On the Evaluation of Seasonal Variability of the Ocean Kinetic Energy

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ABSTRACT

The seasonal cycles of the mean kinetic energy (MKE) and eddy kinetic energy (EKE) are compared in an idealized flow as well as in a realistic simulation of the Gulf Stream (GS) region based on three commonly used definitions: orthogonal, nonorthogonal, and moving-average filtered decompositions of the kinetic energy (KE). It is shown that only the orthogonal KE decomposition can define the physically consistent MKE and EKE that precisely represents the KEs of the mean flow and eddies, respectively. The nonorthogonal KE decomposition gives rise to a residual term that contributes to the seasonal variability of the eddies, and therefore the obtained EKE is not precisely defined. The residual term is shown to exhibit more significant seasonal variability than EKE in both idealized and realistic GS flows. Neglecting its influence leads to an inaccurate evaluation of the seasonal variability of both the eddies and the total flow. The decomposition using a moving-average filter also results in a nonnegligible residual term in both idealized and realistic GS flows. This type of definition does not ensure conservation of the total KE, even if taking into account the residual term. Moreover, it is shown that the annual cycles of the three types of EKEs or MKEs have different phases and amplitudes. The local differences of the EKE cycles are very prominent in the GS off-coast domain; however, because of the spatial inhomogeneity, the area-mean differences may not be significant.

1. Introduction

Energetics analysis has been often used to investigate the temporal variability of ocean currents and eddies (e.g., White and Heywood 1995; Zhai et al. 2008; Jouanno et al. 2012; Rieck et al. 2015; Kang et al. 2016). The eddy state is commonly defined as the deviation from the time-mean state (e.g., Lorenz 1955; Webster 1961; Holland 1978; Cronin and Watts 1996; Von Storch et al. 2012; Chen et al. 2014; Kang and Curchitser 2015). For a given time-mean state, the flow velocity is split into the time-mean (mean flow) and time-varying (eddy) parts. Accordingly, the total kinetic energy (KE) at a given time is decomposed into the mean flow and eddy parts as well as a residual term that carries information of both flows. The residual term vanishes when it is averaged over the same time-mean period as that used in the velocity decomposition. As a result, the time-averaged total KE is exactly split into two parts that precisely represent the time-averaged KEs for the two orthogonal subspaces, that is, mean flow and eddies, respectively. This type of KE decomposition is referred to as the orthogonal decomposition, and the two KE components are commonly defined as the mean kinetic energy (MKE) and eddy kinetic energy (EKE), respectively. The so-defined MKE and EKE have been often used to evaluate the Lorenz energy cycle and examine the eddy–mean flow interactions and variability (e.g., Holton 1992; Penduff et al. 2004; Von Storch et al. 2012; Chen et al. 2014; Kang and Curchitser 2015; Kang et al. 2016).

When evaluating the seasonal variability of the ocean KE and its components, different types of KE decomposition have been used besides the orthogonal one as described above. In some previous studies, the research focus was on the seasonal variability of EKE, so the time-mean state for velocity decomposition was often chosen to be either a climatological mean or a yearly mean to ensure a constant MKE within the annual cycle (e.g., Qiu 1999; Zhai et al. 2008; Scharffenberg and Stammer 2010; Rieck et al. 2015). Because of the different time-mean states for averaging and velocity decomposition, the time-averaged residual term does not vanish. Since the residual term carries information of both the mean flow and eddies, such KE decomposition is no longer orthogonal and the obtained MKE and EKE are not the physically consistent KEs of the mean flow and eddies. Another common way to define MKE and EKE is via the moving-average filtering (e.g., Brachet

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et al. 2004; Jia and Wu 2011; Jouanno et al. 2012). This method provides more details of the temporal variability since it generates a time series for each studied variable. However, the moving-average filtering does not ensure energy conservation, and the obtained MKE and EKE do not precisely represent the KEs of the mean flow and eddies (Liang and Anderson 2007). Although these two types of definitions have been often used when evaluating the seasonal variability of the KE components, the influence of the residual term was often neglected and the validity and accuracy of the so-defined MKE and EKE has not been thoroughly examined in the literature.

In this study, we compare the seasonal variability of the total KE and its components using the three commonly used definitions, as mentioned above. The comparison is performed in an idealized flow and in a 50-yr realistic regional ocean model simulation over the Gulf Stream (GS) region (Kang and Curchitser 2013). We aim to clarify the advantages and limitations of different types of KE decomposition and obtain a comprehensive picture of the seasonal variability in the GS flows.

