Revision Notes to Reviewer's Comments

We have completed a major revision of the earlier version of the manuscript by taking into consideration of the response of each of the reviewers. We hope this revised manuscript addresses all the reviewer's comments.

Reviewer's comments and suggestions greatly improved the structure, content, and the quality of this manuscript. We thank the reviewers for their valuable time spend in careful reading and constructive comments and suggestions. Their critiques gave us an opportunity to approach this research problem from various angles and expanded our understanding about the Northwest Pacific Ocean circulation.

The following revision notes explain details of what we have done to address specific comments from the each of the reviewers. *The reviewer's comments are in red text in italics*. Authors response is in black text. *Changes in the manuscript is in blue text in italics*.

Reply to Comments of Reviewer # 2

1 Major comments

"My major complaint with the manuscript is an assumption that JTECH readers will have the requisite background to understand the issues around acoustic travel-times, ray paths, their properties, and working with the data. There are numerous terms and explanations that require more detail for a reader that has never worked with travel-times or ray paths. Line 143 discusses correcting motions and clock drift and tracking receptions. None of these concepts are readily clear from the previous explanation of the array. Adding statements along the lines of "Over hundreds of kilometers in the open ocean with a source at 800m depth, we would expect roughly XX useful ray-paths for the sound to propagate along to the receiver. The typical time is in the hundreds of seconds with variability in the hundreds of milliseconds. This requires accounting for near-precise location and timing between the source and receiver." Simple context will go a long way to help understand many of the issues presented. There seems to be an assumption that the reader is from a different journal..

Section 2, "2010-2011 NPAL Philippine Sea Experiment," has been expanded to provide more background, including details on the expected size of the travel-time perturbations due to ocean mesoscale variability and on the clock and mooring motion corrections applied to the measured travel times.

2 Minor comments

1. Line 141: what are "vortex-induced-vibrations" that impact the mooring and how do they reduce the acoustic reception?

The sentence in question has been replaced by:

The strong currents in the Philippine Sea frequently caused flow-induced vibration of the mooring cables. The hydrophone mounting arrangement did not isolate the hydrophones from the vibrations, and mechanically-induced noise reduced the SNR of the acoustic receptions during these times.

2. Line 237: "The adjoint model simulation..." Given the recent revision to the Gopalakrishnan (2020) manuscript, this sentence and background should be made consistent with the other manuscript.

We revised this sentence as follows:

In order to suppress the growth of nonlinear instabilities with longer integration times of the order of one or two months, diffusivity and viscosity coefficients in the adjoint of the background model were increased [Hoteit et al.(2005), Kohl et al.(2007)]. In addition to increased diffusivity and viscosity, the KPP mixing parameterization is disabled in the adjoint of the background model to minimize its contribution to the system nonlinearity, allowing longer integration times. A more detailed discussion about the choice of the diffusivity and viscosity coefficients in the adjoint model is provided in Appendix B in GG20.

3. Line 251: Why are weekly averages used for comparison? The authors later state tides, etc. are captured (but lacking in the model), so some temporal filtering is required, but why a 7 day average? The response does not have to be a detailed discussion, but simply the reasoning. This is related to the next point.

The following sentence has been added;

The choice of weekly averages is somewhat arbitrary but was made because one week is short compared to the mesoscale eddy timescale of ~ 100 *days [Qiu and Chen(2010)] while not so short as to be redundant.*

4. Line 255: There are multiple discussions about filtering the observed time-series of travel-times. First for model comparison then again for assimilation. The discussion and explanation on the filtering needs to be expanded. In line 288, it is mentioned that "Thirty long-period harmonics" are used to fit. What are these periods? Are they tied to dynamics of the region? Are they based on variability of temperature in the Philippine Sea? What are their range? Why 30? It may require an appendix, but it is important to be transparent on what is done to the observations for comparison and for assimilation.

Section 4a, "Low-frequency Travel-time Variability," has been significantly expanded to more fully describe the procedure used to estimate and remove tidal variability and construct filtered time series of travel times. Several references have also been added.

