Exceptional multi-year prediction skill of the Kuroshio Extension in a high-resolution decadal prediction system

Who Kim (whokim@ucar.edu)  
National Center for Atmospheric Research  https://orcid.org/0000-0001-5754-9852

Stephen Yeager  
National Center for Atmospheric Research  https://orcid.org/0000-0003-0268-9895

Gokhan Danabasoglu  
NCAR

Ping Chang  
Texas A&M University  https://orcid.org/0000-0002-9085-0759

Article

Keywords:

Posted Date: January 9th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2402942/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: (Not answered)

Version of Record: A version of this preprint was published at npj Climate and Atmospheric Science on August 16th, 2023. See the published version at https://doi.org/10.1038/s41612-023-00444-w.
Exceptional multi-year prediction skill of the Kuroshio Extension in a high-resolution decadal prediction system

Who M. Kim*1, Stephen G. Yeager1, Gokhan Danabasoglu1, and Ping Chang2

1 Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, Colorado, USA
2 Department of Oceanography, Texas A&M University, College Station, Texas, USA

*Correspondence to: Who M. Kim (whokim@ucar.edu)

Manuscript submitted to npj Climate and Atmospheric Science on December 21, 2022
ABSTRACT

The Kuroshio Extension (KE) has far-reaching influences on climate as well as on local marine ecosystems. Thus, skillful multi-year to decadal prediction of the KE state and understanding sources of skill are both societally important and scientifically challenging. Retrospective forecasts using a high-resolution coupled system at an eddy-rich (0.1°) ocean and 0.25° atmosphere horizontal resolution show exceptional skill in predicting decadal KE variability up to lead year 4, substantially higher than the skill found in a similarly configured low-resolution (~1° for all components) system. The exceptional skill is attained because the high-resolution prediction system can more realistically simulate the westward propagation of initialized SSH anomalies in the central North Pacific and their expression within the sharp KE front. These results argue for the use of high-resolution models for future studies that aim to predict changes in the western boundary current systems and associated biological fields.

INTRODUCTION

The Kuroshio Extension (KE) is the offshoot of the Kuroshio – the western boundary current of the North Pacific (NP) subtropical gyre – that flows eastward as an inertial jet after separating from the east coast of Japan around 35°N. KE transports warm tropical and subtropical waters at a rate estimated to be about 100 Sv (1 Sv = 10^6 m^3 s^-1) and provides heat and moisture to the mid-latitude atmosphere through intense air-sea interactions in its upstream region (west of ~155°E)^2-4. KE exhibits multi-scale variability in both time and space, from intraseasonal-to-seasonal, small-scale variability associated with mesoscale eddies and meanders^5-7 to decadal, large-scale variability associated with its meridional shifts or changes in strength^6,8. This multi-scale variability can have substantial impacts on climate from local to remote regions, e.g., the
west coast of the United States\textsuperscript{2–4,9–13} and on local marine ecosystems\textsuperscript{14–16}. Therefore, skillfully predicting KE variability is a scientifically and societally important challenge.

Both observational and modeling studies show distinct decadal variability in KE. The sea surface height (SSH) field derived from satellite altimeter reveals bimodal – stable and unstable – regimes of the KE\textsuperscript{6}. These regimes reflect fluctuations between strengthened and weakened KE states associated with northward and southward meridional shifts of KE, respectively\textsuperscript{6}. This decadal KE variability is evident in the satellite-derived SSH data available for the last three decades\textsuperscript{6,7,17}. The decadal KE variability has been reasonably reproduced in forced ocean simulations\textsuperscript{18,19}, constrained at the surface by atmospheric reanalysis products.

It is well established by numerous previous studies that the decadal KE variability arises from the westward propagation of first baroclinic mode Rossby waves, generated in the central to eastern NP by wind stress curl (WSC) forcing and resultant Ekman pumping\textsuperscript{8,18–21}. Predictions based on linear reduced gravity models suggest that KE can be predicted several years in advance due to well-known properties of Rossby wave propagation\textsuperscript{17,20}. Initialized ocean-only retrospective forecast simulations under climatological surface forcing also suggest potential multi-year predictability of KE for the same reason\textsuperscript{22}. However, it has not been examined whether the decadal KE variability can be predicted on multi-year timescales in more comprehensive, fully coupled prediction systems until very recently. Specifically, a study based on a newly developed decadal prediction system (GFDL-SPEAR\textsuperscript{23}) shows skillful multi-year prediction of KE\textsuperscript{24}, in agreement with the results from previous studies based on simpler models. Although this study connects the source of the skill again to Rossby wave propagation, such a mechanism is not fully demonstrated. Also, these retrospective forecasts use a coarse ocean
model (~1° horizontal resolution), which cannot resolve mesoscale eddies and the fronts
associated with KE that may be essential for the KE dynamics\textsuperscript{6,21,25,26} and thus its prediction.

