<u>Response to Reviewer 2:</u>

General comment:

The effect of a background shear current on the evolution of a mode-2 internal solitary wave is investigated using the MITgcm numerical model. Three features were identified due to the modulation of the mode-2 wave by the background shear, namely, (i) forward-propagating long waves, (ii) an amplitude modulated wave packet behind the mode-2 wave and (iii) an oscillating tail. The distance between the centre of the shear layer and the centre of the pycnocline was varied such that the distance went in incremental values from zero (no offset) to offsets in which the centre of the shear layer was below that of the pycnocline. It was shown that the forward-propagating waves were insensitive to the offset distance while the oscillating tail and the wave packet decreased in their respective amplitudes as the offset was increased. Implications for energy transfer and energy depletion of the original mode-2 wave are discussed and comparison to a related field study (Shroyer et al. 2010) is given.

The paper is original and makes some interesting findings, as such I am in favor of publication but unfortunately the paper is not suitable in its present form. The following comments and suggestions are provided should the authors wish to rework the paper.

Response:

Thank you for your encouraging and constructive comments, which greatly contributed to improving the manuscript. We carefully read and considered the comments and made substantial revisions. We hope you find these revisions acceptable, and we highly appreciate your suggestions and comments. We highlight the main revisions in the manuscript, and the important points are described below.

Question 1

The paper is littered with grammatical and typographical errors. A thorough check is required.

Response:

We have checked and improved the expressions of the revised manuscript. The NPG Language Editing service was contracted to review and polish the revised manuscript before submission.

Question 2

Abstract lines 13-16 : this is not at all clear to the reader. The reader only knows what these features are AFTER reading the paper.

Response:

Thanks for your suggestion. The abstract has been rewritten and improved accordingly.

The related descriptions were revised in the revision as follows (see also Page 1, Lines 12 – 26 in the main text):

"*The evolution of the mode-2 internal solitary waves (ISWs) modulated by background shear currents was investigated numerically. The sensitivity of modulation to the direction, polarity, magnitude, and shear layer thickness of the background shear current was assessed. In addition, the background shear currents were set to overlap or offset the pycnocline centre to investigate the effects on modulation. During the modulation, three observed shear-induced wave structures were categorized as the forward-propagating long wave, oscillating tail and amplitude-modulated wave packet. The amplitudes of the forward-propagating long wave and amplitude-modulated wave packet are proportional to the magnitude of shear but inversely proportional to the thickness of the shear layer. The oscillating tail and amplitude-modulated wave packet show symmetric variation when the background shear current is offset upward or downward, while the forward-propagating long wave was insensitive to the background shear current. The modulation is unaffected by the direction and polarity of shear. We compared the control experiment to the observations of Shroyer* et al. *(2010). In the first 30 periods, ~36% of the total energy was lost at an average rate of 9 W* m^{-1}, *consistent with the* *results of Shroyer* et al. *(2010), who speculated that mode-2 ISWs are highly dissipated in the background shear current.*"

Question 3

Abstract: The definition of delta is not clear e.g. which distance (shear or pycnocline centre) is divided by which ?

Response:

The definition of Δ has been clarified.

The related descriptions were revised in the revision as follows (see also Page 1, Lines 14 – 16; Page 5, Lines 15 - 17 in the main text):

"*In addition, the background shear currents were set to overlap or offset the pycnocline centre to investigate the effects on modulation.*"

"*The asymmetry parameter Δ (Carpenter* et al.*, 2010) is defined as follows:*

$$\Delta = \frac{D_S - z_0}{h/2}$$

where D_s denotes the depth of shear centre and h denotes the thickness of pycnocline."

Question 4

Abstract: long waves are said to be "robust" to delta. What does this mean? Insensitive ? Not affected by ?

Response:

'Insensitive' is more suitable, and the description has been changed accordingly.

The related descriptions were added to the revision as follows (see also Page 1, Lines 20 – 24 in the main text):

"*The oscillating tail and amplitude-modulated wave packet show symmetric variation when the background shear current is offset upward or downward, while the forward-propagating long wave was insensitive to the background shear current.*"

Question 5

Introduction: Mode-2 waves have also been remotely observed please see and reference JACKSON, CHRISTOPHER R., et al. "Nonlinear Internal Waves in Synthetic Aperture Radar Imagery." *Oceanography*, vol. 26, no. 2, 2013, pp. 68–79. *JSTOR*, JSTOR, www.jstor.org/stable/24862037.

Response:

Thank you for your suggestion. This reference has been included to provide evidence for the existence of mode-2 ISWs (see also Page 2, Line 5 in the revised manuscript).