5. Line 277: The line "The assimilation of travel times..." is a perfectly fine sentence, but–to me at least–I read this statement as the second assimilation (after the Gopalakrishnan (2020) results) as assimilating only the travel-times. Originally, this is implied in the abstract that the second assimilation is of the travel-times and it doesn't impact the other data. From the entire manuscript, it is clear that the assimilation in this paper is repeating Gopalakrishnan (2020) and including the new travel-time data. This isn't fully clear until later in the manuscript.

Thank you for the comment. We clarified this in the abstract and in other sections as below:

The measured low-frequency travel-time series are then used in addition to SSH, SST and Argo temperature and salinity observations to further constrain the model, using the same state estimation procedure as for the non-acoustic data (GG20).

6. Line 295: There is a significant lack of discussion about how the "cost function...was modified to include the misfits..." It doesn't require detail about the actual change, but what precisely is being assimilated and how it is compared to the model? Are the data the travel-times with the harmonics removed? Are these compared against the running 7 day average of the model or at the single observation time? Line 304 states "Considerable care was executed...". What is this sentence supposed to mean when there are no details on what is being done. It is impossible to know if you were careful or not. Line 350: "hindcasts from the ASE were compared". How is this comparison the same or different to NSE, and how is the comparison different from the assimilation of those data themselves?

Thank you for this comment. We overlooked this detail about the travel time cost function. We included a paragraph briefly describing how the model equivalent travel times and cost function are computed.

There are 30 acoustic paths between the six acoustic transceivers, when reciprocal transmissions are included. For each acoustic path, there are multiple ray paths, giving over 341 observed travel times that are included in the cost function. Considerable care was executed to generate sound speeds, construct ray paths, and compute accurate travel times using the model solutions. For the computation of model equivalent travel times, pre-specified ray paths were considered. The steps involved in the travel time cost computation are briefly described below. For each ray path of 341 observed travel times, a ray length of 7000 points were considered and the travel times from the model fields were computed for each ray path by integrating over the ray length, for each day of observation. Each ray path include details of incremental arc length (ds), longitude, latitude, azimuth angle, and water depth. As a first step, three-dimensional fields of model temperature, salinity, and pressure are used to *compute the sound speed (C) following [Del Grosso(1974)] formulation. The sound speed routines are calibrated for a constant density of* rho = $1033 kg\ m^{-3}$ *when computing the pressure term. The model equivalent travel times are computed for each day of travel time observation and for each ray path by integrating the term (ds/C) along the ray length. For that, daily averaged fields of sound speed, zonal and meridional velocities were linearly interpolated, first horizontally and then vertically, for each point along the ray length. The azimuth angle information is used to compute the zonal and meridional velocity contributions to the sound speed. The travel time differences between model and observations for each day and for each ray path were used to compute the acoustic travel time cost function, which is weighted sum of squared model–data differences. An assumed travel time uncertainty of 20 ms is used in the travel time cost function.*

Model hindcasts from acoustic state estimates (ASE) and the first-guess solution initialized using non-acoustic state estimates (NSE) were compared with travel times and shown in Figure 4 for the period 01 May - 30 June, 2010. As expected, the differences are much smaller for ASE than for the NSE simulations. Similar results are found for the other assimilation periods. Also Figure 6 compares the means and standard deviations of the model-data travel-time differences over the 341 measured travel times for both the NSE and the ASE solutions.

Modifying the non-acoustic state estimates to fit the measured travel times in addition to SSH, SST and Argo observations, which were previously assimilated to produce the non-acoustic state estimates, left the individual costs of fitting SSH, SST, and the Argo data essentially unchanged (Figure 5a). The implication is that SSH fields and Argo profiles from the ASE are not expected to differ significantly from those from the NSE. This was in fact found to be the case. .

The ASE and NSE comparisons with SSH and Argo temperature and salinity profiles provided with this reply shows that both solutions are not differing significantly.

7. Line 302: change to "There are 30 acoustic paths between..."

We revised this sentence. Thank you.

8. Line 333: Sentence "The evolution of the cost..." is very awkward. Please rephrase.

We revised this sentence as below:

The cost function descent for the observations using the MITgcm-ECCO 4DVAR iterative optimization is shown in Figure 5a for the same assimilation period of 1 May to 30 June 2010.

