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Interactive comment on "The role of turbulence and internal waves in the structure and evolution of a near-field river plume" *by* Rebecca A. McPherson et al.

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Response to Reviewer 1 comments on McPherson et al., 'The role of turbulence and internal waves in the structure and evolution of a near-field river plume'– original comments and responses are headed in bold and italics respectively.

Reviewer Summary:
In this paper the authors focus on structure and dynamics of a near-field part of the buoyant plume formed by the jet-like freshwater inflow with high velocity ($>$ 2 m/s) and relatively small discharge rate (500 - 550 m^3/s) into a deep and isolated

fjord. The authors describe elaborate in situ measurements within the near-field plume and provide comprehensive analysis of the momentum budget of this complex dynamical system based on the obtained data. They report several important features registered by in situ data at the river plume including anomalously high stratification, turbulence dissipation rate, and internal stress. They describe an internal hydraulic jump formed within the near-field plume that generates energetic internal waves. The presented study evaluates the components of the momentum and energy budgets of this dynamical system and demonstrates the important role of internal waves in these budgets. The topic addressed in this manuscript and the obtained results are of great scientific and practical interest because similar processes are observed by satellite imagery in many world coastal areas where mountainous rivers inflow to sea and generate internal waves. Due to high quality and importance of the manuscript, I recommend this article to be published in Ocean Science after minor revision. Below I provide general comments and corrections that should be addressed by the authors.

Response:
The authors thank the Reviewer for their time and helpful suggestions for improvement of the manuscript. We were very pleased to see that they believe these results to be 'of great scientific and practical interest because similar processes are observed by satellite imagery in many world coastal areas where mountainous rivers inflow to the sea and generate internal waves'. Below, we have responded to their comments.

Reviewer Comment:
1. One of the main drawbacks of this work is lack of in situ velocity measurements in the surface layer (top 2.5 m), which were linearly interpolated between the 0 m and 2.5 m measurements. However, the largest turbulence stress divergence was estimated to occur in this surface layer (Fig. 7), and these predicted values dominated the along-term momentum balance for the plume and the shear-stratified interfacial

layer along the first 1 km of the transect (Fig. 9). Thus, usage of the linear interpolation for velocity in the top 2.5 m should be more thoroughly discussed and confirmed. This would provide a firm basis for the main results of the manuscript.

Response:
This is an important point and we can provide the confirmation that the Reviewer seeks. In September 2015, a number of near-surface moorings were deployed in the initial 3 km of in the near-field region of Doubtful Sound, which covers the same area as the control volume in this manuscript (Sept 2015 data presented in McPherson et al., 2019). The moorings consisted of high frequency upwards-facing ADCPs at 10 m that measured velocity up to 1.25 m, and velocimeters measured velocity at approximately 0.2 m depth (Fig. 2 of McPherson et al., 2019). The velocity profiles from the base of the plume to 1.25 m were generally straight, and a linear fit to the velocity data to the surface was in excellent agreement with the velocimeter measurements at approx. 0.2 m (see attached figure 1).

Similarly, the velocity profiles for the March 2016 data, on which this manuscript is based, from approx. 4.5 m to 2.5 m were generally straight (Fig. 5b in manuscript). Therefore, a linear fit to the VMADCP velocity data from 2.5 m to extrapolate velocity data to the surface was also applied. The interpolation to the surface also compared well to the velocity measurements derived from the surface drifters deployed at the tailrace discharge point and discussed in the text. Further discussion on these velocity measurements and methods were added to the manuscript, which now reads:

Horizontal velocity estimates were obtained from a 600 kHz ADCP (RDI Workhorse) mounted on a pole alongside the vessel 1 m below the surface (Fig. 3). Currents were rotated according to the local bathymetry to determine along-channel (u) and across-channel (v) velocities. Velocity profiles were generally straight from the base of

the plume to 2.5 m (Fig 5b), thus near-surface velocities were obtained by applying a linear fit to the velocity data to extrapolate from 2.5 m to the surface. The extrapolated velocity profile was in excellent agreement with velocity measurements from the velocimeters moored at 0.2 m. Near-surface velocity also compared well to surface currents derived from a series of Lagrangian GPS drifter experiments, in which a pack of surface drifters, released at the tailrace discharge point, were advected with the mean plume flow for approximately one hour (3 km). Furthermore, in-situ velocity measurements up to 1.25 m were obtained from previous field campaigns (McPherson et al., 2019), and good agreement was found between the linear fit of the extrapolated data at 1.25 m and the measured velocity in the surface layer.

Reviewer Comment:
2. No well-developed hydraulic jump was registered by in situ thermohaline or velocity measurements (e.g., Page 10, line 178-179). The hydraulic jump is predicted to form at a distance of 1 km from the freshwater inflow point (Fig. 6g), however, variability of the plume depth h at this part of the transect (between 3.5 - 4 and 5 m) was relatively low and did not exceed variability of h at the other part of the transect (Fig. 6b). Other characteristics of the plume also did not show any anomalous values near the predicted point of the hydraulic jump. Why the hydraulic jump was not detected by high-resolution in situ measurements? This issue should be addressed in the manuscript.

