Proposal to CVP - Climate Process Teams - Translating Ocean and/or Atmospheric Process Understanding to Improve Climate Models; Funding#: NOAA-OAR-CPO-2019-2005530

Title: Ocean Transport and Eddy Energy

Abstract

Ocean mesoscale eddies are energetic motions with lateral scales of tens to hundreds of kilometers. These eddies can significantly impact the transport of heat, freshwater, carbon, and nutrients throughout the oceans, and play an essential role in shaping the ocean's strongest mean currents and their variability. Energy exchanged between the ocean and atmosphere, and across reservoirs and scales in the ocean controls the impact of eddies on the circulation and transport, with most of the ocean kinetic energy contained in the mesoscale range. Mesoscale eddies are, at best, partially resolved in ocean climate models, and most of their momentum and tracer transport must be parameterized. Imperfections in these parameterizations lead to biases in modern climate models, including incorrect rates of exchange of heat and carbon with the atmosphere, errors in the position and strength of the ocean's strongest current systems, and incorrect stratification at high latitudes, among other things. Extant parameterizations fail to fully account for the exchanges of mesoscale energy with different scales, or conversions between eddy kinetic and potential energy reservoirs. Recent advances from theory, process studies and longer-term observational records of ocean energetics can now be leveraged to improve the current generation of climate models. Our Climate Process Team (CPT) proposes to vet, improve, and unify new advances in energy-, flow- and scale-aware eddy parameterizations in process studies and global models; constrain parameters and parameterized fluxes through a synthesis of up-to-date observations of ocean energetics and transport; and implement and assess schemes within IPCC-class models at NCAR, GFDL, and LANL. Modernized, energetically-consistent mesoscale eddy parameterizations are expected to significantly reduce model biases in ocean currents, stratification, and transport.

Relevance to the CPT call & NOAA

The goals of our project are directly relevant to the CPT call in that they will provide improved **representation of the ocean eddies and their role in the ocean energy cycle** in climate models by combining recent advances in theory and observations. The CPT will focus on energy-related diagnostics of ocean eddies in order to constrain ocean eddy parameterization. The improvement in ocean and coupled model fidelity via the proper representation of eddy energy cycles is expected to lead to improvement of some of the most stubborn biases in climate models, primarily the strength and position of strong currents, and the ocean's stratification. **Our team includes three leading global coupled modeling centers (including NOAA's GFDL) and will implement our parameterization within IPCC-class models.** Our goals, results and methodology directly align with NOAA's long-term goals and CPO program mission, which includes improving *"understanding [...] and prediction of climate and its impacts"*.

II. Project Narrative/Statement of Work

1. Motivation and Overview

Ocean mesoscale eddies are energetic, turbulent motions with lateral scales of tens to hundreds of kilometers and vertical scales that span most of the ocean's depth. These motions take the form of meanders, fronts, and vortices, and are generated by instabilities of the flow. Surface forcing results in sloping mean isopycnals with a reservoir of available potential energy (APE) 1000 times larger than the combined kinetic energy (KE) of all parts of the circulation [34]. Baroclinic instability taps this well of APE, generating mesoscale eddies. In regions of strong lateral shear, barotropic instability extracts KE from the mean currents into eddies. In turn, nonlinear interactions between eddies transfer energy to different scales. The mesoscale eddies' KE reservoir exceeds that of the mean circulation. **Sources, sinks, and exchange of energy between reservoirs, scales, and locations determine the ocean circulation and its response to forcing.** This includes air-sea coupling, turbulent cascades and interactions with topography. **Eddy parameterizations must respect these energy pathways to ensure model fidelity.**

Eddy Parameterizations: The earliest generations of low-resolution ocean climate models, with horizontal grids of 100 km or larger, were subject to spurious mixing, producing poor representations of the ocean state [35]. Modern climate models at low resolution alleviate this important issue through the use of mesoscale eddy parameterizations ([36,37], hereafter GM/Redi), which combine diffusion of tracers along isopycnals with an eddy-induced circulation that flattens isopycnals [38]. Despite several improvements from GM/Redi in low-resolution ocean models, there are three main aspects of eddy parameterizations that require improvement in modern climate models. These are: (1) the **APE extracted by eddies is not accounted for;** it is simply lost. (2) The role of **eddy momentum fluxes** on ocean currents and the energy budget is neglected. (3) Finally, the present approach is not appropriate for most IPCC-class models with horizontal resolution close to the Rossby radius of deformation — **the gray zone —**, which partially resolve eddies, and baroclinic instability at some latitudes.

Role of eddies in climate & models: Mesoscale and submesoscale (at scales below the mesoscale) **eddies are prominent agents in the transport of momentum and environmentally-significant tracers such as heat, carbon, and oxygen.** They play an important role in setting the ocean's stratification and structuring the ocean's strongest mean currents and their variability. Eddy processes thus play a key role in natural climate variability as well as transient and long-term climate responses to perturbations in forcing [39–41]. **The lack of adequate representation of ocean eddy energy and transport contributes to some of the most prominent biases in the current state-of-the-art climate models**, as highlighted in the Climate Process Team (CPT) White Paper [42], including: incorrect rates of uptake, transport, and storage of tracers [43,44]; errors in the position and strength of the ocean's strongest currents (e.g., the Antarctic Circumpolar Current (ACC), the Gulf Stream, the Kuroshio, and Pacific equatorial jets [45]); displacements of the air-sea fluxes associated with incorrect mean currents [46,47], incorrect sensitivity to wind forcing in the Southern Ocean [41] incorrect stratification and mixed-layer at high latitudes [16]. While increasing model resolution can reduce these biases, parameterizations are still required at the resolutions that will be affordable for at least the next several decades in most modeling intercomparison projects [18]. Upper ocean mixed layer (submesoscale) eddy parameterizations were the focus of one CPT a decade ago [15], yet recent observational, theoretical and process study advances highlight the importance of new constraints imposed by energy transfer across scales for mesoscale eddy closures, as discussed in the CPT White Paper [42].