9. Line 379: The observations used were SST, SSH, Argo, and acoustic travel-times. In a number of places, you state that there was no change in the other data comparisons between NSE and ASE when using the acoustics in ASE; however, Figure 6 and your *text tells a different story. We see that the profiles particularly 300-800m in temperature are changed quite significantly. This means that your SST didn't change, and since there are so few Argo, any change to them is not going to affect the cost. So, I would say there needs to be a clarification somewhere that mentions that the SST-dominated cost did not change, but this doesn't imply there wasn't a change to the temperature structure.*

Thank you for this comment. We included a paragraph discussing this detail.

Although, the costs of fitting SSH, SST, and the Argo data are essentially unchanged for acoustic state estimation, assimilation of travel times induces changes to the subsurface temperature and salinities within the geometry of the tomographic array as shown in Figures 8 and 9. The pronounced cold bias of ASE when compared to NSE and HYCOM/NCODA in the DVLA comparison for water depths above 500 m *(Figure 7) is perhaps due to the adjustments to the initial condition temperature controls which tend to decrease the NSE temperature structure in the vicinity of the DVLA location.*

10. The comparison work with the DVLA exposes some of the points raised in (9). There are stark changes around the DVLA as mentioned in the text with a cooling in the upper waters. The DVLA, however, is but a single point near the crossover between T2-T5 and T1-T4. So, are these changes unique? One way to examine would be to pick other crossover point(s) and compare the change between NSE and ASE at those locations. Is ASE cooling there as well?

Thank you for this comment. We revised this paragraph discussing initial condition control adjustments for temperature and salinity. We also included a new figure showing spatial distribution of adjustments for initial condition temperature and salinity controls at selected depth levels (Figure 8). This new figure shows that the adjustments tend to decrease the NSE temperatures and salinities, compensating for the subsurface warm bias in the NSE estimates between 500 and 1500 m depth. Figure 8 is also provided with this reply. The revised paragraph is provided below:

The mean adjustments to the temperature and salinity initial condition controls from seven acoustic state estimations covering the entire NPAL experiment period are examined for selected depth levels in Figure 8 and for the zonal and meridional sections across the DVLA mooring (21° *21.7418 N,* 126° *00.7867 E) in Figure 9. The adjustments are confined between 250 and 1750* m *with multiple maximum values centered on depths of about 500 m and 1400 m, for both temperature and salinity. This is expected as the ray path depths are mostly confined in the depth range of 250 to 2500 m for the most of the rays between the transceivers T2, T3, T4, and T5, whereas some ray paths between the transceivers T1, T2, T5, and T6 traces deeper depths in the range 2500 to 4000 m. The spatial adjustments are distributed along the ray paths and are confined to the geometry of the ocean acoustic tomographic array. The adjustments are more or less centered on the locations of acoustic transceivers T1 through T5, for both temperature and salinity, perhaps due to increased ray density at those locations (Figure 8). The temperature and* *salinity adjustments near the location of T6 transceiver are moderate when compared to other five transceivers, likely due to its premature failure. For temperature, the vertical adjustments between 250 and 600* m *are more or less uniformly distributed. The adjustments between 600 and 1750* m *are centered on the locations of acoustic transceivers T5 and T2 for the zonal section, and T1 and T4 for the meridional section, for both temperature and salinity. The adjustments tend to decrease the NSE temperatures and salinities, compensating for the subsurface warm bias in the NSE estimates between 500 and 1500* m *depth.*

11. Line 411 discusses changes confined between 250-1750m. What is the min/max/range of ray paths used? Do they all remain in those ranges? Is the area of enhanced cooling where most rays reflect? This goes back to the major point: there is little discussion about these acoustic data and what they are measuring and doing. By examining other points (see 10), you may start to understand if there is something going on inherent in the assimilation.

Section 2, "2010-2011 NPAL Philippine Sea Experiment," has been expanded to include the following paragraph and a new Figure 3 showing the ray weighting functions for the ray paths for which travel times are shown in Figure 2 has been added. Figure 3 showing the ray weighting functions is also provided with this reply.

