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Three regularization models of the Navier–Stokes equations

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We determine how the differences in the treatment of the subfilter-scale physics affect the properties of the flow for three closely related regularizations of Navier–Stokes. The consequences on the applicability of the regularizations as subgrid-scale (SGS) models are also shown by examining their effects on superfilter-scale properties. Numerical solutions of the Clark–α model are compared to two previously employed regularizations, the Lagrangian-averaged Navier–Stokes α-model (LANS-α) and Leray–α, albeit at significantly higher Reynolds number than previous studies, namely, Re ≈ 3300, Taylor Reynolds number of Re₄ ≈ 790, and to a direct numerical simulation (DNS) of the Navier–Stokes equations. We derive the de Kármán–Howarth equation for both the Clark–α and Leray–α models. We confirm one of two possible scalings resulting from this equation for Clark–α as well as its associated k¹ energy spectrum. At subfilter scales, Clark–α possesses similar total dissipation and characteristic time to reach a statistical turbulent steady state as Navier–Stokes, but exhibits greater intermittency. As a SGS model, Clark–α reproduces the large-scale energy spectrum and intermittency properties of the DNS. For the Leray–α model, increasing the filter width α decreases the nonlinearity and, hence, the effective Reynolds number is substantially decreased. Therefore, even for the smallest value of α studied Leray–α was inadequate as a SGS model. The LANS-α energy spectrum ~k¹, consistent with its so-called “rigid bodies,” precludes a reproduction of the large-scale energy spectrum of the DNS at high Re while achieving a large reduction in numerical resolution. We find, however, that this same feature reduces its intermittency compared to Clark–α (which shares a similar de Kármán–Howarth equation). Clark–α is found to be the best approximation for reproducing the total dissipation rate and the energy spectrum at scales larger than α, whereas high-order intermittency properties for larger values of α are best reproduced by LANS-α. © 2008 American Institute of Physics. [DOI: 10.1063/1.2880275]

I. INTRODUCTION

Nonlinearities prevail in fluid dynamics when the Reynolds number Re is large.¹ For geophysical flows, the Reynolds number is often larger than 10⁸ and for some astrophysical flows values of Re = 10¹⁸ is not unreasonable. The number of degrees of freedom (dof) in the flow increases as Re²⁴ for Re ≳ 1 in the Kolmogorov framework²⁴ (hereafter, K41). Such a huge number of dof makes direct numerical simulations (DNS) of turbulence at high Re infeasible on any existing or projected computer for decades to come. Because of this intractability, simulations of turbulence are always carried out in regions of parameter space far from the observed values, either with (a) an unphysical lack of scale separation between the energy-containing, inertial, and dissipative ranges while parametrizing the missing physics, or (b) a study of the processes at much smaller length scales, often with periodic boundaries (unphysical at large scales but used under the hypothesis of homogeneity of turbulent flows). Clearly, modeling of unresolved small scales is necessary.

Given the nonlinear nature of turbulent flows and the ensuing multiscale interactions, the physics of the unresolved scales may not be separable from the properties (e.g., statistics) of the resolvable large scales. However, two main approaches have been developed over the years to model the effects of the unresolved small scales in turbulence on the scales resolved in the simulations. The first approach is large eddy simulations (LES). LES is widely used in engineering, in atmospheric sciences, and to a lesser extent in astrophysics. However, in the LES approach, the Reynolds number is not known. Instead, one attempts modeling the behavior of the flow in the limit of very large Re. As the Kolmogorov assumption of self-similarity is known to be violated (e.g., by intermittency⁶,⁷ and by spectral nonlocality⁸), the value of Re can play an important role; e.g., in the competition between two or more instabilities.⁹ Therefore, another approach models the effects of turbulence at higher Reynolds numbers than are possible with a DNS on a given grid, by using a variety of techniques that can be viewed as filtering of the small scales [the so-called subgrid-scale (SGS) models].

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A rather novel approach to modeling of turbulent flows employs regularization modeling as a SGS model. Unlike closures that employ eddy-viscosity concepts (modifying the dissipative processes), the approach of regularization modeling modifies the spectral distribution of energy. For this reason, they retain a well-defined Reynolds number. Existence and uniqueness of smooth solutions can be rigorously proven, unlike many LES models (e.g., eddy-viscosity), as well as the fact that the subgrid model recovers the Navier–Stokes equations in the limit of the filter width going to zero. Their robust analytical properties ensure computability of solutions. These same properties reenact theoretical possibilities first explored by Leray when he proved the existence (but not smoothness or uniqueness) of solutions to the Navier–Stokes equations in \( \text{Re}^n (n=2,3) \) using the Leray model. This treatment of the small scales, then, enforces a precise type of regularization of the entire solution, which may be studied as an independent scientific question (as compared to either LES or SGS modeling).

Geurts and Holm began using the Leray model with (a three-point invertible approximation of) an inverse-Helmholtz-operator filter of width \( \alpha \). Later it was dubbed Leray–\( \alpha \), and an upper bound for the dimension of the global attractor was established. The global existence and uniqueness of strong solutions for the Leray model is a classical result. Leray–\( \alpha \) has been compared to DNS simulations on a grid of \( N^3 = 192^3 \) in a doubly periodic compressible channel flow domain. Its performance was found to be superior to a dynamic mixed (similarity plus eddy-viscosity) model (with an even greater reduction in computational cost). However, it possessed a systematic error of a slight over-prediction of the large scales accompanied by a slight under-prediction of the small scales. It possessed both forward- and backscatter, but exhibited too little dissipation.

The Leonard tensor-diffusivity model (sometimes known as the Clark model) is the first term of the reconstruction series for the turbulent subfilter stress for all symmetric filters that possess a finite nonzero second moment. This leading order approximation of the subgrid stress is thus generic. In a priori testing, it reconstructs a significant fraction (\( >90\% \), but not all) of the subgrid stress, provides for local backscatter along the stretching directions while remaining globally dissipative, and possesses a better reconstruction of the subgrid stress than the scale-similarity model. Used as a LES, in a posteriori testing the Leonard tensor-diffusivity model required additional dissipation (a dynamic Smagorinsky term) to achieve reasonable gains in computation speed for three-dimensional (3D) periodic flows and for channel flows. The Leonard tensor-diffusivity model does not conserve energy in the nonviscous limit. Cao, Holm, and Titi developed a related (conservative) subgrid model that they dubbed Clark–\( \alpha \). The Clark–\( \alpha \) model applies an additional inverse-Helmholtz filter operation to the Reynolds stress tensor of the Clark model. The global well-posedness of the Clark–\( \alpha \) model and the existence and uniqueness of its solutions were demonstrated, and upper bounds for the Hausdorff (\( d_{H} \)) and fractal (\( d_{F} \)) dimensions of the global attractor were found. This model has yet to be evaluated numerically.

The third regularization model we will consider is the incompressible Lagrangian-averaged Navier–Stokes (LANS–\( \alpha \)-model, also known as the viscous Camassa–Holm equation). It can be derived, for instance, by applying temporal averaging to Hamilton’s principle, where Taylor’s frozen-in turbulence hypothesis (the only approximation in the derivation) is applied as the closure for the Eulerian fluctuation velocity in the Reynolds decomposition, at linear order in the generalized Lagrangian mean description. In this derivation, the momentum-conservation structure of the equations is retained. For scales smaller than the filter width, LANS–\( \alpha \) reduces the steepness in gradients of the Lagrangian mean velocity and thereby limits how thin the vortex tubes may become as they are transported, while the effect on larger length scales is negligible. LANS–\( \alpha \) may also be derived by smoothing the transport velocity of a material loop in Kelvin’s circulation theorem. Consequently, there is no attenuation of resolved circulation, which is important for many engineering and geophysical flows where accurate prediction of circulation is highly desirable. An alternative interpretation of the \( \alpha \)-model is that it neglects fluctuations in the smoothed velocity field, while preserving them in the source term, the vorticity. LANS–\( \alpha \) has previously been compared to direct numerical simulations (DNS) of the Navier–Stokes equations at modest Taylor Reynolds numbers (\( \text{Re}_{\theta} \approx 72 \), \( \text{Re}_{\theta} = 130 \), and \( \text{Re}_{\theta} = 300 \)). LANS–\( \alpha \) was compared to a dynamic eddy-viscosity LES in 3D isotropic turbulence under two different forcing functions (for \( \text{Re}_{\theta} \approx 80 \) and 115) and for decaying turbulence with initial conditions peaked at a low wavenumber (with \( \text{Re}_{\theta} \approx 70 \)) as well as at a moderate wavenumber (with \( \text{Re}_{\theta} \approx 220 \)). LANS–\( \alpha \) was preferable in these comparisons because it demonstrated correct alignment between eigenvectors of the subgrid stress tensor and the eigenvectors of the resolved stress tensor and vorticity vector. The LES effectiveness of the LANS–\( \alpha \) and the Leray–\( \alpha \) regularization models relative to eddy-viscosity and the dynamic mixed model (similarity plus eddy-viscosity) have already been demonstrated in a turbulent mixing layer shear (with \( \text{Re} \approx 50 \)). LANS–\( \alpha \) was found to be the most accurate of these three LES candidates at proper subgrid resolution, but the effects of numerical contamination can be strong enough to lose most of this potential. While LANS–\( \alpha \) has the greatest grid-independent accuracy of the three models, it also requires the greatest resolution. From the LES perspective, this could pose some limitations on the practical use and application of LANS–\( \alpha \) for high Re cases. Indeed, recent high-resolution simulations of LANS–\( \alpha \) showed that energy artificially accumulates in the subfilter scales, giving as a result only a modest computational gain at very high Reynolds number.

