheric DA, and e.g., Weaver et al. (2005); Moore et al. (2011) for oceanographic examples.

Univariate covariance operators are further decomposed into two stages, where spatial correlations are specified first, and then scaled to the appropriate amplitude. In atmospheric DA, it is common to transform the control vector into a wavelet or spherical harmonic basis in order to specify the background error (e.g., Bannister, 2008b). However, for systems with complex boundaries like the ocean, it is far more straightforward to formulate the correlation operator in terms of the original, physical domain. Considering methods that operate in the physical or grid space, there are generally two classes of correlation models that are commonly used. The first class is encapsulated by explicit functional forms, including, for example, the functions developed by Gaspari and Cohn (1999); Gneiting (1999); Gaspari et al. (2006), which have the benefit of providing compact support. The second class of correlation models can generally be described as a filtering approach. Purser et al. (2003b,a) show

correlation functions based on recursive filters, and Dobricic and Pinardi (2008) extend this to be used with complex boundaries. More recently, Purser et al. (2022) show a “beta filter” approach which enables compact support and a highly generalizable correlation shape via an efficient multigrid approach. Alternatively, within this class of models are those based on the solution to a differential equation.

Correlation models that are based on the solution to differential equations have several advantages. Most importantly, these operators handle complex boundaries naturally and the infrastructure required to obtain their solution typically exist within the underlying numerical model. Within oceanographic state estimation, a widely used framework is based on the solution to the diffusion equation (e.g., Nguyen et al., 2021; Forget et al., 2015; Blockley et al., 2014; Moore et al., 2011; Daget et al., 2009; Muccino et al., 2008; Di Lorenzo et al., 2007; Weaver et al., 2003). The diffusion-based framework relies on either an explicit, pseudo-time stepping method (Weaver and Courtier, 2001) or an implicit solution (Mirouze and Weaver, 2010; Carrier and Ngodock, 2010; Weaver and Mirouze, 2013), where the correlation structure underlying the solution corresponds to either a Gaussian or more general auto-regressive function, respectively. Alternatively, Lindgren et al. (2011) (hereafter L11) show an explicit link between the numerical solution to a stochastic partial differential equation (SPDE) and a Matérn-type covariance model. As of yet, however, it has remained unclear how this model could be used to specify univariate correlations with appropriate nonstationarity and anisotropy for an operational variational DA system.

Here, we extend the work by L11 to show how the framework can be used within variational DA. Our emphasis is on oceanographic applications, although the methodology is more general. We show how the mapping method suggested by L11 can be used to formulate a correlation operator that respects anisotropy and nonstationarity in a way that is relevant to many ocean general circulation models. In essence, the mapping method is simply a change of variables between the computational domain and a space where correlations can be described by the analytical Matérn correlation function for isotropic and stationary fields. Here we make practical suggestions on how to define the mapping via normalization length scales. With these normalizing length scales defined, we show how two hyperparameters *separately* control the “range” and shape of the correlation model. As an intuitive example, when the normalizing length scales are defined relative to the model grid, a “range parameter” can be interpreted as the “number of neighboring grid cells” at which correlation drops to an expected value. We show that this interpretation holds no matter how many times the operator is applied, such that the overall shape can change while the correlation length scale remains fixed. It is therefore straightforward to use this approach to achieve desirable anisotropic and nonstationary statistics by simply tuning these two parameters.

The paper is laid out as follows. In Section 2 we give some context for how univariate correlation models are used in variational DA. We provide a review of diffusion based correlation operators, and then review the Matérn type covariance developments in L11 which we build on. In Section 3 we show how the Matérn model can be mapped from its isotropic, stationary form into a more complex computational domain. We then provide suggestions for parameterizing the model so that it can intuitively capture anisotropy and nonstationarity. In Section 4 we show numerical results of this correlation model applied to the global ocean, using the “Lat-Lon-Cap” grid introduced by Forget et al. (2015). Finally, in Section 5 we provide some discussion on the advantages of this model, and a general comparison to the widely used diffusion based models.

2 | MATHEMATICAL CONTEXT AND BACKGROUND

In order to provide some mathematical context for our correlation model developments, we first outline the generic inverse problem that is central to a variety of applications such as numerical weather prediction and state estimation. Our notation closely follows Ide et al. (1997), and we note that matrix notation is used to describe the problem, but these matrices are never formed explicitly. Rather, all matrices presented are described by operators that can be applied scalably in high dimensional inverse problems. We then review correlation models that are based on the application of a diffusion operator (Weaver and Courtier,

2001; Mirouze and Weaver, 2010), which are commonly used for large scale geophysical inverse problems (e.g., Forget et al., 2015; Moore et al., 2011). We then discuss the developments from L11, outlining the connection between the solution to a SPDE and a Gaussian random field with Matérn type covariance. We finish by showing a comparison of auto-regressive and the more general Matérn type correlation functions with a classical Gaussian. These comparisons motivate our development of an anisotropic, nonstationary correlation model, which is presented in Section 3.

2.1 | Data assimilation setting

We consider the general problem of finding the optimal control vector, \mathbf{x} , which minimizes the regularized model-data misfit cost function

$$\mathcal{J}(\mathbf{x}) = \frac{1}{2} \|H(\mathbf{x}) - \mathbf{y}^o\|_{\mathbf{R}^{-1}}^2 + \frac{1}{2} \|\mathbf{x} - \mathbf{x}^b\|_{\mathbf{B}^{-1}}^2.$$

Here $\|\mathbf{v}\|_A = \sqrt{\mathbf{v}^T A \mathbf{v}}$ is a weighted Euclidean norm. The solution to this inverse problem, \mathbf{x}^a , arises from a tradeoff between fitting the observational data, \mathbf{y}^o , via the observation operator, $H(\cdot)$, and minimizing deviations from the background-state \mathbf{x}^b . This tradeoff is governed by the two error covariances, \mathbf{R} and \mathbf{B} , which dictate how much deviation is acceptable in either term. On the one hand, the observational error covariance matrix \mathbf{R} represents our uncertainty in the observational data, together with our confidence in the model's ability to represent the observed values. On the other hand, the background-state covariance matrix \mathbf{B} represents our uncertainty in the prior estimate or background state, \mathbf{x}^b .

To be explicit, we focus on how our correlation model fits into the background-state error covariance, \mathbf{B} . However, we note that the formulation could be used for specifying correlations between observations in a similar fashion to Guillet et al. (2019), but we leave this for future investigation. In the general case, the control vector \mathbf{x} could be multivariate, including initial conditions of the system state, uncertain boundary conditions, or uncertain parameter fields. Here we employ the decomposition proposed by Derber and Bouttier (1999) in order to separate the multivariate (i.e. cross-variable) covariance relationships from the univariate (i.e. assumed independent) covariance relationships. Specifically, the background-state covariance is decomposed as follows

$$\mathbf{B} := \mathbf{K}_b \mathbf{B}_u \mathbf{K}_b^T,$$

where \mathbf{K}_b is a balance operator that deals with the cross-variable correlations. The matrix \mathbf{B}_u describes the covariance for the unbalanced variables and has a block-diagonal structure, such that each covariance is described independently. The unbalanced covariance is further factored as

$$\mathbf{B}_u := \Sigma C \Sigma$$

where Σ is a diagonal scaling matrix, containing the desired pointwise standard deviation values and C is a block diagonal correlation matrix, describing each variable's independent correlation structure. To be concrete, this can be viewed as

$$\mathbf{B}_u = \begin{pmatrix} \Sigma_\alpha \mathbf{C}_\alpha \Sigma_\alpha & 0 & \cdots & 0 \\ 0 & \Sigma_\beta \mathbf{C}_\beta \Sigma_\beta & \cdots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \cdots & \Sigma_\gamma \mathbf{C}_\gamma \Sigma_\gamma \end{pmatrix}$$

where α, β, γ are placeholders for unique variables, and each $\Sigma_\alpha, \mathbf{C}_\alpha$ pair describes the covariance for its particular variable. In this formulation, \mathbf{C}_α describes the spatial correlation structure for the variable α , and is scaled to a proper covariance given the diagonal matrix Σ_α .

The goal of this paper is to formulate a generic operator for \mathbf{C} that could be used in a variational DA system to specify correlations for any variable, e.g., $\mathbf{C}_\alpha, \mathbf{C}_\beta$, etc. As with diffusion based correlation models, we specify \mathbf{C} through its square root $\mathbf{C}^{1/2}$, such that $\mathbf{C} = \mathbf{C}^{1/2} \mathbf{C}^{T/2}$. To provide some additional context for this development, we first review past work that has achieved this with a generalized diffusion-based operator.

2.2 | Diffusion based correlation models

A common method for specifying the correlation structure, \mathbf{C} , in variational DA systems, especially in oceanographic applications, is through the solution of a generalized diffusion equation,

$$\frac{\partial \theta}{\partial t} = \nabla \cdot \kappa \nabla \theta. \quad (1)$$

Here κ is a diffusion tensor that controls anisotropy and nonstationarity, t is a “pseudo-time” coordinate, and the solution to this equation has a Gaussian, or “Gaussian-like”, covariance.