We propose to improve mesoscale eddy parameterizations of both momentum and tracer transport via an energetically-consistent framework, in order to increase model fidelity and potentially *reduce model biases in currents, stratification, and transport* in ocean-only and coupled climate simulations from GFDL, NCAR, and LANL. These advances will be brought to the next generation of ocean climate models through substantial collaboration between those working with observations (Abernathey, Cole, Drushka), turbulence theory (Fox-Kemper, Grooms, Smith) and process studies for the design of parameterizations (Bachman, Jansen, Zanna) together with developers of global general circulation models (Adcroft, Danabasoglu, Griffies, Hallberg, Petersen).

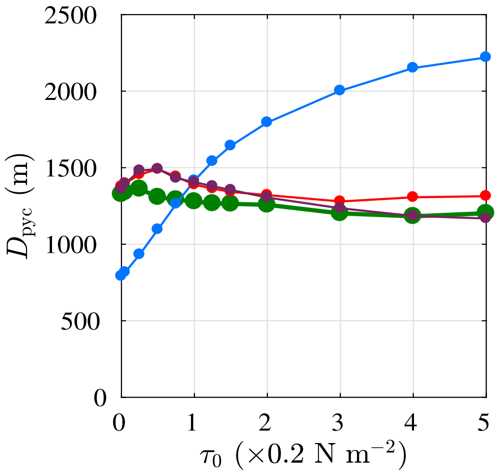
2. Scientific Background

2.1 Theoretical and observational constraints from energetics

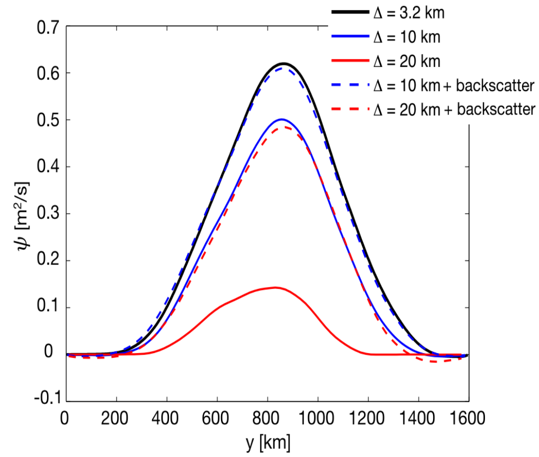
A theoretical focus on the **ocean's energy cycle** [48] provides a useful framework for examining the role that eddy generation, dissipation, and transport play in **energy exchange between reservoirs, scales, and basins and on maintaining the ocean circulation**. KE and PE are often partitioned into mean, and eddy parts, each of which possesses its own budget involving time tendencies, transport, sources and sinks, and conversions from one energy type to another. Specifically, the mean kinetic energy (MKE), the eddy kinetic energy (EKE) and available eddy potential energy (EPE) per volume can be defined as MKE = $\rho_0 \overline{\boldsymbol{u}} \cdot \overline{\boldsymbol{u}}/\mathbf{2}$, EKE = $\rho_0 \boldsymbol{u}' \cdot \boldsymbol{u}'/\mathbf{2}$, EPE = $\rho_0 b'^2/\mathbf{2}\boldsymbol{N}^{\mathbf{2}}$, where $\overline{\boldsymbol{u}}$ is the (spatial or temporal) mean velocity and $\boldsymbol{u}'$ is the eddy velocity (deviation from the mean), b' is the eddy buoyancy, ρ_0 is the reference density and N is the mean buoyancy frequency. Observational estimates of these reservoirs show that EKE at the mesoscale dominates the KE reservoir, the EPE reservoir can be as large as the EKE reservoir [49,50], and EKE can be dissipated over rough bottom topography [51].

Ideas bringing together exchange of energy between reservoirs, using an energetically-constrained framework, have shown promise in idealized ocean models (Sec 2.3), for example allowing for a realistic response of the ACC transport or stratification to wind stress changes in a non-eddying model (Figure 1a), or improving the overturning circulation in an eddy-permitting model (Figure 1b). In both cases, the exchange of energy between eddy and the mean flow and the interplay with dissipation is crucial to maintain the ocean transport. Progress has also been made on understanding a number of important processes relevant to improving energy-based eddy parameterizations. Some of the advances include: eddy energy dissipation in the bottom boundary layer and its dependence on the partitioning between EKE and EPE [52] the role of non-local momentum transport in driving ocean mean flows [53], the large conversion rates of mesoscale eddies to smaller scales in the presence of rough topography [54], the vertical structure of eddy energy and its surface intensification in the presence of bathymetry [55], and the dissipation of potential enstrophy [24].

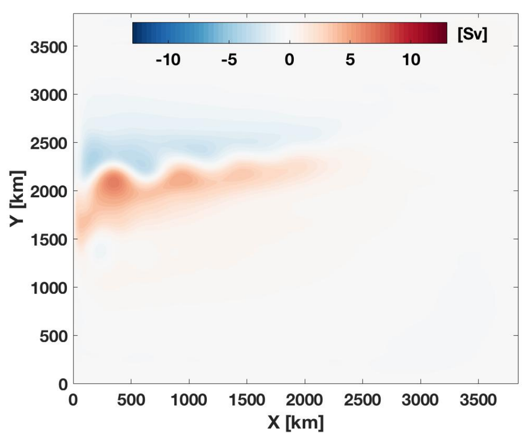
The concept of a turbulent cascade has been fundamental to our understanding of how kinetic energy, enstrophy, and tracer variance are transferred by nonlinear turbulent eddies across space-time scales [56]. Smagorinsky [57] made use of this concept for 3D turbulence, and many theoretical models of geophysical turbulence have been inspired by his pioneering efforts. While the behavior of the cascades in geophysical flows varies from that predicted by Kolmogorov [56] due to the importance of stratification and rotation [58,59], oceanic observations [60,61], reanalysis products [62], and eddy-resolving realistic global models support their existence [19,24,63]. These new studies have highlighted the importance of inverse (transfer from small to large space-time scales) and direct (transfer to small scales) cascades, over a range of geophysical scales in different parts of the World Ocean. **These concepts of turbulent cascades have been leveraged into new subgrid scale momentum closures** (Sec 2.3), which have shown great success by ensuring model fidelity in idealized settings, improving, for example, the strength, location and variability of strong currents (e.g., Fig. 1c), and in realistic models, improving energy spectra (e.g., Fig. 1d) [19].