Studies based on a dynamical framework, so called “thin-jet” theory\textsuperscript{21,25}, suggest that the narrow
meridional structure of KE is essential to the dynamics of the decadal KE variability as the
westward propagation of Rossby waves are trapped and guided by the sharp meridional extent of
KE. Such a narrow KE jet can only be realistically simulated in ocean models that resolve eddies
and frontal scales\textsuperscript{27}. However, utilization of such high-resolution ocean models may not
necessarily guarantee better prediction skill of KE as they also invigorate intrinsic ocean
variability associated with mesoscale eddies. Indeed, eddy-resolving ocean simulations show
intrinsic interannual to decadal KE variability under the absence of interannually-varying
atmospheric forcing (i.e., seasonally-varying climatological forcing only)\textsuperscript{18,28}. This intrinsic
variability appears to complicate prediction of KE variability on interannual and shorter
timescales\textsuperscript{29}. However, recent studies suggest that decadal-scale eddy activity around the KE axis
is paced, together with large-scale KE variability, by remote wind forcing\textsuperscript{18,30,31}. Thus, the
skillful decadal prediction of KE might be achievable in high-resolution models even without
accurate initialization of ocean eddies.

Motivated by these previous studies, in this study, we investigate the predictability of KE and the
source of its predictability from an ensemble (10 member) forecast set using the Community
Earth System Model version 1 (CESM1) High-Resolution Decadal Prediction (HRDP) system [Yeager et al., npj Clim Atm Sci, in revision] (see Methods for details) that can resolve
mesoscale eddies at latitudes around the KE axis\textsuperscript{32}. The predictability from HRDP is compared
to that from a companion low-resolution ensemble (40 members) forecast set using the CESM1
Decadal Prediction Large Ensemble (DPLE) system\textsuperscript{33} (Methods). As will be demonstrated
below, HRDP shows exceptional multi-year prediction skill of KE, substantially better than that of DPLE.

RESULTS

Predictability of KE

Both HRDP and DPLE are initialized with ocean states from a pair of forced ocean–sea-ice simulations (FOSIs) that use the same ocean and sea-ice models as in the coupled prediction simulations (referred to as FOSI-L and FOSI-H for low- and high-resolution, respectively; see Methods). To assess the fidelity of FOSIs, we first examine if the observed decadal KE variability is reasonably reproduced. The observed variability is often inferred from satellite-derived SSH, averaged over an upstream KE region\(^6\). However, because the KE latitudinal position is biased in the models, most notably in the coarse resolution models, it is difficult to define a common KE domain that is suitable for both observations and model simulations. To overcome this difficulty, we first define the observed Kuroshio Extension index (KEI) from SSH from satellite altimeter observations by averaging over a domain identified based on the sum of the first two empirical orthogonal functions (EOFs) (Fig. 1a), both of which show pronounced decadal variability in their principal components. The observed KEI shows a distinct decadal oscillation with peaks (troughs) during the early 2000s and the early to mid 2010s (mid to late 1990s and 2000s; Fig. 1b), consistent with previous studies\(^7,17\).

Simulated KEIs are defined from FOSIs by averaging over the respective regions where the correlations with the observed KEI are the highest (Fig. 1c-d). Both FOSIs show the highest correlations along the climatological KE, that is, where the climatological SSH gradient is the largest. However, because of the broader meridional KE extent in FOSI-L than in FOSI-H (only
the latter shows a comparable meridional KE extent to that observed), the high correlations also
span a broader region in FOSI-L. We note that, although the positions of the KEI domains differ
between FOSI-H (33°-36°N, 140°-156°E) and FOSI-L (35.5°-38.5°N, 142°-158°E), the
latitudinal and zonal extents of the domains are identical. As expected, KEIs from both FOSIs
are highly correlated ($r \sim 0.8$) with the observed KEI (Fig. 1b). Although the phase of the KEI
variability in FOSI-L reasonably matches the observed KEI, its amplitude ($\sigma = 3.8$ cm) is much
weaker than the observed amplitude ($\sigma = 10.3$ cm), which is more comparable to that of FOSI-H
($\sigma = 9.8$ cm).

The KEI is computed from HRDP and DPLE by averaging over the same domain as FOSI-H and
FOSI-L, respectively (Supplementary Fig. 1). Anomaly correlation coefficients (ACC) of the
ensemble average KEI from DPLE and DPHR are computed against the KEIs from respective
FOSIs for the period of 1987-2017 and against observed KEI for the period of 1993-2017 as a
function of lead year (LY) in Fig. 2. HRDP shows high ACC against both FOSI-H and
observations with significant (95% confidence level) scores up to LY 4 (Methods), and
substantially higher scores than the persistence forecast through LY 5. Even at LY5, ACC is
reasonably high (0.4-0.5) against both FOSI-H and observations, and it remains statistically
significant at the 90% confidence level. This exceptional skill is also readily deducible from the
time series of KEIs (Supplementary Fig. 1a-d). In contrast, DPLE shows rather poor skill, always
lower than the skill of HRDP in predicting both FOSI-L and observed KEIs. ACC against FOSI-
L is significant through LY 2, but rapidly drops from LY 2 to 4. Significant skill of DPLE
against the observations is only found for the first year. We account for differences in ensemble
size between HRDP and DPLE by considering the distribution of ACC from randomly
subsampled 10-member DPLE (blue shading in Fig. 2; Methods). ACC from HRDP is always
above the upper limit of the subsampled DPLE range, except at LY 1 against the observations, suggesting that the higher skill of HRDP is unlikely to arise by chance. While the skill of HRDP is higher than that recently reported using GFDL-SPEAR\textsuperscript{24}, the skill of DPLE (with resolution comparable to that of GFDL-SPEAR) is noticeably lower. The HRDP skill is also higher than that obtained using a linear reduced gravity model\textsuperscript{17} where forcing is only wind-driven Ekman pumping (thus less contamination of the predictable signal by other forcings and processes).