We propose to pursue these previous studies of Leray–\( \alpha \) and LANS–\( \alpha \) further at higher Reynolds number, and to use them as a benchmark for evaluation of Clark–\( \alpha \). One goal is to contrast the subfilter-scale physics of the three models to determine the relevant features from which to build improved models. As the three regularizations are related via truncation of subfilter stresses, such a comparison can be illuminating. For LANS–\( \alpha \), the predicted subfilter-scale spec
tra is \( \sim k^{-1} \). This scaling has been observed to be subdominant to an energy spectrum \( \sim k^1 \), which corresponds to "enslaved rigid body" or "polymerized" portions of the fluid.\(^{34}\) The subfilter scaling observed in the third-order structure function corresponded to the predicted \( \sim k^{-1} \) scaling of the energy spectrum. However, regions were observed in the flow where no stretching was acting in the subfilter scales. These regions, which give no contribution to the energy cascade, and hence do not affect the third-order structure functions, are responsible for the \( \sim k^1 \) scaling in the LANS-\( \alpha \) energy spectrum. For Clark-\( \alpha \), the correct time scale for vortex stretching is difficult to determine and its spectrum is found to range between \( \sim k^{-1} \) and \( \sim k^{-7/3} \).\(^{21}\) Leray-\( \alpha \) has the same difficulty and the spectrum can range between \( \sim k^{-1/3} \) and \( \sim k^{-5/3} \).\(^{14}\) The determination of these scaling laws is needed to quantify the computational gain if each model is to be used as a SGS model. As a result, we seek to determine empirically the subfilter-scale spectra. Our second goal is to evaluate the applicability of these three regularizations as SGS models. This is accomplished both through prediction of computational gains from observed subfilter-scale properties and through directly testing their capability to predict superfilter-scale properties at high Re.

We present the three models and describe how they are related, derive the de Kármán–Howarth equation for Clark-\( \alpha \) and Leray-\( \alpha \) (from which exact scaling laws for third order quantities follow), and review theoretical predictions of inertial range scaling in Sec. II. We examine the subfilter-scale properties of the three regularizations in Sec. III. We first compute a fully resolved DNS of the Navier–Stokes equations at a resolution of 1024\(^3 \) (\( \nu = 3 \times 10^{-4} \), \( \text{Re} = 3300 \), and \( \text{Re}_\lambda = 790 \)). We then perform model runs with the exact same conditions at a resolution of 384\(^3 \). We take \( \alpha \) to be 1/13 the box size, which was found in an earlier study to be large enough to exhibit both Navier–Stokes and subfilter-scale LANS-\( \alpha \) dynamics.\(^{34}\) This large filter case is important because it gives insight into the behavior of the models at scales much smaller than the filter width without requiring higher resolution than is feasible. We compare the three regularizations as subgrid models in Sec. IV. Guided by a previous study of LANS-\( \alpha \),\(^{34}\) we take \( \alpha \) to be 1/40 the box size. This choice was found to produce an optimal \( \alpha \)-LES (in the sense of being optimal for the class of LANS-\( \alpha \) models, with respect to the value of \( \alpha \)). Finally, we review bounds on the size of the attractors and use these bounds to comment on the computational savings of the three regularizations viewed as SGS models.

II. THE THREE REGULARIZATION MODELS

A. Clark-\( \alpha \)

The incompressible Navier–Stokes equations are given in Cartesian coordinates by

\[
\frac{\partial u_i}{\partial t} + \frac{\partial (u_j u_i)}{\partial x_j} + \frac{\partial p}{\partial x_i} = \nu \frac{\partial^2 u_i}{\partial x_j^2}, \quad \frac{\partial u_i}{\partial x_j} = 0.
\]

(1)

Filtering these equations with a convolution filter, \( L : z \rightarrow \widetilde{z} \), in which \( \widetilde{z} (z) \) denotes the filtered (unfiltered) field, yields

\[
\frac{\partial \widetilde{u}_i}{\partial t} + \frac{\partial (u_j \widetilde{u}_i)}{\partial x_j} + \frac{\partial \widetilde{p}}{\partial x_i} = \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_j^2}, \quad \frac{\partial \widetilde{u}_i}{\partial x_j} = 0.
\]

\( \widetilde{z} \) (\( z \)) in which by convention we denote \( u_i = \widetilde{u}_i \) and the Reynolds turbulence stress tensor, i.e., \( \tau_{ij} = v \frac{\partial \widetilde{u}_i}{\partial x_j} \), represents the closure problem. Equation (2) can represent either a LES or a SGS model. As the difference between the two is primarily philosophical (e.g., the scale at which filtering is applied, dissipative versus dispersive, the factor by which computational resolution may be decreased, etc.), we briefly define our terminology. Many LES include eddy-viscosity (i.e., \( \nu \frac{\partial \widetilde{u}_i}{\partial x_j} \)) includes a \( v \tau_{ij} \) term such that \( \nu \tau_{ij} \gg \nu \). This amounts to approximating the \( \nu = 0 \) problem and no finite Reynolds number can be defined. More generally, a LES applies the filtering in the inertial range and reduces the necessary computational linear resolution by at least an order of magnitude. Different from this previous case, a SGS model employs a finite value of \( \nu \) (and a well-defined Reynolds number) and addresses instead the question: For a given Re, how far can we reduce the computational expense while retaining as much of the detailed large-scale properties (such as high-order statistics) as possible? For the case of LANS-\( \alpha \), for example, it has already been shown that the reduction in computational expense is rather modest (a factor of about 30). Therefore, while calling it a SGS model is justified by Eq. (2), the label LES does not really apply.

It is the case for both LES and SGS models that though a single filtering is indicated in Eq. (2), numerical solution implies a second filtering at the grid resolution (see, e.g., Ref. 20). Systematic studies requiring a database of computed solutions have been made in the past for LES\(^{35}\) and for the LANS-\( \alpha \) regularization model.\(^{33,15,34}\) These studies show that the ratio of the two filter widths (i.e., the subfilter resolution) can affect greatly the model’s performance. To avoid this complication, the subfilter resolutions employed in this study are rather large. Determination of the optimal subfilter resolution is a detailed study that should be undertaken for both Clark-\( \alpha \) and Leray-\( \alpha \), but is beyond the scope of this present paper.

It has been shown\(^{19,20}\) that for all symmetric filters possessing a finite nonzero second moment, the first term of the reconstruction series for the turbulent subfilter stress is

\[
\tau_{ij} = - \frac{d^2 \hat{G}(k)}{dk^2} \bigg|_{k=0} \partial_k u_i \partial_k u_j + \cdots ,
\]

(3)

where \( \hat{G}(k) \) is the Fourier transform of the convolution kernel \( \{G(r)\} \) is the convolution kernel, where \( [L^2(\mathbf{r})] = \iint G(r-\mathbf{r}') \alpha(r') d^2 \mathbf{r}' \). This approximation of the subgrid stress is then generic and is known as the Leonard tensor-diffusivity model\(^{17}\) (or, often, the Clark model\(^{18}\)). Related to this model, the Clark-\( \alpha \) model is

\[
\partial \widetilde{u}_i + \mathcal{H} \frac{\partial (u_j \widetilde{u}_i)}{\partial x_j} + \nu \frac{\partial^2 \widetilde{u}_i}{\partial x_j^2} + \alpha^2 \frac{\partial^2 u_j u_i}{\partial x_j^2} = \nu \partial_j \widetilde{u}_i ,
\]

and its subgrid stress for \( \alpha \ll 1 \) is given by

\[
\tau_{ij} = \mathcal{H}^{-1} \alpha^2 (\partial_k u_i \partial_k u_j) = \alpha^2 (\partial_k u_i \partial_k u_j) + \mathcal{O}(\alpha^2).
\]