2. Definitions of MKE and EKE

We define the mean and eddy states as the time mean and its deviation. For a given time-mean state T_0, the velocities (u, v) are split into their time-mean $(\overline{u}, \overline{v})$ and time-varying $(u-\overline{u}, v-\overline{v})$ parts, where $\overline{(\ )}$ represents the time average of a variable over the period T_0. Based on the velocity decomposition, the time-dependent horizontal total KE density, in units of joules per cubic meter, is split as

$$\underbrace{\frac{1}{2}\rho_0(u^2+v^2)}_{E_k} = \underbrace{\frac{1}{2}\rho_0(\overline{u}^2+\overline{v}^2)}_{E_{k0}} + \underbrace{\frac{1}{2}\rho_0[(u-\overline{u})^2+(v-\overline{v})^2]}_{E'_k} + \underbrace{\rho_0[\overline{u}(u-\overline{u})+\overline{v}(v-\overline{v})]}_{E'_{k0}}, \quad (1)$$

where ρ_0 is a constant reference density, which is chosen to be $\rho_0 = 1000\,\mathrm{kg\,m^{-3}}$ in this study. The terms E_{k0} and E'_k represent the mean flow and eddy parts of the time-dependent KE, respectively, while E'_{k0} is the anomaly residual term, which has been shown to play an important role in the eddy–mean flow interactions (Murakami 2011; Murakami et al. 2011; Chen et al. 2016). The residual term E'_{k0} vanishes when it is averaged over the same time period $T = T_0$ (i.e., $\overline{E'_{k0}} = 0$). Therefore, taking the time average of Eq. (1) over $T = T_0$ gives the time-averaged total KE and its two components as

$$\mathrm{KE} = \overline{E_k} = \frac{1}{2}\rho_0\overline{(u^2+v^2)}, \quad (2)$$

$$\mathrm{MKE} = \overline{E_{k0}} = \frac{1}{2}\rho_0(\overline{u}^2+\overline{v}^2), \quad \text{and} \quad (3)$$

$$\mathrm{EKE} = \overline{E'_k} = \frac{1}{2}\rho_0\overline{[(u-\overline{u})^2+(v-\overline{v})^2]}. \quad (4)$$

The two KE components are commonly defined as the mean kinetic energy and eddy kinetic energy, which precisely represent the time-averaged KEs for the orthogonal mean flow and eddy subspaces, respectively. Besides this orthogonal definition, there have been other commonly used methods to define MKE and EKE as described in the introduction.

In this study, we compare three types of KE decompositions: an orthogonal one with $T = T_0$, a nonorthogonal one with $T \neq T_0$, and a moving-average filtered one with $T = T_0$. In the orthogonal decomposition, we choose $T = T_0 = 1$ month and obtain the monthly averaged KE components as

$$\mathrm{KE}^m = \frac{1}{2}\rho_0\overline{(u^2+v^2)}^m, \quad (5)$$

$$\mathrm{MKE}^m = \frac{1}{2}\rho_0[(\overline{u}^m)^2+(\overline{v}^m)^2], \quad \text{and} \quad (6)$$

$$\mathrm{EKE}^m = \frac{1}{2}\rho_0\overline{[(u-\overline{u}^m)^2+(v-\overline{v}^m)^2]}^m, \quad (7)$$

where $\overline{(\ )}^m$ denotes the monthly average of a variable. The term KE^m represents the monthly averaged total KE of the flow, while MKE^m and EKE^m exactly represent the monthly averaged KEs of the mean flow (monthly mean flow) and eddies (monthly varying flow), respectively. In the time-mean-based definition, the eddy is not referred to the actual circular physical feature as examined in Kang and Curchitser (2013). The terms MKE^m and EKE^m include contributions of the actual eddies that persist longer and shorter than a month, respectively.

In some cases, to ensure a constant MKE within the annual cycle, T_0 was often chosen to be either a climatological mean or a yearly mean, which is longer than T. Here, we consider this type of KE decomposition with $(T = 1\ \text{month}) \neq (T_0 = 1\ \text{yr})$. Accordingly, the monthly averaged KE components are given by

$$\mathrm{KE}^y = \frac{1}{2}\rho_0\overline{(u^2+v^2)}^m = \mathrm{KE}^m, \quad (8)$$

$$\mathrm{MKE}^y = \frac{1}{2}\rho_0[(\overline{u}^y)^2+(\overline{v}^y)^2], \quad (9)$$