**Source of Skill**

Previous studies emphasize the westward Rossby wave propagation induced by WSC forcing in the central to eastern NP as the primary source of predictability of KE\textsuperscript{17,18,20,22,24}. In FOSI-H, lead-lag correlation maps of annual-mean SSH onto its KEI (Fig. 3a) suggest a westward propagation of SSH anomalies from the central NP (lag -3 and -2) to near Japan (lag 0 and 1) over roughly a 3-year time span, consistent with the timescale of long Rossby waves propagating from the central to eastern NP. The initial SSH anomalies show a broad meridional extent roughly between 30° and 40°N in the central to eastern NP (lag -3 and -2), which then converge into a meridional strip along the KE axis once they reach west of 160°E (lag -1 through 1). These lead-lag correlations from FOSI-H are in good agreement with those from observations (Supplementary Fig. 2). In contrast, the westward propagation of SSH anomalies is less obvious in FOSI-L (Fig. 4a) with a pre-existing anomaly near Japan at lag -2 and a sustained or even eastward propagating anomaly in the eastern NP at later lags. Also, the meridional extent of the SSH anomalies is largely unchanged from the western to eastern NP. That is, there is no meridional focusing of the SSH anomalies toward the west, as might be expected from the coarse resolution of the ocean model.
The nature of the westward propagation in FOSI-H and observations is more evident in lead-lag correlations in the time-longitude plane of monthly-mean SSH averaged over the respective KEI latitudes onto each monthly-mean KEI (Fig. 5a, b). The SSH anomalies from both FOSI-H and observations take about 3 years to travel from around 160°W to the western boundary. In contrast, the westward propagation of SSH anomalies in FOSI-L appears to take only about 1 year, which is too fast to be considered as long Rossby wave propagation (Fig. 5c). Figure 5 also shows WSC correlations for FOSIs averaged over the same latitudes as SSH. In FOSI-H (Fig. 5b), negative WSC anomalies are found over the positive SSH anomalies in the central NP (negative lags), which is consistent with Ekman pumping that can generate westward propagating Rossby waves. Also, the WSC anomalies appear to march westward in tandem with positive SSH anomalies as far west as 160°E. This suggests a possible coupled feedback between the ocean and the atmosphere during the westward propagation of SSH anomalies that can maintain or even enhance the SSH signal on its way to the western boundary. In contrast, WSC anomalies in FOSI-L are not well aligned with and precede by about a year the SSH anomalies. This further suggests that Rossby wave propagation may not be the dominant mechanism that gives rise to KE variability in FOSI-L.

We explore whether Rossby wave propagation is the relevant predictability mechanism in the retrospective forecasts by performing lead-lag correlations as done for FOSIs, but across LYs (Fig. 3b and Fig. 4b). The purpose of this analysis is to find the source of the predicted KE variability. Therefore, we use KEI from FOSI as the independent variable, instead of KEI from the retrospective forecasts. Because the KEI ACC analysis suggests that both retrospective forecasts have some skill in predicting KEI from FOSIs at LY 3 (Fig. 2), although the skill is not statistically significant in DPLE, we compute the simultaneous correlation at LY3, then the lead-
lag correlations are computed across LYs. Specifically, SSH from the retrospective forecasts leads KEI from FOSI by 1 and 2 years at LY 2 and LY 1, respectively, and lags by 1 year at LY 4. We note that choosing either LY 2 or LY 4 for the lag-0 correlations gives very similar results, but for LY 2, the analysis can only go back in time one year. Indeed, the correlation maps from HRDP suggest that the westward propagating SSH signal from the initialized SSH anomaly in the central NP (LY 1 in Fig. 3b), which should be consistent with an anomalous state in FOSI-H between lag -3 and -2, leads to significant skill in predicting KEI at LY 3-4. The spatiotemporal evolution of the SSH anomalies is strikingly similar between FOSI-H and HRDP, including the convergence of anomalies into the KE axis near the western boundary (LY 3-4). The correlation maps from DPLE, however, do not show a clearly propagating SSH signal (Fig. 4b) and do not match, in general, those of FOSI-L (Fig. 4a). Although there is an indication that some skill of the KEI prediction at LY 3 in DPLE is associated with an earlier SSH anomaly in the central to eastern NP (LY1-2), it is not clear if the signal is propagating westward. In particular, an SSH anomaly exists just south of KE at LY 1, thus some of the KEI prediction skill at LY 3 may simply arise from this local source.

