Comments from Reviewer 1:

This manuscript presents a comprehensive investigation of the interannual variability of summer shelf circulation in the Northern South China Sea (NSCS) from 2000 to 2022 based on ROMS modeling. The study makes significant contributions to understanding the differential impacts of ENSO and Pearl River Estuary (PRE) freshwater runoff on NSCS circulation dynamics. While the paper is generally well-structured and scientifically sound, several aspects require clarification and improvement before publication.

Response: We sincerely thank Reviewer for the positive assessment and the thoughtful suggestions. In response, we have revised the manuscript to improve clarity and robustness. Specifically, we clarified the methodological choices and diagnostics, strengthened the statistical treatment and significance testing, refined attributions to ENSO and PRE runoff, and improved figure readability and terminology consistency. All changes are tracked in the revised file; below, we respond point-by-point and indicate where each revision appears.

1. Line 57-66, I recommend incorporating this study's findings and conclusions to more explicitly identify the shortcomings of existing research in quantifying the impacts of ENSO and river runoff on cross-shelf transport in the northern South China Sea.

Response: Thank you for this helpful suggestion. We agree that the Introduction should more explicitly articulate where prior studies fall short in quantifying the respective impacts of ENSO and Pearl River runoff on cross-shelf transport in the NSCS. We have revised the last paragraph of the Introduction (Lines 57 – 66) to (i) summarize specific gaps in the literature and (ii) state how our analysis addresses those gaps. The new text is quoted below.

[Line 59-82]: Previous studies of NSCS shelf circulation have primarily examined seasonal patterns and their wind-driven dynamics (Hu, 2000). Short-term summer variability in the shelf current has also been explored: Geng et al. (2024) demonstrated that tides modulate sea surface height, influencing shelf pressure gradients, while Liu et al. (2020) showed that cross-isobath exchanges during upwelling and downwelling winds are sensitive to along-shelf pressure gradients shaped by complex bathymetry. The intensity of this upwelling exhibits notable interannual variability, often linked to the El Niño–Southern Oscillation (ENSO) (Shu et al., 2018). For example, during the summer of 1998—an El Niño year—enhanced alongshore wind stress substantially intensified coastal upwelling (Jing et al., 2011). Despite these advances, the interannual variability of summer shelf circulation remains poorly constrained, particularly in quantifying the depth structure of cross-isobath transport and attributing it to distinct forcings. While expanded observational datasets, satellite products, and high-resolution modeling (Hong & Wang, 2008; Shu et al., 2011; Zu et al., 2020) have refined our understanding of NSCS dynamics, the combined effects of ENSO, PRE runoff, and regional current meandering have rarely been assessed within a unified, shelf-wide framework that computes cross-isobath transport and partitions the pressure-gradient forcing (e.g., JEBAR vs. bottom-related terms).

This study investigates the interannual variability of NSCS shelf circulation during summer from 2000 to 2022, using long-term observations and numerical modeling. We examine how ENSO modulates regional atmospheric and oceanic forcing, how the PRE runoff controls freshwater plume behavior, and how vorticity-related processes—including JEBAR, bottom stress curl, and nonlinear vorticity advection—govern cross-isobath exchanges and meandering shelf currents. Our study also provides a quantitative attribution of ENSO and river runoff impacts on cross-shelf transport in the NSCS, by explicitly computing depth-resolved cross-isobath transport (positive onshore) and decomposing the pressure-gradient/vorticity terms (JEBAR, bottom stress curl, nonlinear relative vorticity advection). By integrating these processes, our study provides new insight into how regional and remote forcings interact to shape NSCS shelf circulation, with implications for hydrographic structure and ecosystem variability.

2. Section 2, the authors have presented comparison results between observations and model simulations for temperature, salinity, and sea level. However, they did not mention the more crucial current observation data. How does the model perform in simulating shelf circulation? Of course, I understand that current observation data is relatively scarce, and model simulations of circulation may have greater errors. It would be preferable to provide some validation of circulation observations here.