Question 6

Introduction line 6: "in slope" not sure why the authors make specific reference to a slope here, e.g. can we infer that convex and concave are observed as much as one another in areas where there is not a slope ?

Response:

We revised this sentence following *Yang* et al. (2010) to clearly summarize the observation of mode-2 ISWs. As introduced by *Yang* et al. (2010), a concave slope is seldom observed because it requires a 'thick' middle layer, and this stratification is rare on the continental slope and shelf.

The related descriptions were added to the revision as follows (see also Page 2, Lines 9 – 10 in the main text):

"*In contrast, concave mode-2 ISWs are seldom observed because the stratification with a thick middle layer is rare (Yang* et al., *2010)*"

Question 7

P4 line 4 - define viscosities, what do the sub scripts stand for ?

Response:

We added the definition of viscosities in the revision. The subscripts '*v*' and '*h*' stand for 'vertical' and 'horizontal', respectively.

The related descriptions were added to the revision as follows (see also Page 4，Lines 18 - 19 in the main text):

"*The viscosity parameters were set to* 10^{-3} m^2s^{-1} *for horizontal viscosity* v_H *and* 10^{-4} $m^2 s^{-1}$ *for the vertical viscosity* v_v *in the present study.*"

Question 8

P4 line 19 - it would be useful to have a figure here explaining exactly what Δ is. The authors may also like to consider adopting a similar definition and symbols to what others already use in the literature. For example see Neil Balmforth's work on identifying unstable modes in stratified flows.

Response:

We appreciate your constructive suggestion. We followed *Carpenter*, *Balmforth* and *Lawernce* (2010) to introduce the definition of an asymmetry parameter Δ to describe the asymmetry of the background shear current. We also improved Figure 3 in the revised manuscript to demonstrate the asymmetry parameter Δ.

Question 9

Figure 1: The authors have chosen to set the centre of the pycnocline at mid depth but in the field this is not the case and others (e.g Olsthoorn et al 2013 and Carr et al 2015) have shown that the location of the pycnocline relative to mid depth has a crucial influence on the shape and form of a mode-2 wave. This warrants discussion.

Response:

As suggested by *Olsthoorn* et al. (2013), the essential patterns of the mode-2 ISW generation processes are the same for both asymmetric and symmetric conditions, suggesting that the basic structure of a mode-2 ISW with an offset pycnocline is similar to that for a mid-depth pycnocline. However, the asymmetric stratification can amplify the existing instability and induce asymmetrical instability (*Olsthoorn* et al., 2013), leading to more complicated circumstances, which makes it difficult to investigate the modulation process of mode-2 ISWs due to the presence of shear currents. To examine the influences of the background shear currents on the evolution process of a mode-2 ISW, a symmetric stratification was used in the present work following previous mode-2 works (*Terletska* et al., 2016; *Deepwell* and *Stastna*, 2016; *Deepwell* et al., 2017).

Question 10

Figure 2: The figure shows that the larger Δ is, the smaller Ri can be. This is interesting. Can the authors explain this finding ? Has it been reported elsewhere ? Eg Balmforth again.

Response:

As introduced by *Lamb* (2014), the Richardson number is defined as $Ri = N^2/u_z^2$, where N^2 is the buoyancy frequency and u_z is the shear. The shear remains unaffected to the position of the shear centre. In larger Δ cases, the shear centre was offset from the pycnocline centre. A relatively small N^2 appears at this location, but the shear remains unchanged, causing a smaller Ri.

A similar result was observed by *Lamb* and *Farmer* (2011). In their work, a smaller *Ri* number could be found when the shear centre was located farther from the centre of pycnocline. *Carpenter*, *Balmforth* and *Lawrence* (2010) repositioned the centre of pycnocline, and when the shear centre offset the pycnocline, a higher Richardson number appeared because of a larger buoyancy frequency.

Question 11

P 6 line 5. It is misleading to reference mode 1 work here as the initial condition (set up behind the gate) is different and in fact it is the initial condition that is crucial in generating a mode-2 wave (as opposed to mode-1). It would be more appropriate to reference just Brandt & Shipley along with mode-2 papers such as Olsthoorn et al 2013 and/or Deepwell & Statsna 2016, and/or Statsna et al 2015.

Response:

Accepted. The citation has been modified.