The sampling properties of the ray paths are given by the ray weighting functions [Munk et al.(1995)]. To first order, the perturbation in travel time $\Delta\tau_n$ for each path n relative to the travel time in an assumed background sound-speed field C_0 is given by

$$\Delta\tau_n = -\int_{\Gamma_n} ds \frac{\Delta C}{C_0^2} \tag{1}$$

where Γ_n is the ray path in the background sound-speed field, s is arc length, and ΔC is the sound-speed perturbation. The ray weighting function ds/C_0^2 gives the weighting with which ΔC contributes to $\Delta\tau_n$. In general, the background sound-speed field and the sound-speed perturbations vary in both depth and range. The ray weighting functions for the paths for which travel times are shown in Figure 2 are given in Figure 3. Here the weights ds/C_0^2 have been summed in 10-m depth bins between each source and receiver to show the vertical sampling properties of the rays. The ray travel times are most sensitive to sound-speed perturbations at the upper and lower turning depths of the rays.

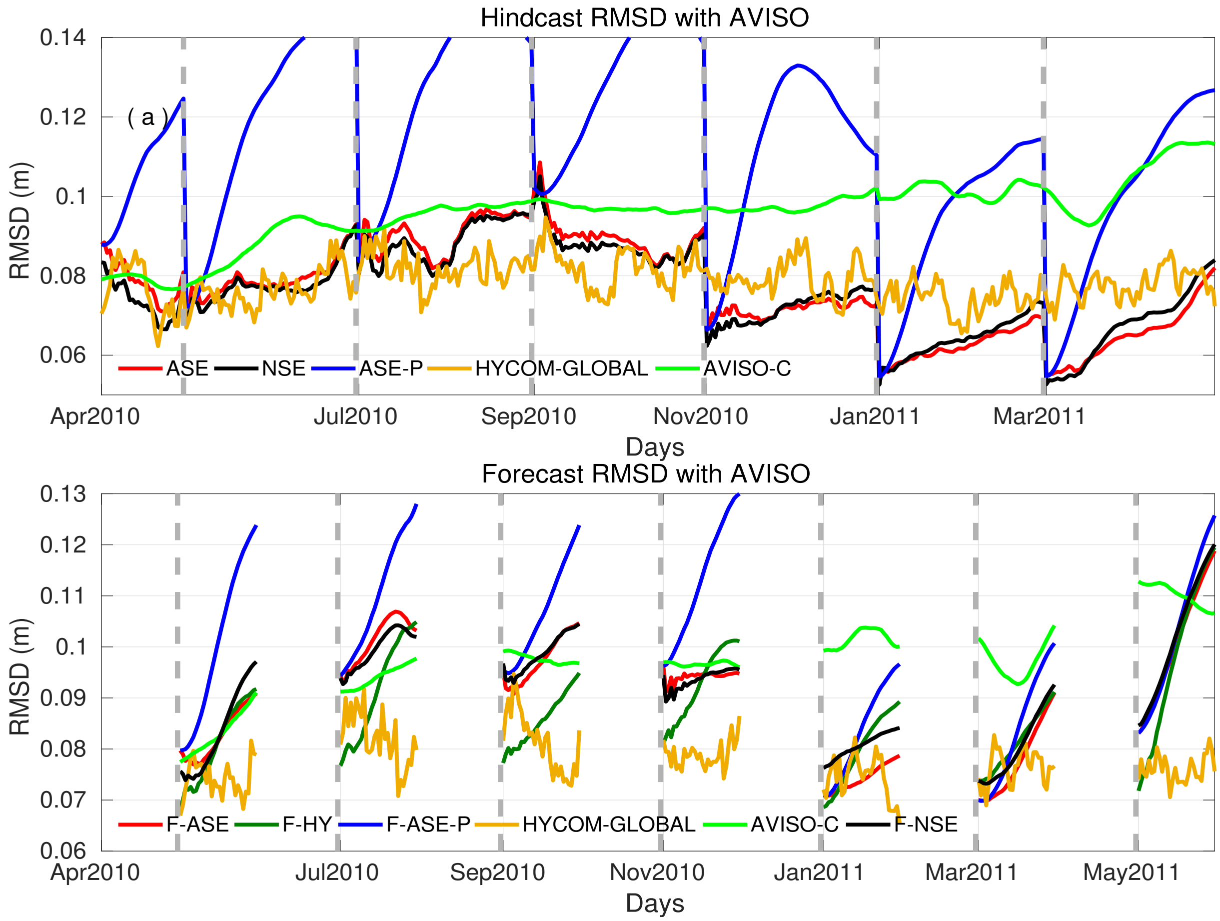

Figure 1: Top panel: SSH hindcast *rmsd* (m) for several different state estimates for the NPAL experiment period. The vertical gray dashed lines separate the state estimates. The *rmsd* is computed with respect to AVISO gridded SSH data over the assimilation region (16°–23°N, 122°–170°E) for the daily averaged SSH fields from the optimized state estimate (ASE: red), model persistence (ASE–P: blue), reference model solution (NSE, from iteration 1: black), HYCOM/NCODA daily global analysis (HYCOM–GLOBAL: golden), and AVISO SSH climatology (C–AVISO: green). Bottom panel: SSH forecast *rmsd* (m) for 30-day forecasts of each state estimate for the NPAL experiment period. The vertical gray dashed lines mark the start date of each forecast. The *rmsd* is computed with respect to AVISO gridded SSH data over the assimilation region for the daily averaged SSH fields from the optimized forecast (F–ASE: red), persistence forecast (F–ASE–P: blue), reference forecast (F–NSE: black), and forecast initialized using HYCOM/NCODA global daily analysis (F–HY: dark green). The *rmsd* for HYCOM/NCODA daily global analysis (HYCOM–GLOBAL: golden) and AVISO SSH climatology (C–AVISO: green) are also shown.

