Interactive comment on "Internal tides in the Solomon Sea in contrasted ENSO conditions" by Michel Tchilibou et al.

Response to reviewer 1

Anonymous Referee #1

Overall this is very interesting work and without a doubt will eventually be a solid contribution. The large differences in baroclinic energy between ENSO states is striking. The major area in need of improvement is to provide a quantitative assessment of what has changed the baroclinic energy between ENSO states. There is a change in eddy energy, which is clearly shown. However, the actual path by which baroclinic energy changes is not identified. A model is used and so a definitive answer should be found. See works by Zilberman et al and Rainville et al for some possible methods to evaluate how energy changes during generation and propagation.

Some obvious model-data comparison is missing. Mode 1 and mode 2 energy flux is calculated. The results could be compared to altimetric observations by Zhao et al, although not for different ENSO states. Another point of observational comparison is Pinkel et al who observed internal waves propagating northward from Solomon St. A new mixing parameterisation is used, but not compared to existing methods in this area (Alberty et al).

We would like to thank the reviewer for his careful reading, and we are pleased that our work has been well received.

The reviewer has two main concerns about 1) a quantitative assessment of what has changed the baroclinic energy between ENSO states, and 2) model-data comparison.

Below, we try to answer on the different comments, and to address the two main concerns.

comments by line

55 - Jeffreys 1920 actually first identified marginal seas as likely sites

Thank to cite the geophysicist Sir Harold Jeffreys that we discover. We do not find the reference Jeffreys (1920) to include it in the paper. We think that Munk and Wunsch (1998) is a strong reference for our purpose.

64 - internal waves originating from this topography is also noted by Pinkel et al (1997, doi:10.1029/97gl01610)

Yes, you are right. This reference was cited in Gourdeau et al. (1998). But we modify the corresponding sentence to include it:

Old:"Internal tides have been observed at 2°S-156°E from a TOPEX/Poseidon crossover and a Tropical Atmosphere-Ocean (TAO) mooring, propagating northeastward from the Solomon Islands (Gourdeau et al., 1998). "

→

New: "). Internal tides with phase locked solitary waves have been observed during the COARE experiment, and they appear to propagate northeastward from the Solomon Islands (Pinkel, 1997; Gourdeau et al., 1998).

100 - ": : :first attempt: : :" I'm not sure this is correct or perhaps it's just a poor choice of words. Robin Robertson has several publications in this area and in general there are mixing parameterizations aplenty.

Yes, you are right: this is a poor choice of words.

The sentence has been modified:

Old: "The parameterization described above is a first attempt to take into account…"

→

New: “This tidal parameterization is applied over the entire marginal sea, and aims to take into account the general effects of internal tides in an ocean model.”

103-113 - The references are inappropriate in some cases here and elsewhere in the manuscript. I suggest referencing the first work and then the latest or most important work in these areas:
Altimetry - Ray & Mitchum
Regional models around Hawaii from the HOME experiment - Merrifield and Holloway paper(s) or Rudnick 2003
Indonesia - Robertson as noted earlier
Ok, we check the references, and replace some by your suggestions:

Old: “A global view of their generation, propagation, and dissipation has emerged in recent years, mainly from satellite altimetry observations **(Dushaw, 2015; Egbert and Ray, 2017; Ray and Zaron, 2016; Zhao et al., 2016, 2018**) and global high-resolution numerical models (**Arbic et al., 2010; Müller et al., 2012; Shriver et al., 2012; Simmons et al., 2004, Niwa and Hibiwa, 2014**). A lot of studies focus on the low mode M2 internal tides, and the Pacific Ocean is particularly investigated because of numerous archipelago are sources of internal tide generation. Numerous regional studies based on insitu/satellite data and regional models have documented internal tides at the Hawaiin ridge (**Zaron and Egbert, 2014; Nash et al., 2006; Chavanne et al., 2010; Zhao et al., 2010**), at the Indonesian archipelago (**Nagai and Hibiya, 2015; Nughoro et al., 2017; Koch Larrouy et al., 2015**), at the East China Sea (Niwa and Hibiwa, 2004; Rudnick et al., 2013).”
→
New: “A global view of their generation, propagation, and dissipation has emerged from satellite altimetry observations (**Ray and Mitchum, 1997; Ray and Zaron, 2016; Zhao et al., 2018**) and global high-resolution numerical models (**Arbic et al., 2010; Shriver et al., 2012; Simmons et al., 2004; Niwa and Hibiwa, 2014**). A lot of studies focus on the low mode M2 internal tides, and the Pacific Ocean is particularly investigated because of numerous archipelago are sources of internal tide generation. Numerous regional studies based on insitu/satellite data and regional models have documented internal tides at the Hawaiin ridge (**Merrifield and Holloway, 2002; Nash et al., 2006; Chavanne et al., 2010; Zhao et al., 2010**), at the Indonesian archipelago (**Robertson and Ffield, 2008; Nagai and Hibiya, 2015; Nughoro et al., 2017**). “