Building on work from Derber and Rosati (1989); Egbert et al. (1994); Bennett et al. (1996), Weaver and Courtier (2001) showed that an explicit, forward Euler solution to Equation (1) provides a scalable approach to defining correlations in complex domains. That is, the solution $\theta(T)$ is given by forward pseudo-time stepping

$$\theta(T) = (I + \nabla \cdot \kappa \nabla)^p \theta(t_0), \quad (2)$$

which requires p applications of the operator

$$\mathcal{A}_{\text{ED}} := (I + \nabla \cdot \kappa \nabla),$$

where p is chosen in order to achieve numerical stability (see Weaver and Courtier, 2001, for details regarding the discretized form of this operator, and extensions of the model briefly shown here). The solution $\theta(T)$ is shown to have an approximately Gaussian covariance structure. A correlation model is thus defined by estimating the pointwise variance of $\mathcal{A}_{\text{ED}}^p \cdot \hat{\sigma}^2(\mathbf{s})$, in order to define the normalization matrix

$$\Lambda := \text{diag}\{1/\hat{\sigma}_n\}_{n=1}^{N_\theta},$$

where we use n to refer to each grid cell, such that the correlation matrix is defined through its square root as

$$\mathbf{C}_{\text{ED}}^{1/2} := \Lambda \mathcal{A}_{\text{ED}}^p. \quad (3)$$

The explicit diffusion-based correlation model as briefly summarized here directly approximates a Gaussian structure. However, a limitation of this approach is that in some cases, many iterations are required to keep the scheme stable (i.e. a large value of p is required in Equation (2)). As such, Mirouze and Weaver (2010) and Carrier and Ngodock (2010) developed

correlation models based on the *implicit* solution of Equation (1):

$$(I - \nabla \cdot \kappa \nabla)^M \theta(T) = \theta(t_0), \quad (4)$$

which is unconditionally stable. In this case, a square-root correlation operator is defined through the “implicit diffusion operator”

$$\mathcal{A}_{\text{ID}} := (I - \nabla \cdot \kappa \nabla) \quad (5)$$

as

$$\mathbf{C}_{\text{ID}}^{1/2} := \Lambda \mathcal{A}_{\text{ID}}^{-M}, \quad (6)$$

with Λ defined based on the operations that precede it.

Mirouze and Weaver (2010) provide the theoretical underpinnings for the implicit diffusion approach, and show details regarding its implementation in general curvilinear coordinates. Additionally, the authors show that this correlation model corresponds with an M th order auto-regressive (AR) function, which is a subclass of Matérn type correlation models (see Weaver and Mirouze, 2013, for more description of the parameters controlling this model). Thus, the correlation model has a more general shape, which in the limit $M \rightarrow \infty$, approaches a classical Gaussian structure (see Section 2.4).

In this work, we formulate a correlation operator in a similar fashion by directly parameterizing the elliptic PDE that corresponds to the more generic Matérn type correlation (or covariance) structure. In the following subsections, we provide some background on this general correlation structure to give our developments some context and motivation.

2.3 | Review of the Matérn correlation structure

The Matérn covariance function between two points, $\hat{\mathbf{s}}_1, \hat{\mathbf{s}}_2 \in \hat{\Omega} = \mathbb{R}^{N_d}$ can be expressed as:

$$c(\hat{\mathbf{s}}_1, \hat{\mathbf{s}}_2) = \frac{\hat{\sigma}^2}{2^{\epsilon-1} \mathcal{G}(\epsilon)} \left(\sqrt{\hat{\delta}} \|\hat{\mathbf{s}}_2 - \hat{\mathbf{s}}_1\| \right)^\epsilon \mathcal{B}_\epsilon \left(\sqrt{\hat{\delta}} \|\hat{\mathbf{s}}_2 - \hat{\mathbf{s}}_1\| \right). \quad (7)$$

Here \mathcal{G} is the Gamma function, \mathcal{B}_ϵ is the modified Bessel function of the second kind and order ϵ , $\hat{\delta} > 0$ is a scaling parameter, and $\epsilon > 0$ controls the mean-square differentiability of the underlying statistical process described by the Matérn covariance. We note that in the limit of $\epsilon \rightarrow \infty$, the Matérn-type covariance becomes a classical Gaussian. Throughout, we refer to a “Matérn field” as any random field that has covariance described by the Matérn covariance function, Equation (7). Additionally, we note that this analytical function only pertains to fields where the assumptions of stationarity and isotropy hold, and we use notation with “hats” ($\hat{\cdot}$) when this is the case. The marginal variance of such a Matérn field has the analytical form

$$\hat{\sigma} = \frac{\mathcal{G}(\epsilon)}{\mathcal{G}(\epsilon + N_d/2) \hat{\delta}^\epsilon (4\pi)^{N_d/2}}, \quad (8)$$

where N_d is the dimensionality of the field being described. Thus, the Matérn covariance can be described via a correlation function, $r(\hat{\mathbf{s}}_1, \hat{\mathbf{s}}_2)$, that is scaled by the marginal variance:

$$c(\hat{\mathbf{s}}_1, \hat{\mathbf{s}}_2) = \hat{\sigma} r(\hat{\mathbf{s}}_1, \hat{\mathbf{s}}_2).$$

The key relationship discussed in L11 is that any discrete solution to the elliptic SPDE,

$$\left(\hat{\delta} - \hat{\nabla} \cdot \hat{\nabla}\right)^M \hat{\theta}(\hat{\mathbf{s}}) = \mathcal{W}(\hat{\mathbf{s}}), \quad (9)$$

is a Matérn field, for any triangulation or rectangular lattice of \mathbb{R}^{N_d} . Here \mathcal{W} is a white noise process defined on the space $\hat{\Omega}$ and $M \geq 1$ is the total number of times that the inverse of the operator

$$\hat{\mathcal{A}} := (\hat{\delta} - \hat{\nabla} \cdot \hat{\nabla})$$

is applied to obtain the solution. This number is related to the mean differentiability and dimensionality of the field via the relation

$$M = \epsilon/2 + N_d/4. \quad (10)$$

For our purposes, we consider M as a parameter which can be tuned to obtain the desired correlation shape (see Section 2.4). In order to simplify the solution process, we consider positive integer values of M , although the theory underlying more general operators for which $M = q/2$ with $q \in \mathbb{Z}^+$ is covered in L11.

Throughout this paper we use the empirical relation discussed by L11 to specify $\hat{\delta}$ via

$$\hat{\rho} = \sqrt{\frac{8\epsilon}{\hat{\delta}}}. \quad (11)$$

The so-called “range parameter”, $\hat{\rho}$, defines the distance between two points at which correlation drops to 0.14. We note that the range parameter used here is larger by a factor of 2 than what is sometimes used (e.g., Rasmussen and Williams, 2006), but we prefer this definition because of its intuitive interpretation. With M and $\hat{\rho}$ defined, we provide an explicit form of the Matérn correlation function which will be used throughout:

$$r(d; \hat{\rho}, M) = r(d; \hat{\rho}, \epsilon(M)) = \frac{1}{2^{\epsilon-1} \mathcal{G}(\epsilon)} \left(\sqrt{8\epsilon} \frac{d}{\hat{\rho}} \right)^{\epsilon} \mathcal{B}_{\epsilon} \left(\sqrt{8\epsilon} \frac{d}{\hat{\rho}} \right), \quad (12)$$

where d is the distance between two points and $\epsilon = \epsilon(M)$ is defined via Equation (10).

In Section 3, we suggest to define a correlation operator through the elliptic operator in Equation (9). For an isotropic and stationary case, the operator would be defined as

$$\mathbf{C}_{\text{iso,stat}}^{1/2} = \mathbf{\Lambda} \left(\hat{\delta} - \hat{\nabla} \cdot \hat{\nabla} \right)^{-M}, \quad (13)$$

with $\mathbf{\Lambda}$ appropriately defined, but we extend this to a more general case in Section 3.