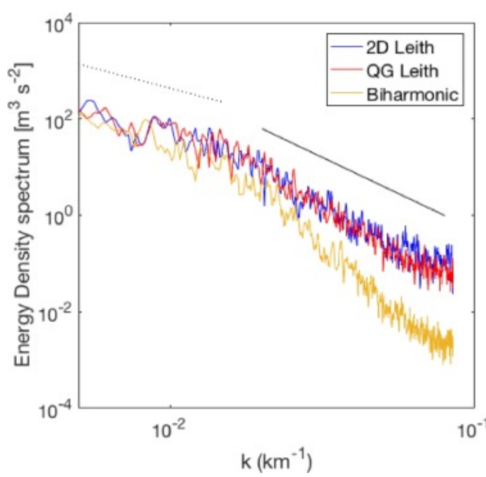
(a) Global stratification as a function of wind stress for idealized high-resolution simulations (green), and for coarse-resolution simulations with GM (blue), and energetically-constrained GM (red & purple) (Mak et al 2018).



(b) Meridional overturning transport in MOM6 channel model at 3.2 km (black), 10 km (blue) & 20km (red) resolution. Dashed and solid lines show simulations with and without energetically-constrained backscatter parameterization (Jansen et al. 2015).



(c) Bias reduction in MOM6 ocean barotropic transport in a double-gyre model using an energetically-constrained Non-newtonian stress parametrization (Zanna et al. 2017).



(d) Energy spectrum in global ocean models, showing reduced energy loss with QGLeith (Pearson et al 2017).

2.2 Current challenges in global ocean/climate models

Global ocean models at spatial resolutions coarser than about ¼° generally use the **GM/Redi parameterization** (Sect 1). The GM/Redi parameterization represents the bulk effect of mesoscale eddies in providing both an advective (GM) and downgradient (Redi) - along neutral directions - diffusive transport as part of **the tracer equation**. From an energetics perspective, GM represents a net sink of APE extracted from the resolved flow. However, the APE extracted is "lost" because subsequent transfers across scale, and location are not tracked. The amount of APE extracted depends on the GM transfer coefficient, κ, whose magnitude and flow-dependence are critical to adequately capture the oceans' mean flow, as well as its response to changes in surface forcing [64,65]. While there is general agreement that κ should depend on the resolved flow, i.e., be "flow-aware

", the specific formulation and parameter(s) for flow-awareness remain poorly constrained. Similar issues apply to the Redi tracer diffusivity, which is often chosen to be similar to or equal to the GM coefficient [66], despite evidence that these coefficients are not equal, but whose vertical structure might be linked [67,68]. Therefore, one immediate action is to best constrain the GM/Redi parameters on the resolved flow and **account for the transfer of energy between reservoirs.**

A second challenge is that of representing the inverse cascade. Eddy momentum fluxes in ocean models are typically parameterized via purely dissipative Laplacian and/or bi-harmonic viscosities [17,69,70], stabilizing the numerical simulations. However, this approach also tends to spuriously dissipate energy, inhibiting the expected inverse energy cascade for simulations in the gray zone, as shown in both idealized and realistic models [63,71,72]. In addition, there are many examples where horizontal eddy momentum converges to accelerate rather than dissipate jets with important consequences for tracer transport and uptake, e.g., [73,74]. Finally, only rarely is the momentum flux closure treated alongside the buoyancy (GM/Redi) parameterization [20,75,76]. **Connections between momentum and buoyancy in process-model studies have emerged** in support of understanding energy conversion between reservoirs with implications for transport and ventilation of tracers [53,74,77,78].

The third challenge is that of representing sub-grid scale eddies in eddy-permitting simulations. The current generation of parameterizations (e.g., GM/Redi) used in ocean climate models has been designed specifically for non-eddying models, where they need to represent the net effect of the entire spectrum of turbulent motions. However, as resolution is refined **sub-grid parameterizations need to become "scale-aware" in order to adequately represent the scale-dependent transfers of energy,** enstrophy, and tracer variance. Scale-awareness often arises naturally in parameterizations if they are formulated with clear specifications of how they depend on enstrophy, resolved and unresolved energy reservoirs and cascades [17,20,57,73,78,79].

2.3. Recent advances in eddy parameterizations

Novel parameterization approaches have appeared in the recent literature that are all designed to address aspects of the three main limitations of existing oceanic eddy closures discussed in Sec. 1 and 2.2. Many of these schemes, developed by PIs involved in this CPT, have been tested in idealized simulations. The closures, which are too detailed to be presented fully here [20,52,78–80], are **shovel-ready for implementation, intercomparison, and unification in global climate models (Sec 3.2).** The main closures are described briefly below.

Studies have considered the effects of a prognostic equation for the eddy energy [52,53,81,82]. For example, a 3D EKE equation has been in use in prototype climate models [53], a depth-integrated (2D) version of the EKE equation has been explored at GFDL [52,81], and a 2D total eddy (kinetic + potential) energy equation used in idealized simulations [82]. The time-dependent equations heuristically capture sources and sinks from the sub-grid scale parameterizations. Integrating this additional equation requires its own set of closures for unresolved processes, but also comes with the promise of greater realism with more accurate representation of exchange of energy between reservoirs. The eddy energy has been used to construct GM parameters in coarse-resolution models (Fig. 1a), and to reinject energy lost from sub-grid dissipation into the large-scale flow in eddy permitting models -- referred to as eddy backscatter [71] (Fig. 1b). New parameterizations have also been developed with imposed constraints on energy and enstrophy built-in. For example, QG Leith specifies the GM/Redi and viscosity coefficients in eddy-resolving models to match a resolved forward potential enstrophy cascade [20].