111 - East China Sea is irrelevant here. I don’t know of any tidal studies in the SW Pacific myself, but it would be better to say “As far as we know, no dedicated studies: : :”
Words on the East China Sea has been suppressed
Yes, we agree with your suggestion. The sentence has been changed accordingly.
Old:” No dedicated studies have focused on internal tides in the South West tropical Pacific despite high semi diurnal baroclinic tidal energy (**Niwa and Hibiwa, 2011; Shriver et al., 2012**).”
→
New:”As far as we know, no dedicated studies have focused on internal tides in the South West tropical Pacific despite high semi diurnal baroclinic tidal energy (**Niwa and Hibiwa, 2011; Shriver et al., 2012**).”

121 - There are again older references on incoherent tides - Munk and Colosi 1998(?)- and observations showing the deflection of internal tide trajectories - Rainville et al 2003(?).
We don’t find the Munk and Colosi (1998) reference but a Colosi and Munk (2006) paper that effectively deals with the temporal modulation of internal tides by the time-variable density structure from a long time series at the “Venerable Honolulu tide gauge”. We add this reference:
→ “ Several mechanisms contribute to the incoherence of internal tides. First, the internal tide generation may vary in time due to local changes in stratification (**Colosi and Munk, 2006**; Chavanne et al., 2010).”

124 - reference?

We add two references: Ponte and Klein (2015) and Zilberman et al. (2011):

→"Second, the propagation of the low-mode internal tides is modulated by spatial and temporal variability in stratification, currents, and vorticity with detectable changes in tidal SSH (Zilberman et al., 2011; Ponte and Klein, 2015)."

199 - Vertical modes are invalid over sloping topography.

Sloping topography is mostly an issue for w-modes (bottom boundary condition), but not really for u-modes and p-modes (which are the base modes for tidal energy budget). In addition, the w bottom boundary condition (w-BBC) fails only if significant internal tide currents meet a sloping topography, which occurs only on some locations. Finally, the w-BBC does not fundamentally alter the w-mode profiles. So, despite its limitation, the vertical mode approach remains the most efficient ones to separate barotropic and baroclinic dynamics.

210- Here and elsewhere, subscripts are traditionally used.

Ok, done

221 - Nonlinearity of the internal tide in this area is not necessarily small. Large amplitude internal waves are generated (Pinkel et al, 1997). In areas with shallow topography, tidal harmonics are often noted elsewhere.

Regarding this matter, we would like to distinguish between non-linear wave and energy transfer from linear to non linear tides. In particular, we believe that large non-linear internal wave generation does not mean that energy transfer from linear to non-linear tides is also large. We suspect that the reviewer writes about solitary waves that cannot be simulated in such non hydrostatic model. In the paper we refer to the energy equation for baroclinic tides.

231 - Is this not just C = wp' ? Surely there is an earlier reference.

Yes, the conversion term is often written as you suggest but the underlying hypothesis is that w=u(barotrope) grad h. Here we don't degrade the expression that is rigorous when using a modal approach (Kelly and Nash, 2010)

We change the reference Nugroho (2017) to that of Kelly and Nash (2010)

- ➔ "It is defined as in Kelly and Nash (2010):"

231b - Also this relation is often linearized. Is that the case here? wp' is evaluated at a constant depth level z = 0 (neglecting any topography and where the surface would be at z = h). z=-h and grad_h is a bit confusing. Maybe the depth could be H.