The source of predictability is further explored by focusing on individual events of the KE variability from the retrospective forecasts. KEI from the observations and FOSIs all show a well-defined positive peak in the early 2000s (Supplementary Fig. 1). We trace the monthly SSH anomalies averaged over KEI latitudes from the retrospective forecasts initialized on November 1, 1998 as a function of lead time (Fig. 6b, d) and compare to the same SSH anomalies from respective FOSIs (Fig. 6a, c). In FOSI-H, a positive SSH anomaly is initially located in the central NP, then propagates westward and appears to be related to the positive KEI peak in 2002-2003 (Fig. 6a). This progression of the SSH anomaly is in good agreement with observations
The HRDP retrospective forecast ensemble initialized from the state of FOSI-H on November 1, 1998 exhibits a close match to FOSI-H (Fig. 6b). Although the amplitude of the anomaly is weaker (likely due to ensemble averaging), HRDP reveals a predictable westward propagating SSH signal through lead time that likely contributes to the predicted KEI peak at LY 4-5 (corresponding to 2002-2003). Thus, this HRDP result supports the previously proposed mechanism of westward Rossby wave propagation leading to the high KEI skill score.

While a similar initial SSH anomaly exists in the central NP in both FOSI-L and DPLE, it does not propagate westward and lead to a KEI peak in 2003-2004 or LY 4-5 (Fig. 6c-d). Instead, the KEI peak in 2001 appears to be independent of the anomaly in the central NP, which remains at the same longitude (or perhaps, propagates eastward). We note that the color scale for FOSI-L and DPLE is reduced by half from that for FOSI-H and HRDP. We have also traced the negative KEI peak in the late 2000s and found indications of westward propagating signals in the coarse-resolution simulations (Supplementary Fig. 4c-d), similar to the observations (Supplementary Fig. 3b) and the high-resolution simulations (Supplementary Fig. 4a-b). However, this signal is much weaker (note again the different color scales between the high- and coarse-resolution simulations). It is also interesting to note that FOSI-L shows positive anomalies near the western boundary in 2007 to 2009, which do not exist either in the observations or FOSI-H, that appear to overpower the signal propagating from the east. These positive anomalies are not predicted in DPLE, thus the westward propagating signal contributes to a skillful prediction of the observed negative peak at the right timing.

Several previous studies have proposed air-sea coupled feedbacks as a mechanism involved in generating the quasi-oscillatory, decadal variability of KE\textsuperscript{13,17,34,35}. A possible coupling is also
suggested in our analysis from FOSI-H as WSC anomalies (largely determined by observation-based wind forcing) propagate to the west in tandem with SSH anomalies (Fig. 5b) that are similar to those seen in nature (Fig. 5a). Given the high horizontal resolution of HRDP, which can invigorate air-sea coupling compared to the low resolution DPLE [Yeager et al., npj Clim Atm Sci, in revision], it is possible that the higher predictive skill of KE in HRDP may be contributed by predicted feedbacks from the atmosphere. Figure 7a shows lead-lag regression maps from FOSI-H of winter (January to March) sea surface temperature (SST; shading) and SLP (contours) onto KEI. The SLP regressions show a meridional dipole anomaly resembling the North Pacific Oscillation\textsuperscript{19} (NPO) – the second most dominant mode of atmospheric variability in the NP sector\textsuperscript{36} – at lag -3. The positive SLP anomaly in the mid-latitudes corresponds to negative WSC anomalies in the central to eastern NP that can generate Rossby waves (Fig. 5b). The positive SLP anomaly extends to the west through lag -1 along with the SSH anomaly, consistent with the WSC anomaly (Fig. 5b). At the same time, the center of the SLP anomaly also moves northeastward to the west coast of Canada (lag -3 to lag -1) and then to the Gulf of Alaska (lag 0 to lag 2). By this time, a negative SLP anomaly emerges in the central NP, suggesting a phase reversal of the NPO. This counter-clockwise procession is consistent with previous studies\textsuperscript{13,34} that propose this procession as evidence of a coupled feedback between KE and the atmosphere that maintains the quasi-decadal variability in the NP. The phase reversal of the NPO is also associated with a tropical SST anomaly that resembles central Pacific El Niño-Southern Oscillation (CP-ENSO) that is of opposite sign to initial tropical Pacific SST anomalies (cf. Fig. 7a, lags -3, +1). Therefore, it is possible that the decadal variability of KE is phased by atmospheric teleconnections triggered by the CP-ENSO anomalies, as suggested by other studies\textsuperscript{35,37}. 
Whether the atmospheric forcing is a coupled feedback within mid-latitudes or from the tropical Pacific, HRDP is not able to predict the atmospheric conditions associated with the KE variability (Fig. 7b). Within a few months of initialization, the central tropical Pacific SST anomaly is greatly enhanced from the initialized state (LY 1), which should be close to the FOSI-H anomalies at lag -2. In addition, an SST anomaly in the eastern tropical Pacific, which is absent in FOSI-H, also develops. Likely because of these SST anomalies, the predicted SLP anomalies strongly project onto the Aleutian Low mode (AL) rather than the NPO, which is the most dominant mode of atmospheric variability in the NP sector and the typical ENSO teleconnection pattern. Because (negative) WSC anomalies associated with this AL-like SLP anomaly are centered north of 40°N (Supplementary Fig. 5a), they do not appear to be able to reinforce the initialized SSH signal. After the first winter, predicted SLP anomalies are generally very weak (implying a lack of consistency across ensemble members) and do not resemble those identified in FOSI-H, although predicted SST anomalies do resemble those in FOSI-H, particularly along 40°N up to LY 4 (Fig. 7). Based on these results, it is reasonable to conclude that the highly predictable KEI in HRDP primarily results from the initialization of the anomalous ocean states in the central NP and that air-sea coupling does not appear to play a significant role in HRDP predictions of KE, although it could provide additional skill if predicted.