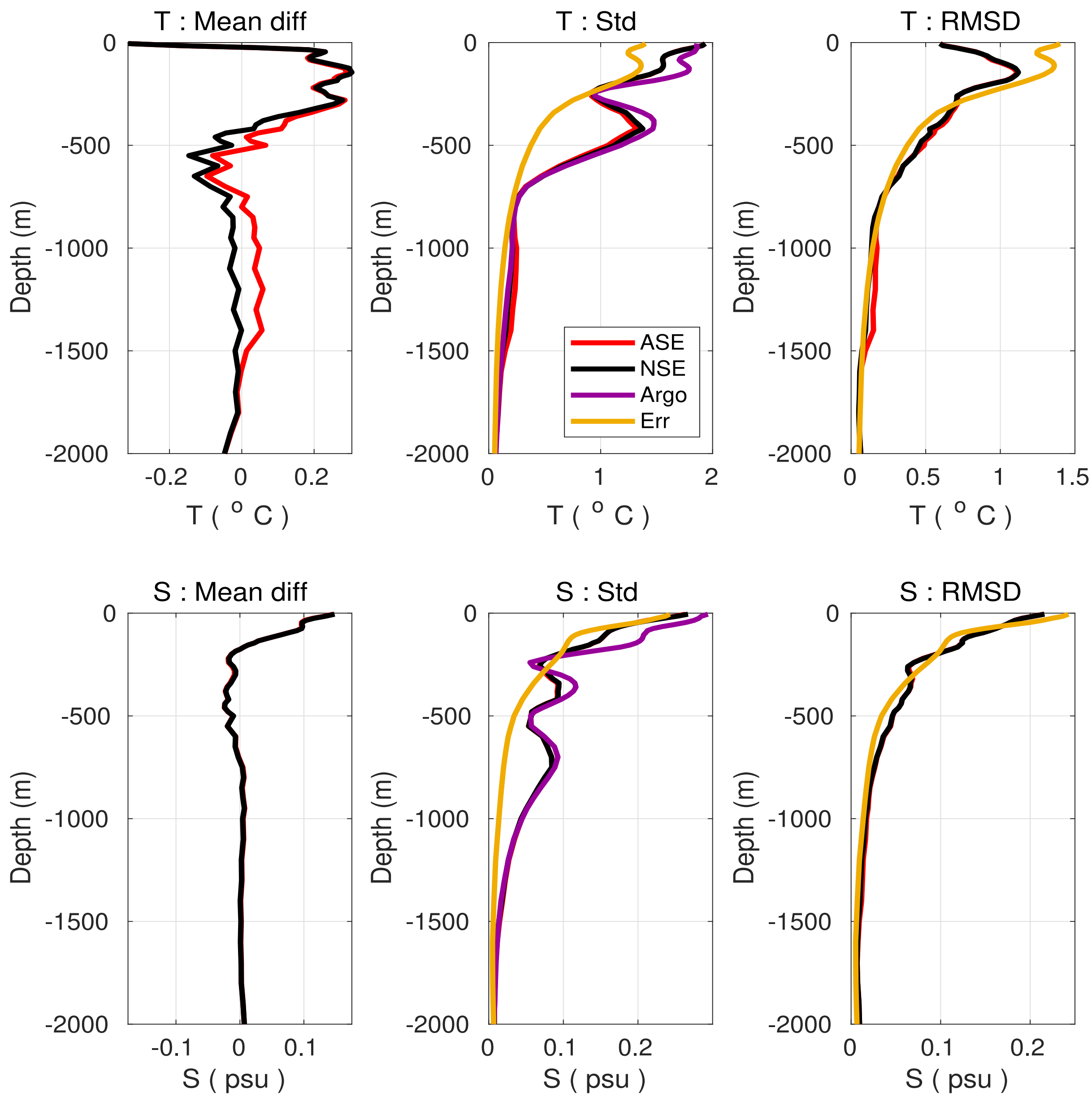

Figure 2: Hindcast Argo comparison. Top panels shows the model–data comparison with respect to Argo temperature data (°C) as functions of depth, with left panel showing showing mean temperature differences (model–data) for ASE and NSE, middle panel showing standard deviations for ASE, NSE, Argo data, and the standard deviation of the observation uncertainty used in the state estimates, and right panel showing standard deviation of temperature differences (model–data) for ASE and NSE, along with the standard deviation of the observation uncertainty used in the state estimates. Bottom panels are similar to top panels, but show comparisons with respect to Argo salinity data (psu). To show the detailed structure, the x-axis scales are different for each panel