Eddy momentum parameterizations have also emerged to allow for upgradient fluxes. The scheme GM+E uses upgradient momentum fluxes to re-inject directly the APE lost by the GM/Redi parameterizations in coarse-resolution simulations [80]. Other schemes have been developed specifically to target the inverse cascade of energy, including a non-Newtonian stress parameterization based on spatio-temporal gradients of potential vorticity (PV) [78,83,84], and the eddy backscatter described above [71], both for eddy-permitting models. Finally, PV closures have been proposed to link momentum and buoyancy flux closures, mimicking conversion of APE to EKE [53]. Some of the proposed schemes above are currently being used in idealized and prototype climate models [85] but need to be further explored to improve parameterization robustness and consistency.

Finally, while some of the new schemes are scale- and flow-aware (e.g., non-Newtonian stress and QG Leith), other schemes old or new are not (GM/Redi). In the GFDL models, scale-awareness is introduced by modulating the non-scale aware parameterized fluxes by a function of local resolution which zeroes out the local fluxes when the local cell size passes below a locally computed eddy scale proportional to first baroclinic deformation radius [79].

3. Aims and Relevance to CPT call

3.1 Aims

The aim of this effort is to thoroughly vet, improve, unify, and constrain sub-grid eddy parameterizations of both momentum and tracer transport in climate models via an energetically-consistent framework, with the goal to increase model fidelity and reduce ocean model biases. We will primarily rely on recent advances from process studies on ocean eddy energetics and multiscale interactions, to improve the ocean energy budget in models, a key element for realistic representations of **ocean circulation and transport.** We will also exploit a wide variety of existing observations to improve the understanding of eddy energetics and their links to ocean circulation. A major novelty of the present CPT is the development and implementation of eddy parameterizations across a range of spatial resolutions (from coarse to mesoscale-permitting) relevant to present and near-future global climate models, with applications encompassing weather forecasting, paleoclimate, and climate predictions and projections. We propose the following **goals**:

1. **Support a uniform implementation** of the extant suite of ocean eddy parameterizations in use at different modeling centers for side-by-side comparisons in *realistic applications* with *uniform modern numerics* (i.e., all implemented in MOM6 and MPAS-Ocean). Such comparisons are rare [86] but fundamental to accelerate progress on our new schemes

2. **Evaluate, develop, and unify** through ocean energetics the new and existing scale- and flow-aware sub-grid eddy parameterizations for a range of applications in coarse- and mesoscale-permitting global ocean and climate models.
3. **Increase model fidelity** via improved ocean energetics potentially leading to the **reduction of biases** in ocean currents, stratification, ventilation, and transport.
4. **Curate observational and high-resolution model-based diagnostics** to improve understanding of ocean eddy energetics, constrain parametrization and facilitate intercomparison exercises. These diagnostic datasets will be made available to the community alongside the parameterizations.

3.2 Relevance of an ocean eddy CPT

Each of the new parameterizations discussed in Sec 2.1 and 2.3 has shown promise in idealized flow scenarios with respect to imitating the phenomenology of large-scale turbulence and bias reduction (compared to high resolution simulations). Several of these parameterizations are already available or are presently being coded into state-of-the-art ocean models (MOM6, MITgcm, POP, NEMO, MPAS). However, quantification of the fidelity of these parameterizations in realistic climate models is unknown. Given the growth in the number of untested but promising closures based on recent theoretical advances, the set of extant and nascent eddy parameterizations is primed for simultaneous advancement and unification. From an observational standpoint, the increasing number of long-term global and regional datasets (e.g., SSH, Argo, mooring arrays) is overdue for a **comprehensive analysis and synthesis of eddy energetics**. While eddies have long been investigated through observations [6,87,88], studies are often limited geographically or in depth and employ a variety of analysis techniques that complicate attempts to compare between studies. Adopting an energy framework to synthesize existing observations in parallel to modeling efforts is much needed.

With the proposed concerted effort combining theory with simulations and observations to constrain and evaluate the parameterizations of ocean eddies and energetics, the ocean and climate modeling community has a unique and important opportunity to make substantial progress on these problems in a relatively short time, leading to improved simulations of ocean transport and circulation. The “research ready” status of these parameterizations means that the important evaluation steps can be performed straightforwardly using standard realistic configurations [89].

The **goals set in this project are directly relevant** to the CPT call by providing improved understanding and representation of ocean turbulent eddy processes as well as their life and energy cycle in climate models by combining theory, process-studies and observations to improve climate models. *The focus on ocean eddies and energetics, the current limitation of eddy parameterizations in climate models, and the readiness of novel advances in eddy closures combined with the integral involvement of global modelers dictate a CPT approach.* **Our team includes three leading global coupled modeling centers (NCAR, GFDL, LANL) that will implement our parameterization(s) within IPCC-class models.** Our goals, results and methodology will include improving *understanding and prediction of climate and its impacts.*

4. Tools

4.1 Numerical Experiments

Unless stated otherwise, all numerical experiments will use MOM6, the ocean component of coupled climate models at GFDL. MOM6 will soon replace POP at NCAR for use in CESM, and will become the ocean model for the NOAA Climate Forecast System (CFS). This code choice will speed the implementation of new parameterizations into global models, and ensure a clean comparison of outcomes. Our tests of modified GM/Redi will be compared to current work being done at LANL within MPAS (funded under a DOE grant). In addition, our vetted unified eddy parameterization will be implemented and tested by Petersen's team in MPAS-Ocean, which uses an unstructured mesh and will therefore provide a strong test for the scale-awareness of our parameterizations. Groups will focus efforts on two fundamental model configurations to evaluate parameterizations and diagnose eddy energy transport:

Idealized channel+basin: Composed of a re-entrant channel with topography connected to a narrow sector that extends beyond the equator. The reduced domain size will allow us to conduct many experiments under different combinations of transient forcings (wind and buoyancy), sub-basins (e.g., channel-only, gyre sector-only, cross-equatorial), boundary conditions, bottom roughness, and a wide range of horizontal resolutions. This configuration can be used to target several key regimes in which eddies play an important role in the ocean circulation and where their influence on model bias is large as stated in Sec 1. It is a key principle of this research that all potentially useful parameterizations will be developed sufficiently to be evaluated in both realistic and idealized simulations.