2.4 | Comparing the Matérn and auto-regressive functions

To provide some motivation behind our developments of the Matérn correlation function, we compare its structure to auto-regressive (AR) (corresponding to the operator $\mathcal{A}_{\text{ID}}^{-M}$; (Mirouze and Weaver, 2010)) and Gaussian functions. Figure 1(a) shows a comparison of these 1D correlation structures as a function of distance, d , where each use a representative length scale of 4. The Matérn function and Gaussian consistently reach an approximate correlation of 0.14 when distance is equal to $\hat{\rho}$. The consistency here makes using the Matérn correlation structure intuitive in practice: no matter what value of M is used (or equivalently no

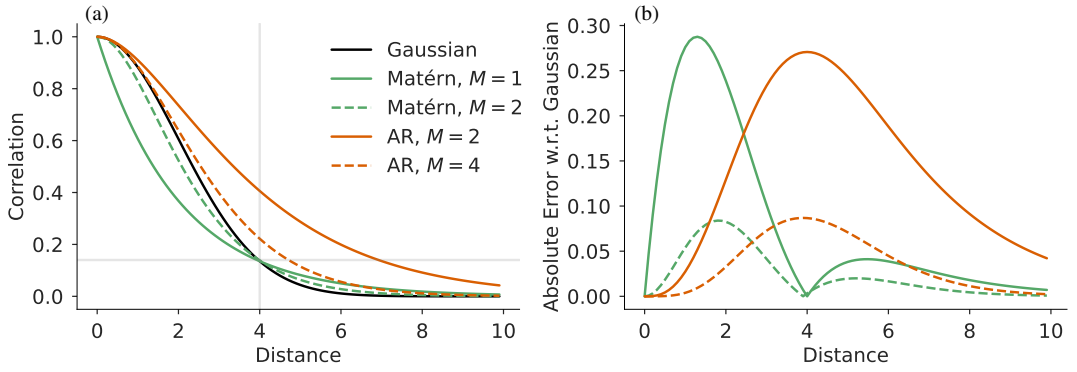


FIGURE 1 (a) Correlation as a function of distance given by Matérn (green; Equation (13)), auto-regressive (AR; orange), and Gaussian (black; $r_g(d) = \exp(-2(d/4)^2)$) functions. For each, we choose a length scale of $\hat{\rho} = 4$, noting for comparison purposes that this corresponds to $L = 2$ using the notation in Mirouze and Weaver (2010) for the auto-regressive function. Finally, we note that we use $N_d = 3$ to compute $\epsilon(M)$ (see Equation (10)) since this corresponds to our numerical experiments in Section 4. (b) Absolute error considering the difference between the Matérn and AR functions with respect to a Gaussian with the same length scale.

matter what shape is desired), we can expect this approximate relationship to hold.

Additionally, Figure 1(b) shows the error in each Matérn and AR functions relative to a Gaussian. We note that error for the Matérn function is comparable to the AR function, although M is halved. This has practical implications, since in both cases M corresponds to the number of inverse elliptic operator applications required for achieving a correlation structure via the implicit diffusion approach via $\mathcal{A}_{\text{ID}}^{-M}$ (AR) or the approach proposed here (Matérn). Thus, if the goal is to approximate a Gaussian, then using the direct Matérn shape results in half the required inverse elliptic solves. However, we also stress that the desired shape of the correlation function will be application dependent, and so we present a comparison from which practitioners can take their pick.

3 | A NONSTATIONARY AND ANISOTROPIC MATÉRN CORRELATION OPERATOR

Here we propose to use the SPDE operator described by L11 as a means to describe an anisotropic, nonstationary correlation model in a similar manner to the diffusion-based methods described in Section 2.2. To do so, we employ the “mapping method” described by L11 which we show for the general M th order SPDE in Section 3.1. In summary, the basic idea we present is to use the mapping method to nondimensionalize or re-scale the elliptic operator. We provide a simple scaling argument for why this is a good idea in Section 3.2, and discuss practical choices for the nondimensionalization based on the grid scale in Section 3.3.

3.1 | Mapping method or change of variables

In L11 it is suggested that solving the SPDE in a transformed coordinate system allows one to readily incorporate anisotropy and nonstationarity into a Matérn covariance model. In this mapping method, we consider solutions to the isotropic, stationary SPDE (9) to be defined in a transformed, or “deformed” (Sampson and Guttorp, 1992), space $\hat{\Omega}$. Then, assume that we have a mapping

φ that maps between this transformed space and our computational domain, Ω :

$$\varphi : \hat{\Omega} \ni \hat{\mathbf{s}} \rightarrow \mathbf{s} \in \Omega .$$

With this mapping, we can employ a change of variables (Smith, 1934) to rewrite the SPDE in the computational domain as:

$$\left(\frac{\hat{\delta}}{\det(\Phi(\mathbf{s}))} - \nabla \cdot \frac{\Phi(\mathbf{s})\Phi(\mathbf{s})^T}{\det(\Phi(\mathbf{s}))} \nabla \right)^M \theta(\mathbf{s}) = \det(\Phi(\mathbf{s}))^{-1/2} \mathcal{W}(\mathbf{s}) .$$

Here we have defined the Jacobian as

$$\Phi(\mathbf{s}_0) := \frac{\partial \varphi}{\partial \hat{\mathbf{s}}} \Big|_{\varphi^{-1}(\mathbf{s}_0)} ,$$

and for now we assume that $\varphi^{-1}(\mathbf{s}_0)$ is well defined. For our purposes, this turns out to be the case, but this becomes clear when Φ is defined in Section 3.2. With the following definitions:

$$K(\mathbf{s}) := \frac{\Phi(\mathbf{s})\Phi(\mathbf{s})^T}{\det(\Phi(\mathbf{s}))} \quad \delta(\mathbf{s}) := \frac{\hat{\delta}}{\det(\Phi(\mathbf{s}))} \quad \mathcal{A} := (\delta(\mathbf{s}) - \nabla \cdot K(\mathbf{s})\nabla) \quad (14)$$

the SPDE in Equation (9) can be written in the computational domain's coordinate system as

$$\mathcal{A}^M \theta(\mathbf{s}) = \det(\Phi(\mathbf{s}))^{-1/2} \mathcal{W}(\mathbf{s}) , \quad (15)$$

where zero flux, Neumann boundary conditions are applied at the boundaries (see Appendix A for details).

Here, we propose to use this generic form to define a square root of the correlation matrix in a similar fashion to Weaver and Courtier (2001); Mirouze and Weaver (2010); Carrier and Ngodock (2010) as follows,

$$\mathbf{C}^{1/2} := \mathbf{\Lambda} \mathcal{A}^{-M} \det(\Phi(\mathbf{s}))^{-1/2} , \quad (16)$$

where $\mathbf{\Lambda}$ is once again a variance-preserving normalization matrix defined by the operations that precede it. In this model, anisotropy and nonstationarity are controlled by $\Phi(\mathbf{s})$, and in the following sections we discuss how this can be assigned for practical applications in geophysical inverse problems. We note that in this discussion we loosely mix the use of finite dimensional matrices and infinite dimensional operators in order to ease the presentation, but we provide a more careful derivation of their discretized forms relevant to our numerical experiments in Appendix A.

3.2 | Scaling the Laplacian term for anisotropy

Here we focus on parameterizing $\Phi(\mathbf{s})$ in order to achieve an anisotropic correlation model that is relevant for variational DA. We illustrate our choice with a scaling argument focusing on how $K(\mathbf{s})$ influences correlation length scales.

Consider a 3D field $\theta(\mathbf{s}) \sim \Theta$ that exhibits spatial variability at the length scales, L_x , L_y , and L_z in the direction of longitude, latitude, and height, respectively, where $L_x, L_y \gg L_z$, such that the field exhibits highly anisotropic fluctuations. This is a common situation in large scale geophysical fluid dynamics, where fields (e.g., temperature, velocity) exhibit length scales of variability that are much greater in either horizontal dimension compared to the vertical (e.g., Vallis, 2006). Without any

rescaling, i.e. without K , the Laplacian term in \mathcal{A} is unbalanced

$$\begin{aligned} \nabla^2 \theta(\mathbf{s}) &\sim \frac{\Theta}{L_x^2} + \frac{\Theta}{L_y^2} + \frac{\Theta}{L_z^2} \\ &\simeq \frac{\Theta}{L_z^2}. \end{aligned} \tag{17}$$

As a result, the correlation model will have unrealistically large (small) correlations in the vertical (horizontal). Our goal is therefore to define the elements of K such that each term is of the same order of magnitude.

To achieve this balance between Laplacian terms, we suggest a straightforward, perhaps obvious, specification of Φ :

$$\Phi = \begin{pmatrix} L_x & 0 & 0 \\ 0 & L_y & 0 \\ 0 & 0 & L_z \end{pmatrix},$$

where we simply ignore the off-diagonal elements of Φ . The determinant in this case is $\det(\Phi) = L_x L_y L_z$ and according to the definitions in Equation (14):

$$K = \begin{pmatrix} 1/L_z & 0 & 0 \\ 0 & 1/L_z & 0 \\ 0 & 0 & L_z/(L_x L_y) \end{pmatrix},$$

so that

$$\nabla \cdot K \nabla \theta(\mathbf{s}) \sim \frac{3}{L_x L_y L_z} \Theta.$$

The key is that K scales each term in the Laplacian so that they are approximately the same order of magnitude, and the operator is balanced in all directions. In the case of nonstationarity, we simply require this balance to apply locally and allow the length scales L_x , L_y , and L_z to vary in space.

3.3 | Harnessing the grid scale for nonstationarity

At this point, we must prescribe values for the normalizing length scales $L_x(\mathbf{s})$, $L_y(\mathbf{s})$, and $L_z(\mathbf{s})$ in order to fill $\Phi(\mathbf{s})$. Considering the scaling analysis of the Laplacian in Section 3.2, a simple yet reliable choice for these is to use the underlying grid-scale of the numerical model (e.g., the ocean or atmosphere general circulation model).