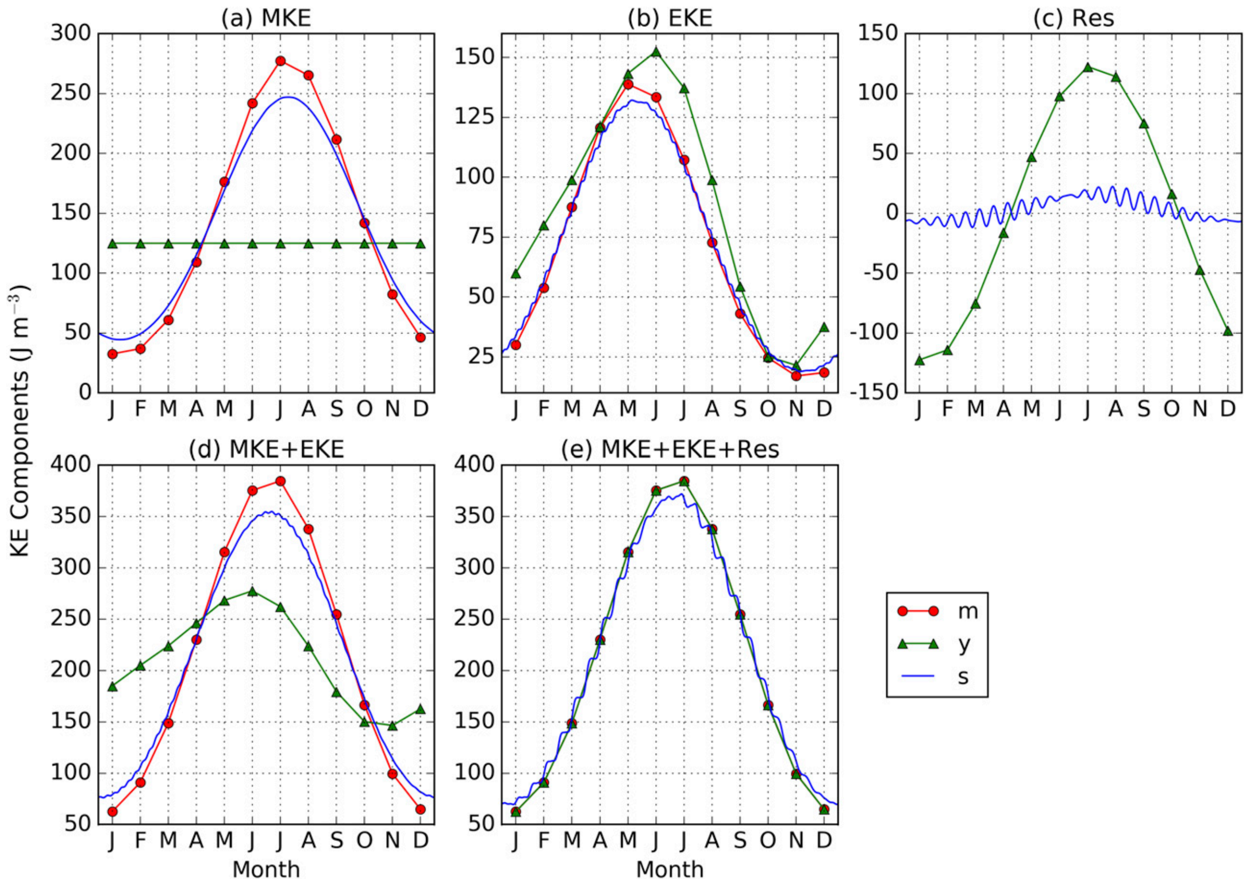

FIG. 1. Seasonal cycles of (a) MKE, (b) EKE, (c) Res, (d) MKE + EKE, and (e) total KE for the idealized flow Eq. (18) using the three definitions.

$$\mathrm{EKE}^y = \frac{1}{2}\rho_0\overline{[(u-\overline{u}^y)^2 + (v-\overline{v}^y)^2]}^m, \quad \text{and} \tag{10}$$

$$\mathrm{Res}^y = \rho_0[\overline{u}^y(\overline{u}^m - \overline{u}^y) + \overline{v}^y(\overline{v}^m - \overline{v}^y)], \tag{11}$$

where $\overline{(\ )}^y$ denotes the yearly average of a variable. In this definition, MKE^y is a constant within a year, while EKE^y and Res^y both vary monthly. Based on Eq. (11), the seasonal variability of the residual term Res^y is mainly determined by the monthly mean flow since the yearly mean flow is a constant. This indicates that the seasonal variability of the eddies (i.e., yearly varying flow for $T_0 = 1$ yr) is partially determined by Res^y. As a result, the annual cycle of EKE^y does not precisely measure the seasonal variability of the eddies. Moreover, the connection of EKE^y to EKE^m is given by

$$\mathrm{EKE}^y - \mathrm{EKE}^m = \frac{1}{2}\rho_0[(\overline{u}^m - \overline{u}^y)^2 + (\overline{v}^m - \overline{v}^y)^2] \geq 0, \tag{12}$$

which indicates that EKE^y is never smaller than EKE^m, and their difference is proportional to the square of the difference between the monthly mean and yearly mean velocities. Similarly, $\mathrm{MKE}^y + \mathrm{Res}^y$ is never larger than MKE^m because

$$(\mathrm{MKE}^y + \mathrm{Res}^y) - \mathrm{MKE}^m = -\frac{1}{2}\rho_0[(\overline{u}^m - \overline{u}^y)^2 + (\overline{v}^m - \overline{v}^y)^2] \leq 0. \tag{13}$$

Another popular method to decompose KE is via filtering. Here, we consider a KE decomposition using the moving-average filtering with a centered window of $T = T_0 = 1$ season. The obtained KE components are given by

$$\mathrm{KE}^s = \frac{1}{2}\rho_0\overline{(u^2 + v^2)}^s, \tag{14}$$

$$\mathrm{MKE}^s = \frac{1}{2}\rho_0\overline{[(\overline{u}^s)^2 + (\overline{v}^s)^2]}^s, \tag{15}$$

$$\mathrm{EKE}^s = \frac{1}{2}\rho_0\overline{[(u-\overline{u}^s)^2 + (v-\overline{v}^s)^2]}^s, \quad \text{and} \tag{16}$$

$$\mathrm{Res}^s = \rho_0\overline{[\overline{u}^s(u-\overline{u}^s) + \overline{v}^s(v-\overline{v}^s)]}^s, \tag{17}$$