In our case the relation is not linearized, and the w is taken at the bottom, z=-h. We agree that the convention H for the bottom topography would be better and we applied it at all equations. Also we change grad_h by ∇H (see following comment)

236 - Please proofread all your equations here and elsewhere and use accepted mathematical notation. Alternate or non-traditional notation distracts unnecessarily. Use nabla ndot vector{F}_{bt}. dz is missing too. Same for tidal components such as M_2 and K_1. Using an overbar for barotropic is unusual and with velocities is taken to mean vector. Are you only considering the u component of velocity or is u intended to be a vector?

Ok, we try to use more traditional notations but such notations vary a lot with papers.

The use of "bt" and " bc" are classically used (e.g. Niwa and Hibiwa, 2004)

We use them now as subscripts.

F, D, and C are also classically used for flux, dissipation, conversion (e.g. Buijsman et al., 2017)

We express the conversion term as in Kelly and Nash (2010).

The divergence of the energy flux is expressed as in Nagai and Hibiya (2015).

M2 and K1 are rewritten in the text as M_2 and K_1.

Old:

"The generation, propagation, and dissipation of the barotropic and baroclinic tide is investigated with the time-averaged and depth-integrated barotropic and baroclinic energy equation (Niwa and Hibiya, 2004; Carter et al., 2008; Nagai and Hibiwa, 2015, Simmons et al., 2004; Buijsman et al., 2014, Nughoro et al. 2017]. In each barotropic and baroclinic equation, the depth-integrated energy is partitioned into tendency, flux divergence, non-linear advection, barotropic to baroclinic conversion, and dissipation. We can ignore the rate of change term as the period of averaging (month and year) makes this term orders of magnitude smaller than the other terms in equations (1 & 2). Similarly, the internal-tide self-advection is also small (Simmons et al., 2004; Buijsman et al., 2014). The non-linear advection terms are assumed to be small in both the barotropic and baroclinic equations. This means that little energy is transferred between tidal harmonics. The equations resume to:

$$\nabla.\mathrm{Fbt} + \mathrm{Dbt} + \mathrm{C} = 0 \quad (1)$$
$$\nabla.\mathrm{Fbc} + \mathrm{Dbc} - \mathrm{C} = 0 \quad (2)$$

Where bt indicates the barotropic term and bc indicates the baroclinic terms, F=(Fx;Fy) are the fluxes in the x(east-west) and y(north-south) directions, D is dissipation, and C is the barotropic to baroclinic energy conversion. D is computed as the residual of the flux divergence and conversion terms. The conversion term is identical in the barotropic and baroclinic equations; and it appears as a sink in the barotropic equation and a source in the baroclinic equation. It is defined as in Nughoro et al. (2017):

$$C = (\bar{u}p')_{z=-h}\,\nabla_h d$$

Where p' is the perturbation pressure, $\bar{u}$ is the M2 harmonic fit for the barotropic velocity, h the bottom depth, and d is the total depth (d=h+η, η the surface elevation).

The propagation of barotropic and baroclinic tides are examined through the divergences of the barotropic (Fbt) and baroclinic (Fbc) energy flux, respectively, and defined as in Nughoro et al. (2017):

$$Div(Fbt) = \int_d^\eta \nabla_h\,\overline{up}$$
$$Div(Fbc) = \int_d^\eta \nabla_h\,u'p'$$

The overbar sign is for barotropic velocity (u) and pressure (p), and u', p' is the velocity perturbation and pressure perturbation, respectively."

→

New:

" The generation, propagation, and dissipation of the barotropic and baroclinic tide is investigated with the time-averaged and depth-integrated barotropic and baroclinic energy equation (Niwa and Hibiya, 2004; Carter et al., 2008; Nagai and Hibiwa, 2015, Simmons et al., 2004; Buijsman et al., 2017). In each barotropic and baroclinic equation, the depth-integrated energy (E) is partitioned into tendency, flux divergence, non-linear advection, barotropic to baroclinic conversion, and dissipation. We can ignore the rate of change term since the short averaging period (3-months and 3-years) makes this term orders of magnitude smaller than the other terms. Similarly, the non-linear advection terms are assumed to be small in both the barotropic and baroclinic equations (Simmons et al., 2004; Buijsman et al., 2017). This means that little energy is transferred between tidal harmonics. The equations resume to:

$$\nabla.\mathbf{F}_{\mathrm{bt}} + D_{\mathrm{bt}} + C = 0 \quad (1)$$
$$\nabla.\mathbf{F}_{\mathrm{bc}} + D_{\mathrm{bc}} - C = 0 \quad (2)$$