Realistic global: Global simulations will be used at several resolutions and using different grids for the evaluation of the subgrid scale parameterizations. The parameterizations will be tested in **forced ocean/sea-ice** simulations (i.e., OMIP-type) using the ¼^o, ½^o, and 1^o GFDL versions of MOM6 (OM4) and ¼^o and ⅔^o NCAR versions of MOM6. Additional simulations of the **coupled IPCC-class models** — GFDL-SPEAR at 1^o, GFDL-CM4 at ¼^o, NCAR CESM3 at nominal 1^o with a ⅔^o ocean (MOM6) component, LANL E3SM coupled simulations with ½^o ocean component — will also be used to test the successful unified parameterizations in the final year. The parameterizations in all global configurations will be evaluated using metrics defined in Sec 4.3 compared to observations and existing higher-resolution global simulations, including global 0.1^o eddy-rich ocean-only and coupled models (e.g., MPAS-Ocean, GFDL CM2.6, CESM).

4.2. Observational Datasets

Observational Datasets will be used to improve understanding of ocean eddy energetics as well as to evaluate ocean models and parameterizations in a scale-aware way by (re-)analyzing and synthesizing existing data in a consistent and comprehensive manner. We will utilize a number of datasets that have already been analyzed in terms of their mean and variance (Table 1), in addition to creating several new diagnostic products (Table 2). The focus will be on long-term records of the primary physical variables of temperature (*T*), salinity (*S*), and horizontal velocities (*u*, *v*), as well as tracers such as oxygen, nutrients, and CFCs when possible (which will be valuable for validation but not analyzed further here).

Platform (location): existing products and selected references	**Analyzed**
Satellite SST*, SSH, SSS (surface global): *T*, *S*, SSH, *u,v* variance [90,91]	SSH
Surface drifters* (surface global): *u*,*v* mean, variance, covariance [92]	No

Volunteer Observing Ship* SST, SSS (surface quasi-global): *T*, *S* mean, variance [93]	No
WOCE / GO-SHIP* (full depth global): CFCs, O_2, nutrients	No
Fukushima-related cruises (upper western Pacific): *T*, *S*, cesium isotopes [94]	No
Argo* (0-2000 m, global): *T*, *S* mean and variance, mixed layer depth, EPE, structure functions [6,50,95,96]	*T*, *S*
Repeat ADCP, XBT lines* (~0-1000 m. Drake Passage and other locations): *u*,*v* T [97–100]	*T, u*,*v*
Global tropical moored buoy array* (~0-500 m global equatorial): [101]	*T*, *S*, *u*,*v*
Other moorings* (HOTS, BATS, OOI, VOCALS, RAPID, Line W, OSNAP, SAMOC; ~full depth, location varies): [102] [103]	*T*, *S*, *u*,*v*
CalCOFI* (0-500 m, Eastern Pacific): *T*, *S*, *u*,*v*, O_2, nutrients [104]	If needed

*Table 1: Observational datasets to be used in the proposed work, including relevant existing products and data that will be analyzed here. * = datasets funded in part by NOAA.*

4.3 Diagnostics and Metrics

Our diagnostic framework will facilitate scale-discriminating intercomparison between different models and observations, and understanding the role of eddy energy transfer in maintaining the ocean circulation. All diagnostics will focus on the 10 to 300 km mesoscale range of lateral scales.

a. Eddy diagnostics: used to evaluate the fidelity of the parameterized models when compared to observations and high-resolution simulations. Eddy diagnostics will include: fluxes of *T*, *S*, *u*, and *v*; partitioning of MKE, EKE and EPE; horizontal variance of *T*, *S*, *u*, and *v*, band-passed to specific scales (submesoscale, mesoscale, and larger); variance wavenumber and frequency spectra, and structure functions [19,90,96,105,106].

b. Large-scale ocean & climate metrics: Climatological metrics will be developed to evaluate model bias improvements in parameterized GCMs through comparison with observations. These will be used to assess the major targeted model improvements addressed by the proposed work: **biases in circulation, transport**, **vertical temperature and salinity structure, and ventilation**. *In both ocean-only and coupled climate models,* circulation and transport biases will be assessed through the mean and variance of SST, SSS, SSH, surface geostrophic current and meridional transport of heat and salt. Key regional transport biases will be evaluated via several metrics: Atlantic MOC transport, the strength of the equatorial undercurrent, the location and transport of the ACC, Gulf Stream, and Kuroshio, and horizontal transport in the western Pacific Ocean [94]. Vertical temperature and salinity structure will be assessed via comparison of mixed-layer depth, thermocline depth, and stratification strength. We will compare modeled ventilation to observed transient ventilation rates from CalCOFI and WOCE/GO-SHIP lines (CFCs, oxygen, nutrients). We will use additional metrics based on theoretical predictions, in particular sensitivity experiments to wind and buoyancy forcing and the degree of eddy compensation and saturation to stratify the parameterized simulations versus those that better resolve mesoscale eddies [39,82,107].

Product	**Data Source (location)**
T,S and/or *u,v* variance, spectral slope, structure function (also N^2, mixed layer error)	Argo, XBT, moorings (global), ADCP/XBT and moorings (quasi-global), VOS and satellite fields (surface global)
Covariances (e.g., *u'T'*, *u'v'*)	ADCP/XBT and moorings (quasi-global), satellite (surface global)
MKE vs. EKE partition	SSH (surface global), ADCP and moorings (quoi-global)
EPE	Argo (global), moorings, possibly XBT (quasi-global)
EKE+EPE, EPE vs. EKE partition	ADCP/XBT and moorings (quasi-global)

Table 2: Diagnostic products that will be created and made available as part of this CPT.