Predictability of subsurface temperature

In this subsection, we examine the potential predictability of subsurface temperature associated with the decadal KE variability. In both FOSIs, KEI is strongly correlated with subsurface temperature variability around the KE axis in the respective zonal KEI domains (Fig. 8a, d). Although correlations greater than 0.8 are seen throughout the upper ocean in both FOSIs, the
regressions of temperature show that the center of action is located at about 400 m in FOSI-H (Fig. 9b), but near the surface in FOSI-L (Fig. 9c), roughly coinciding the regions where the respective temperature variance maximizes in both FOSIs. The subsurface-centered variability in FOSI-H is consistent with observations (Fig. 9a). In particular, regression of observed temperature onto observed KEI also shows a center of action at about 400 m, but negligible anomalies near the surface. The high subsurface variability in FOSI-H and observations further supports the notion that the KE variations are associated with the Rossby wave propagation mechanism and associated fluctuations in the thermocline depth and the increased fidelity of the simulated subsurface temperature variability associated with KE variations in FOSI-H compared to FOSI-L. We also note that FOSI-H shows a negative anomaly north of the KE axis, which is also hinted at in observations.

The temperature profile ACC against respective FOSIs shows some degree of skill in both retrospective forecasts with some elevated ACC around the respective KE axis, particularly in HRDP (Supplementary Fig. 6). However, the ACC patterns are noisy and do not obviously reflect skill associated with the KE variability. To isolate the skill directly related to the KE variability, we compute correlations against KEI from the respective FOSIs as a function of LY (only LY 1 and 4 are shown; Fig. 8b-c, e-f). At LY 1, the correlation coefficients around the KE axis in the subsurface exceed 0.8 (0.7) in HRDP (DPLE). The spatial patterns of the correlations also closely resemble those of FOSIs (Fig. 8a, d). However, we note that the high correlation in the subsurface in DPLE is associated with minimal variability as indicated by the regression map from FOSI-L (Fig. 9c). Although the spatial patterns are generally maintained, these correlations wane with lead time, but remain statistically significant below 200 m in HRDP even at LY 4 (Fig. 8c), consistent with the significant skill in predicting KEI at this lead time (Fig. 2). The
subsurface temperature of DPLE is no longer significantly correlated with FOSI-L KEI at LY 4 (Fig. 8f), also consistent with the KEI skill of DPLE (Fig. 2), although significant correlations are found below 700 m where variability is minimal.

**DISCUSSION**

We have shown exceptional skill of HRDP in predicting KE variability 4 years ahead, significantly higher than that of DPLE. The source of skill is initialized anomalous ocean states; specifically, SSH anomalies in the central to eastern NP induced by Ekman pumping that propagate westward towards Japan as baroclinic Rossby waves. The westward propagating signal appears to be trapped and guided by the sharp KE front in the high-resolution simulations\textsuperscript{21,25}, resulting in a meridional convergence of initially broad SSH anomalies in the central NP as they approach the western boundary. This feature could be an important factor accounting for the exceptional skill in HRDP, because such convergence of the signal could accumulate energy within a narrow meridional extent. We do not find evidence of skill at predicting large-scale air-sea coupled feedbacks that could augment the skill for KE variability\textsuperscript{17,34,35}. However, we cannot rule out the possibility that coupled air-sea interaction associated with ocean mesoscale eddies\textsuperscript{26} could be playing some role in HRDP. While HRDP does represent this process, it does not appear to feed back significantly onto large-scale SLP anomalies (Fig. 7), and in-depth study of its role in KE variability and predictability requires further investigation.