Where bt indicates the barotropic term and bc indicates the baroclinic terms, **F**=(*Fx*; *Fy*) are the fluxes in the x and y directions. Dissipation (D) is computed as the residual of the flux divergence and conversion (C) terms. The conversion term is identical in the barotropic and baroclinic equations; and it appears as a sink in the barotropic equation and a source in the baroclinic equation. It is defined as in Kelly and Nash (2010):

$$C = \nabla H . \overline{\mathbf{U}_{\mathrm{bt}} p_{\mathrm{bc}}}|_{z=H+\eta} \qquad [\mathrm{W/m^2}] \qquad (3)$$

Where $\mathbf{U} = (U,V)$ is the surface-tide velocity with components U and V along the x and y directions, p is the baroclinic pressure, the overbar indicates a tidal average, z = H defines the bottom, ∇H is the topographic gradient, and η is the surface elevation.

The propagation of barotropic and baroclinic tides are examined through the divergences of the barotropic ($\mathbf{F}_{\mathrm{bt}}$) and baroclinic ($\mathbf{F}_{\mathrm{bc}}$) energy flux defined as in Nagai and Hibiya (2015):

$$\nabla . \mathbf{F}_{\mathrm{bt}} = \nabla_h . \int_H^\eta \overline{\mathbf{U}_{\mathrm{bt}}\, p_{\mathrm{bt}}}\, dz \qquad [\mathrm{W/m^2}] \qquad (4)$$

$$\nabla . \mathbf{F}_{\mathrm{bc}} = \nabla_h . \int_H^\eta \overline{\mathbf{U}_{\mathrm{bc}}\, p_{\mathrm{bc}}}\, dz \qquad [\mathrm{W/m^2}] \qquad (5)$$

Where ∇_h is the horizontal divergence.

250 - Complex demodulation or a wavelet transform would be a better way to determine the incoherent fraction.

We agree that complex demodulation is well adapted to analyze the variability of internal tides. Because most of the diagnostics on tides are based on harmonic analysis we don't use a complex demodulation method. We use a similar methodology than Buijsman et al. (2017) or Kumar et al. (2019) that estimate the incoherent fraction as the difference between the band-passed and harmonic times series.

291 - cm^2/s^2 - please use SI convention cm^2 s^-2 or even better 0.2 m^2 s^-2 in this case
Fig 3 - Cm is incorrect, cm is correct. Use letter labels to identify panels.
Fig 4 - psu or S (psu) would be better.
What are the black contours?

Ok, the references have been corrected

Thanks, we have forgotten to mention the black contours in the reference. These contours are just here to highlight the 23.5 and 25.5 density level that characterize the upper thermocline layer.

323 - Looks to me more like a NE-SW propagation direction. Perhaps a section in that direction would be better.

Yes, the beam of internal tides is not purely meridional, and the sentence has been changed.

Old: "Because the internal tide propagates meridionally across the central Solomon.."

→

New: "Because the internal tide propagates mainly in the meridional direction across the central Solomon…"

May be it could be a little bit better to use a more complex section than just a meridional one crossing the Solomon Sea from the two generation sites. But we don't think it changes our messages. There are two Figures that illustrate this section. Figure 4 that is used to validate the mean model state and to illustrate the contrast between the two ENSO phases. For this purpose, the choice of the section is not so crucial. Figure 11 shows the meridional flux along the section. The purpose is to illustrate the contrast between El Nino and La Nina for the northward and southward flux inside the Solomon Sea. The last remark of the review is about this figure which shows a flux of same sign on both sides of the topography at Solomon strait. But the strait is large and to the north east there are seamounts (e.g. Fig. 1) and strong internal tide generation propagating on each side (e.g. Fig. 9). We suspect a northward flux to cross the section as suggested by the plot. So we choose to keep this section because we are not sure to find a more suitable section.