Response:
The Reviewer correctly points out that there are no significantly anomalous values at the 1 km mark where the transition in Froude number occurs. The tailrace inflow itself is variable (Fig. 2a) and the variability in plume characteristics and vertical structure is high (Fig. 6) (O'Callaghan and Stevens, 2015; McPherson et al., 2019). This high variability in plume structure makes it difficult to identify clearly a hydraulic jump.

However, there are signals in the measurements at 1km that *are* characteristic of a hydraulic jump. The increase in plume thickness at 1 km by almost 2 m (Fig. 6b) was the largest change in plume thickness over the length of the fjord, and is consistent with the thin supercritical flow matching the thicker sub-critical layer. There was also a large decrease in surface velocity from 1.2 to 0.8 m/s (Fig. 6c), and the abrupt deceleration indicates the fast super-critical flow transitioning into a slower sub-critical flow and forming a hydraulic jump. Furthermore, while turbulence dissipation is enhanced throughout the near-field due to shear-stratified mixing (McPherson et al., 2019), a peak in Epsilon > 10-3 W/kg was observed at 1 km (Fig. 6e), suggestive of the intense turbulence generally observed within hydraulic jumps. These points are now clarified in the text, which reads:

Hydraulic jumps have previously been observed in Deep Cove, caused by variable discharge rates, as the fast surface plume discharged into the deep, stationary ambient presents an ideal environment for their generation (O'Callaghan and Stevens, 2015). These jumps can alter the vertical structure of the stratified flow by intensifying density gradients, accelerating the flow and modifying vertical shear (Nash and Moum, 2001). While variability in along-channel plume structure and behavior was high (Fig. 4, 6), thus identifying clearly a hydraulic jump is difficult, changes in the plume structure at 1 km downstream were characteristic of a hydraulic jump. At the jump location in Deep Cove, an increase in plume thickness from 3.2 m to 5 m (Fig. 6b) indicates where the thin near-surface supercritical flow matches the thicker sub-critical layer. While not anomalous, the sudden increase by almost 2 m is the largest change in h over the length of the fjord, and the plume continues to gradually thicken past 2 km downstream. A decrease in surface velocity from 1.2 to 0.8 m/s (Fig. 6c) indicates the abrupt deceleration of the fast super-critical flow as it transitions into a slower sub-critical flow and forms a hydraulic jump. Furthermore, jump-occurrence was corroborated by intense turbulence dissipation in the near-surface (Epsilon > 10-3 W/kg) (Fig. 6e). When flow dominated by kinetic energy (a supercritical flow) transitions into a flow dominated by its potential energy (a sub-critical flow), mechanical energy is released and is either radiated away by internal waves or dissipated locally (Nash and Moum, 2001; Klymak et al., 2004; Osadchiev, 2018).

Reviewer Comment:
3. Internal waves generated by inflow of rivers at high speed to coastal sea are commonly visible at satellite and aerial images. Is it the case of the internal waves generated in the Deep Cove? Did you analyze this kind of data? The paper might be strengthened by the related analysis.

Response:
Due to the steep and narrow topography of Fiordland and Doubtful Sound, and extended periods of cloud cover (there are approximately 200 days/year of rainfall in Doubtful Sound), consistent and reliable satellite images of the plume are not available. However, internal waves propagating away from the plume were identified visually using a shore-mounted GoPro camera (see attached photo). Though interesting qualitatively, using this data quantitatively to add to the current analysis is beyond the scope of this manuscript.

Reviewer Comment:
4. Page 14, line 254. Why the depth of the plume was fixed equal to 2 m, while the depth of the shear-stratified interfacial layer was variable? It seems to be more appropriate to fix the depth of the shear-stratified interfacial layer and have variable plume depth. This point should be clarified.

Response:
While there was pronounced temporal and spatial variability in the vertical structure of the water column (Fig. 5, 6) (McPherson et al., 2019), stratification was used to delineate the distinct surface and interfacial layers from the ambient below. The depth of maximum N^2 best described the base of the interfacial layer (i.e., the base of the plume) (Fig 5a, c). The value of 2 m used to define the surface layer was the thickness of the surface layer in the mean density profile and, having reviewed the individual profiles, this definition of the surface layer was generally appropriate because it agreed with the thickness of the surface layer in a majority of density and stratification profiles. We did trial a threshold value of N^2 = 0.1 s^{-2} for the surface layer but less than 2% of the total measurements changed definition (from surface to interface, or vice versa). As the results did not vary significantly with this N2 threshold, it suggests that for practical purposes the definition of the surface layer at 2 m is reasonable. Certainly the Reviewer's point would hold when looking at longer experiments where seasonal drivers would influence the 2 m scale.

Reviewer Comment:
5. Page 3, line 88 – page 4, line 89. Tidal amplitudes are relatively large, 1.5-2.5 m. What are values of tidal velocities? Do they influence mixing of the near-field part of the plume?