(5)

Here the filter is the inverse of a Helmholtz operator; i.e., \( L = \mathcal{H}^{-1} = (1 - \alpha^2 \nabla^2)^{-1} \). The Clark-\( \alpha \) model conserves energy in the \( H^1(\mathbf{u}) \) norm instead of the \( L^2(\mathbf{u}) \) norm,
\[ \frac{dE_\alpha}{dt} = -2\nu \Omega_\alpha, \]  
\[ (u - \alpha^2 \nabla^2 u) \cdot \mathbf{\omega} = \frac{1}{D} \int_D \frac{1}{2} \mathbf{v} \cdot \mathbf{u} d^3x, \]  
\[ \Omega_\alpha = \frac{1}{D} \int_D \frac{1}{2} \mathbf{\omega} \cdot \mathbf{\omega} d^3x, \]  
where \( \mathbf{\omega} = \nabla \times \mathbf{v} \) and \( \bar{\mathbf{\omega}} = \nabla \times \mathbf{u} \). For \( L = \mathcal{H}^{-1} \), we note that \( \bar{\mathbf{G}} = (1 + \alpha^2 k^2)^{-1} \), which implies that the turbulent subfilter stress tensor for the tensor-diffusivity model given by Eq. (3) is

\[ \tau_{ij}^C = 2\alpha^2 (\partial_i \mathbf{u} \partial_j \mathbf{u}) + \cdots, \]  
which is proportional to the Clark-\( \alpha \) stress tensor to second order in \( \alpha \). Hence, the \textit{a priori} tests of \( 19 \) should apply to Clark-\( \alpha \), at least at this order.

1. de Kármán–Howarth equation for Clark-\( \alpha \)

In 1938, de Kármán and Howarth\(^{36} \) introduced the invariant theory of isotropic hydrodynamic turbulence, and derived from the Navier–Stokes equations the exact law relating the time derivative of the two-point velocity correlation to the divergence of the third-order correlation function. The corresponding de Kármán–Howarth theorem for LANS-\( \alpha \) in the fluid case was derived in Ref. \( 37 \). The relevance of the de Kármán–Howarth theorem for the study of turbulence cannot be underestimated. As a corollary, rigorous scaling laws in the inertial range can be deduced. In this section, we derive these results for the Clark-\( \alpha \) case.

For the sake of simplicity, we consider the case \( \nu = 0 \), since the dissipative terms may be added at any point in the derivation. We denote \( \mathbf{u}' = \mathbf{u}(\mathbf{x}', t) \) and begin our investigation of the correlation dynamics by computing the ingredients of the partial derivative \( \partial_i (u'_j u'_k') \). The Clark-\( \alpha \) motion equation (4) may be rewritten as

\[ \partial_t u'_i + \partial_m (u'_j u'_m + u'_j u'_m) + p \delta_{ij} - \alpha^2 \partial_i \mathbf{\omega} \partial_j \mathbf{u} = 0. \]

Combining Eqs. (2) and (5), we arrive at the fluctuation-velocity equation

\[ \partial_t u'_i + \partial_m (u'_j u'_m + p' \delta_{ij} + \alpha^2 G \otimes \tau_{ij}^C) = 0, \]  
where \( \tau_{ij}^C = \mathcal{H}^{-1} \alpha^2 \tau_{ij}^C \) \( (L = \mathcal{H}^{-1}) \). Multiplying Eq. (2) by \( u'_j \) and Eq. (11) by \( v'_i \), then adding the result yields

\[ \partial_t (v'_i u'_j) = \frac{\partial}{\partial r_m} \left( \langle (u'_j u'_m + u'_j u'_m - u'_j u'_m - \alpha^2 \partial_i \mathbf{\omega} \partial_j \mathbf{u} \rangle u'_j \right) 
\]

\[ + \frac{\partial}{\partial r_m} \langle p' u'_j \delta_{ij} - \bar{p}' v'_j \delta_{jm} \rangle 
\]

\[ - \frac{\partial}{\partial r_m} \langle (u'_j u'_m + \alpha^2 G \otimes \tau_{ij}^C) v'_j \rangle, \]

where we have used statistical homogeneity

\[ \frac{\partial}{\partial r_m} \langle \cdot \rangle = \frac{\partial}{\partial r'_m} \langle \cdot \rangle = -\frac{\partial}{\partial \delta_m} \langle \cdot \rangle. \]

We symmetrize Eq. (12) in the indices \( i, j \) by adding the corresponding equation for \( \partial_t (v'_i u'_j) \). We then use homogeneity again as

\[ \langle v'_i u'_j u'_m + v'_j u'_i u'_m \rangle = -\langle v'_j u'_i u'_m + v'_i u'_j u'_m \rangle, \]

and define the tensors

\[ Q_{ij}^C = \langle v'_i u'_j + v'_j u'_i \rangle, \]

\[ T_{jm}^C = \langle (u'_j u'_i + v'_i u'_j + v'_j u'_i - u'_j u'_i - u'_j u'_i) u'_m \rangle, \]

\[ + (u'_j u'_i + u'_j u'_i) u'_m \rangle, \]

\[ \Pi_{jm}^C = \langle (p' u'_j - \bar{p}' v'_j) \delta_{jm} + (p' u'_j - \bar{p}' v'_j) \delta_{jm} \rangle, \]

\[ S_{jm}^C = \langle \delta_{jm} (\partial_i u'_j \partial_i u'_m) u'_i + (\partial_i u'_j \partial_i u'_m) u'_i + G \otimes \tau_{jm}^C v'_i \rangle + G \otimes \tau_{jm}^C v'_i, \]

We can drop \( \Pi_{jm}^C \) because the terms with the pressures \( p \) and \( \bar{p}' \) vanish everywhere, as follows from the arguments of isotropy.\(^{36} \) Finally, we obtain

\[ \partial_t Q_{ij}^C = \frac{\partial}{\partial r_m} (T_{jm}^C - \alpha^2 S_{jm}^C). \]

This is the de Kármán–Howarth equation for Clark-\( \alpha \) [compare to Eq. (3.8) in Ref. \( 37 \) for LANS-\( \alpha \)].

By dimensional analysis, the energy dissipation rate in Clark-\( \alpha \) is \( \varepsilon_{\alpha}^C \sim \delta_i Q_{ij}^C \) and Eq. (19) implies

\[ \varepsilon_{\alpha}^C \sim \frac{1}{\ell} \left( v u^2 + u^3 + \frac{\alpha^2}{L} u^3 \right). \]

For large scales \( (l \gg \alpha) \), we recover the Navier–Stokes scaling known as the four-fifths law: \( \varepsilon \sim l \varepsilon \). Here, \( \delta_t (l) = \langle \mathbf{v} (x + 1) - \mathbf{v} (x) \rangle \cdot 1/l \) is the longitudinal increment of \( \mathbf{v} \). Strictly speaking, the four-fifths law expresses that the third-order longitudinal structure function of \( \mathbf{v} \), i.e., \( S^3_3 (l) = \langle (\delta_t)^3 \rangle \), is given in the inertial range in terms of the mean energy dissipation per unit mass \( \varepsilon \) by

\[ S^3_3 = -\frac{5}{2} \varepsilon \ell, \]

or, equivalently, that the flux of energy across scales in the inertial range is constant. We also recover the Kolmogorov 1941\(^{2/3} \) energy spectrum, i.e., \( E(k) k^{-5/3} \sim \varepsilon^{2/3} k^{2/3} \) or, equivalently,
For subfilter scales \((l \ll \alpha)\), we have \(u \sim \nu^2/\alpha^2\) and the first and third right-hand terms in Eq. (20) are equivalent. In this case, we are left with two different possibilities depending on the prefactors in Eq. (20). If the first (or third) right-hand term is dominant, our scaling law becomes

\[ E(k) \sim e^{2/3} k^{-5/3}. \tag{22} \]

This result is the same as for the \(\alpha\)-model.\(^{29}\) If, however, the second right-hand term in Eq. (20) is dominant, then the K41 results are recovered, with \(u\) substituted for \(v\). In that case, one finds the alternative Clark–\(\alpha\) subfilter-scale spectral energy scaling,

\[ E_a^C(k) \sim k^{1/3}. \tag{25} \]