326 - CARS is nonstandard climatology. Please explain in methods/data section.
Ok, we add a paragraph on the method/data section

New: "2.2 CARS climatology
CARS is a global ocean climatology on a ½ degree grid of seasonal ocean water properties delivered by CSIRO (www.cmar.csiro.au/cars). CARS differs from other climatologies as it employs extra in-house quality control of input data, and the mapping algorithm uses an adaptive-length scale loess filter to maximize resolution in data-rich regions, and takes into account topographic barriers. The result is an improved definition of oceanic structures and more accurate point values (Dunn and Ridgway, 2002). The CARS climatology will be used to provide some model validation, given the short period of the simulation including two extreme events."

353- Upper ocean N^2 has been mentioned. What about deep N^2? Seems pretty similar and unlikely to affect generation?
Generation occurs mainly in the higher part of the ocean (where geometrical constriction due to topography will trigger the most significant vertical velocity/isopycnal displacements), allowing for changes in internal tide generation (magnitude, mode spectra) even with deep stratification being the same.

Fig 7 - Bathymetry source could be acknowledged or mentioned in the methods section. I does not have to be included in figures: "Isobathymetric lines are from the NOAA/ETOPO2v2 bathymetric file from the Smith & Sandwell database (doi:10.7289/V5J1012Q)"
We agree with you but it is a request of the editor
Fig 7 - I'm not sure a comparison to a nested model is that valuable. Validation with tide gauges or some other data source is better.
The model is forced only at its boundary with FES2014, so it is an essential step to ensure that inside the Solomon Sea the barotropic tide from the model looks like FES2014. It is not really a validation step.
What could be seen as a validation is the comparison of the baroclinic tide from the model with results from altimetry: the figure 8. But the variation of the results over two different periods prevents us from using this as a real validation.
There are very few in situ data available to validate the high frequency signal from the model. We present below some works using different in situ data sources that have been published in the Tchilibou's thesis (http://thesesups.ups-tlse.fr/4209/), but we don't include this work in the paper because we want a reasonable size for the paper, and this part does not bring new physical elements. We just add a sentence in section 2.2 to mention this work:
"Very few in situ data exist to validate the high frequency signal from the model. Some comparisons with tide gauges and a mooring at Solomon Strait present satisfactory results (e.g. Tchilibou, 2018a). "

We looked at the tide gauge located at Honiara during the common time period with the model (Fig. 1). The two SSH time series look alike very much despite a little bit lower standard deviation in the model compared to the tide gauge (16,47 cm and 17,19 cm, respectively) as shown by their SSH frequency spectra. Both spectra exhibit similar peaks at tidal frequency.

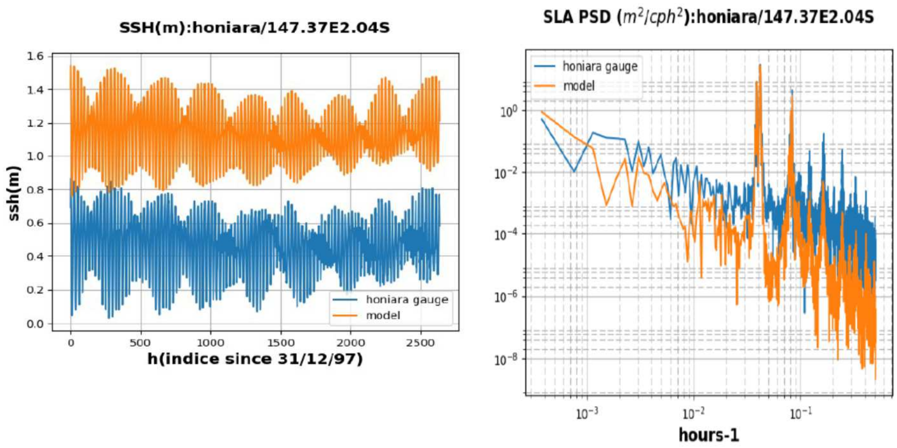


Figure1:Left) SSH time series at the location of the Honiara tide gauge for the model (orange) and the in situ data (blue). Right) the corresponding frequency spectra

Some moorings have been deployed/recovered in the Solomon Sea during the Pandora and MoorSpice cruises in 2013/2014. Only one mooring located at Solomon strait (5,14°S-154,3°E) can be used to infer internal tides. Despite different time periods between the model and the mooring, we can try to compare both. First, the frequency spectra of potential density in the thermocline layer look similar (Fig. 2). The semi diurnal frequency with the M2 component is the most energetic signal. The baroclinic energy flux estimated from the mooring clearly shows the dominance of mode 1 and a South West propagation in accordance with the model results (e.g. Fig 9, 10).