We consider using the length scale of the grid elements to be reasonable because a baseline level anisotropy and nonstationarity is usually encoded into the grid. A prime example of this nonstationarity is represented by the vertical axis of ocean model grids, which are designed to capture a variety of behavior in a computationally efficient manner (Griffies, 2004). Toward the surface, the ocean is tightly coupled to the atmosphere, sea ice, and rivers, and ocean models use a finely resolved vertical grid to capture the ocean component of these coupled processes. In the interior ocean, well below the mixed layer, the ocean acts more like stacked layers, and variation in properties like temperature and salinity occurs over much larger distances than at the surface (Talley, 2011). Vertical grids are correspondingly much coarser at depth than near the surface. As a concrete example, the height-based vertical grid we use in Section 4 varies from $\sim 5 - 10$ m near the surface, and spacing increases to $O(100)$ m below 1,000 m (Figure 3(f)). By using the grid elements directly, our correlation model can capture the nonstationarity motivated

by the physical processes which influence the model grid's development.

Another justification for using the grid elements to specify $\Phi(\mathbf{s})$ is that this provides a practical and intuitive nondimensionalization. With this definition, the correlation model exhibits isotropic and stationary behavior within the nondimensional space defined by the computational grid. As such, the idealized correlation function (Equation (13)) applies relative to the grid spacing, and one can view $\hat{\rho}$ as an intuitive, nondimensional parameter controlling the “number of neighboring grid cells” at which correlation decays to 0.14. Our numerical experiments in Section 4 show that this is a good approximation in the case of a realistic global ocean model grid.

4 | APPLICATION TO THE GLOBAL OCEAN

Here we show results from a numerical implementation of the correlation model described in Section 3. For this application we use the “Lat-Lon-Cap” (LLC) grid used by the ECCOV4 state estimate (see their Section 2 of Forget et al., 2015, for a complete description of the grid). The overall goal with these numerical experiments is to show that even in this relatively complicated global grid, the correlation model generally follows the expected Matérn correlation structure (Section 4.1), while maintaining anisotropy and nonstationarity that is relevant to the physical system (Section 4.2). Additionally, we show how Neumann boundary conditions to the differential operator affect the solution in Section 4.3. We finish by showing that the model can be applied efficiently with a relatively imprecise solver tolerance (Section 4.4) and that it is relatively cheap even when the number of applications, M , is greater than one (Section 4.5).

For all experiments, we compute statistical quantities from 1,000 samples (see Appendix A and specifically Equations (21) and (22) for sampling details). We use a block-Successive Over Relaxation (SOR) method (Appendix B) to find numerical solutions to the elliptic SPDE, using a tolerance of 10^{-3} for all results except where specified in Section 4.4. Additionally, we use the following normalizing length scales $L_x(i, j) = \Delta x_g(i, j)$, $L_y(i, j) = \Delta y_g(i, j)$, and $L_z(k) = \Delta r_f(k)$ (Figure 7) where we have switched from the spatial coordinate $\mathbf{s} \in \Omega$ to the computational grid indices i, j, k . All experiments are performed with a 3D field, which could represent an ocean state property like temperature or salinity.

4.1 | Correspondence with theoretical correlation structure

We first show that the sample correlation structure computed on the LLC grid corresponds with the analytical Matérn-type correlation function (Equation (13)). For this comparison we compute the correlation field in the transformed space $\hat{\Omega}$, where it can be considered isotropic and stationary. Because we use the grid spacing to define this mapping, the correlation distances are computed simply by counting the number of neighboring grid cells in each direction from the point in consideration.

Figure 2 shows the comparison between the theoretically expected correlation structure (black) and the numerically computed sample correlation structure for $\hat{\rho} = \{5, 10, 15, 20\}$ (color) using $M = \{1, 2, 4, 8\}$ (panels). Recall that as M increases, the correlation structure approaches a Gaussian shape, such that there is little visible difference between e.g., $M = 4$ and $M = 8$. The correlation is computed in the direction of longitude, indicated by δi . The shading indicates the spread between the first and ninth deciles of the sample correlation, computed at all depth levels and latitudes from 70°S to 37°N at 127.5°W - a subset chosen simply to ease the calculation. Similar plots showing correlation in the meridional and vertical directions are shown in the Supplemental Material.

Generally speaking, the colored curves match the analytical expression well, and each colored curve intersects the horizontal gray line, indicating a correlation value of 0.14, where $\hat{\rho} = \delta i$. We note that the largest spread in the computed correlation structure occurs when $M = 1$, especially for larger values of $\hat{\rho}$. Considering an analogy to Laplacian versus biharmonic damping in ocean models (e.g., Holland, 1978; Griffies and Hallberg, 2000), we suggest that there is more spread when $M = 1$ because

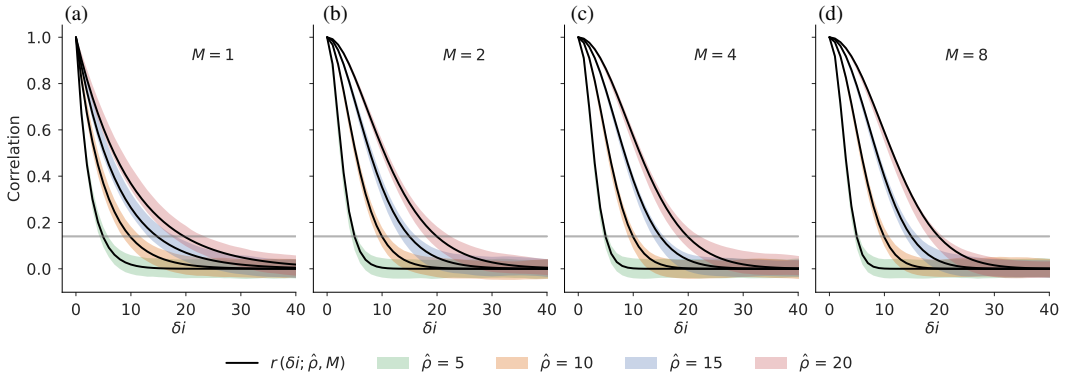


FIGURE 2 Correlation structure computed from the theoretical Matérn correlation function (black; Equation (13)) and from 1,000 samples using a subset of the “Lat-Lon-Cap” grid within the Pacific Ocean (shaded coloring). The sample correlation is computed in the zonal direction, δi , indicating the number of neighboring grid cells from 127.5°W. The shading indicates the spread between the first and ninth deciles, based on sample correlations at all depth levels and latitudes from 70°S and 37°N. Similar plots showing correlation as a function of meridional and vertical distance are provided in the Supplemental Material. Recall that as $M \rightarrow \infty$, the Matérn correlation function approaches a Gaussian (cf. Figure 1).

the operator \mathcal{A}^{-1} contains only a Laplacian term. Compared to the cases when $M > 1$, which contain biharmonic and higher order Laplacian terms in \mathcal{A}^{-M} , the Laplacian case is less scale-selective. That is, the operator does not cutoff higher frequency variability sharply, allowing noise to pollute the sample statistics (see Griffies and Hallberg, 2000, Section 2 for a quantitative description of this cutoff in frequency space). We note, however, that the spread still allows for a reasonable interpretation that the operator \mathcal{A}^{-1} captures the behavior of the analytical Matérn correlation function.

4.2 | Sample correlation maps

Maps of the sample correlation field on the LLC grid are shown in Figure 3, at (0.2°N, 127.5°W, 722 m depth) and (10.5°N, 87.5°W, 5 m depth) in panels (a & d) and (b & e), respectively. These two locations are chosen to highlight local anisotropy in the latitude-longitude plane and nonstationarity in the vertical axis. For these calculations we use a perhaps unrealistically large correlation length scale defined by $\hat{\rho} = 20$ for illustrative purposes.

Comparing panels (a) and (b) of Figure 3, we see that near the equator, the correlation structure is stretched zonally, while poleward of $\sim 10 - 15^\circ$ the structure is closer to being isotropic. Elongated zonal correlation length scales at the equator are consistent with observations (Meyers et al., 1991), so we consider this anisotropic behavior to be desirable. In our case, we achieve this anisotropy via local refinements in the meridional grid scale near the equator, which are specifically designed to capture tropical zonal currents (Forget et al., 2015). Specifically, Figure 3(c) shows how the meridional grid spacing (Δy) refines near the equator, while the longitudinal grid spacing (Δx) slightly increases near the equator. The result of this grid refinement is that near the equator, a range of $\hat{\rho}$ grid cells covers a shorter distance meridionally than it does at e.g., 15° N. Overall, this example highlights how details in the model grid can be harnessed to achieve physically relevant correlation structures. However, we note that if this correlation shape is desired but would not immediately occur due to a different model grid definition, then the normalizing length scales could easily be modified with a weighting function to achieve the desired structure.