2. Phenomenological arguments for Clark–\(\alpha\) inertial range scaling

We review here the derivation by dimensional analysis of the spectrum which follows the scaling ideas originally due to Kraichnan\(^\text{19}\) and which is developed more fully in Ref. 21. In examining the nonlinear terms in Eq. (4), it is not entirely clear which of three possible scales for the average velocity for an eddy of size \(k^{-1}\),

\[ U_k^{(0)} = \left( \frac{1}{D} \int_D |v_i|^2 d^3x \right)^{1/2}, \tag{26} \]

\[ U_k^{(1)} = \left( \frac{1}{D} \int_D u_i \cdot v_i d^3x \right)^{1/2}, \tag{27} \]

or

\[ U_k^{(2)} = \left( \frac{1}{D} \int_D |u_i|^2 d^3x \right)^{1/2}, \tag{28} \]

should result. Therefore, three corresponding “turnover times” \(\tau_k\) for such an eddy may be proposed,

\[ \tau_k^{(n)} \sim 1/(kU_k^{(n)}) \quad \text{with} \quad n = 0, 1, 2. \tag{29} \]

The term “turnover time” is used advisedly here, since only the velocity \(U_k^{(2)}\) is composed of the fluid transport velocity. We define the (omnidirectional) spectral energy density \(E_a(k)\) from the relation

\[ E_a = \int_0^\infty \int E_a(k) dk \]d\(k\)

\[ \int_0^\infty \int E_a(k) dk. \tag{30} \]

Since \(u_k \cdot u_k = u_k \cdot v_k / (1 + \alpha^2 k^2) = E_a(k) / (1 + \alpha^2 k^2)\), we have

\[ U_k^{(n)} = \left( \int E_a(k)(1 + \alpha^2 k^2)^{(1-n)} dk \right)^{1/2} \]

\[ \sim [kE_a(k)(1 + \alpha^2 k^2)^{(1-n)}]^{1/2}. \tag{31} \]

The total energy dissipation rate \(e_a\) is then related to the spectral energy density by

\[ e_a \sim \left[ (\frac{1}{k})^{n-1} \int E_a(k) dk \right] \sim k^{3/2} \cdot E_a(k)^{3/2} (1 + \alpha^2 k^2)^{(1-n)/2}, \tag{32} \]

which yields, finally, the predicted energy spectra for Clark–\(\alpha\), \(E_a^C(k)\),

\[ E_a^C(k) = (\frac{\alpha}{C^2})^{2/3} k^{-5/3}, \tag{33} \]

whereas for scales much smaller than \(\alpha (ak \ll 1)\), the Kolmogorov scaling for Navier–Stokes is recovered,

\[ E_a^C(k) \sim (\frac{\alpha}{C^2})^{2/3} k^{-5/3}, \tag{34} \]

These arguments constrain the Clark–\(\alpha\) subfilter-scale spectrum to lie between \(k^{-1}\) and \(k^{-7/3}\).

B. Leray–\(\alpha\)

The Leray model in Cartesian coordinates is

\[ \partial \psi + \partial_j (u_i \psi_i) + \partial_i P = \nu \partial_j \psi_i + \partial_j \psi_i = 0, \tag{36} \]

where the flow is advected by a smoothed velocity \(u\). By comparison with Eq. (2) we see that the Leray model approximates the subgrid stress as \(\bar{\tau}_{ij} = \lambda(u, \nu_j) - u_j u_i\), or, with \(L = H^{-1}\),

\[ \bar{\tau}_{ij} = H^{-1} \alpha^2 (\partial_i u_j + \partial_j u_i) \tag{37} \]

As has been noted previously,\(^{13}\) the subgrid stress of Clark–\(\alpha\) in Eq. (5) is a truncation of the subgrid stress of Leray–\(\alpha\), in Eq. (37). For Leray–\(\alpha\), the \(L^2(u)\) norm is the quadratic invariant that is identified with energy,

\[ \frac{dE}{dt} = -2 \nu \Omega, \tag{38} \]

where

\[ E = \frac{1}{D} \int_D \frac{1}{2} |v| d^3x \tag{39} \]

and

\[ \Omega = \frac{1}{D} \int_D \frac{1}{2} |\omega|^2 d^3x. \tag{40} \]

As was pointed out in Ref. 39, the incompressibility of the velocity field \(v\) only implies a divergenceless filtered velocity \(u\) under certain boundary conditions for Leray–\(\alpha\). When \(\partial_i u_i \neq 0\), the energy \(E = \int_D |v|^2\) is no longer conserved (helicity and Kelvin’s theorem are not conserved for Leray–\(\alpha\)). In our numerical study, we employ periodic boundary condi-
tions, for which \( \partial \nu_l = 0 \) implies \( \partial \mu_l = 0 \) and Leray-\( \alpha \) conserves energy in the usual sense of \( L^2(\nu) \).

1. de Kármán–Howarth equation for Leray-\( \alpha \)

In this section we derive the de Kármán–Howarth equation for the Leray-\( \alpha \) case. Following Sec. II A 1, we begin our investigation of the correlation dynamics by computing the ingredients of the partial derivative \( \partial_l(\nu_l \nu_l') \). Equation (36) may be rewritten as

\[
\partial_l \nu_l + \partial_l(\nu_l \nu_m + P \delta_{lm}) = 0. \tag{41}
\]

Multiplying Eq. (41) by \( \nu_l' \) yields

\[
\partial_l(\nu_l \nu_l') = \frac{\partial}{\partial r_m}(\nu_l \mu_m) + \frac{\partial}{\partial r_m}(P \nu_l' \delta_{lm}). \tag{42}
\]

We can make this equation symmetric in the indices \( i, j \) by adding the equation for \( \partial_l(\nu_i \nu_i') \). We define the tensors

\[
Q_l^{ij} = \langle \nu_l \nu_j' + \nu_i \nu_i' \rangle, \tag{43}
\]

\[
T_{ijm}^L = \langle (\nu_l \nu_j' + \nu_i \nu_i') \mu_m \rangle, \tag{44}
\]

\[
\Pi_{ijm}^L = \langle P \nu_l' \delta_{jm} + P \nu_i' \delta_{jm} \rangle. \tag{45}
\]

Again, we may drop \( \Pi_{ijm}^L \) because the terms with the pressure \( P \) vanish everywhere, and thereby obtain

\[
\partial_l Q_l^{ij} = \frac{\partial}{\partial r_m} T_{ijm}^L. \tag{46}
\]

This is the de Kármán–Howarth equation for Leray-\( \alpha \).

The energy dissipation rate for Leray-\( \alpha \) is denoted by \( e^L \), and it satisfies \( e^L \sim \partial_l Q_l^{ii} \). By dimensional analysis, Eq. (46) implies

\[
e^L \sim \frac{1}{l} \nu^2 u. \tag{47}
\]

For large scales (\( l \gg \alpha \)), we recover the Navier–Stokes scaling [Eqs. (21) and (22)]. For subfilter scales (\( l \ll \alpha \)), our scaling law becomes

\[
\langle [\partial_l U_l(l)]^2 [\partial_l U_l(l)] \rangle \sim e^L l. \tag{48}
\]

For our small-scale energy spectrum, we would then have \( E^L(k) \sim v^2 \sim (e^L)^{2/3} \alpha^4 k^{2/3} \) (where we employed \( u \sim v^2 / \alpha^2 \)), or, equivalently [cf. Eq. (25)],

\[
E^L(k) \sim (e^L)^{2/3} \alpha^4 k^{2/3}. \tag{49}
\]

2. Phenomenological arguments for Leray-\( \alpha \) inertial range scaling

We review here the derivation by dimensional analysis of the spectrum for Leray-\( \alpha \) as we did for Clark-\( \alpha \) in Sec. II A 2. This analysis is developed more fully in Ref. 14. We argue again that there are three possible scales for the average velocity for an eddy of size \( k^{-1} \) [Eqs. (26)–(28)], with the turnover time \( t_k^{(n)} \) given by Eq. (29). Since \( u_k^2 = v_k^2 / (1 + \alpha^2 k^2)^2 = E(k) / (1 + \alpha^2 k^2)^2 \), we have

\[
(U_k^{(n)}) = \left( \int E(k) (1 + \alpha^2 k^2)^{-n} dk \right)^{1/2} \sim (kE(k) (1 + \alpha^2 k^2)^{-n})^{1/2}, \tag{50}
\]

Then, the total energy dissipation rate \( e^L \) is then related to the spectral energy density by

\[
e^L \sim (t_k^{(n)})^{-1} \int E(k) dk \sim k^2 U_k^{(n)} E(k) \sim k^{5/2} E(k) (1 + \alpha^2 k^2)^{-n/2}, \tag{51}
\]

which yields, finally, the predicted energy spectra for Leray-\( \alpha \), \( E^L(k) \),

\[
E^L(k) \sim (e^L)^{2/3} k^{-5/3} (1 + \alpha^2 k^2)^{n/3}. \tag{52}
\]

For scales much larger than \( \alpha \) (\( ak \ll 1 \)), the K41 spectrum is recovered [Eq. (22)], and for scales much smaller (\( ak \gg 1 \)), the spectrum is

\[
E^L(k) \sim (e^L)^{2/3} \alpha^{2n/3} k^{(2n-5)/3}. \tag{53}
\]

These arguments constrain the Leray-\( \alpha \) subfilter-scale spectrum to lie between \( k^{-1/3} \) and \( k^{-5/3} \).