Response:
This is a good point and was addressed in McPherson et al. (2019). The tidal signal was observed during steady tailrace discharge rates in the near-field region of Deep Cove by increases in plume thickness of approx. 0.2 m and velocity of approx. 0.2 m/s (Fig. 2a in McPherson et al., 2019). However, there was no correlation between estimates of turbulence dissipation rates over the surface layer and the tidal phase. Comparable maximum estimates of Epsilon were measured during both the ebb

and flood tide in the near-field plume region (Figure 10b in McPherson et al., 2019). O'Callaghan and Stevens (2015) noted that the headwaters of the fjord absorbed the momentum of tidal oscillations, which would in turn reduce the impact of tides on turbulent mixing in the near field. The manuscript has been amended to address this question, and now reads:

The tides are predominantly semidiurnal with ranges of 1.5 m and 2.5 m for neap and spring tides respectively (Walters2001) however, the headwaters of the fjord absorb the momentum of tidal oscillations (O'Callaghan and Stevens, 2015) thus tides do not influence near-field mixing (McPherson et al., 2019).

Reviewer Comment:
6. Page 9, line 173. Fig 5e -> Fig. 5d

Response:
Noted and changed.

Interactive comment on Ocean Sci. Discuss., https://doi.org/10.5194/os-2019-120, 2019.

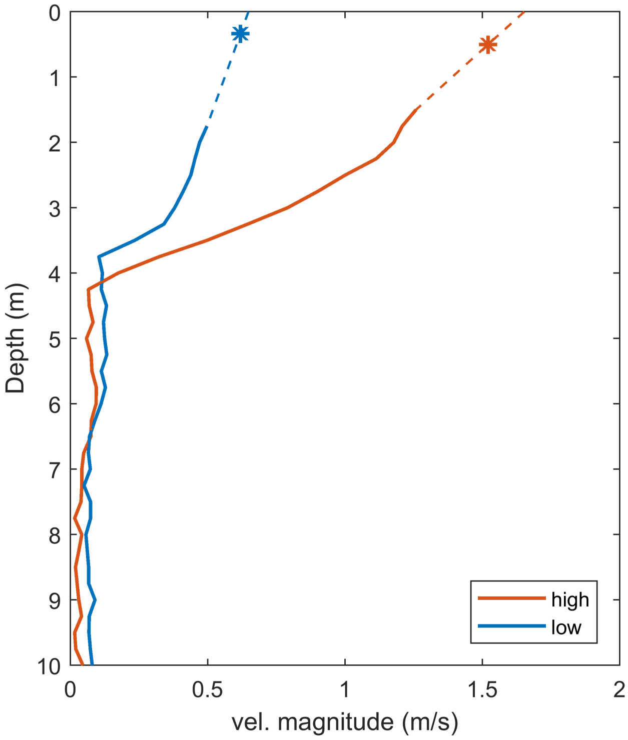

Fig. 1. Linear interpolation of velocity profiles for high (orange) and low (blue) near-surface velocities at 1 km downstream. Velocity from moored ADCP (solid), velocimeter (stars), interpolated (dashed)

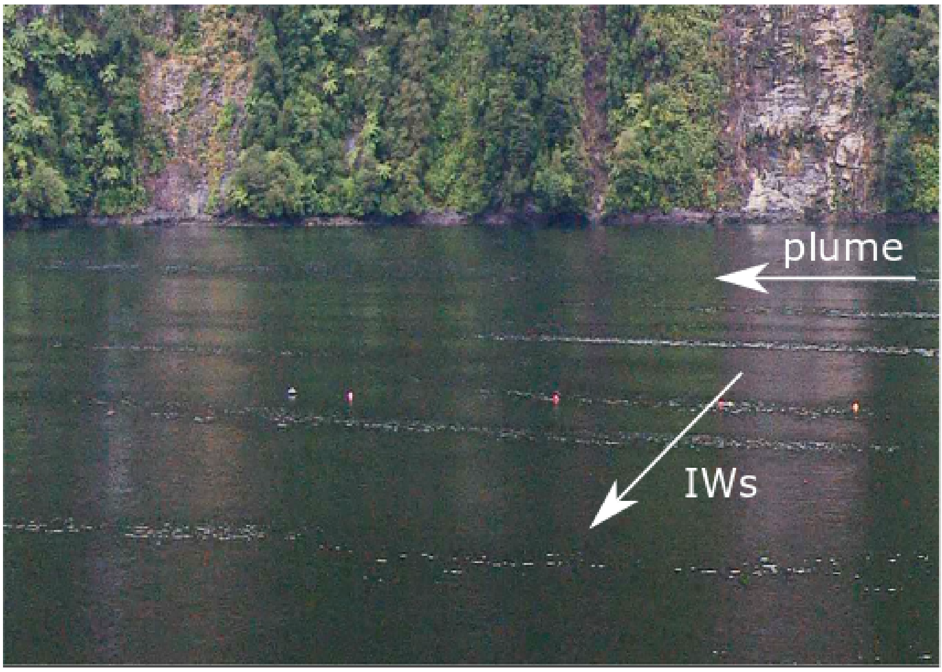

Fig. 2. Internal waves visually identified propagating away from the plume (screenshot from shore-mounted GoPro video)