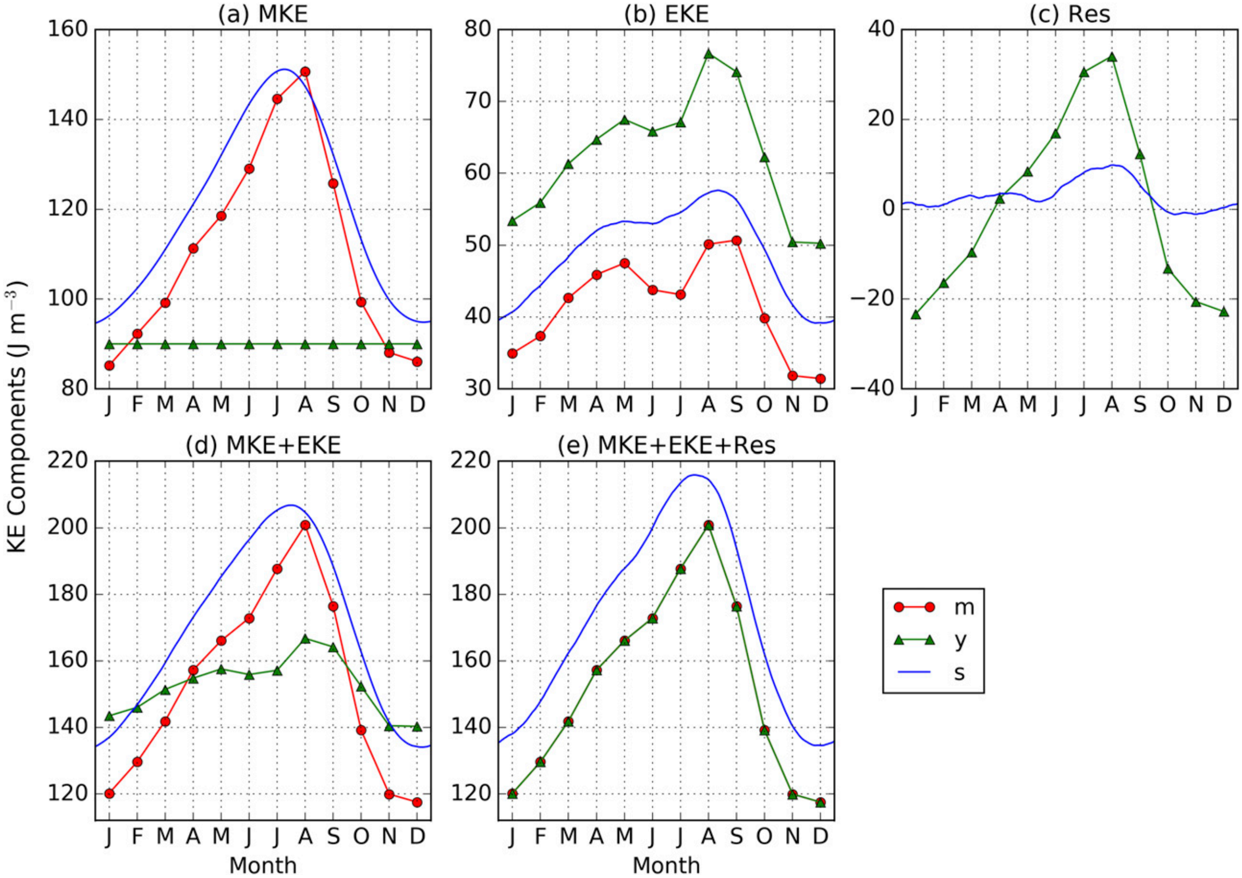

FIG. 2. Seasonal cycles of the area-mean surface (a) MKE, (b) EKE, (c) Res, (d) MKE + EKE, and (e) total KE for the GS along-coast domain averaged over 50 years (1958–2007).

where $\overline{(\ )}^s$ represents the seasonal moving average of a variable. In this definition, $\overline{\overline{u}^s}^s$ is not necessarily equal to $\overline{u}^s$ because the moving average of a variable is a function of time within the averaging time period. As a result, there is a nonvanishing residual term Res^s despite the choice of $T = T_0$, and the so-defined MKE^s and EKE^s are not the physically consistent KEs of the mean flow and eddies, respectively. In fact, this is a common issue for the energy decomposition using the low-pass or bandpass filter, such as the Butterworth filter. Recently, Liang and Anderson (2007) developed a new filter-related method, the multiscale window transform, which can split the energy into multiple orthogonal parts and conserve the total energy (Yang and Liang 2016).