In coupled simulations, we will define additional metrics, which includes air-sea fluxes and climate variability indices to help discriminate between parameterizations' influence on global climate. Modeled air-sea momentum, heat and freshwater fluxes will be assessed using observational syntheses [108,109]. The main climate indices will include: the Madden-Julian Oscillation and North Atlantic Oscillation on intra-seasonal timescales; El-Nino and the Southern Oscillation indices on interannual timescales; and Pacific Decadal and Atlantic Multi-Decadal Variability indices on decadal timescales.

The decision to select or discriminate between parameterizations will rely first on eddy fluxes diagnostics (Sec 4.3a) to test model fidelity, then on the reduction of model biases based on the metrics in Sec 4.3b. Evaluation of eddy parameterizations will also consider model response (e.g. sensitivities) and allow for re-tuning of unrelated parameterizations. Given the large number of diagnostics, metrics and eddy parameterizations, we propose the use of a Taylor Diagram [110] to help the evaluation and summarize the many aspects of model performance.

5. Work plan

The Work Packages (**WP**) and Tasks (**T**) to achieve the goals outlined in Sec. 3 are detailed below. Each individual WP involves a synergy between observations, process study and theory to immediately result in improved implementation of eddy parameterizations in global climate models to enhance their fidelity. The timeline is summarized in Table 3.

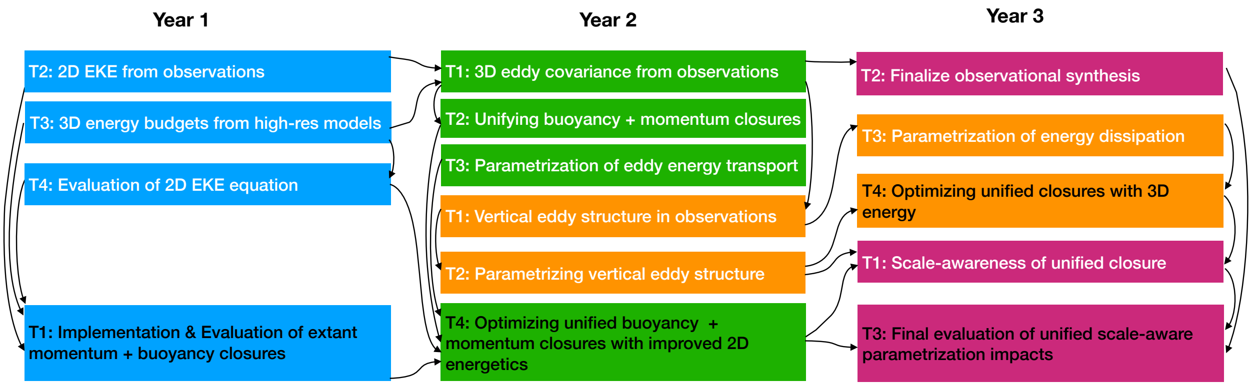


Table 3: Summary of Work Plan

5.1 WP1: Evaluation of buoyancy, momentum and energy-based eddy closures

We will evaluate energetics from both observations and high-resolutions simulations and assess existing parameterizations of eddy momentum, buoyancy and 2D energy.

T1: *Implementation, in MOM6, of extant closures in current use* in different global ocean or coupled models (described in Sec 3.1). The closures include: **a. Tracer equations** with different variants of GM/Redi coefficients based on: baroclinic instability [111], stratification N^2 [112], mixing length [113], 2D EKE equation [81]. **b. Momentum equations:** non-Newtonian stress [78], PV closures [53], QG Leith [20], GM+E [80], backscatter [71]. Additional developer effort will be required to adapt these schemes to the generalized coordinates of MOM6 and MPAS-Ocean. Evaluation will be conducted in both the idealized and realistic configurations at GFDL (OM4, CM4) and LANL; and in realistic configurations at NCAR in the context of CESM. The evaluation of closures in all subsequent tasks will employ diagnostics and metrics from Sec 4.3.

T2: *Characterizing scale-dependent EKE from observations*. We will assess the partition between MKE and EKE, focusing on gridded and along-track satellite altimetry observations. The impact of filtering type (spatial or temporal) and scale will be investigated. Analyses of ADCP velocity measurements will provide further context in specific regions.

T3: *Energy budgets from high-resolution simulations.* We will perform an analysis similar to T2 using the already available realistic eddy-rich global configurations of CESM [114], GFDL CM2.6, and MPAS-Ocean. Despite their own set of biases, these simulations allow for extensive analysis with higher spatio-temporal frequency than observations alone. The models have sufficient output to estimate complete 3D energy budgets, will serve as additional benchmarks to assess the parameterized simulations. Numerical model output will also be subsampled similarly to the observations to provide error bounds on the observational estimates from T2.

T4: *Assessment of the parameterized 2D eddy energy equation.* a) We will assess the 2D depth-integrated EKE fields from the parameterized EKE runs (T1) using the energy diagnostics from observations and high-resolution models generated via T2 and T3. b) The 2D EKE equation will be recast into total (kinetic + potential) eddy energy and compared with observations, as in [31,77] who have shown this leads to improved simulation of eddy saturation and compensation.

Milestones Year 1: 1) Implementation in MOM6 of existing buoyancy and momentum closures and assessment of their impact on model fidelity (energetics) and biases (currents and stratification) in MOM6 an MPAS-Ocean. **2)** Synthesis of 2D scale-dependent MKE & EKE from observations. **3)** Diagnostics of 3D energy reservoirs and budgets from high-resolution simulations. **4)** Evaluation of the parameterized 2D EKE and total (EKE + EPE) equations.

5.2 WP2: Unifying buoyancy and momentum closures via energetics

We will unify closures of buoyancy and momentum using parameterized exchange of energy between reservoirs. Energetics from observations and high-resolution simulations will guide the parameterization of a depth-integrated eddy energy equation.