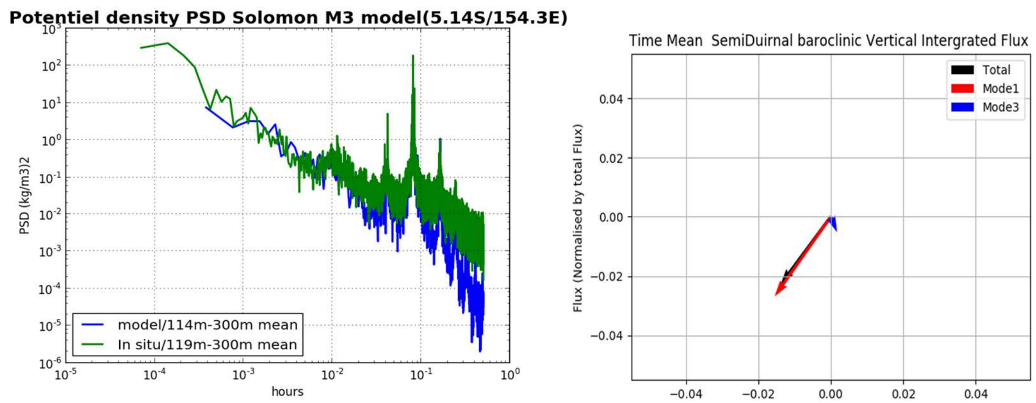


Figure 2: Left) Frequency spectra of the potential density in the thermocline layer at the mooring location at Solomon strait for the model (blue) and in situ data (green). Right) Estimation of the depth integrated M2 baroclinic energy flux from the in situ data (To be compared with model results in Fig. 10 of the paper.

388 - I don't understand this point about coherent SSH being used to correct altimtery. (1) Correct what? (2) Altimetry measures total SSH = coherent internal tides SSH + incoherent internal tides SSH + everything else. Or are you talking about correcting the M2 amplitude?

Yes, we are talking about a M2 amplitude correction in the altimetric data set including both the barotropic and the coherent baroclinic components.

We modify the sentence:

"we access only the coherent part of the internal tides that has the advantage to be predictable, and so provides a correction for altimetric measurements." →

"we access only the coherent part of the internal tide that has the advantage to be predictable, and can thus provide a SSH correction for altimetric measurements."

393 - Solomon Strait not Solomon strait. Also elsewhere.
Ok, we check

403- What is the surface displacement of a mode 1 tide of 10-m amplitude under the conditions in Fig 5? What do the modes for these conditions look like at the generation site? Is the mode-1 maximum aligned with topographic height in some way?
The reviewer addresses several questions on the modal decomposition at the generation sites under the contrasted El Nino/La Nina conditions, and the propagation of mode 1.
For this last point it is expected that mode1 propagate from its source orthogonally to the bathymetry. It is what we observe at Solomon strait by example: The bathymetry is oriented in the northeast/southwest direction (see Fig.1 of the paper) and the mode energy flux is observed to be southwestward (see the plot above).
For the other point, we have performed a modal decomposition of the density energy that is discussed below in 504, 670 and 697.

414 - strong flow is generally associated with high Reynolds number which is generally more turbulent and not more laminar: : :? Perhaps you want to rephrase in terms of mesoscale eddy activity.
Yes, we agree that the sentence needs to be rewritten
Old: "During El Niño, when the LLWBCs are strong and the flow relatively laminar, the coherent baroclinic tides explains 67% of the variance of the full internal tides, and only 50% during La Niña when mesoscale is strongly active."
→
New: "During El Niño, when the LLWBCs are strong and stable and dominate the circulation, the coherent baroclinic tides explains 67% of the variance of the full internal tides. Whereas during La Niña, when the mesoscale activity is stronger because of the interactions between the LLWBCs and the SSI, only 50% of the baroclinic tide is coherent."