3. Seasonal variability of KE in an idealized flow

We use an idealized 1D flow to highlight the differences and connections of the above three definitions in evaluating the seasonal variability of the KE components. The time evolution of the velocity at a fixed location is expressed by

$$u(t) = k[2 - \cos(2\pi t/T_1 + \varphi_1)] + k[2 - \cos(2\pi t/T_1 + \varphi_2)]\cos(2\pi t/T_2). \quad (18)$$

For simplicity, we define a 360-day year, consisting of 12 months of 30 days each. The two time periods are chosen to be $T_1 = 360$ days and $T_2 = 15$ days, respectively. The remaining parameters are given by $k = 1/4$, $\varphi_1 = -\pi/8$, and $\varphi_2 = \pi/5$. Figure 1 compares the annual cycles of the KE components using the three types of definitions for this idealized flow.

There are a couple of differences between the orthogonal (red line with dots) and nonorthogonal (green line with triangles) cases. First, MKE^m has a prominent annual cycle, while MKE^y has no annual cycle (Fig. 1a). Second, EKE^m and EKE^y show different seasonal variability that peaks in May and June, respectively, and EKE^y is never smaller than EKE^m (Fig. 1b), as predicted by Eq. (12). Moreover, there is

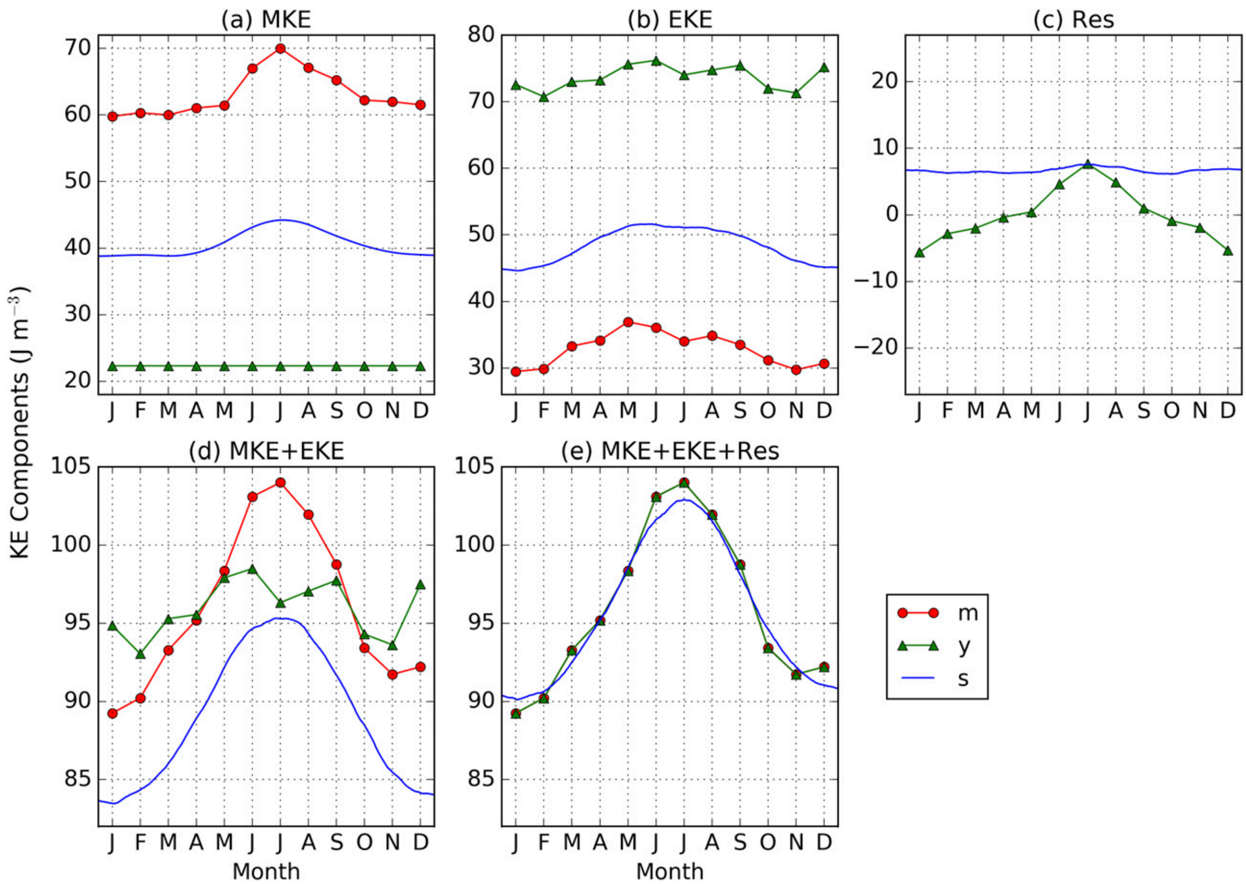

FIG. 3. As in Fig. 2, but for the GS off-coast domain.

no residual term in the orthogonal case, while the residual term Res^y in the nonorthogonal case exhibits a prominent annual cycle (Fig. 1c). Finally, in the nonorthogonal case, neglecting the influence of Res^y leads to an inaccurate evaluation of the total KE variability in both amplitude and phase (Fig. 1d). As shown in section 2, in this nonorthogonal case, the seasonal variability of the eddies (i.e., yearly varying flow for $T_0 = 1$ yr) is determined by both EKE^y and Res^y. For this idealized flow, the annual cycle of Res^y is more prominent than that of EKE^y and therefore dominates the seasonal variability of the eddies and the total flow (Figs. 1d,e).