Response: Thank you for underscoring the importance of current validation. We agree and have added a concise comparison between our NSCS simulation and summertime high-resolution buoy/ADCP observations over the shelf off the Pearl River Estuary reported by Liu et al. (2020). Given the scarcity of public inner-shelf current records, we re-use that dataset and evaluate our simulation for the same location and period. As shown in Fig. R1a – b, the depth-averaged along- and cross-shelf (zonal/meridional) velocities reproduce the observed velocities fluctuations with realistic amplitude and phase. The residual (de-tided) sea level at Waglan Island likewise exhibits consistent subtidal variability between observations and the model (Fig. R1c). Together with the SST/SSS/SLA validations in Section 2, these checks indicate that the model represents the summertime shelf circulation with sufficient skill for the diagnostics presented here, while we acknowledge greater uncertainty on the innermost shelf due to limited observations.

We introduce this supplementary plot in the revised Section 2:

Moreover, to assess currents where observations exist, we compare our simulation with summertime high-resolution ADCP records over the shelf off the Pearl River Estuary reported by Liu et al. (2020) for the same site and period, and we examine residual (de-tided) sea level at the Waglan Island tide gauge. The simulated along- and cross-shelf velocities reproduce the observed fluctuations with realistic amplitude and phase, and the residual sea level shows consistent subtidal variability (Fig. A1).

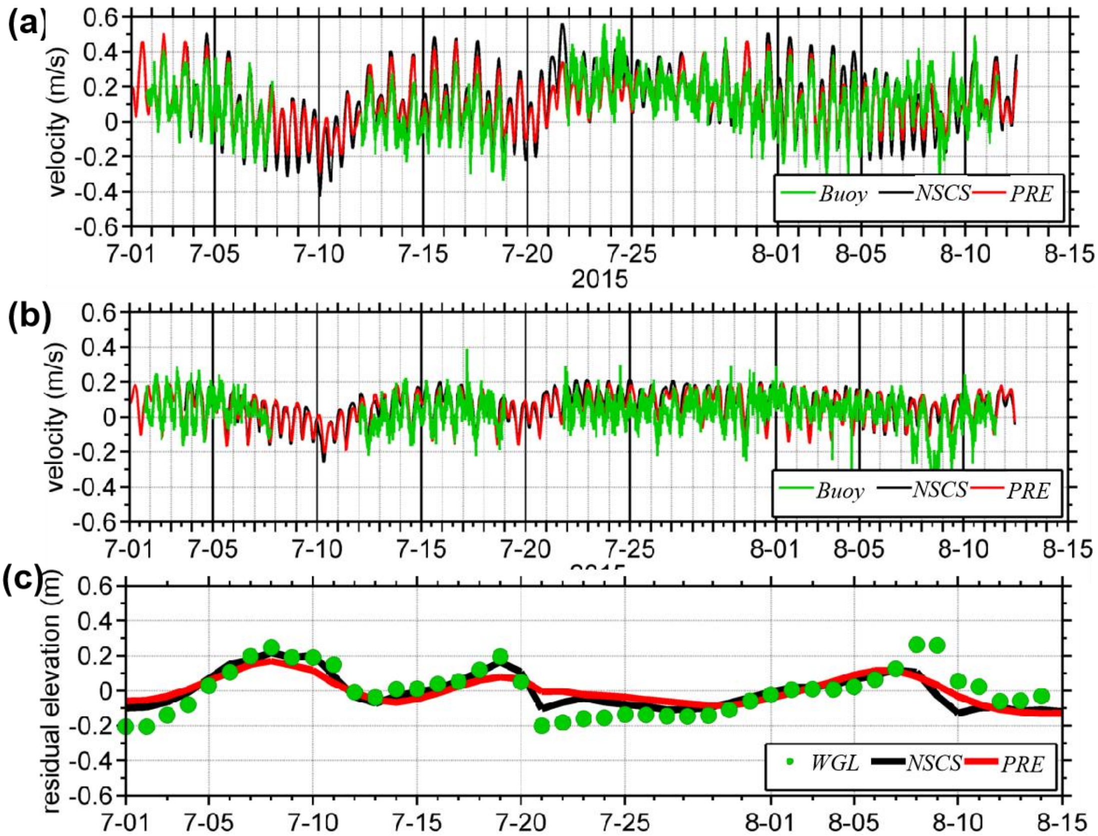

Figure A1. Time series of depth-averaged velocities—(a) zonal and (b) meridional—at the buoy/ADCP station, and (c) residual (de-tided) sea level at Waglan Island (WGL) during July–August 2015. Observations are shown in green, the NSCS simulation (**this study**) in black, and the PRE simulation from Liu et al. (2020) in red. Units: m s^{-1} for (a–b) and m for (c).