Fig 9 - units need a space kW[space]mˆ-1 for example
Done

435 - Do Zhao et al have altimetric fluxes in this area? How do they compare to the model? I believe Zhao now uses modes 1 and 2 in his calculations.
Yes, Zhao's results (2016, 2018) should be valuable sources of information. In this paper, we have used Ray and Zaron's results to compare to the model. It could be a good opportunity to look at Zhao's dataset. We will try to do that in the next time.

470 - doubles is not accurate
Ok, the text has been modified
Old: "The baroclinic flux radiating out of the box doubles during El Niño (1.27 GW against 0.75 GW strait during La Niña)"
→
New: "The baroclinic flux radiating out of the box increases during El Niño (1.27 GW against 0.75 GW strait during La Niña)"

479 - The overall difference in internal tide energy and dissipation between the 2 states is established nicely. The explanation though is not so clear.
This remark was also done by reviewer 2.
We have rewritten this summary, and hopefully it is now clearer:

Old: "In summary, there are three areas where a large part of the barotropic flux energy is converted into baroclinic energy (63 to 79%), and a considerable fraction of the excited baroclinic energy is dissipated locally (46 to 80%). The two main generation sites radiating baroclinic tidal energy into the Solomon Sea are at Solomon strait and at the Southeast extremity of PNG. The generation box at Solomon strait radiates most of the baroclinic energy, especially during the La Ni.a state with a 27% increase of the energy flux compared to El Ni.o. There is a strong modification of the circulation at this site between the two periods, since the strong northward LLWBC current exiting the Solomon Sea during El Ni.o is replaced by the southward SSI current during the La Ni.a period that favors the advection of the tidal baroclinic energy inside the Solomon Sea. Most of this baroclinic energy is dissipated in the northern Solomon Sea as illustrated by Figure 9f, showing higher dissipation in the northern Solomon Sea during La Ni.a compared to El Ni.o. Indeed, the higher EKE level during La Ni.a than during El Ni.o (Fig. 2) favors stronger interactions between eddies and internal tides. This appears to render the internal tide more incoherent (e.g. Fig. 3gh) and to increase the tidal dissipation. The impact of ENSO is particularly visible at the southern Solomon Sea with a 70% increase of the baroclinic flux radiating away from this generation site during El Ni.o compared to the La Ni.a period. The EKE is strongest in this area duringLa Ni.a with higher dissipation and in consequence, there is a lower baroclinic energy flux radiating away."

→

New: "In summary, there are three areas where a large part of the barotropic flux energy is converted into baroclinic energy (63 to 79%). Most of the excited baroclinic energy is dissipated locally (46 to 80%), and only two generation sites at Solomon Strait and at the Southeast extremity of PNG radiate significant baroclinic tidal energy into the Solomon Sea.

Solomon Strait radiates most of the baroclinic energy into the Solomon Sea, especially during the La Niña state with a 27% increase of the energy flux compared to El Niño. Most of this baroclinic energy is dissipated in the northern Solomon Sea as illustrated by Figure 9f, with higher dissipation here during La Niña compared to El Niño. This is likely to be impacted by the contrasted circulation and mesoscale activity in this area between the El Niño and La Niña periods. The strong northward LLWBC current exiting the Solomon Sea during El Niño is replaced by the southward SSI current during the La Niña period (see Fig. 2) that favors the advection of the tidal baroclinic energy inside the Solomon Sea. Also, the higher EKE level during La Niña than during El Niño (Fig. 2) favors stronger interactions between eddies and internal tides. This appears to render the internal tide more incoherent (e.g. Fig. 3gh) and to increase the tidal dissipation (Fig. 9f).

At the Southeast extremity of PNG (Fig. 9f, blue) crossed by the strong NGCU the tidal baroclinic energy exhibits no contrasted situations between the two ENSO phases."