The related descriptions were added to the revision as follows (see also Page 7, Lines 3 – 5 in the main text):

"*A rank-ordered mode-2 ISW train was generated by the "lock-release" method (Brandt and Shipley, 2014; Olsthoorn* et al.*, 2013; Deepwell and Stastna 2016; Stastna* et al.*, 2015).*"

Question 12

Figure 3: The authors have chosen to offset the shear centre downward of the pycnocline. Do they expect to see similar results (but symmetrically reversed) if it were to be offset in the upward direction? Presumably as the pycnocline centre is at mid-depth. What would happen however if the pycnocline centre were not at mid depth? Also the authors have chosen the shear such that the current in the top layer is in the same direction as the wave - this is similar to the overtaking cases in the work by Stastna et al 2015 and some comparison with that work should be given. Do the authors expect to see the same or different dynamics if the polarity of the shear current is reversed?

Response:

We improved and enriched the configuration of the experiment to generalize our research on the evolution of mode-2 ISWs in shear currents. We also added a comparison to *Stastna* et al. (2015) in the revision.

When the background shear current is shifted upward, the amplitude of the oscillating tails and amplitude-modulated wave packet show nearly symmetrical variation trends compared to those with downward shifts. The amplitude of the forward-propagating long wave was insensitive to the offset of shear current (Figure 1 (a) and (b)). The energy losses of mode-2 ISW are also negatively proportional to the asymmetry parameter Δ in both upward and downward conditions (Figure 2(a) and (b)).

A polarity-reversal background shear current only reversed the polarity of the amplitude-modulated wave packet, oscillating tail and forward-propagating long wave.

Second, as we described in the response to Question 9, an asymmetric stratification can amplify existing instability and induce asymmetrical instability (*Olsthoorn* et al., 2010) as well as additional energy loss in mode-2 ISWs (*Carr* et al., 2015). Therefore, a higher energy loss rate is expected in the asymmetrical stratification.

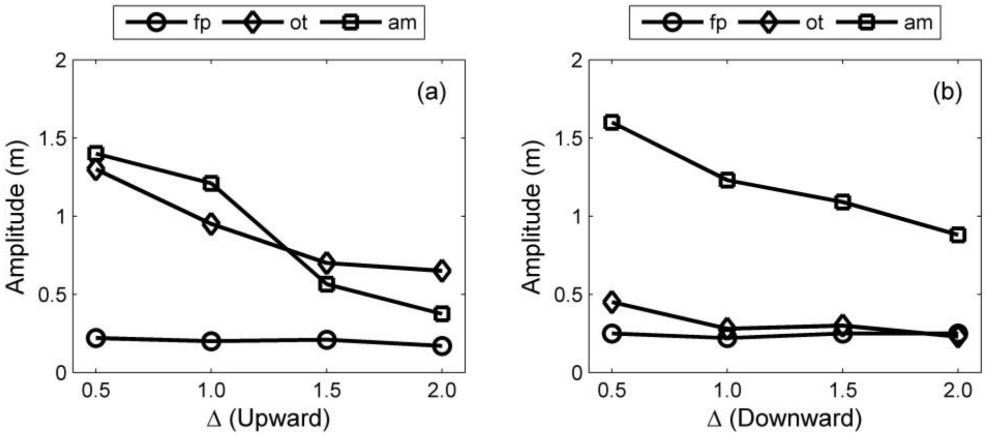

Figure 1. The summarized results of the amplitudes of the forward-propagating long wave (denoted by ‘fp’), oscillating tail (denoted by ‘ot’) and amplitude-modulated wave packet (denoted by ‘am’) with the presence of (a) upward offset background shear currents at 30 T and (b) downward offset background shear currents at 30 T.

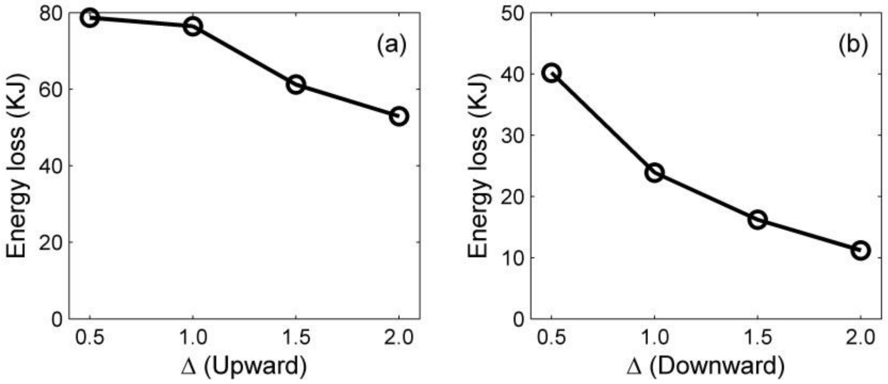

Figure 2. The summarized results of the energy loss of the mode-2 ISW at 30 T with the presence of (a) upward offset background shear currents and (b) downward offset background shear currents.