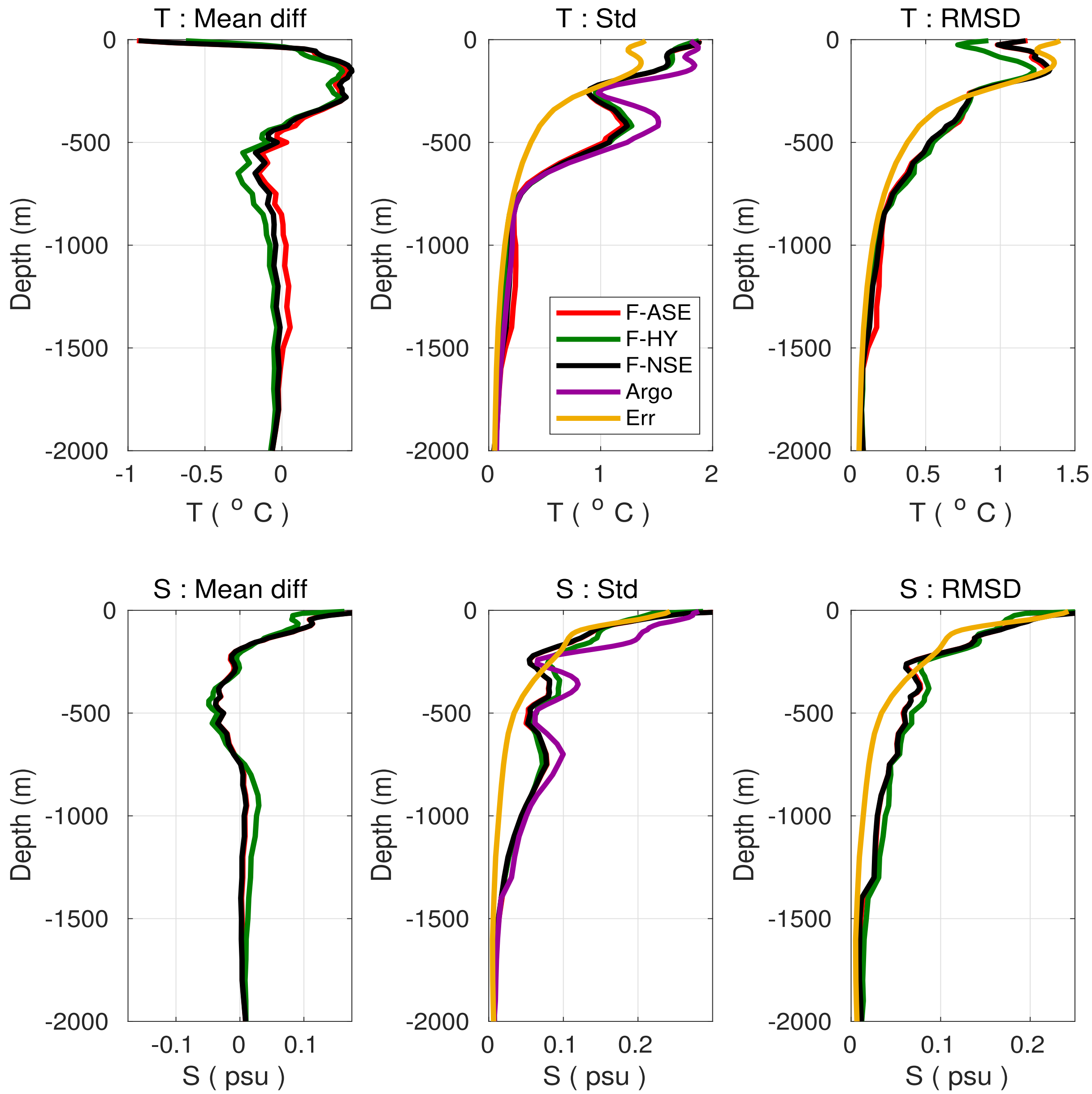

Figure 3: Forecast Argo comparison. Top panels shows the model–data comparison with respect to Argo temperature data (°C) as functions of depth, with left panel showing showing mean temperature differences (model–data) for F–ASE, F–NSE, and F–HY, middle panel showing standard deviations for F–ASE, F–NSE, F–HY, Argo data, and the standard deviation of the observation uncertainty used in the state estimates, and right panel showing standard deviation of temperature differences (model–data) for F–ASE, F–NSE, and F–HY, along with the standard deviation of the observation uncertainty used in the state estimates. Bottom panels are similar to top panels, but show comparisons with respect to Argo salinity data (psu). To show the detailed structure, the x-axis scales are different for each panel