T1: *Quasi-3D eddy buoyancy and momentum statistics from observations.* 3D synthesis products will be generated which provide estimates of T/S variance, EKE/MKE partition, EPE/EKE partition, and eddy covariance, e.g. eddy buoyancy and momentum fluxes [115,116]. We will also estimate the divergence of the surface fluxes with geostrophic velocities from altimetry. Both spatial and temporal variability in eddy statistics will be used to inform parameterizations.

T2: *Unified buoyancy and tracer closures.* Using a suite of idealized simulations of varying resolution (from well- to un-resolved mesoscale eddies), under a range of stratifications, topographies, mean flow/shears (varying Burger, Rossby, and Reynolds numbers), we will assess and merge buoyancy-momentum closures to make these consistent with energetics constraints, by selecting the most successful approaches determined in WP1 T1 (e.g., [80,84,117]).

T3: *Parameterization of mesoscale eddy energy transport.* The eddy energy transport in the 2D EKE equation is currently laterally isotropic, however theory and idealized models suggest it is anisotropic [31,32]. Using observations and idealized simulations (WP2 T2) [118,119], we will consider the impact of the anisotropic nature of the lateral eddy transport and propose improvement to the transport in the parameterized 2D eddy energy equation.

T4: *Updating, unifying, and optimizing the parameterizations.* Informed by the outcomes of other tasks, we will undertake the following steps to improve, optimize and further evaluate the parameterizations: **a. Implementation of 2D total eddy energy scheme** (WP1 T4), and anisotropic energy transport (WP2 T3); **b. Implementation of a consistent GM-Redi relationship** based on [67], and assessed in WP3 T2, and constraining the GM coefficient via the 2D energy equation from **(a)** as in [40]; **c. Closing the energy budget by** reinjecting energy from subgrid scale eddy parameterizations into the momentum equations (WP2 T2).

Milestones Year 2: 1) Unification of tracer and momentum closures with improved 2D energy constraints. **2)** Global observational datasets of 3D eddy statistics (heat, energy, momentum).

5.3 WP3: Improving the Vertical Structure of Eddy Energy

We will constrain the vertical profile of eddy energy by targeting both flow-aware vertical coefficients for eddy momentum and buoyancy closures and a 3D parameterized eddy energy equation.

T1: *Analysis of vertical eddy structure in observations.* The quasi-global observational products (from [6,50,96], WP1+2, and Argo data) will be investigated based on mean flow characteristics such as the large-scale horizontal and vertical shear or large-scale stratification – to assess flow-awareness, and also compared to local bathymetry [51]. This includes standard statistics such as total eddy energy, as well as horizontal wavenumber spectra and/or structure functions [105]. Vertical mode decomposition [55] will be used to further quantify and understand the vertical structure of eddy energy and variability.

T2: *Assessment and parameterization of vertical eddy energy structure in models.* Using simulations from WP2 T2 and observations high-resolution diagnostics (WP1 T3, WP2 T1), we will assess: **a.** the diagnosed **vertical structure of eddy fluxes** and that predicted using vertical modes (as in T1). This will be used to constrain the vertical eddy energy flux in the **vertically-dependent eddy energy equation** [53], to be implemented in WP3 T4; **b. parameterizations directly specifying vertical structure of eddy coefficients** ([67,112] in WP2 T4b).

T3: *Improving energy dissipation in the eddy energy equation.* Using the results of T2, we will improve the model of direct dissipation of eddy energy by bottom friction in the 2D and 3D eddy energy equations (WP3 T2). The idealized model simulations of WP2 T1 will be used to assess the relative magnitude of dissipation of eddy energy by other mechanisms including ageostrophic instabilities, topographic wave generation, and interaction with the atmosphere.

T4: *Testing of improved eddy energy constraints in global simulations.* We will **a. update the vertical structure** of the eddy transfer coefficients (tracer and momentum) based on WP3 T2-a and update the 2D eddy energy equation with transport and dissipation terms derived in WP2 and WP3; **b. implement the 3D eddy energy equation,** informed by WP3 T1-3. The choice between using **a** or **b** in WP4 will depend on model fidelity after testing.

Milestones: 1) Year 2 Dataset of vertical structure of eddy energy and partitioning of EPE and KE. **2) Year 3** Improved set of parameterizations incorporating vertical structure of eddy energy.

5.4 WP 4: Scale-aware unified buoyancy-momentum-energy closures

For the unified parameterization to be used seamlessly across a range of resolutions, we will optimize our closures by linking theory with numerical implementation, guided by observations.

T1: *Parameterization of the gray zone.* We will derive linear instability modes as in [75] in the gray zone, from WP2 T2 simulations, to improve our theoretical basis for parameterizations in this regime. As resolution varies, this will help a) refine the parameterizations of eddy momentum fluxes (backscatter [71], non-Newtonian stress [78], GM+E [80]) and their connection to PV and buoyancy fluxes; b) serve as a guide for sharpening the physics-based criteria of the scale-aware cutoff [79] for the use of different parameterizations in global simulations.

T2: *Finalize observational synthesis.* Detailed case studies of the energetics of specific regions (equatorial, Southern Ocean, western boundary current extensions) will be produced focusing on the mesoscale / submesoscale partition and cross-scale energy exchange. Synthesis products will be finalized and made available; they will include regional and global eddy statistics (Table 2) from each type of platform, incorporating seasonal variability and error estimates.

T3: *Finalize the implementation and evaluation* of the unified scale- and flow-aware formulation of the parameterization for eddy fluxes constrained via 3D energetics. Summative assessment of the impacts of improved parameterizations on key ocean and coupled climate model biases will be conducted.

Milestones (Year 3): 1) Datasets of buoyancy, momentum and energy and covariances. **2)** Scale-aware unified buoyancy-momentum-energy parameterization for coarse- and eddy-permitting resolution. **3)** Overall assessment of impacts in global climate models.