The related descriptions were added to the revision as follows (see also Page 12, Lines 6 – 12; Page 15, Line 27 – Page 16, Line 3 ;Page 26, Line 4 – Page 27, Line 2 in the main text):

"*In case P1, the polarity-reversal background shear current was initialized in the model. Both in case P1 and the control experiment, the forward-propagating long wave, oscillating tail and amplitude-modulated wave packet could be clearly observed. The properties of the wave structures in the two cases were compared and no significant difference were found. The polarity of the forward-propagating long wave, oscillating tail and amplitude-modulated wave packet are reversed in case P1. This result indicates that the polarity of those shear-induced wave structures is closely related to the polarity of the background shear current.*"

"A similar variation trend could be found in the upward offset cases (Fig .9 (c)). The amplitudes of the oscillating tail and amplitude-modulated wave packet decreased monotonically as the shear current was offset upward. The forward-propagating long wave was barely affected by Δ and remained constant at approximately 0.2 m in all offset cases."

"*Stastna* et al. *(2015) investigated the mode-2 ISW interaction with mode-1 ISW at the same scale. The authors concluded that the shear current is vital, while the* *deformation of the pycnocline only slightly altered the structure of the mode-2 ISW. For our results, we focused on the effect of shear current, which could be induced by baroclinic eddies, baroclinic tides or wind. We found a high energy loss rate during the modulation of mode-2 ISWs in the presence of background shear current, which is coincident with conclusion given by Stastna* et al. *(2015).*"

Question 13

P. 7 line 6 - it'd be useful if c_p were given and/or c presented in non-dimensional form.

Response:

The nondimensional form has been used in the revised paper (see also Page 8, Line 8).

Question 14

Figure 4 caption: (a) "wave form" is this temperature ? What quantity and scale is the colour bar ?

Response:

The 'wave form' is the density field of the initial mode-2 ISW. The caption has been modified, and the quantity and scale were added.

Question 15

Page 9 text and figures - it is difficult to see the forward propagating waves - can this be improved ?

Response:

This figure has been re-plotted, and the corresponding description has been revised.

Question 16

Page 13 line 8 - what are x_r and x_l taken to be though ?

Response:

The definitions of x_l and x_r have been clarified. x_l and x_r are denoted as the left and right boundaries, respectively, where the available potential energy flux equals zero (*Lamb*, 2010).

The related descriptions were added to the revision as follows (see also Page 17, Lines 6 – 8 in the main text):

"*x_r and x_l are the boundary locations of the integration region, and x satisfies $x_l \leq x \leq x_r$. During the calculation of the wave energy, x_r and x_l are denoted as the left and right boundaries, respectively, where the available potential energy flux equals zero (Lamb, 2010)*"

Question 17

Page 14 line 19 - confusing grammar suggests mode-1 are also short lived

Response:

Improved.

The related descriptions were added to the revision as follows (see also Page 19, Lines 9 – 11 in the main text):

"*Modulated by the background shear current, the mode-2 ISW exhibits a highly dissipated nature, and the high energy loss rate is comparable to that of the longer mode-1 ISW (Lamb and Farmer, 2011; Shroyer* et al.*, 2010).*"

Question 18

Page 17 line 22 - are the authors referring to the field here or their simulations?

Response:

The references have been included to support our finding.

The related descriptions were added to the revision as follows (see also Page 24, Lines 16 – 18 in the main text):

"*The superposition of an initially stable shear current and the mode-2 ISW induced a low Ri region with a minimum value of less than 0.01 in our simulation, indicating a possible development of shear instability (Barad and Fringer, 2010).*"

Question 19

Figs 13 and 14 and related discussion. If shear instability is present would you not expect to see overturning isopycnals ?

Response:

A zoom-in plot of the density contour at 2.8 T for the control experiment (case O5, Δ = 0) is provided to show the overturning process (Figure 3). The region of interest corresponds to Figure 16 (b) in the revised manuscript, which is accompanied by low Ri values. We included this comment and plot in the revision.