C. LANS-\( \alpha \)

LANS-\( \alpha \) is given by

\[
\partial_l \nu_l + \partial_l (u \nu_l') + \partial_l u + v j \partial_l u_j = v \partial_l \nu_l, \quad \partial_l v_l = 0. \tag{54}
\]

For LANS-\( \alpha \), the usual choice of filter is again \( L=H^{-1} \). With this filter, the subgrid stress tensor is given by

\[
\tau_0^L = H^{-1} \alpha^2 (\partial_m u_i \partial_m u_j + \partial_m u_j \partial_m u_i - \partial_m u_i \partial_m u_j). \tag{55}
\]

As has been previously noted, \( \alpha \) the subgrid stress of Leray-\( \alpha \), Eq. (37), is a truncation of the subgrid stress of LANS-\( \alpha \) equation (55). Like Clark-\( \alpha \), energy is conserved in the \( H^2_0(u) \) norm instead of the \( L^2(u) \) norm. Additionally, LANS-\( \alpha \) is the only model of the three examined here that conserves a form of the helicity (and Kelvin’s circulation theorem).

For LANS-\( \alpha \) in the fluid case the de Kármán–Howarth theorem was derived in Ref. 37. We summarize here the dimensional analysis argument for the LANS-\( \alpha \) inertial range scaling that follows from this theorem, beginning from Eq. (3.8) in Ref. 37. In the statistically isotropic and homogeneous case, without external forces and with \( v=0 \), taking the dot product of Eq. (54) with \( u_l' \) yields the equation

\[
\partial_l Q_l^{ii} = \frac{\partial}{\partial r_m} (T_{ijm}^\alpha - \alpha^2 S_{ijm}). \tag{56}
\]

The trace of this equation is the Fourier transform of the detailed energy balance for LANS-\( \alpha \);

\[
Q_l^{ii} = \langle u \nu_l' + v \mu_l' \rangle \tag{57}
\]

is the second-order correlation tensor, while

\[
T_{ijm}^\alpha = \langle (u \nu_l' + v \mu_l' + u_i' u_j + v_j' u_i) u_m \rangle \tag{58}
\]

and
are the third-order correlation tensors for LANS-α and $\tau_{ij}^m = \mathcal{H}^{-1} u^2 \tau_{ij}^m$ is the subfilter-scale stress tensor. For $\epsilon=0$ this reduces to the well-known relation derived by de Kármán and Howarth. The energy dissipation rate for LANS-α, i.e., $\epsilon_\alpha$, satisfies $\epsilon_\alpha \propto \partial_t Q_{ij}$. By dimensional analysis in Eq. (56) we arrive at

$$\epsilon_\alpha \sim \frac{1}{l} \left( \frac{\epsilon}{\alpha} + \frac{\alpha^2}{l^3} \right).$$

(60)

For large scales ($l \gg \alpha$), we recover the Navier–Stokes scaling equations (21) and (22). For subfilter scales ($l \ll \alpha$) our scaling law becomes Eq. (23) and our subfilter-scale spectra are given by

$$E_\epsilon(k) \sim \epsilon_\alpha^{2/3} \alpha^{-2/3} k^{-1}.$$  

(61)

In this case, by the phenomenological arguments, we know that eddies of size $k^{-1}$ are advected by the smoothed velocity [Eq. (28)]. This scaling is confirmed in Ref. 34, but it coexists with rigid bodies or “polymerized” portions of fluid that do not contribute to the turbulent energy cascade.

### III. SUBFILTER-SCALE PHYSICS

Only by examining the subfilter scales can we hope to derive new, improved models, and, ultimately, to gain an understanding of turbulence. A knowledge of the differences between closures and Navier–Stokes is fundamental to enabling the derivation of better physical models of turbulence at small scales. In this section, then, we will be interested in both the similarities and the differences between the regularizations and Navier–Stokes. A more immediate goal of predicting the computational savings at higher Reynolds numbers can be achieved through the correct prediction of the scaling at small scales.

To this end, we compute numerical solutions to Eqs. (1), (4), (36), and (54) in a three-dimensional (3D) cube with periodic boundary conditions using a parallel pseudospectral code.40,41 We employ a Taylor–Green forcing,52

$$F = \begin{bmatrix} \sin k_0 x \cos k_0 y \cos k_0 z \\ - \cos k_0 x \sin k_0 y \cos k_0 z \\ 0 \end{bmatrix}$$

(62)

(with $k_0=2$), and employ dynamic control33 to maintain a nearly constant energy with time. The Taylor–Green forcing [Eq. (62)] is not a solution of the Euler’s equations, and as a result small scales are generated rapidly. The resulting flow models the fluid between counter-rotating cylinders44 and it has been widely used to study turbulence, including studies in the context of the generation of magnetic fields through dynamo instability.45 We define the Taylor microscale as $\lambda = 2 \pi \sqrt{\langle \omega^2 \rangle / \langle \omega^3 \rangle}$, and the mean velocity fluctuation as $v_{rms} = \sqrt{\left\langle \frac{1}{2} \int_{k} E(k) \right\rangle}$, which is proportional to the dissipation ($\epsilon = \nu \langle \omega^2 \rangle$ or $\epsilon_\alpha = \nu \langle \omega^2 \rangle$ depending on the case). Also shown is a well-resolved 512³ DNS of a less turbulent flow ($\nu = 1.5 \times 10^{-5}$, $Re = 1300$, $Re_\alpha = 490$) long-dashed line. Here, each run is calculated only until it reaches a steady state.

The Clark-α, Leray-α, and LANS-α equations (as well as other SGS models based on spectral filters) are easy to implement in spectral or pseudospectral methods. As an example, in Fourier based pseudospectral methods, the Helmholtz differential operator can be inverted to obtain $\mathcal{H}^{-1} = (1 + \alpha^2 k^2)^{-1}$, where the hat denotes Fourier transformed. In this way, the filter reduces to an algebraic operation, and Eqs. (4), (36), and (54) can be solved numerically at almost no extra cost. If other numerical methods are used, the inversion can be circumvented for example by expanding the inverse of the Helmholtz operator into higher orders of the Laplacian operator.31,46

To compare the three regularizations (Clark-α, Leray-α, LANS-α) we compute a fully resolved DNS of the Navier–Stokes equations at a resolution of 1024³ ($\nu = 3 \times 10^{-4}$, $Re = 3300$) and model runs with the exact same conditions at a resolution of 384³. The details of the flow dynamics of the DNS have already been given.44,45 In particular, the Reynolds number based on the integral scale $\mathcal{L} = \frac{2}{\sqrt{\pi}} E(k) \Delta k / \langle E \rangle \approx 1.2$ (where $E$ is the total energy) is $Re_\perp = E \mathcal{L} / \nu = 3900$, where $\mathcal{L}$ is the rms velocity and the Reynolds number based on the Taylor scale is $Re_\perp = 790$. The DNS was run for nine turnover times ($\mathcal{L} / U$) (in the following results, time $t$ is in units of the turnover time). We employ a filter width of $\alpha = 2 \pi / 13$ for which LANS-α exhibits both Navier–Stokes and LANS-α inertial ranges in the third-order structure function.43 From these we hope to obtain the behavior of the models for scales much smaller than $\alpha$.

In Fig. 1, we present the time evolution of the enstrophy $(\langle \omega^2 \rangle)$ for Leray-α and in the DNS, $(\omega \cdot \omega)$ for LANS-α and Clark-α. DNS (Re = 3300) is shown as solid black lines, LANS-α as dotted red, Clark-α as dashed green, and Leray-α as blue dash-dotted. The cyan long-dashed line represents a 512³ DNS (Re = 1300, Re_α = 490). Here each run is calculated only until it reaches a statistical steady state. Leray-α reduces the dissipation, $\epsilon = \nu (\omega^2)$, and increases the time scale to reach a statistical turbulent state. Both effects are greater as $\alpha$ is increased. By comparison with the Re = 1300 run, we see that these two effects are consistent with a reduced effective Reynolds number. A smaller reduction in flux (but not an increase in time to steady state) is also observed for LANS-α and is likely related to its rigid bodies.
The energy flux in the DNS is constant in a wide range of scales, but the compensated spectrum has a more complex behavior. The spectra of all three regularizations clearly differ from that of Navier–Stokes.