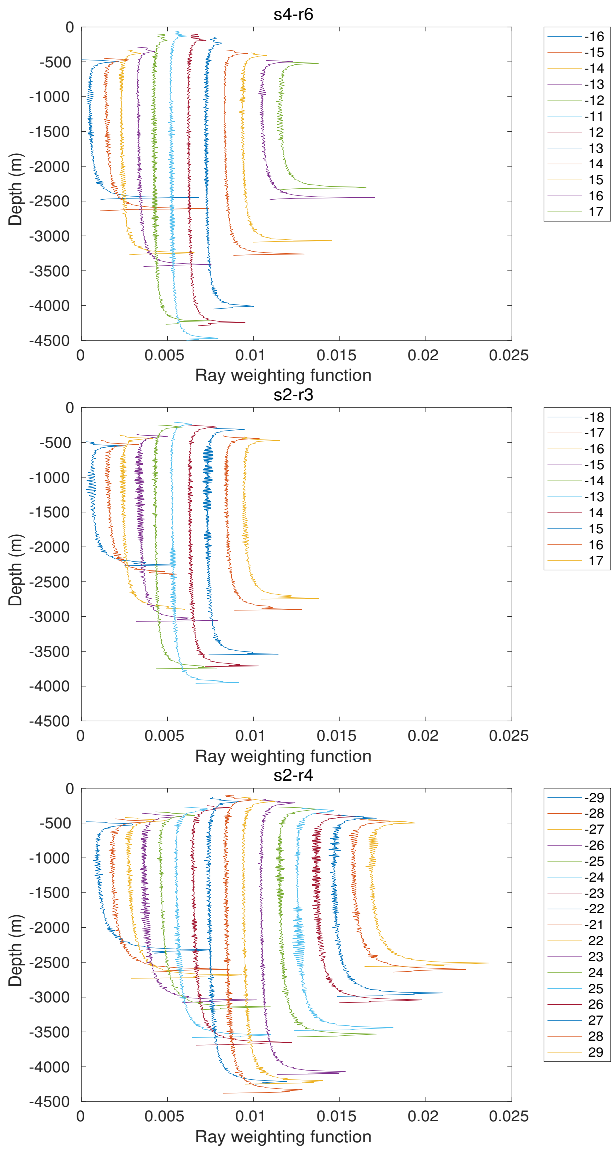

Figure 4: Ray weighting function binned every 10 m depth for different source-receiver pair ray paths shown in Figure 2. The weighting function for each ray path is offset by a value of 10^{-3} in the x-axis to make the rays distinguishable.

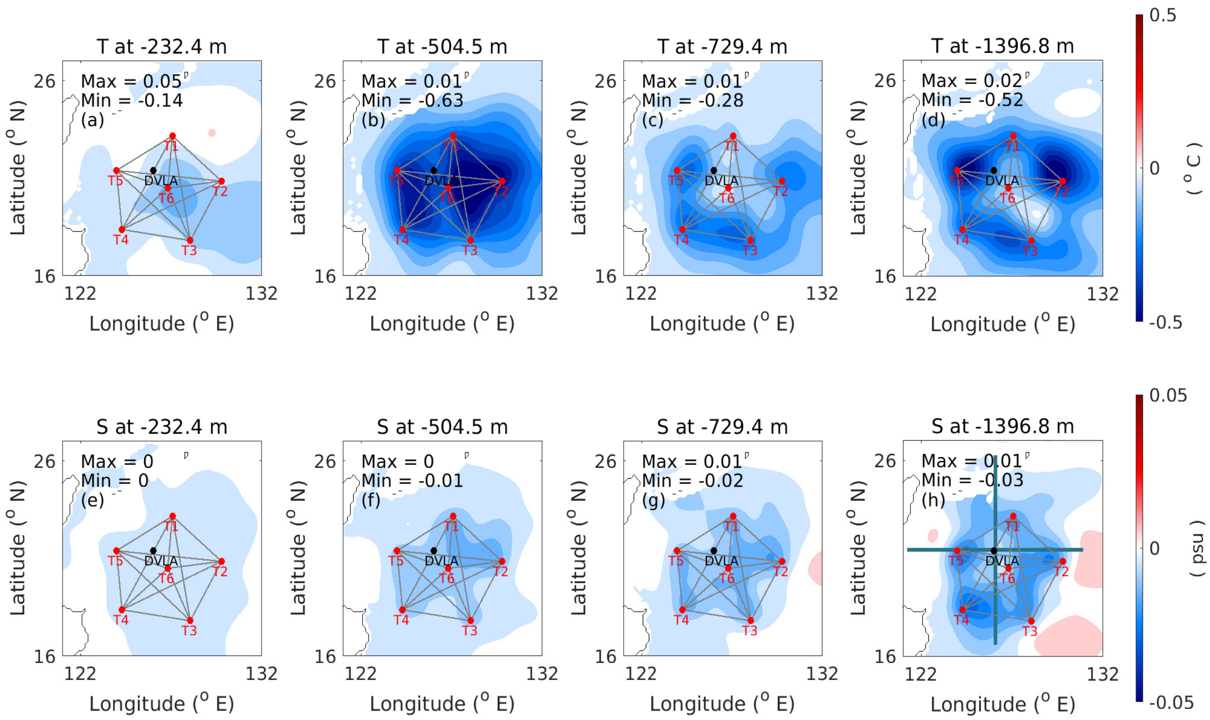

Figure 5: Mean corrections over seven state estimation experiments to the initial condition controls of temperature (top panels) and salinity (bottom panels) for selected depth levels. The location of acoustic transceivers (T1 – T6) and DVLA are marked. The green lines centered on the DVLA location in panel (h) marks the zonal and meridional sections shown in the next Figure. The plots were zoomed to show the geometry of the tomography array.

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