It is rather unexpected to see a very weak signature of wave propagation in the coarse-resolution simulations, given the large-scale nature of long Rossby waves. One may ask whether the initial SSH anomalies in the central NP are weaker in FOSI-L, which is used to initialize DPLE. The
amplitude of SSH anomalies in the central NP is indeed comparable between the two FOSIs (Supplementary Fig. 7), indicating that the weak propagating signal in FOSI-L is not related to the amplitude of the initialized SSH anomalies. A clue for the weak wave propagation, which is likely a critical reason for the low skill for KE variability in DPLE, can be found in the vertical structure of the anomalous ocean temperature associated with KEI. While the correlations of temperature show deep structure in both FOSIs, as shown in Fig. 8, the temperature regressions show an anomaly centered near the surface around 41°N in FOSI-L (Fig. 9c), in contrast to those centered in the subsurface around the KE axis in observations and FOSI-H (Fig. 9a-b). In FOSI-L, 41°N is also where the variances of the upper ocean temperature and SSH are the largest.

Lead-lag regressions of temperature at 100-m depth onto KEI from FOSI-L show that a temperature anomaly develops locally at this latitude off the east coast of Japan and appears to extend to the east as KEI reaches its peak (from lag -3 to 0 in Supplementary Fig. 8). In contrast, the anomaly at this latitude is negligible for all depths in observations and FOSI-H (Fig. 9a-b).

The mechanisms that explain this local anomaly are not clear and beyond the scope of this study, but it appears to be a common symptom of coarse-resolution models. At this resolution (~1°), KE is much too broad and extends too far to the north (gray contours in Fig. 8d), and thus there is no clear distinction between KE and the Oyashio Current. Therefore, it is possible that while these current systems have independent dynamics in reality and in high-resolution models, the two systems are interdependent in coarse-resolution models, generating spurious variability.

Another possible reason for the weak westward propagation in FOSI-L is that the first baroclinic Rossby wave propagation is contaminated by higher baroclinic modes whose amplitudes can be greater in the coarse-resolution models. Using a vertical modal decomposition analysis, Thompson and Ladd show that the second baroclinic mode propagates eastward around the KE
latitudes in an ocean model with a $2^\circ$ horizontal resolution. We see indications of such eastward propagation in our coarse-resolution simulations (Fig. 4b and Fig. 6c-d). Therefore, it seems possible that KEI in the coarse-resolution simulations is dominated by the spurious local variability discussed above while westward propagating first baroclinic Rossby waves are impeded by higher modes. This might confer predictability in DPLE that results from a local source, which is likely more short-lived than predictability achieved via Rossby wave propagation from a remote source in the central NP (that takes 3-4 years to reach the western boundary).

Observations suggest that surface biomass, as represented by chlorophyll, in the upstream KE region varies in tandem with the decadal KE variability$^{14,15}$. Lin et al.$^{16}$ show from a high-resolution regional model coupled with a biogeochemistry (BGC) model that nutrient anomalies propagate westward along with thermocline (thus SSH) anomalies to the upstream KE region, which appears to modulate upper ocean chlorophyll there through vertical mixing. Based on the realistic representation of the westward propagating signal and its high predictability in HRDP, it seems reasonable to expect skillful prediction of nutrients and thus upper ocean chlorophyll in the upstream KE in high-resolution systems. Unfortunately, the BGC component was not activated in HRDP due to resource limitations, but the results of this study clearly support use of a BGC component in future high-resolution prediction studies. If the predictability of KE BGC fields is shown to be viable, an application of multi-year to decadal predictions using high-resolution models could be very helpful for managing marine resources and fisheries for communities that rely heavily on fisheries for food.

**CONCLUSIONS**
We have shown in this study promising skill in predicting KE variability in a decadal prediction system at an eddy-resolving resolution (HRDP), far greater than the skill found in a coarse-resolution system using the same model framework (DPLE). The reason for the enhanced skill is that HRDP can realistically simulate the westward propagation of initialized anomalies as baroclinic Rossby waves. In contrast, the westward Rossby wave propagation is missing or very weak in DPLE possibly because at this horizontal resolution (~1°), the model cannot accurately simulate some of the necessary dynamics (i.e., a sharp KE front), and it may overemphasize the higher baroclinic modes that can interfere with the first baroclinic mode. Therefore, the results of this study warrant the use of high-resolution models for future studies that aim to predict multi-year to decadal variability of the western boundary currents.

METHODS

Prediction Systems

The decadal prediction systems used in this study are identical to Yeager et al. [npj Clim Atm Sci, in revision]. Readers are referred to Yeager et al. [npj Clim Atm Sci, in revision] for further details and a general comparison of the two systems. We only summarize a few key aspects of the systems below.

The CESM High Resolution Decadal Prediction (HRDP) system [Yeager et al., npj Clim Atm Sci, in revision] uses the CESM1 model configured at high horizontal resolution (~0.1° for the ocean and sea-ice; 0.25° for the atmosphere and land). The ocean and sea-ice components are initialized from a forced ocean–sea-ice (FOSI) simulation at the same resolution constrained at the surface by reanalysis-derived (Japanese 55-year Reanalysis; JRA55) atmospheric states following the protocol of the Ocean Model Intercomparison Project version 2 (OMIP2). The
atmosphere initial conditions are from regridded JRA55 analysis fields and the land initial conditions are taken from a high-resolution atmosphere-land simulation forced with observed sea surface temperatures\(^{45}\). All components use full field initialization. HRDP is comprised of 10-member ensembles initialized every other year on November 1 between 1982 and 2016 and integrated for 62 months. The ensemble spread is generated by applying round-off level perturbations to the atmosphere temperature initial conditions.