The energy spectrum at the turbulent steady state, for all the runs in Fig. 1. The isotropic energy spectra are calculated as follows:

\[ E(k) = \sum_{k_{\text{eff}}=k^{-1/2}} v_i^2(k_{\text{eff}}) + v_j^2(k_{\text{eff}}) + v_k^2(k_{\text{eff}}), \]

where \( k_{\text{eff}} = k^{1/2} \) [the \( H_2^0(u) \) norm is employed for Clark-\( \alpha \) and LANS-\( \alpha \)]. The length scale \( \alpha \) is indicated by a vertical dashed line and the plotted energy spectra are compensated by \( k^{3/5} \) (i.e., leading to a flat K41 \( k^{-5/3} \) spectrum).

The energy flux in the DNS is constant in a wide range of scales, but the compensated spectrum has a more complex structure. The salient features of this spectrum are well known from previous studies. Small scales before the dissipative range show the so-called bottleneck effect with a slope shallower than \( k^{-5/3} \). Dashed line indicates the length \( \alpha \). The Clark-\( \alpha \) result is consistent with a \( k^4 \) scaling [Eq. (23)], and clearly inconsistent with a \( k^0 \) scaling as would arise from the middle term in Eq. (20). The results for Leray-\( \alpha \) are again consistent with a reduced effective Re.

The spectrum of Leray-\( \alpha \) in Fig. 2 gives a good approximation to the \( \text{Re} = 1300 \) DNS in the range \( k \in [5,20] \) (i.e., to \( \nu = 1.5 \times 10^{-3} \) rather than to \( \nu = 3 \times 10^{-4} \), which was employed). This result, Leray-\( \alpha \)’s increased characteristic time scales, and its reduced dissipation, imply that the Leray-\( \alpha \) model is operating at a much lower effective Reynolds number. This is also clear from the rapid drop in the spectrum at small scales, shown in Fig. 2. Indeed, we can build an effective Reynolds number in the large scales as \( \text{Re}_{\text{eff}} = \frac{E(3,4)}{L^3} V^2 \). Since \( L \) is controlled in this simulation by the forcing scale, the drop in the dissipation rate implies a reduced nonlinearity in Leray-\( \alpha \). This is also consistent with a direct comparison of the nonlinear terms in Leray-\( \alpha \) with, for instance, LANS-\( \alpha \). The nonlinear terms in LANS-\( \alpha \) [Eq. (54)] may be written as \( u \cdot \nabla v + \nabla u^T \cdot v \) (where the suffix \( T \) denotes a transposition), while the nonlinear term in Leray-\( \alpha \) [Eq. (36)] is only \( u \cdot \nabla v \). Both nonlinear terms in LANS-\( \alpha \) are of order \( O(1) \), so the absence of one of the nonlinear terms in Leray-\( \alpha \) could be understood as a reduction in the nonlinearity.

Validation of the de Kármán–Howarth equation scalings [Eqs. (23) and (48)] enables us to measure scaling laws in the inertial range and, thus, compare the intermittency properties of the models. The third-order correlations involved in the theorems, namely,

\[ L^2(l) = \langle [\delta u_l(l)]^2 \rangle \]

for Clark-\( \alpha \) and LANS-\( \alpha \),

\[ L^2(l) = \langle [\delta u_l(l)]^2 \langle \delta u_l(l) \rangle \rangle \]

for Leray-\( \alpha \), and \( L(l) = S(l) \) for Navier–Stokes, are plotted versus \( l \) in Fig. 3. In Fig. 3 we can see validation of the de
Kármán–Howarth scaling for scales smaller than $\alpha$ for both LANS-$\alpha$ and Clark-$\alpha$. In particular, we note the observed scaling for Clark-$\alpha$ verifies the $\nu u^3 \sim l$ scaling and not the (theoretically possible) $\nu u^3 \sim l^{-1}$ (or $u^3 \sim l$) scaling. The predicted scaling is not observed in Leray due to its reduced effective Reynolds number. With these scalings in hand, we may proceed to observe the scaling of the longitudinal structure functions,

$$S'_p(l) = \langle |\partial \xi_j|^{\alpha-2} \rangle,$$

where we again replace the $H^1_\alpha$ norm, i.e., $\langle |\partial \xi_j| \partial u_i \rangle$, for the $L^2$ norm, i.e., $\langle |\partial \xi_j|^2 \rangle$, in the case of Clark-$\alpha$ and LANS-$\alpha$. We utilize the extended self-similarity hypothesis, which proposes the scaling

$$S'_p(l) \approx [L^{'\alpha L}(l)]^2,$$

and normalize the results by $\xi_3$ to better visualize the deviation from linearity (which serves as a measure of intermittency). As we will show in the next section, our flow is anisotropic in the $z$ direction. Therefore, structure functions are computed in horizontal planes only. The results are displayed in Fig. 4.

In Fig. 4, we may observe the intermittency properties of the models at subfilter scales. We note a reduced intermittency for both Leray-$\alpha$ and the Re $\approx 1300$ DNS. This is consistent with the smoother, more laminar fields (due to the reduction of the effective Re) possessed by both. Interestingly, though LANS-$\alpha$ and Clark-$\alpha$ both possess the same cascade scaling [Eq. (23), as confirmed in Fig. 3], the Clark-$\alpha$ model is markedly more intermittent than LANS-$\alpha$. If artificially truncated local interactions (in spectral space) is taken as a cause of enhanced intermittency, then the increased intermittency observed in Clark-$\alpha$ is the expected result of truncation of the higher-order terms in the subfilter-stress tensor. Moreover, if the LANS-$\alpha$'s $\sim k^1$ spectrum is indeed associated with rigid bodies, these would serve to decrease the intermittency (no internal degrees of freedom being available in a rigid body), which is consistent with the results shown here. Due to this effect, LANS-$\alpha$ of the three regularization models most resembles the high-order intermittency of Navier–Stokes at subfilter scales.

IV. SGS POTENTIAL OF THE REGULARIZATIONS

A. Reproduction of superfilter-scale properties

The differences at subfilter scales between the regularizations and Navier–Stokes are important to understand how the models may be improved upon. From a practical standpoint, an equally important question is how they predict the superfilter-scale properties of a DNS when employed as models. This gives an indication of their SGS modeling potential. For this, we choose $\alpha = 2\pi/40$ corresponding to an optimal $\alpha$-LES. Note that the value of $\alpha$ has been optimized for neither Clark-$\alpha$ nor Leray-$\alpha$; as a consequence, these models might perform better in other parameter regimes than the results indicate in this study.

Figure 5 gives the time evolution of the enstrophy of the DNS and the models along with that of an under-resolved Navier–Stokes solution at a resolution of $384^3 \times 3$-times 10$^4$, (pink online) dash-triple-dotted line]. We see that both LANS-$\alpha$ and Clark-$\alpha$ reproduce the proper amount of dissipation and are within 10% of the time required by the DNS to reach a statistical turbulent steady state. As has been observed before, Leray-$\alpha$ is under-dissipative. We also note that it takes longer than the other models to reach a steady state even with the smaller filter width (2$\pi/40$, as opposed to 2$\pi/13$). When compared to the larger $\alpha$ case, we see that the dissipation is much greater and the time scale to reach a turbulent steady state is decreased for Leray-$\alpha$.

Compensated spectra averaged over several eddy turnover times are shown for the SGS case (i.e., $k_F = 40$) in Fig. 6. Note that as the subgrid models are averaged over a different time interval, no meaningful comparison to the DNS is possible for $k_F = 40$. Even without an optimal choice for the value of $\alpha$, Clark-$\alpha$ best reproduces the DNS spectrum for scales larger than $\alpha$. We compute root-mean-square spectral errors as recently introduced in Ref.
the under-resolved 3843, 0.20 for LANS-

p
diction. We see that only Clark-

low to accurately model the DNS flow. Either a decrease in

As previously argued, its effective Reynolds number is too

the three regularization models, but it is also not optimized.

As this is dynamically controlled in our experiment, we find

deviation from the DNS spectrum is counted positive, how-

This large-scale feature of the flow is missing only from

horizontal bands where the forcing causes a maximum shear.