Panels (d) and (e) of Figure 3 illustrate nonstationary correlation structures obtained along the vertical axis. As discussed in Section 3.3, it would be reasonable to expect shorter correlation lengths near the ocean surface due to localized processes there, and relatively longer correlation length scales in the interior ocean. This general behavior is shown in panel (e), where correlation

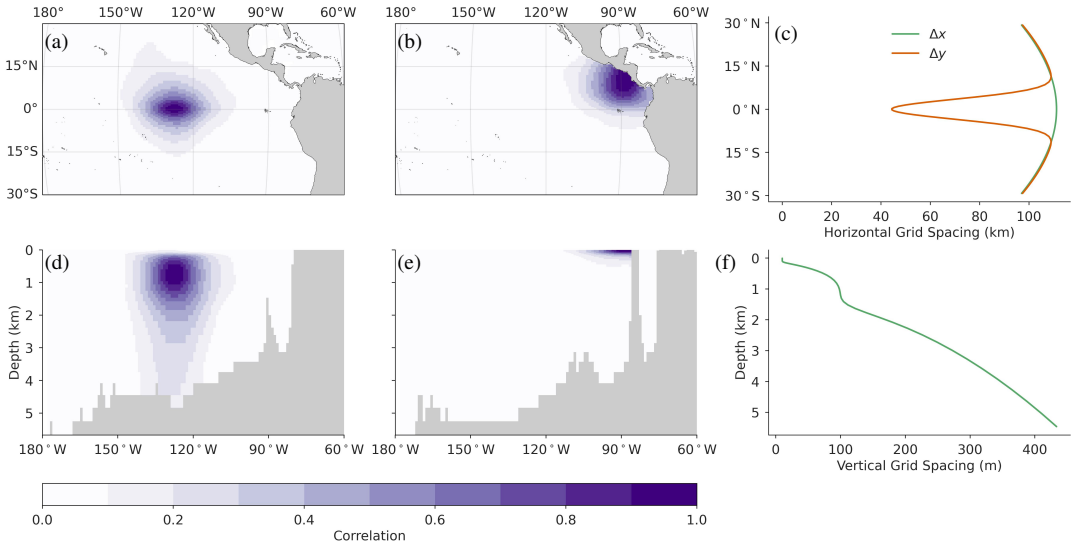


FIGURE 3 Two sample correlation fields and a depiction of the computational grid. (a & b) Sample correlation field in the latitude-longitude plane at (0.2°N, 127.5°W, 722 m depth) and (10.5°N, 87.5°W, 5 m depth), respectively. (c & d) The same sample correlation fields as above, shown in the depth-longitude plane. (e & f) The local horizontal and vertical grid spacing, respectively. The correlation fields are computed with $\hat{\rho} = 20$ and $M = 2$.

> 0.1 is confined to the upper hundred meters of the ocean, while in panel (d), correlation > 0.1 spans the full depth of the ocean. Once again, the correlation structures shown here correspond directly to the vertical grid spacing, which is shown in Figure 3(f).

4.3 | Pointwise sample standard deviation

The pointwise, sample standard deviation is shown in Figure 4, where it is represented as a ratio with respect to the “expected” value from Equation (8) for an isotropic, stationary Matérn field. Throughout most of the domain, the sample standard deviation is approximately equal to the theoretical value. Near continental boundaries, however, the standard deviation is inflated, especially for large values of $\hat{\rho}$ and in regions of tightly confined topographic boundaries such as in the Caribbean Sea. This deviation near the boundaries is expected for correlation models based on the solution of differential equations (e.g., Weaver and Courtier, 2001; Lindgren et al., 2011), as a result of the zero flux, Neumann boundary conditions used to find the solution. Thus, the theoretical value cannot be used directly and it is necessary to calculate or estimate the true variance of the operator in order to formulate the normalization matrix $\mathbf{\Lambda}$. Throughout this work, we have used the estimated standard deviation shown in Figure 4 to fill $\mathbf{\Lambda}$, based on 1,000 random samples. Given that the numerically computed correlation structure compares well to the theoretical value (Section 4.1), this normalization method appears to be reliable. We also note this method is convenient because it is embarrassingly parallel, and scales well to arbitrarily high dimensional fields. However, for cases when the correlation operator is to be updated repeatedly, e.g., in cycled DA, other normalization methods could be explored for use with this operator as in Weaver et al. (2021).

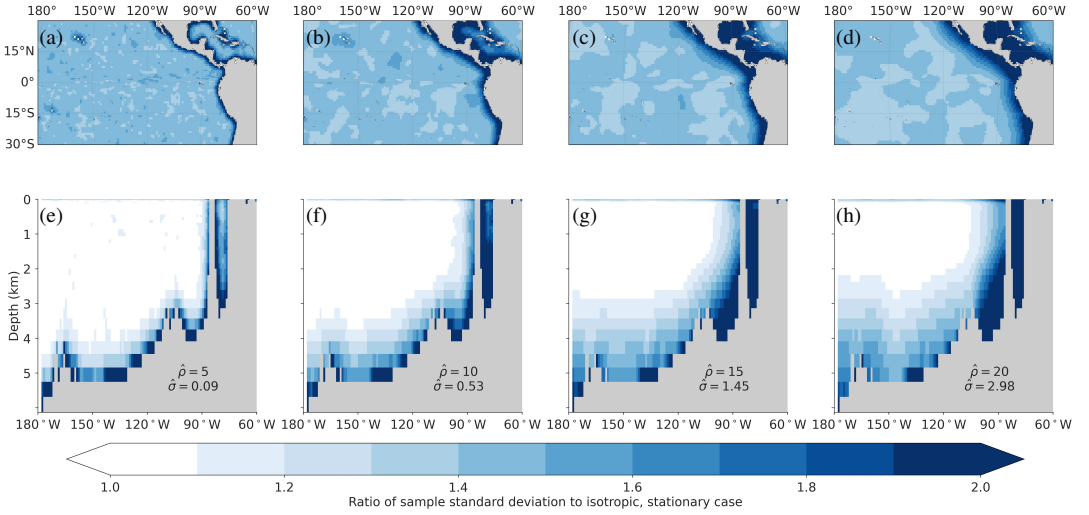


FIGURE 4 The ratio of the sample standard deviation to the value computed from Equation (8) for an isotropic, stationary Matérn field (indicated in the bottom row by $\hat{\sigma}$). Panels (a-d) show the ratio in the latitude-longitude plane at the surface for $\hat{\rho} = \{5, 10, 15, 20\}$, respectively. Panels (e-h) show the corresponding fields in the depth-longitude plane along 10.5°N. The largest deviations from the theoretical value are near the boundaries, as expected. All fields use $M = 2$.

4.4 | High efficiency with low precision

The numerical results shown in this section have employed the iterative algorithm in Appendix B to obtain approximate correlation statistics. As with any iterative algorithm, one must specify a tolerance that can be used to determine when the algorithm has converged to an approximate solution. Within this framework, one can always set a tolerance based on the numerical precision being used to be confident that the solver has converged. However, in this section we show that this is likely to be unnecessarily ambitious.

To be specific, Figure 5(a) shows the relative error in the approximation that correlation is equal to 0.14 when $\hat{\rho} = \delta i$ for $\hat{\rho} = \{5, 10, 15, 20\}$ (i.e. corresponding to the curves in Figure 2). The error in the approximation is shown for a range of solver tolerances, where 10^{-15} is chosen as an approximate lower bound tolerance for double precision. For tolerances at 10^{-3} and smaller, the error converges to roughly the same value, indicating that the desired statistics of the correlation model are obtained even with a relatively imprecise solve. We note that Carrier and Ngodock (2010) describe similar findings with the implicit diffusion correlation model.

The motivation for using a high tolerance is indicated by Figure 5(b), which shows how the number of iterations required to converge increases with the specified tolerance. Solving to a tolerance of 10^{-15} requires a factor of 6-13 more iterations than are required with a tolerance of 10^{-3} . Of course, the specific computational savings obtained will depend on the iterative method that is being used, but we provide this as a concrete example to highlight that an imprecise solve is both valid and advantageous.

4.5 | Rapid convergence for $M > 1$

For applications where a Gaussian correlation structure is desired, the correlation model presented here requires $M > 1$ to approach the Gaussian structure (Figure 1). Moreover, it could also be desirable to use \mathcal{A}^{-M} with $M > 1$, given that $M = 1$ produces larger spread in the correlation structure (Figure 2(a)), and because the correlation structure drops off much more

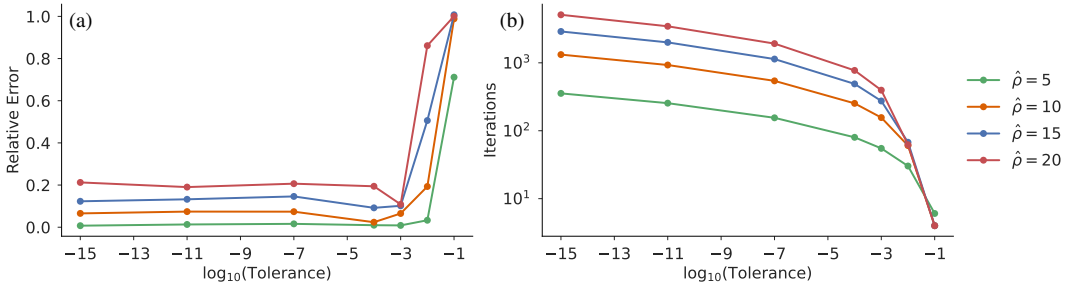


FIGURE 5 (a) The relative error in the approximation that correlation equals 0.14 when $\hat{\rho} = \delta i$, as a function of the tolerance used for the iterative block-SOR method described in Appendix B. Each curve is computed as the error between the theoretical (black) curve and the average of each shaded curve shown in Figure 2. (b) The number of iterations required for the block-SOR method to converge to the specified tolerance. Averages are computed from 1,000 samples using $M = 1$.

rapidly for neighboring points. For these cases, it may be natural to assume that using this model with $M > 1$ would be less efficient than when $M = 1$ because it requires multiple applications of an inverse elliptic operator. However, here we show that this is not necessarily true and it can be *more* efficient to use $M > 1$ than $M = 1$.