In the moving-average filtered case (blue line), we also observe a residual term Res^s, whose annual cycle peaks in summer (Fig. 1c). The annual cycle of MKE^s (EKE^s) has smaller amplitude than that of MKE^m (EKE^m; Figs. 1a,b), and the KE^s cycle also has smaller amplitude than the KE^m cycle even if taking into account the residual term (Fig. 1e). This shows that the moving-average filtering does not ensure the conservation of the total KE, although it provides more detailed temporal variability of the KE components.

4. Seasonal variability of KE in the Gulf Stream region

In this section, we use a 50-yr (1958–2007) regional ocean model simulation of the northwest Atlantic (Kang and Curchitser 2013) to further compare the different evaluations of the seasonal variability in the realistic GS flow. The simulation was performed using the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams 2003, 2005). The simulation domain covers the GS path in the northwest Atlantic [Fig. 5 (below)]. The model grid has a horizontal spacing of 7 km and 40 vertical terrain-following levels. The model outputs are averaged and stored daily. Details about the model setup and evaluations are described in Kang and Curchitser (2013, 2015).

Kang et al. (2016) has examined the seasonal variability of MKE^m and EKE^m in the GS region and explored the possible underlying mechanisms. In this study, we focus on the comparison of the three evaluations in order to clarify their differences and connections. Figures 2–3 compare the annual cycles of the area-mean surface KE components using the three