Kármán–Howarth theorem for Navier–Stokes is well repro-

duce this feature well

duce this feature well

 righteous solutions of the three models and re-

is the sub-

energy spectrum. Leray-α’s performance is the poorest.

ture introduced in Ref.35 is given by

\[ \epsilon_p^b = \left( \sum_{k|k_p} k^{2p} \left( E_{\text{model}}(k) - E(k) \right)^2 \right)^{1/2}, \]  \tag{67}

where \( k_p \) is the wavenumber for the forcing scale, \( E(k) \) is the

DNS spectrum [in the \( L^2(\nu) \) norm], and \( E_{\text{model}}(k) \) is the sub-

grid model spectrum (in the appropriate norm). Another mea-

ure introduced in Ref. 35 is given by

\[ \epsilon_p^d = \left( \sum_{k|k_p} k^{2p} \left( E_{\text{model}}(k) - E(k) \right)^2 \right)^{1/2} / \left( \sum_{k|k_p} k^{2p} E(k)^2 \right)^{1/2}. \]  \tag{68}

With \( p=0 \), we find the error in the total energy; i.e., \( \epsilon_p^d = \epsilon_p^d \).

As this is dynamically controlled in our experiment, we find

zero in all cases. For \( p=2 \), we find the error in the total

dissipation, i.e., \( \epsilon_p^d = \epsilon_p^d \), which is observed in Fig. 5. Every

deviation from the DNS spectrum is counted positive, how-

ever, in \( \epsilon_p^d \). For \( p=0 \), we find the error in the energy

spectrum: In decreasing order, \( \epsilon_p^d \) for Leray-α, 0.23 for the

under-resolved 3843, 0.20 for LANS-α, and 0.16 for

Clark-α. Both LANS-α and Clark-α improve the estimate

over the under-resolved run, but Clark-α makes the best pre-

diction. We see that only Clark-α improves the estimate of

the power spectrum at this resolution for each scale consid-

ered separately (see Fig. 6). Leray-α performs the poorest

of the three regularization models, but it is also not optimized.

As previously argued, its effective Reynolds number is too

low to accurately model the DNS flow. Either a decrease in

the viscosity \( \nu \), or a decrease in the filter size \( \alpha \) (and, hence,

an increase in the nonlinearity), or both would likely im-

prove the accuracy of Leray-α as an SGS model. Due to its

frozen-in (or enslaved) rigid-body regions and its conserva-

tion of total energy, the LANS-α model cannot reproduce the

DNS spectrum at superfilter scales unless \( \alpha \) is only a few times

larger than the dissipation scale. 34

Another measure of the success of a subgrid model is the

reproduction of structures in the flow. In Fig. 7 we have 3D

volume rendering of the enstrophy density \( \omega^2 \) (\( \omega \cdot \omega \) for

LANS-α and Clark-α) for the DNS, the three SGS-model simu-

lations (\( k_{\gamma}=40 \)), the 3843 under-resolved Navier–Stokes

solution, all at a Reynolds number of \( \approx 3300 \), and the

Re \( \approx 1300 \) DNS. Due to the late times depicted (longer than a

Lyapunov time) there can be no point-by-point comparison

between the simulations. Instead, we note that there are four

horizontal bands where the forcing causes a maximum shear.

This large-scale feature of the flow is missing only from

Leray-α and the Re \( \approx 1300 \) run. The three other runs repro-

duce this feature well (note that the apparently thicker tubes

present in Clark-α are vortex tube mergers). The results lead

again to the conclusion that the under-resolved Navier–

Stokes, the Clark-α, and the LANS-α models are better sub-

grid models than Leray-α due to its reduced effective Re.

For the SGS models, the predicted \( l^1 \) from the de

Kármán–Howarth theorem for Navier–Stokes is well repro-

duced by all models at superfilter scales (not depicted here).

We may then proceed in Fig. 8 to analyze the SGS model

intermittency results. We see that all models reproduce the

intermittency up to the tenth-order moment within the error

bars (although there is a small decrease in intermittency for

Leray-α). Thus, we conclude that with adequately chosen

values of \( \alpha \) (and of \( \nu \) for Leray-α), all three models can

reproduce the intermittency of the DNS (to within the error

bars).

The subfilter-scale physics of Leray-α shows that it pos-

sesses the smoothest solutions of the three models and re-

duces the effective Re. We have seen that this strongly ham-

pers its effectiveness as a SGS model. “Rigid bodies” are

observed in the subfilter scales of LANS-α (Ref. 34) that

strongly influence even the superfilter-scale energy spectrum

but not the subfilter-scale dissipation nor intermittency pro-

perities. These affects also carry over to its application as a

SGS model in that very small filter widths are required to

properly predict the large-scale spectrum. Clark-α’s approxi-

mately \( k^{-1} \) subfilter energy spectrum is the closest to \( k^{-5/3} \)

of the three models and is seen to cause the least contamin-

ation of the superfilter-scale spectrum when employed as a SGS

model. Finally, when the filter width is small enough, the

enhanced intermittency of Clark-α is nearly eliminated.

\subsection{B. Computational gains}

The rationale behind using a SGS model is that it leads

to adequate solutions at a reduced computational cost, be-

cause it computes fewer dof; indeed, for an SGS model, the

ratio of Navier–Stokes’s dof to the model’s dof, a prediction

for memory savings and hence computation time savings for
numerical simulation, is a crucial factor. Consequently, analytical bounds on the sizes of the attractors for the three regularization subgrid models may be useful indicators of their computational savings. The dof for LANS-α is derived in Ref. 29 and confirmed in Ref. 34,

\[ \text{dof}_\alpha \propto \frac{L}{\alpha} \text{Re}^{3/2}, \]  

where \( L \) is the integral scale (or domain size). We may compare this to the dof for Navier–Stokes,

FIG. 7. (Color online) Volume rendering of the enstrophy density \( \omega^2 (\omega \cdot \omega) \) for LANS-α and Clark-α. The four lengths depicted are integral length scale \( L \), Taylor scale \( \lambda \), filter width \( \alpha \), and dissipative scale \( \eta_k \) as calculated separately for each simulation. First row, first column: Re ≈ 3300 DNS. Second row, first column: Clark-α. First row, second column: LANS-α. Second row, second column: Under-resolved Navier–Stokes. For the first two rows, the snapshot is for \( t=9 \). Third row, first column: Leray-α for \( t=16 \). Third row, second column: Re ≈ 1300 DNS for \( t=19 \), corresponding to their slower development of turbulence. For Leray-α, the locations of vortex tubes are consistent with a lower Re flow, while the other models (including under-resolving) reproduce the large-scale pattern of the flow well. The color scale indicates the strength of the enstrophy density, with dark grey shades (purple online) stronger than light grey shades (green online).
The reduction in dof is independent of Re scales and consequent contamination at superfilter scales via itly specify its dissipation wavenumber fore, combining the Clark-H20849She-Lévêque formula

We then have

It follows that

This is similar to the prediction for LANS-α, but as energy spectra are more easily reproduced for larger values of α than with LANS-α (but not the intermittency properties), it may be the case that α is not tied to the Kolmogorov dissipation scale ηK. If so, then the computational saving might increase as Re^{3/4}, which is promising for use of Clark-α as an LES model. This conclusion is bolstered to the extent that the results in Sec. IV A for k_α=40 (α=7 ηK) are acceptable. If even further separation from the dissipative scale is not possible, there is still a greater reduction in dof (a factor of 20) for Clark-α than for LANS-α.

For Leray-α, we have the following upper bounds on the Hausdorff dimension (d_H) and fractal dimension (d_F) of the global attractor,

where ηK^1 is the dissipation length scale for Leray-α.14 Again, we estimate the dissipation wavenumber for Leray-α k_η~1/ηK. From Eqs. (38) and (49), that is, assuming the k^{-1/3} spectrum resulting from the de Kármán–Howarth equation, we find

Consequently we have

It follows that

Our results suggest that for an effective LES the viscosity ν_L must be chosen to be smaller than ν. This leads to an upper bound on the computational savings for Leray-α,

where ηK^1 is the Kolmogorov dissipation length scale corresponding to the Clark-α model. From its observed k^{-1} spectrum, we may estimate ηK^C or, equivalently, k_η^C~1/ηK^C. For dissipation the large wavenumbers dominate and, therefore, combining the Clark-α energy balance Eq. (6) with its subfilter scale energy spectrum Eq. (24) allows us to implicitly specify its dissipation wavenumber k_η^C by

It was found, however, that to reproduce the superfilter-scale energy spectrum of an equivalent DNS, the filter width α must be no larger than a few times the dissipation scale ηK.34 This is the result of the “polymerization” of the flow in LANS-α, and the associated E(k)~k^1 scaling at subfilter scales and consequent contamination at superfilter scales via energy conservation. With this added caveat, it follows that the reduction in dof is independent of Re (and a net factor of about 10). Our study here illustrates that the high-order structure functions may be reproduced for much larger values of α. Therefore, in applications where the spectrum is not of great concern, much greater reduction in numerical resolution would be feasible.