Figure 6(a) shows the total number of iterations required to find a solution to Equation (16), for a variety of combinations of $\hat{\rho}$ and M . Here, “total iterations” refers to all block-SOR iterations required by the algorithm in Appendix B, summing over all applications of \mathcal{A}^{-M} . Evidently, using $M > 1$ actually requires *fewer* total iterations to converge to a solution than when $M = 1$. The reason for this is as follows. For any value of $\hat{\rho}$, δ increases linearly with M , which increases the amplitude of the diagonal elements of the matrix representation of \mathcal{A} . In each case, the off-diagonal matrix elements, determined by the Laplacian operator, remain fixed. Thus, the matrix becomes more diagonally dominant: the amplitude of the diagonal elements increases relative to the sum total of off-diagonals. The degree of diagonal dominance is an important property for determining the convergence of our SOR-based elliptic solver, where a more diagonally dominant matrix tends to converge faster (Golub and Van Loan, 2013). Evidence of this behavior can be seen in Figure 6(b), which shows the number of iterations required for each individual application of \mathcal{A}^{-1} to converge. Here we see that each application gets cheaper as M , and therefore δ , increases. The improvement per iteration is evidently enough to reduce the total iterations, shown in panel (a). The exception to this behavior is when $\hat{\rho} = 5$, where for $M \geq 4$ the total number of iterations overtakes the case of $M = 1$ due to the repeated solves.

We note that Jacobi, Gauss-Seidel, and SOR methods are rarely used for modern applications (an exception being the line-SOR method in the sea-ice solver of the MITgcm (Losch et al., 2010)). For example, the main source code of the MITgcm (Marshall et al., 1997; Campin et al., 2021) uses a conjugate gradient method for the pressure solve at each time step. However, given the performance benefits noted here and the simplicity of implementing the SOR scheme, it could be used as an efficient preconditioner in the event that a different solution method becomes overly expensive for $M > 1$.

5 | DISCUSSION

In this work we have shown a general methodology which can be used to achieve nonstationary and anisotropic Matérn type correlation structures within a domain with complex boundaries. To summarize, the general procedure is as follows. First, one chooses a normalization length scale for each dimension, thereby defining (the Jacobian of) a mapping between a space where correlation is isotropic and stationary, and the more complex domain. These normalizing length scales are essential because they determine the local anisotropy and nonstationarity of the correlation operator. Next, one must choose a range parameter,

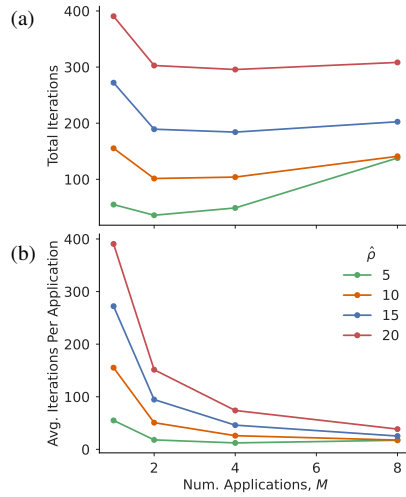


FIGURE 6 (a) Total number of iterations required to compute $\theta = \mathcal{A}^{-M}\mathbf{z}$, for a standard normally distributed vector $\mathbf{z} \in \mathbb{R}^{N_d}$. “Total iterations” is represented as the average number of total iterations from 1,000 random samples. (b) The average number of iterations per application of \mathcal{A}^{-M} , as a function of M . For all $\hat{\rho}$ and M combinations, each application gets cheaper as M increases. To compute the “average iterations per application”, we take the average iteration per application of \mathcal{A}^{-M} , and compute the sample average of this quantity from 1,000 random samples.

determining the distance relative to the normalizing length scales at which correlation drops to 0.14. Finally, one selects the shape of the correlation structure, which also sets the number of times the elliptic PDE must be solved.

Our presentation has focused on the practical application of this correlation operator within an ocean general circulation model. As such, we set the normalizing length scales based on the local grid scale. With this setting, the range parameter is shown to be a highly intuitive dial, controlling correlation length scales as a simple function of the number of neighboring grid cells. Using this definition was further shown to be beneficial at the equator, for example, because grid scale refinements there result in correlation length scales that are longer zonally than meridionally, coinciding with observed autocorrelation structures (Meyers et al., 1991). However, we recognize that there could be features that are desirable to capture in a correlation model that are not represented in the definition of the underlying model grid. In this case, the normalizing length scales could be further tuned with local factors or functions to achieve these desired features. Alternatively, these length scales could be set entirely independently of the grid, for instance as a function of a phenomenological length scale such as the local Rossby radius of deformation.

A key feature of the correlation model shown here is that the range parameter, $\hat{\rho}$, and the number of inverse elliptic operator applications, M , control the correlation length scale and shape *separately*. We consider this to be an attractive feature when compared to the implicit diffusion approach. Even when the “length scale” is fixed in the implicit diffusion model, changing M modifies the shape of the correlation function in such a way that there is no consistent characteristic distance, for instance at which correlation would drop below a threshold value (Figure 1, and also Figs. 1 and 2 from Guillet et al. (2019)). We note that in the Matérn correlation model presented here that the parameter $\hat{\delta}$ changes with M while in the implicit diffusion approach, $\delta(\mathbf{s}) \rightarrow I$. Apparently the simple variation in this parameter is enough to balance the multiple applications of \mathcal{A}^{-1} , such that the resulting correlation structure maintains a consistently identifiable length scale via $\hat{\rho}$.

As noted in Mirouze and Weaver (2010); Carrier and Ngodock (2010), a drawback to the explicit diffusion approach from Weaver and Courtier (2001) is that it requires many iterations to satisfy numerical stability. In our experimentation with this

model on the LLC grid as implemented in the MITgcm (Campin et al., 2021), we have found the number of iterations required for numerical stability to be roughly a factor of three larger than the necessary (but insufficient) lower bound for numerical stability. We therefore find approaches based on the implicit solution of a PDE to be more straightforward, as it is more intuitive to specify a solution tolerance rather than guess the number of iterations required for convergence. Moreover, our numerical experiments indicate that an imprecise solution (to a tolerance of $\sim 10^{-3}$) is sufficient for capturing the desired statistical behavior of the model, and therefore its implementation is highly efficient. Finally, because the correlation model shown here is formulated through an inverse elliptic operator, we have access to the inverse correlation operator, which could be used directly as regularization while solving an inverse problem (e.g., Bui-Thanh et al., 2013), or for specifying spatial correlations within the inverse observation error covariance as in Guillet et al. (2019).

For some applications it could be desirable to specify oscillating or “lobed” correlation models, which can be achieved with the explicit or implicit diffusion models (Weaver and Courtier, 2001; Weaver and Mirouze, 2013). We suggest that such extensions are possible for the Matérn type correlation operator shown here, based on results shown by L11 in the complex plane with a tunable oscillation parameter. These more general shapes could be explored in future work for the case of multi-dimensional fields as shown here.

A | DISCRETIZATION OF THE MATÉRN SPDE

In the following analysis we consider a 3D field $\theta(\mathbf{s})$, $\mathbf{s} \in \Omega$ and show the discretized form for \mathcal{A}^{-M} . We begin by showing the form for $M = 1$, and then simply illustrate how the operator can be applied iteratively for $M > 1$. We carry out the discretization on a structured, nonuniform, Arakawa C grid (Arakawa and Lamb, 1977) according to the finite volume method - as is the general setting in the MITgcm. We note that our development is similar to Fuglstad et al. (2014), who show a differential operator for a 2D field on a uniform grid.

Figure 7 shows the general structure of the grid, and defines the various grid cell distances used in the derivation. We begin by integrating Equation (15),

$$\begin{aligned} \int_{\Omega} \delta(\mathbf{s}) \theta(\mathbf{s}) d\mathbf{s} - \int_{\Omega} \nabla \cdot K(\mathbf{s}) \nabla \theta(\mathbf{s}) d\mathbf{s} &= \int_{\Omega} \mathcal{W}(\mathbf{s}) \det(\Phi(\mathbf{s}))^{-1/2} d\mathbf{s} \\ \sum_{i,j,k} \int_{E_{i,j,k}} \delta(\mathbf{s}) \theta(\mathbf{s}) d\mathbf{s} - \sum_{i,j,k} \int_{E_{i,j,k}} \nabla \cdot K(\mathbf{s}) \nabla \theta(\mathbf{s}) d\mathbf{s} &= \sum_{i,j,k} \int_{E_{i,j,k}} \mathcal{W}(\mathbf{s}) \det(\Phi(\mathbf{s}))^{-1/2} d\mathbf{s}, \end{aligned} \quad (18)$$

where in second line we distribute the integral across each grid cell $E_{i,j,k} \subset \Omega$ and i, j, k indicates indices in longitude, latitude, and depth, respectively.