The CESM Decadal Prediction Large Ensemble (DPLE) system\(^ {33}\) uses a slightly different version of CESM1\(^ {46}\). The horizontal resolutions of all components of DPLE are nominal 1°. The atmosphere component uses a finite volume dynamic core instead of the spectral element used in HRDP. The ocean and sea-ice components are initialized similarly as HRDP, but from a coarse-resolution FOSI performed following the protocol of the Ocean Model Intercomparison Project version 1 (OMIP1)\(^ {47}\) where the base atmospheric state variables are largely taken from the NCEP reanalysis. The initial conditions for the atmosphere and land components come from a single member of the CESM1 Large Ensemble\(^ {46}\). In contrast to HRDP, DPLE is initialized (full field) every year on November 1 between 1954 and 2017 and integrated for 122 months. The strategy for the generation of ensemble spread (40 members) is identical to HRDP.

We note that although DPLE includes more start dates (64) and longer lead times (122 months) than HRDP, DPLE has been sampled to match HRDP in terms of start dates (18) and lead times (62 months). Both high- and coarse-resolution FOSIs used for the initialization of the respective prediction systems are used in the analyses of the study and referred to as FOSI-H and FOSI-L, respectively.

**Statistical Methods**
Statistical analyses are based on ensemble mean forecast anomalies from HRDP and DPLE. The forecast anomalies are relative to the model climatology for 1987-2017 for odd lead years (i.e., lead years 1, 3, and 5) and for 1986-2016 for even start years (i.e., lead years 2 and 4) because of the discontinuity in time for HRDP as a result of even-year initialization. Anomalies of FOSIs and observations are defined in the same way.

The significance of ACC scores (Fig. 2) is tested using a bootstrapping method. We first randomly resample the Kuroshio Extension index (KEI) from the forecast ensembles with replacement across both the time and member dimensions, and compute ACC against KEI from both respective FOSIs or observations. To account for temporal autocorrelation, the resampling in time selects 2 consecutive time values (equivalent to 4 years because HRDP is available for every other start year). This process is repeated 3000 times to generate a distribution of ACC skill scores. The ensemble mean ACC score is deemed significant if it is found above the 97.5 percentile from the resampled distribution.

To account for the different ensemble size between HRDP (10) and DPLE (40), we randomly resample (3000 times with replacement) 10-member ensembles from DPLE and compute ACC against KEI from both FOSI-L and observations. The resultant distribution (2.5 to 97.5 percentile) of ACC scores is displayed in Fig. 2.

The statistical significance of correlations and regressions in Figs. 3-4 and 7-9 is assessed at the 95% confidence level through a two-sided Student’s t test with the effective degree of freedom accounting for lag 1 autocorrelation.

**Observational Datasets**
Observational datasets used in the analyses are: monthly sea surface height dataset from SSALTO/DUCAS altimetric mean dynamic topography distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS); monthly NOAA Optimum Interpolation Sea Surface Temperature version 2 (OISSTv2)\textsuperscript{49}; monthly gridded ocean temperature profiles from the Met office EN4.2.1\textsuperscript{50}; monthly sea level pressure data from the NCEP\textsuperscript{51} and JRA55\textsuperscript{52} reanalysis products.

**DATA AVAILABILITY**

The full DPLE dataset is available from NCAR’s Climate Data Gateway at

https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm4.CESM1-CAM5-DP.html. Either the full or a subset of HRDP dataset will be made available upon the publication of the manuscript.

**ACKNOWLEDGMENTS**

This work was supported by the Department of Commerce through the Climate Variability and Predictability program of NOAA OAR’s Climate Program Office under award NA20OAR4310408. The National Center for Atmospheric Research (NCAR) is a major facility sponsored by the National Science Foundation (NSF) under Cooperative Agreement 1852977. The CESM project is supported primarily by the NSF. The computing resources for HRDP were provided by the Texas Advanced Computing Center (TACC) under award ATM20005.

**AUTHOR CONTRIBUTIONS**

W.M.K. conceptualized the study with a contribution from S.G.Y. in refining the scope of the study. W.M.K. conducted the analysis and wrote the initial draft. All authors contributed to
interpreting the results and editing the manuscript. S.G.Y., G.D., and P.C. led the funding acquisition.

COMPETING INTERESTS

The authors declare no competing interests.