Reference:

Liu, Z. and Gan, J.: A modeling study of estuarine-shelf circulation using a composite tidal and subtidal open boundary condition, Ocean Modelling, 147, doi:10.1016/j.ocemod.2019.101563, 2020.

3. Section 3.1, the MVEOF analysis serves as a critically important tool in this study. However, for readers unfamiliar with this methodology, the current paper provides insufficient explanation. I had to search online to understand the fundamental principles of this method before being able to properly follow the article's discussion. The introduction of MVEOF should be moved to Section 2 (Methods), and requires more detailed explanation.

Response: Thank you for this constructive suggestion. We agree that a brief methodological explanation of MVEOF will help readers unfamiliar with the approach. In the revision, we have moved the MVEOF description to Section 2 (Methods) and added the following concise paragraph. Section 3.1 now simply applies the method and refers back to Methods. In the revised section 3.1, we included: We use Multivariate Empirical Orthogonal Function (MVEOF) to extract the dominant coupled spatio-temporal modes shared by multiple, related variables. The method extends conventional EOF by forming a joint covariance structure that includes cross-covariances among the selected fields (e.g., sea-surface height, temperature, and velocity), thereby identifying patterns that maximize joint variance across variables. Each mode is paired with a principal-component (MVPC) time series that describes its temporal evolution, and with variable-wise spatial maps (from regressing the MVPC back onto each field) that show how the variables co-vary in space.

4. Line 147, there is an extra closing parenthesis ")" in this line.

Response: Thanks for your scrutiny, and it is corrected in this revised version.

5. All variables in the equations should be clearly defined in the text. For example, the H and tao in Equ. 2.

Response: We are sorry for this inadvertent omission, and the definitions of the items have now been fully restored in the revised manuscript.

6. As a researcher specializing in shelf material transport, I find the subject of this paper particularly compelling. The study provides in-depth dynamic analysis of ENSO and runoff impacts on cross-isobath transport, but lacks quantitative information that would be most useful for practical applications. For instance: （1） Missing baseline metrics: What is the approximate summer cross-shelf transport velocity in the northern South China Sea? This could be calculated from Figure 4b. Without concrete values, the results are difficult for other researchers to directly utilize. (2) Quantification of forcing contributions: Can the relative contributions of ENSO versus river discharge to cross-isobath transport be quantified? Including these quantitative results in the abstract or conclusions would significantly enhance the paper's citation potential and appeal to a broader scientific audience.

Response: Thank you for emphasizing the need for practical, quantitative guidance. We share the concern that a single "baseline number" can be misleading for a heterogeneous shelf system: cross-isobath velocity varies with depth, local bathymetry, wind/tide events, and model configuration (e.g., resolution). To balance interpretability and uncertainty, we now report order-of-magnitude ranges using $O(\cdot)$ notation rather than decisive values. Specifically, summertime cross-isobath flow is $O(10^{-2}$ m/s$)$ on average, with localized peaks up to $O(10^{-1}$ m/s$)$ near dynamical hotspots (e.g., Taiwan Shoal; Fig. 4b). This conveys practical magnitude while avoiding over-precision.

Regarding the relative influences of ENSO and Pearl River discharge, we now emphasize a domain-aware qualitative partition — PRE discharge as the principal control on the inner/mid shelf and ENSO exerting a larger influence toward the slope —supported by the MVEOF co-variability patterns and the dynamical decomposition. Because percentage splits are sensitive to episodic events, we refrain from quoting a single percentage without a full uncertainty framework; instead, we highlight where each forcing is most influential and note that the sign and spatial patterns are robust across years.