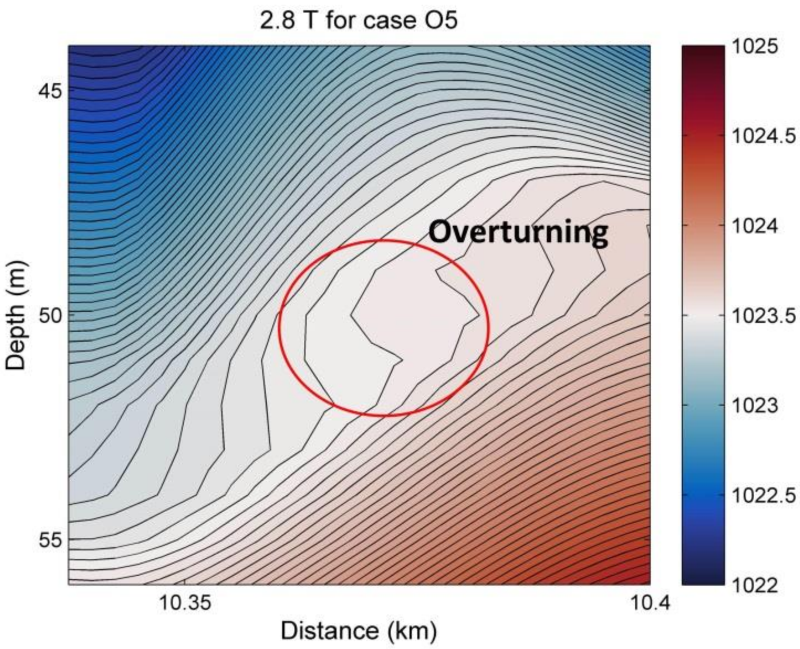

Figure 3. The density contour plot at 2.8 T for the control experiment (case O5).

The related descriptions were added to the revision as follows (see also Page 24, Lines 23 – 24 in the main text):

"*The overturning process in the isopycnal could also be observed in the corresponding low Ri region (Fig. 17).*"

Question 20

Page 19 Line 6 onward. Nice discussion which makes things a lot clearer for the reader, may be this should be given much earlier in the paper.

Response:

Thank you for your constructive suggestion. We have polished the structure of this paragraph and improved the description. It has been repositioned earlier in the revision. (See also Page 23, Lines 1 - 16 in the main text)

Question 21

Page 20 line 2. This is not clear - there was no background shear in the papers cited in line 1. What do the authors mean here by shear?

Response:

This sentence has been revised, and some closely related works have been cited.

The related descriptions were added to the revision as follows (see also Page 24, Lines 2 – 4 in the main text):

"*An oscillating tail induced by shear was also observed in similar studies (Carr* et al.*, 2011, Stamp and Jacka, 1995). The generation of this feature could be related to the shear, and the tail was sustained by continuous energy input.*"

Reference

Carpenter J R, Balmforth N J, Lawrence G A. Identifying unstable modes in stratified shear layers[J]. Physics of Fluids, 22(5): 054104, 2010.

Carr M, Davies P A, Hoebers R P. Experiments on the structure and stability of mode-2 internal solitary-like waves propagating on an offset pycnocline[J]. Physics of Fluids, 2015, 27(4): 046602.

Deepwell D, Stastna M. Mass transport by mode-2 internal solitary-like waves[J]. Physics of Fluids, 28(5): 056606, 2016.

Deepwell D, Stastna M, Carr M, et al. Interaction of a mode-2 internal solitary wave with narrow isolated topography[J]. Physics of Fluids, 29(7): 076601, 2017.

Lamb K G. Energetics of internal solitary waves in a background sheared current[J]. Nonlinear Processes in Geophysics, 17(5): 553, 2010.

Lamb K G. Internal wave breaking and dissipation mechanisms on the continental slope/shelf[J]. Annual Review of Fluid Mechanics, 46: 231-254, 2014.

Lamb K G, Farmer D. Instabilities in an internal solitary-like wave on the Oregon shelf[J]. Journal of Physical Oceanography, 41(1): 67-87, 2011.

Olsthoorn J, Baglaenko A, Stastna M. Analysis of asymmetries in propagating mode-2 waves[J]. Nonlinear Processes in Geophysics, 20(1): 59-69, 2013.

Stastna M, Olsthoorn J, Baglaenko A, et al. Strong mode-mode interactions in internal solitary-like waves[J]. Physics of Fluids, 27(4): 046604, 2015.

Terletska K, Jung K T, Talipova T, et al. Internal breather-like wave generation by the second mode solitary wave interaction with a step[J]. Physics of Fluids, 28(11): 116602, 2016.

Yang Y J, Fang Y C, Tang T Y, et al. Convex and concave types of second baroclinic mode internal solitary waves[J]. Nonlinear Processes in Geophysics, 17(6): 605, 2010.