REFERENCES


**Fig. 1. Definitions of the KEI.**

(a) Obs SSH EOF1+2

(b) KEI

- Sum of the first two EOFs, which together explain 36% of the total variability, of SSH from satellite altimetry.
- Time series of the KEIs from the satellite altimetry (black), FOSI-L (blue), and FOSI-H (red) averaged over the boxed regions in (a), (c), and (d), respectively.
- Correlation maps of SSH from FOSI-H against the observed KEI.
- Same as in (c), but for FOSI-L. The dark gray contours in (a), (c), and (d) are the climatological SSH in each dataset with contour intervals of 15 cm. Note that the global average is removed from satellite altimetry SSH to be consistent with the definition of SSH in the models.
Fig. 2. Prediction skill for KEI. a ACC against respective FOSI KEI as a function of LY for HRDP (solid red) and DPLE (solid blue) ensemble means for the period of 1987-2017. b Same as in a, but against the KEI from satellite observations for the period of 1993-2017. Crosses indicate that ACC is significant at the 95% confidence level determined using a bootstrapping method (Methods). The light blue shade represents the spread (2.5-97.5 percentile) of ACC scores obtained from subsampled 10-member ensembles of DPLE (Methods). Also shown are damped persistence forecasts of FOSI KEI in a (dashed red and blue from FOSI-H and FOSI-L, respectively) and KEI from the satellite altimeter in b (dashed black).
Fig. 3. Correlation maps of SSH against KEI in FOSI-H and HRDP. a Lead-lag correlations of SSH against KEI from FOSI-H. b Same as in a, but ensemble average SSH from HRDP and lead-lag correlations across LYs with lag 0 corresponding to LY3. Note that the predictor in b is KEI from FOSI-H. The SSH fields lead (lag) KEI at negative (positive) lags for FOSI-H and at LY1-2 (LY4) for HRDP. The black contours indicate statistically significant correlations at the 95% confidence level. The boxed region (blue) indicates the KEI domain used in both FOSI-H and HRDP.
Fig. 4. Correlation maps of SSH against KEI in FOSI-L and DPLE. a Lead-lag correlations of SSH against KEI from FOSI-L. b Same as in a, but ensemble average SSH from DPLE and lead-lag correlations across LYs with lag 0 at LY3. Note that the predictor in b is KEI from FOSI-L. The SSH fields lead (lag) KEI at negative (positive) lags for FOSI-L and at LY1-2 (LY4) for DPLE. The black contours indicate statistically significant correlations at the 95% confidence level. The boxed region (blue) indicates the KEI domain used in both FOSI-L and DPLE.
**Fig. 5.** Hovmöller diagrams of SSH and WSC correlations on KEI. 

(a) Correlations of the meridionally averaged, monthly SSH over the KE latitudes against monthly KEI from satellite observations plotted as a function of longitude and lag. 

(b) Same as in a, but from FOSI-H. Also shown in contours are the same correlations of WSC with solid (dashed) lines for positive (negative) correlations with contour intervals of 0.2 (zero contours are omitted). 

(c) Same as in b, but from FOSI-L. All time series are smoothed with a 12-month running mean before the computation of the correlations. SSH and WSC lead (lag) KEI for negative (positive) lags.
Fig. 6. SSH anomalies as a function of time and longitude. a Monthly SSH anomalies, meridionally averaged over the KEI latitudes, from FOSI-H during 1999-2003. b Same as in a, but from HRDP (ensemble average) from LY1 through LY5 (corresponding to 1999-2003) of the November 1, 1998 start. c Same as in a, but from FOSI-L. d Same as in b, but from DPLE. The time series are smoothed with a 12-month running mean. The dashed lines indicate the eastern edge of each KEI domain.
Fig. 7. Regressions of winter SST and SLP onto KEI. a Lead-lag regressions of January to March (JFM) SST (shading) and SLP (contours) onto KEI from FOSI-H. b Same as in a, but ensemble average JFM SST and SLP from HRDP and lead-lag regressions across LYs with lag 0 at LY3. Note that the independent variable in b is KEI from FOSI-H. The SST and SLP lead
(lag) KEI at negative (positive) lags for FOSI-H and at LY1-2 (LY4) for HRDP. The gray contours indicate statistically significant SST regressions at the 95% confidence level. Contour intervals for SLP are 0.4 hPa and zero contours are omitted.
Fig. 8. Correlations of the temperate profile in the KEI region. a, d Correlation of the vertical potential temperature profile from FOSI-H (a) and FOSI-L (d), zonally averaged over the respective KEI longitudes, against respective KEI. b-c Same as in a, but from the ensemble average potential temperature profile of HRDP at LY1 (b) and LY4 (c). e-f Same as in b-c, but from DPLE. Note that the predictors in b-c and e-f are KEIs from respective FOSIs and all correlations are simultaneous. The black contours in b-c and e-f indicate statistically significant correlations at the 95% confidence level. The green (gray) contours in a and d are the climatological potential temperature (zonal velocity) profile from respective FOSIs.
Fig. 9. Regressions of the temperate profile in the KEI region. a-c Regression of the vertical potential temperature profile from observations (a), FOSI-H (b), and FOSI-L (c), zonally averaged over the respective KEI longitudes, against respective KEI. The dark gray contours are the variance of the potential temperature from the respective datasets with the contour intervals of 0.5°C^2.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- KYDC22KEpredsupplsubmitted.pdf