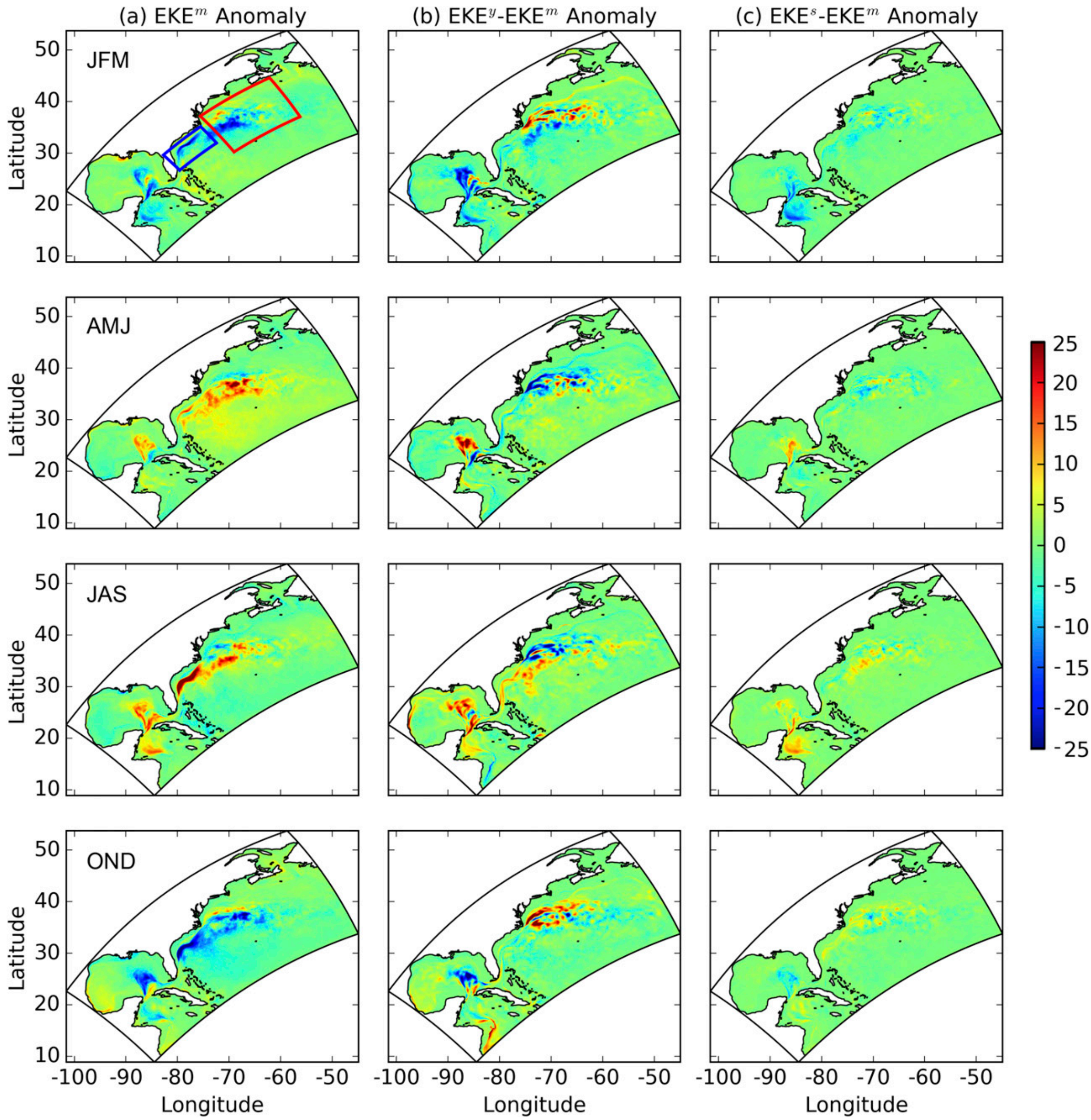

FIG. 4. Seasonal cycles of the anomalous surface (a) EKE^m, (b) EKE^y − EKE^m, and (c) EKE^s − EKE^m (J m^{-3}) in the Gulf Stream region averaged over 50 years (1958–2007). The small blue and red boxes in the upper-left plot outline the Gulf Stream along-coast and off-coast subdomains, respectively.

definitions for the GS along-coast and off-coast domains, which are outlined by the blue and red boxes, respectively, in the upper-left plot of Fig. 4a. Figures 4–5 compare the spatial distributions of the surface KE anomalies in the four seasons. All these results are averaged over the 50-yr simulation period.

In the GS along-coast domain (Fig. 2), the annual cycles of the area-mean surface MKE^m and MKE^s both peak in summer, but the latter has a smaller amplitude and a half-month lead in phase (Fig. 2a). The annual cycles of EKE^y, EKE^s, and EKE^m peak in August, August–September, and September, respectively, and they all indicate a secondary peak in May (Fig. 2b). Overall, the differences among the area-mean MKEs and EKEs are not significant. The slight phase shift between the annual cycles of EKE^y and EKE^s was also