6. Intellectual Merit

The energy budget of the climate system imposes a fundamental constraint on the ocean circulation. In particular, the exchange of energy between the ocean and atmosphere, and across reservoirs and scales maintains the circulation and its response to external forcing. However, this energy budget is frequently neglected in the design of parameterization for global ocean climate models. The aim of this effort is to thoroughly vet, improve, unify, and constrain sub-grid eddy parameterizations of both momentum and tracer transport in climate models via an energetically-consistent framework, with the goal to increase model fidelity and reduce ocean model biases. We will primarily rely on recent advances from process studies on ocean eddy energetics and multiscale interactions, to improve the ocean energy budget in models, a key element for realistic representations of ocean circulation and transport. We will also exploit a wide variety of existing observations to improve the understanding of eddy energetics and their links to ocean circulation. A major novelty of the present CPT is the development and implementation of eddy parameterizations across a range of spatial resolutions (from coarse to mesoscale-permitting) relevant to present and near-future global climate models, with applications encompassing weather forecasting, paleoclimate, and climate predictions and projections. The collaboration between observationalists, modelers, and theoreticians in this CPT will unify and extend recent research directions on ocean eddy energetics and parameterization, therefore improving both our knowledge of this process and its representation in ocean climate models. Newly generated datasets for ocean energetics and transport, together with the increased fidelity of climate models, will advance our understanding of the role of mesoscale eddies in the climate system in particular through their role in the energy budget.

7. Team responsibilities, management plan and computing

Zanna will be the lead PI for this CPT. She, together with PIs at modeling centers Adcroft & Griffies (Princeton/GFDL), Bachman (NCAR), Petersen (LANL), will be responsible for the scientific coordination of the collaborating PIs, the delivery and reporting of scientific and model development targets, the organization of annual PI workshops and the creation of a webpage. Given the large number of tasks involving implementation in numerical models, synthesis of observational data, and unification of existing theories and process-studies, we request 4 postdocs to be supervised by core institutional PIs. Zanna will lead efforts on WP1 T3, WP2 T2, WP3 T2, WP4 T1. She and Smith will supervise a postdoc at NYU who will concentrate on expressing results from process-studies into an improved framework for buoyancy and momentum parameterizations across spatial scales, with input from Fox-Kemper and Bachman. Grooms will lead efforts on WP1 T4, WP2 T3, WP3 T3. He will supervise a postdoc at CU Boulder to produce an improved eddy energy equation for use in climate models, in close collaboration with Jansen. The synthesis of global datasets for informing and validating the parameterizations will be led by Cole (WP1 T2, WP2 T1, WP3 T1, WP4 T2). She will supervise a postdoc at WHOI, with significant effort from Drushka, Abernathey, and Fox-Kemper. For the successful translation of theory, observations and process-modeling into global climate models on a short timescale, Adcroft will lead the implementation into MOM6 (WP1 T1, WP2 T4, WP3 T4, WP4 T3). He will supervise a postdoc at Princeton/GFDL who will implement the parameterizations and evaluate their success in the GFDL global coupled and uncoupled configurations (CM4 and OM4), with input from Griffies and Hallberg. Hallberg will be responsible for the idealized MOM6 model configuration used throughout the project. In addition, existing NCAR staff supervised by Bachman and Danabasoglu will help to configure the realistic CESM configuration, which is based on MOM6 but with a different grid and different sets of mixed-layer, viscosity, etc. parameterizations than those used at GFDL. Bachman and Danabasoglu will led the evaluation of the schemes in CESM3. Petersen at LANL with his team and a postdoc funded under a DOE grant will participate in the evaluation of a subset of current parameterizations (WP1 T1) and will implement the recommended parameterization in the final year into E3SM (WP3 T4 and WP4 T3).

Regular meetings for this CPT will take place. Postdocs will visit different PIs to ensure timely progress. Small teams will meet virtually every month to discuss the progress of specific tasks within WPs. Additional termly virtual meetings between lead CPT, lead modeling groups, and supervising PIs will occur to review progress and any issues arising.

Computing resources at GFDL, NCAR, LANL for numerical implementation and assessment of parameterizations in idealized and global simulations will be allocated to the team, following internal guidelines of the centers. For process studies, primarily at NYU and CU Boulder, and also at Brown and Chicago, the teams will use allocations from their own institutions (at no cost). However, if additional computing time or data storage are required later in the project, we will submit a request, well in advance, to the appropriate agencies. Data and information sharing are described in the "Data Management Plan".

8. Broader Impacts

To further exchange ideas, report on progress, sharpen our work plan and include the community, we will host annual workshops (at NYU, Princeton/GFDL, Boulder) bringing together all team members, additional collaborators, and the members of the community in the US and from abroad. We plan to organize and/or chair sessions on ocean eddies and the energy cycle at AGU fall meetings, and a 1-day event or a session on constraining ocean models with energetics at AGU Ocean Sciences 2020 and 2022 together with Carsten Eden's team. Eden, in addition to having developed many parameterizations for ocean eddies to be implemented as part of this CPT, currently leads a multi-institution project to create oceanic and atmospheric models which are energetically-consistent (TRR 181: "Energy transfers in Atmosphere and Ocean").

Ultimately, the main broader impact of our proposed work is the improvement of climate models (discussed in detail above), meaning better forecasts of weather, and climate variability, with broad benefits across society, and for the oceanographic and atmospheric community. Our broader impacts work will involve a partnership with the NSF-Earthcube sponsored Pangeo project (Abernathey is lead PI) aimed at making all of our (model and observations) datasets truly accessible and useful to scientists and students anywhere, including for scientists and educators which serve underrepresented groups. NCAR participation in this CPT project will rapidly transfer validated developments in the representation of ocean eddies into the ocean component (MOM6) of the CESM. Ongoing NCAR support will include coding and performance optimizations across the CESM suite of community compute platforms and will be ongoing beyond the period of performance of this proposal. Broader impacts of the project will emanate from the ability of the CESM and its large community of users to use the eddy parameterizations resulting from this CPT and the models emanating from both NCAR and GFDL. Physical oceanography strives to increase the retention of female scientists [120]. Finally, our project has a female lead (Zanna), and two additional female PIs (Cole, Drushka).

The availability of prominent female role models has been shown to contribute to increased female retention in STEM fields [121].

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