Starting with the first term,

$$\begin{aligned} \delta_{i,j,k} &:= \frac{1}{V_{i,j,k}} \int_{E_{i,j,k}} \delta(\mathbf{s}) d\mathbf{s} \\ &= \frac{\hat{\delta}}{V_{i,j,k}} \int_{E_{i,j,k}} \frac{1}{\det(\Phi_{i,j,k})} d\mathbf{s} \end{aligned}$$

so that

$$\int_{E_{i,j,k}} \delta(\mathbf{s}) \theta(\mathbf{s}) d\mathbf{s} = \hat{\delta} \frac{V_{i,j,k}}{\det(\Phi_{i,j,k})} \theta_{i,j,k}$$

where $V_{i,j,k} = \Delta x_g^{ij} \Delta y_g^{ij} \Delta r_f^k$ is the grid cell volume, indicated by Figure 7. We note that a cartesian style notation is used to

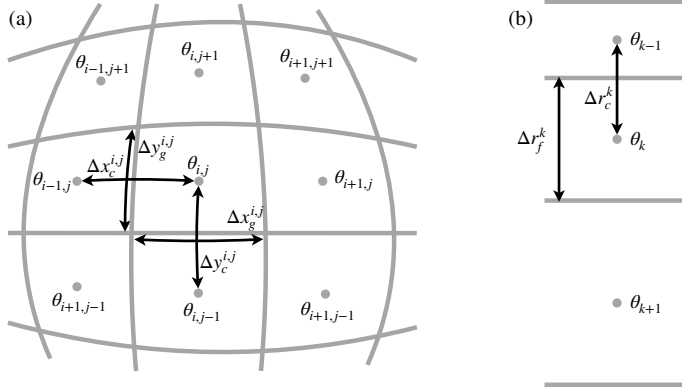


FIGURE 7 The structured finite volume grid used in the MITgcm. (a) The horizontal (latitude-longitude) plane viewed from above. (b) The vertical grid. The circles denote the tracer location at the grid cell center, where fields like temperature and salinity are located.

ease the presentation, but a more general curvilinear coordinate system is used in the computation in order to support the various sectors of the Lat-Lon-Cap (LLC) grid (see Section 2 and Appendix A of Forget et al., 2015, for more details on the LLC grid).

The third term is, from the definition of a white noise process (Adler and Taylor, 2007),

$$\int_{E_{i,j,k}} \det(\Phi(\mathbf{s}))^{-1/2} \mathcal{W}(\mathbf{s}) d\mathbf{s} = \sqrt{\frac{V_{i,j,k}}{\det(\Phi_{i,j,k})}} z_{i,j,k}$$

where $z_{i,j,k}$ is an uncorrelated (independent) standard Gaussian at each grid cell center i, j, k , and we used:

$$\det(\Phi_{i,j,k}) := \frac{1}{V_{i,j,k}} \int_{E_{i,j,k}} \det(\Phi(\mathbf{s})) d\mathbf{s}.$$

The second term, containing the Laplacian is handled as follows

$$\int_{E_{i,j,k}} \nabla \cdot K(\mathbf{s}) \nabla \theta(\mathbf{s}) d\mathbf{s} = \int_{\partial E_{i,j,k}} K(\mathbf{s}) \nabla \theta(\mathbf{s}) \cdot \hat{\mathbf{n}} d\mathbf{s}$$

where $\hat{\mathbf{n}}$ is an outward normal to the cell boundary $\partial E_{i,j,k}$. Throughout this work, we assume the tensor $K(\mathbf{s})$ to be represented as the diagonal matrix:

$$K(\mathbf{s}) = \begin{pmatrix} \kappa^{ux}(\mathbf{s}) & 0 & 0 \\ 0 & \kappa^{vy}(\mathbf{s}) & 0 \\ 0 & 0 & \kappa^{wz}(\mathbf{s}) \end{pmatrix},$$

which could be generalized in future work. We represent the discretized form of this tensor as

$$\mathbf{K}_{i,j,k} = \begin{pmatrix} \kappa_{i,j,k}^{ux} & 0 & 0 \\ 0 & \kappa_{i,j,k}^{vy} & 0 \\ 0 & 0 & \kappa_{i,j,k}^{wz} \end{pmatrix},$$

where the elements $\kappa_{i,j,k}^{ux}$, $\kappa_{i,j,k}^{vy}$, and $\kappa_{i,j,k}^{wz}$ determine the flux in and out of the grid cell:

$$\kappa_{i,j,k}^{ux} := \frac{1}{\Delta y_g^{ij} \Delta r_f^k} \int_{\partial E_{i,j,k}^W} \kappa^{ux}(\mathbf{s}) d\mathbf{s}$$

$$\kappa_{i,j,k}^{vy} := \frac{1}{\Delta x_g^{ij} \Delta r_f^k} \int_{\partial E_{i,j,k}^S} \kappa^{vy}(\mathbf{s}) d\mathbf{s}$$

$$\kappa_{i,j,k}^{wz} := \frac{1}{\Delta x_g^{ij} \Delta y_g^{ij}} \int_{\partial E_{i,j,k}^B} \kappa^{wz}(\mathbf{s}) d\mathbf{s}$$

where $\partial E_{i,j,k}^W$, $\partial E_{i,j,k}^S$, and $\partial E_{i,j,k}^B$ are the western, southern, and bottom boundaries of the grid cell. The discretized gradient is approximated via the finite difference directional derivative at each cell face:

$$\begin{aligned} \frac{\partial \theta}{\partial x}(\mathbf{s}_{i,j,k}^W) &\simeq \frac{\theta_{i,j,k} - \theta_{i-1,j,k}}{\Delta x_c^{ij}} & \frac{\partial \theta}{\partial x}(\mathbf{s}_{i,j,k}^E) &\simeq \frac{\theta_{i+1,j,k} - \theta_{i,j,k}}{\Delta x_c^{i+1,j}} \\ \frac{\partial \theta}{\partial y}(\mathbf{s}_{i,j,k}^S) &\simeq \frac{\theta_{i,j,k} - \theta_{i,j-1,k}}{\Delta y_c^{ij}} & \frac{\partial \theta}{\partial y}(\mathbf{s}_{i,j,k}^N) &\simeq \frac{\theta_{j+1,k} - \theta_{i,j,k}}{\Delta y_c^{i,j+1}} \\ \frac{\partial \theta}{\partial z}(\mathbf{s}_{i,j,k}^T) &\simeq \frac{\theta_{i,j,k-1} - \theta_{i,j,k}}{\Delta r_c^k} & \frac{\partial \theta}{\partial z}(\mathbf{s}_{i,j,k}^B) &\simeq \frac{\theta_{i,j,k} - \theta_{i,j,k+1}}{\Delta r_c^{k+1}} \end{aligned}$$

for the west, east, south, north, top, and bottom cell faces, respectively. Note that the vertical coordinate is somewhat “flipped” when compared to the other dimensions, where the index $k = 1$ at the surface and $k = N_k$ at depth. Putting these definitions together,

$$\begin{aligned} \int_{\partial E_{i,j,k}} \mathbf{K}(\mathbf{s}) \nabla \theta(\mathbf{s}) \cdot \hat{\mathbf{n}} d\tau := & \left[\left(\frac{\kappa^{ux} \Delta y_g \Delta r_f}{\Delta x_c} \right)_{i+1,j,k} (\theta_{i+1,j,k} - \theta_{i,j,k}) - \left(\frac{\kappa^{ux} \Delta y_g \Delta r_f}{\Delta x_c} \right)_{i,j,k} (\theta_{i,j,k} - \theta_{i-1,j,k}) \right] + \\ & \left[\left(\frac{\kappa^{vy} \Delta x_g \Delta r_f}{\Delta y_c} \right)_{i,j+1,k} (\theta_{i,j+1,k} - \theta_{i,j,k}) - \left(\frac{\kappa^{vy} \Delta x_g \Delta r_f}{\Delta y_c} \right)_{i,j,k} (\theta_{i,j,k} - \theta_{i,j-1,k}) \right] + \\ & \left[\left(\frac{\kappa^{wz} \Delta x_g \Delta y_g}{\Delta r_c} \right)_{i,j,k} (\theta_{i,j,k-1} - \theta_{i,j,k}) - \left(\frac{\kappa^{wz} \Delta x_g \Delta y_g}{\Delta r_c} \right)_{i,j,k+1} (\theta_{i,j,k} - \theta_{i,j,k+1}) \right]. \end{aligned} \quad (19)$$