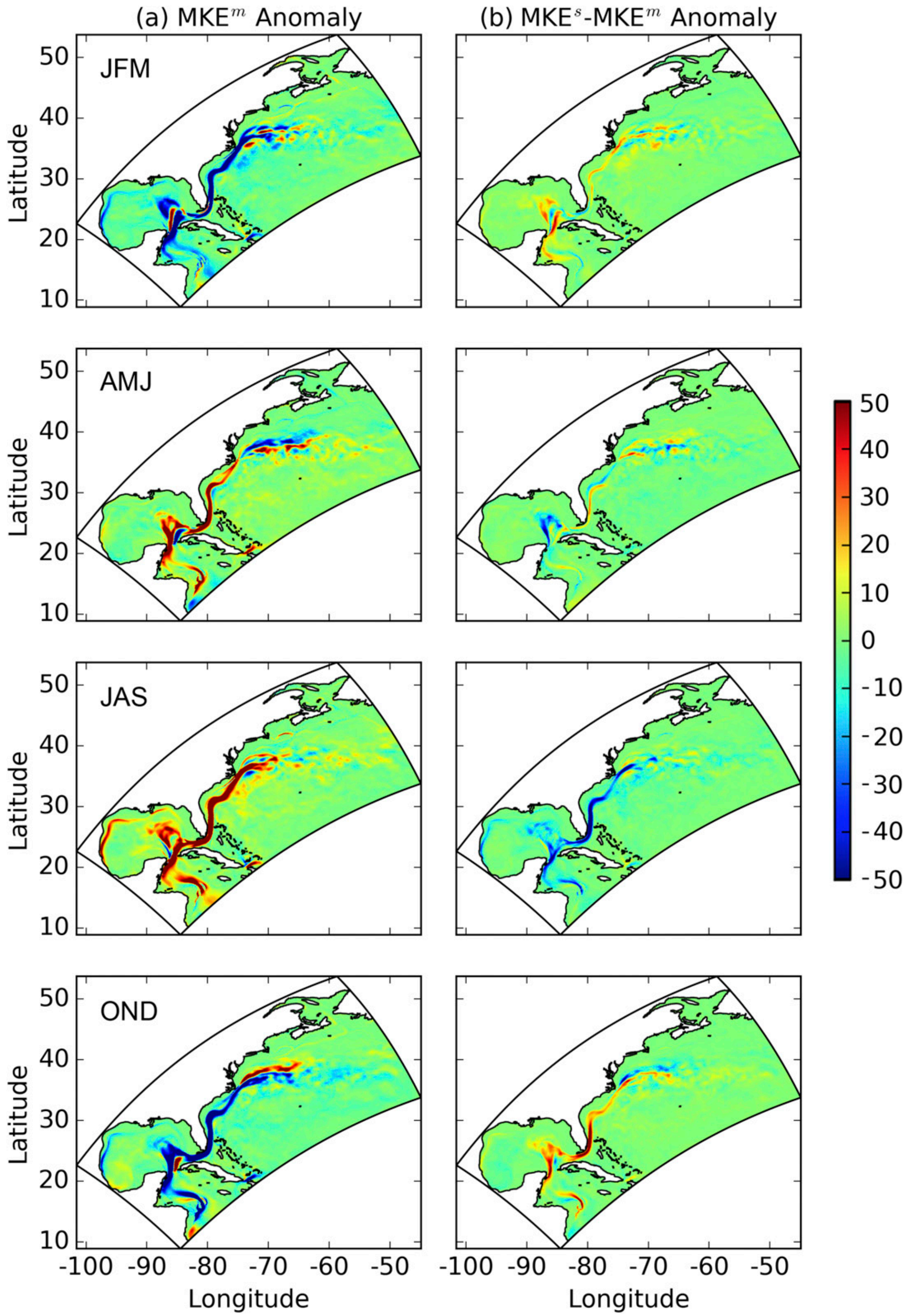

FIG. 5. Seasonal cycles of the anomalous surface (a) MKE^m and (b) MKE^s − MKE^m (J m^{-3}) in the Gulf Stream region averaged over 50 years (1958–2007).

observed in a North Pacific domain by Rieck et al. (2015). The nonorthogonal and moving-average filtered KE decompositions both result in a residual term, whose annual cycle peaks in summer (Fig. 2c). As discussed in sections 2 and 3, both EKE^y and Res^y determine the seasonal variability of the eddies (i.e., yearly varying flow). In the GS along-coast domain, the annual cycle of Res^y is more prominent than that of EKE^y and therefore dominates the seasonal variability of the eddies as well as the total flow. If we only consider the contributions from MKE and EKE while neglecting that from the residual term, the total KE variability will be inaccurately evaluated (Fig. 2d). The moving-average filtering does not ensure conservation of the total KE even if taking into account Res^s (Fig. 2e).

In the GS off-coast domain (Fig. 3), the annual cycles of the area-mean surface MKE^m and MKE^s both peak in July, and the latter has a slightly smaller amplitude (Fig. 3a). The annual cycles of the area-mean surface EKE^m, EKE^s, and EKE^y peak in May, May–June, and June, respectively (Fig. 3b). Overall, their differences are not significant. The area-mean surface Res^y shows a more prominent annual cycle than that of EKE^y, whereas Res^s is nearly a positive constant without clear seasonal variability (Fig. 3c). It is shown once more that the residual term cannot be neglected when evaluating the total KE variability (Fig. 3d). Finally, the moving-average filtering does not ensure conservation of the total KE even if taking into account Res^s (Fig. 3e).

Overall, the area-mean KE components in the GS off-coast domain exhibit less significant seasonal variability than those in the along-coast domain. This is due to the inhomogeneous spatial distribution (Figs. 4–5) and interannual variation of the seasonal variability with different phases in the off-coast domain. The anomalous EKE^m and MKE^m exhibit nearly homogenous seasonal variability in the GS along-coast domain, while they show inhomogeneous spatial pattern in the off-coast domain (Figs. 4a, 5a). The difference between EKE^y and EKE^m anomalies is most prominent in the GS off-coast domain, where it is of the same order of magnitude as the EKE anomaly itself (Fig. 4b). Based on Eqs. (12)–(13), this difference is also equal to the difference between MKE^m and Res^y anomalies. The difference between EKE^s and EKE^m anomalies is bigger in the off-coast domain than in the along-coast domain, but overall it is not significant (Fig. 4c). The difference between MKE^s and MKE^m anomalies is prominent in both domains (Fig. 5b). These results show that even if the area-mean differences among the annual cycles of MKEs or EKEs are not significant (Figs. 2a,b, 3a,b), their localized difference can be very prominent (Figs. 4b, 5b).

5. Conclusions

In this study, we compare the seasonal variability of the total KE and its components in both idealized and realistic Gulf Stream flows based on three commonly used KE decompositions: orthogonal, nonorthogonal, and moving-average filtered decompositions. Only with an orthogonal KE decomposition can we define the physically consistent MKE and EKE that precisely represent the KEs of the mean flow and eddies, respectively. The nonorthogonal KE decomposition results in a residual term Res^y, which partially determines the seasonal variability of the eddies, and therefore the obtained EKE^y is not precisely defined. We show that Res^y exhibits a more prominent annual cycle than EKE^y in both idealized and realistic GS flows. Neglecting the influence of Res^y leads to an inaccurate evaluation of the seasonal variability of both the eddies and the total flow. The moving-average filtering also results in a nonnegligible residual term Res^s, and the so-defined MKE^s and EKE^s are not the physically consistent KEs of the mean flow and eddies. This type of decomposition does not ensure energy conservation of the total KE, even if taking into account the influence of Res^s. Moreover, we show that the annual cycles of the three sets of EKEs or MKEs have different phases and amplitudes. Even if the area-mean differences of the EKE or MKE cycles are not significant, their localized differences can be very prominent. These conclusions are not limited to the seasonal time scale and the ocean KE. This study will contribute to a more accurate evaluation and prediction of the ocean and climate variability.

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