For Clark-α there is an upper bound on the Hausdorff (d_H) and fractal (d_F) dimensions of the attractor,

where ηK^C is the Kolmogorov dissipation length scale corresponding to the Clark-α model.21 From its observed k^{-1} spectrum, we may estimate ηK^C or, equivalently, k_η^C~1/ηK^C. For dissipation the large wavenumbers dominate and, therefore, combining the Clark-α energy balance Eq. (6) with its subfilter scale energy spectrum Eq. (24) allows us to implicitly specify its dissipation wavenumber k_η^C by

FIG. 8. (Color online) Normalized structure function scaling exponent ξ/ξ vs order p. The dashed line indicates K41 scaling and the solid line the She-Lévêque formula (Ref. 53). The DNS results are indicated by black × marks. LANS-α by red asterisks, Clark-α by green diamonds, Leray-α by blue triangles, and pink boxes for the under-resolved Navier–Stokes run. With a small enough filter-width α, the intermittency properties of the DNS can be reproduced with all three models.
\[ \frac{\text{dof}_{\text{NS}}}{\text{dof}_{\text{Leray}}} < C \left( \frac{\text{Re}^{45/28}}{\alpha} \right)^{6/7} \left( 1 + \frac{L}{\alpha} \right)^{9/14}, \] 

If we further assume that \( \alpha \) is directly proportional to the dissipative scale \( \eta_k \), we arrive at

\[ \frac{\text{dof}_{\text{NS}}}{\text{dof}_{\text{Leray}}} < C \text{Re}^{27/56}, \] 

which is not exceedingly promising for use as a LES. All such estimates are, however, purely conjectural until the proper choices of \( \alpha \) and \( \nu_f \) are determined.

V. DISCUSSION

We derived the de Kármán–Howarth equations for the Leray-\( \alpha \) and Clark-\( \alpha \) models. These two models may be viewed as successive truncations of the subfilter-scale stress of the Lagrangian-averaged Navier–Stokes \( \alpha \)-model (LANS-\( \alpha \)). In the case of Clark-\( \alpha \) two different inertial range scalings follow from the dimensional analysis of this equation. The case of Leray-\( \alpha \) is simpler as a single scaling is predicted. This is the case for Navier–Stokes and LANS-\( \alpha \) as well. To our knowledge, we computed the first numerical solution of the Clark-\( \alpha \) model, the results of which are encouraging for further study. We compared these to solutions for a 1024\(^3\) DNS under periodic boundary conditions (\( \nu=3 \times 10^{-5}, \text{Re} = 3300 \)) using a 384\(^3\) resolution under the same exact conditions for LANS-\( \alpha \), Leray-\( \alpha \), Clark-\( \alpha \), and an under-resolved 384\(^3\) solution of the Navier–Stokes equations. We employed two different filter widths \( \alpha \). The first choice \( \alpha = 2\pi/13 \) was used to understand the subfilter-scale physics and the second choice \( \alpha = 2\pi/40 \) was employed to test the SGS potential of the models. In comparing these two choices, we found for Leray-\( \alpha \) that an increase in \( \alpha \) substantially decreases the nonlinearity (and hence decreases the effective Reynolds number \( \text{Re} \)). For this reason, we were unable to confirm either the inertial range scaling from its de Kármán–Howarth equation or its subfilter-scale energy spectrum. For Clark-\( \alpha \), we were able to determine the dominant de Kármán–Howarth inertial range scaling to be \( u^3 \nu \sim l \), which leads to the associated \( k^{-1} \) energy spectrum, also indicated by our results.

The performance of the three regularizations as SGS models (for a resolution of 384\(^3\) and \( k_{\nu_f} = 40 \)) was comparable to that of the under-resolved Navier–Stokes solution in reproducing the DNS energy spectrum at superfilter scales. Only Clark-\( \alpha \) showed a clear improvement in approximating the spectrum. From 3D volume rendering of enstrophy density, we found that Clark-\( \alpha \) and LANS-\( \alpha \) were comparable to the under-resolved solution. Even at \( \alpha = 2\pi/40 \), Leray-\( \alpha \)'s 3D spatial structures are consistent with a significantly reduced Re flow (e.g., comparable to a Re \( \approx 1300 \) DNS). We note that the value of \( \alpha \) was chosen optimally for LANS-\( \alpha \) at the resolution of 384\(^3\), and that for Clark-\( \alpha \) (and especially for Leray-\( \alpha \)) smaller resolutions (greater computational savings) may have comparable results for this value of \( \alpha \). Such a comparison is beyond the scope of the present work.

Although LANS-\( \alpha \) and Clark-\( \alpha \) exhibit the same inertial range scaling arising from similarities in their de Kármán–Howarth equations, Clark-\( \alpha \) is decidedly more intermittent than Navier–Stokes at subfilter scales. At the same time, LANS-\( \alpha \) is only slightly more intermittent than Navier–Stokes. These results are consistent with the artificial truncation of local nonlinear interactions (in spectral space) in the SGS stress tensor of each model. This effect is reduced for LANS-\( \alpha \) by the “rigid-body regions” enslaved in its larger scale flow which possess no internal degrees of freedom. The reduced intermittency observed for Leray-\( \alpha \) is related to its smoother, more laminar fields as a result of its reduced effective Re.

Finally, we analyzed the reduction in the number of dof in the models, as compared to Navier–Stokes (and, hence, their LES potential based on their computational savings). We noted that as LANS-\( \alpha \) reproduces the intermittency properties of a DNS quite well even for larger values of \( \alpha \), some further reduction in numerical saving might be achieved provided the contamination due to its \( k! \) rigid-body energy spectrum were not important in a given application. As Clark-\( \alpha \) possesses a similar reduction in dof to LANS-\( \alpha \), its LES potential is tied to the optimal value of \( \alpha \) for LES. Our study indicates that Clark-\( \alpha \) may be applicable (especially with regards to the energy spectrum) for larger values of \( \alpha \) than LANS-\( \alpha \). In fact, if its optimal value is not a function of Re, the computational resolution savings increases as \( \text{Re}^{-1/4} \) for Clark-\( \alpha \). For the case of Leray-\( \alpha \), the prediction is complicated by the effective reduction in Re as \( \alpha \) increases. Prediction of optimized values of \( \alpha \) and of effective dissipation \( \nu_f \) are required to assess its LES potential. Future work should include such a study for both Leray-\( \alpha \) and Clark-\( \alpha \).

All three regularizations were shown to be successful, in that their control of the flow gradient reduces the degrees of freedom and saves computation while preserving a properly defined Reynolds number (albeit for Leray-\( \alpha \) that definition is not yet demonstrated). Clark-\( \alpha \) accurately reproduces the total dissipation, the time scale to obtain a turbulent statistical steady state, and the large-scale energy spectrum of a DNS. These results seem to result from Clark-\( \alpha \) being an order \( \alpha^2 \) approximation of Navier–Stokes. We have shown that Leray-\( \alpha \) reduces the effective Reynolds number of the flow. The last of the three models, LANS-\( \alpha \) restores Kelvin’s circulation theorem (advected by a smoothed velocity) and the conservation of a form of helicity. Using spectra as a measure of the success of a subgrid model, LANS-\( \alpha \) is less than optimal, due to its contamination of the superfilter-scale spectrum. However, other measures of the success of a subgrid model are possible: For example, in regard to intermittency, LANS-\( \alpha \) may be considered a superior model. For Clark-\( \alpha \), intermittency may be a function of filter width while for LANS-\( \alpha \), intermittency does not vary much with \( \alpha \).

Through examination of these three systems of nonlinear partial differential equations in comparison to Navier–Stokes, we have demonstrated that intermittency can be preserved with careful modification of the nonlinearity. This was seen with the LANS-\( \alpha \) model and may be related to the conservation of small-scale circulation. Besides intermittency, the nonlinear terms also play a role in the energy spec-
trum (at both subfilter and superfilter scales) and in the dissipation. These terms must model both the nonlocal interactions (to recover the intermittency) but also the local interactions (which are too strongly suppressed inside the rigid bodies of LANS-α). Finally, we have demonstrated that regularization modeling can be employed to reduce the computational cost while preserving the high-order statistics of the flow.

We remark that the computational gain thus far achieved by any of these regularizations is insufficient for applications at very high Reynolds numbers, and the three subgrid stress tensors discussed here may need to be supplemented with an enhanced effective viscosity to be employed as LES. This is a common practice when implementing the Clark model (see, e.g., Ref. 19 for a study of this model with an extra Smagorinsky term). In this light, the present study may be useful as an analysis of the properties of the SGS tensors of the regularizations, and to pick best candidates, before the addition of enhanced dissipation. Studies similar to that in Ref. 34 will also need to be done for the cases of Clark-α and Leray-α to quantify their computational savings before the addition of such dissipative terms.

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