The discretized form of this operator is generated by defining the coefficients that form the seven point numerical stencil:

$$\begin{aligned} c_{\text{east}}^{i,j,k} &:= \left(\frac{\kappa^{ux} \Delta y_g \Delta r_f}{\Delta x_c} \right)_{i+1,j,k} & c_{\text{west}}^{i,j,k} &:= \left(\frac{\kappa^{ux} \Delta y_g \Delta r_f}{\Delta x_c} \right)_{i,j,k} \\ c_{\text{north}}^{i,j,k} &:= \left(\frac{\kappa^{vy} \Delta x_g \Delta r_f}{\Delta y_c} \right)_{i,j+1,k} & c_{\text{south}}^{i,j,k} &:= \left(\frac{\kappa^{vy} \Delta x_g \Delta r_f}{\Delta y_c} \right)_{i,j,k} \\ c_{\text{top}}^{i,j,k} &:= \left(\frac{\kappa^{wz} \Delta x_g \Delta y_g}{\Delta r_c} \right)_{i,j,k} & c_{\text{bottom}}^{i,j,k} &:= \left(\frac{\kappa^{wz} \Delta x_g \Delta y_g}{\Delta r_c} \right)_{i,j,k+1} \end{aligned}$$

$$c_{\text{center}}^{i,j,k} := -c_{\text{east}}^{i,j,k} - c_{\text{west}}^{i,j,k} - c_{\text{north}}^{i,j,k} - c_{\text{south}}^{i,j,k} - c_{\text{top}}^{i,j,k} - c_{\text{bottom}}^{i,j,k}.$$

With these definitions we define the matrix \mathbf{L} such that $\mathbf{L}\theta \simeq \int_{\Omega} \nabla \cdot K(\mathbf{s}) \nabla \theta(\mathbf{s}) d\mathbf{s}$ where the row corresponding to the index i, j, k

$$[c_{\text{top}} \cdots c_{\text{south}} \cdots c_{\text{west}} c_{\text{center}} c_{\text{east}} \cdots c_{\text{north}} \cdots c_{\text{bottom}}]_{i,j,k}$$

With each term in Equation (18) defined above, we have the system of equations in matrix form:

$$\begin{aligned} (\mathbf{D}_{\delta} - \mathbf{L})\theta &= \mathbf{D}_z \mathbf{z} \\ \mathbf{A}\theta &= \mathbf{D}_z \mathbf{z} \end{aligned} \tag{20}$$

where

$$\mathbf{D}_{\delta} := \text{diag} \left\{ \hat{\delta} \frac{V_n}{\det(\Phi_n)} \right\}_{n=1}^{N_{\theta}} \quad \mathbf{D}_z := \text{diag} \left\{ \sqrt{\frac{V_n}{\det(\Phi_n)}} \right\}_{n=1}^{N_{\theta}} \quad \mathbf{A} := (\mathbf{D}_{\delta} - \mathbf{L})$$

where for notational simplicity we index each grid cell with n . Note that when we prescribe Φ as in Section 3, then $\det(\Phi_n) = V_n$ so that $\mathbf{D}_{\delta} = \hat{\delta} \mathbf{I}$ and $\mathbf{D}_z = \mathbf{I}$. The solution, θ , is the discretized form of a Matérn field with covariance $\mathbf{D}_z \mathbf{A}^{-2} \mathbf{D}_z$. The solution for cases when $M > 1$ is simply obtained through an iterative application of \mathbf{A}^{-1} (see also Theorem 4 in Appendix C.4 of L11), i.e. for $M > 1$:

$$\mathbf{A}^{M-1} \theta_M = \theta$$

A.1 | Neumann boundary conditions

Throughout this work we use zero flux, Neumann boundary conditions as follows:

$$K(\mathbf{s}) \nabla \theta(\mathbf{s}) \cdot \hat{\mathbf{n}} = 0 \quad \mathbf{s} \in \partial \Omega_{\text{solid}}.$$

These boundary conditions are implemented by zeroing out the flux terms in the definition of \mathbf{L} along the boundary. More specifically, these are defined using a “mask” field which has values of one in the ocean and 0 on land. The mask is used to

modify the coefficients of \mathbf{L} as follows:

$$\begin{aligned} c_{\text{east}}^{i,j,k} &:= c_{\text{east}}^{i,j,k} m_{i,j,k} m_{i+1,j,k} & c_{\text{west}}^{i,j,k} &:= c_{\text{west}}^{i,j,k} m_{i,j,k} m_{i-1,j,k} \\ c_{\text{north}}^{i,j,k} &:= c_{\text{north}}^{i,j,k} m_{i,j,k} m_{i,j+1,k} & c_{\text{south}}^{i,j,k} &:= c_{\text{south}}^{i,j,k} m_{i,j,k} m_{i,j-1,k} \\ c_{\text{top}}^{i,j,k} &:= c_{\text{top}}^{i,j,k} m_{i,j,k} m_{i,j,k+1} & c_{\text{bottom}}^{i,j,k} &:= c_{\text{bottom}}^{i,j,k} m_{i,j,k} m_{i,j,k-1} \end{aligned}$$

where $m_{i,j,k}$ is used to denote the mask value at each grid cell.

A.2 | Correlation operator

The discretized form of the correlation operator used in this work is more formally defined as

$$\mathbf{C} := \mathbf{A} \mathbf{A}^{-M} \mathbf{D}_z. \quad (21)$$

To estimate the sample standard deviation used to fill \mathbf{A} , we draw 1,000 independent standard normal vectors $\mathbf{z}_l \in \mathbb{R}^{N_\theta}$ $l \in \{1, 2, \dots, 1000\}$, solve

$$\mathbf{A}^M \theta_l = \mathbf{D}_z \mathbf{z}_l \quad l \in \{1, 2, \dots, 1000\}, \quad (22)$$

and compute the pointwise standard deviation from $\{\theta_l\}_{l=1}^{1000}$.

A.3 | Code availability

This study used the MITgcm (Campin et al., 2021), with modifications that can be found at github.com/timothyas/MITgcm/tree/matern-correlation, for solving the presented linear system on the LLC grid. The grid files that make up the LLC grid can be found with the ECCOV4 data, which were accessed at (ECCO Consortium et al., 2020). All code used to generate, postprocess, and analyze the results in this paper can be found at Smith (2022). The python packages `xmitgcm` (Abernathy et al., 2021), `xarray` (Hoyer and Hamman, 2017), `dask` (Dask Development Team, 2016), and `zarr` (Miles et al., 2020) were essential for these tasks.

B | A BLOCK SUCCESSIVE OVER RELAXATION METHOD

Applying the correlation operator described in this paper, $\mathbf{C}^{1/2}$, requires the solution to an elliptic equation. Here we describe the block-Successive Over Relaxation (SOR) method that was implemented to solve this problem. We note that both preconditioned conjugate gradient algorithms exist in the MITgcm for 2D (in the latitude longitude plane) and 3D fields. However, the preconditioner for these solvers is designed specifically for the pressure solve at each time step (Marshall et al., 1997), and so may not be generally applicable to our problem. As such, we opted to implement the SOR algorithm outlined here because it was simple to do so, and efficient enough for our purposes.

The SOR method is an iterative method for solving $\mathbf{A}\mathbf{x} = \mathbf{b}$. At iteration k , the elements of \mathbf{x} are x_i^k , and we seek the update:

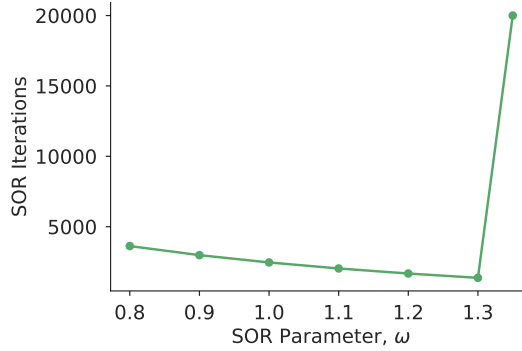


FIGURE 8 Performance of the SOR algorithm for various settings of ω using 10 samples, $\hat{\rho} = 10$, tolerance of 10^{-15} , and $M = 1$.

$$\bar{x}_i^{k+1} = (1 - \omega)x_i^k + \frac{\omega}{a_{ii}} \left(b_i - \sum_{j < i} a_{ij} \bar{x}_j^{k+1} - \sum_{j > i} a_{ij} x_j^k \right), \quad i = 1, 2, \dots, N, \quad (23)$$

where the elements of \mathbf{x} are x_i^k (and similarly for \mathbf{A} and \mathbf{b}), and ω is the SOR parameter. Here the notation \bar{x}_i^{k+1} refers to the fact this is a local update, i.e. there is no communication between the processes assigned to each portion of the computational domain. The only areas where this local update causes the algorithm to deviate from a standard SOR method is when neighboring elements $\bar{x}_j^{k+1}, i \neq j$ are in the “halo” regions of a process’s subdomain which are only updated at the end of each iteration. In this case, these neighboring elements take on the value from the previous iteration: $\bar{x}_j^{k+1} = x_j^k$.

We find this simple implementation to be an effective method for solving the linear system. Figure 8 shows the number of iterations required for convergence as a function of the parameter ω , with an optimal value of approximately $\omega^* = 1.3$. We note that the number of iterations required to converge at this optimal value is about half that of $\omega = 1$, which coincides with a (block) Gauss-Seidel algorithm (again differing from its true form due to the halo updates). Of course, Figure 8 shows the major drawback of the SOR algorithm: near the “optimal” value for the SOR parameter, efficiency is highly sensitive. For our implementation, at $\omega = 1.35$, we see that the algorithm does not fully converge and runs until set limit of 20,000 iterations.

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