504 - "One explanation for such a difference is the change in stratification between the two ENSO states, with stratification closer to the surface during El Niño that favors the excitation of higher order modes (Fig. 5)." This explanation is a little vague. You have calculated the various source and sink terms. Which ones does it affect? Once you have determined that, which quantity is affected p' or u' or something else? And by what? Eddies, changes instratification, changes in currents, etc? See: Zilberman et al (2011) doi: 10.1175/JPO-D-10-05009.1â˘A´l

The analysis is limited to the main terms of the energy equations and the respective contribution of the two first modes. It is beyond the scope of this paper to go too much further on the analysis of each terms. As suggested in the next remark, energy density is a helpful scalar to look at the contribution of the modes. We present below the energy density for mode 1 and mode 2 during El Nino and La Nina. We retrieve the result of the paper based on the energy flux that is the dominance of mode 1 inside the Solomon Sea, but also a clear mode 2 propagation during El Nino not visible during La Nina. The difference in mode 2 during El Nino compared to La Nina is mainly the contribution of kinetic energy (KE) and not of potential energy (PE). The large scale condition during El Nino with a stratification close to the surface could favor the propagation of energy by higher modes.

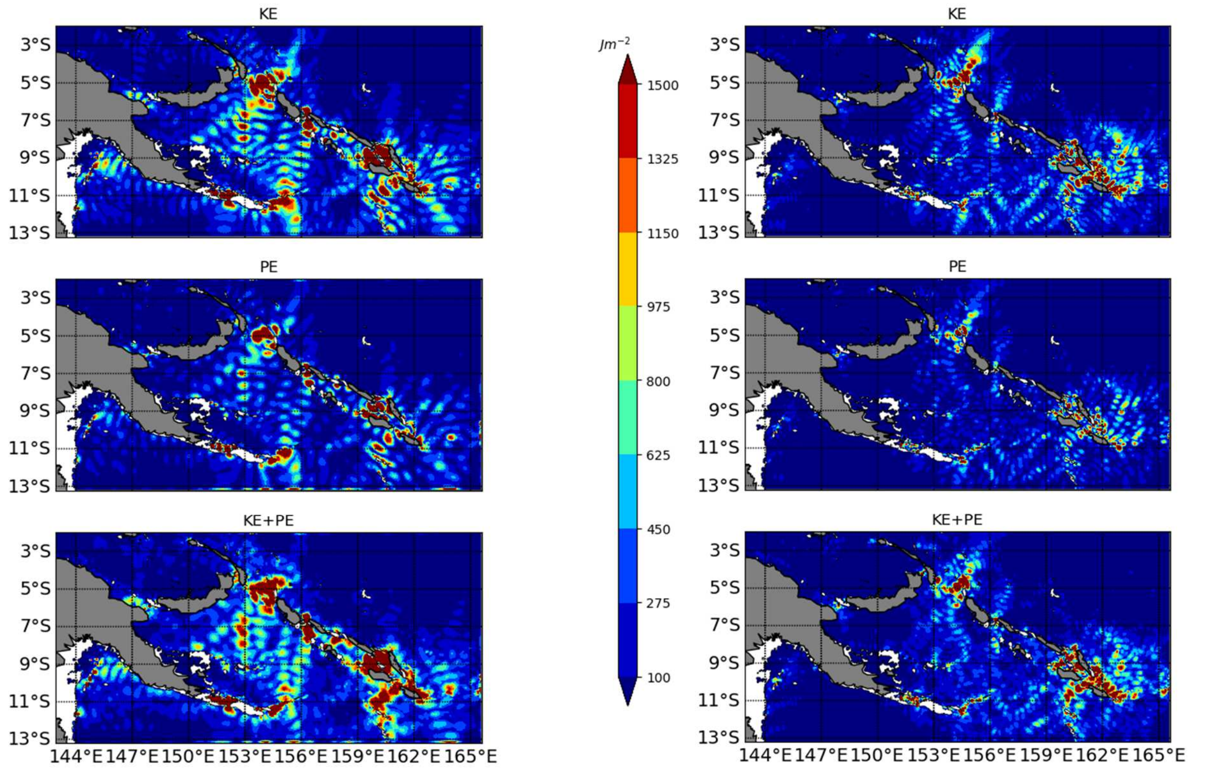


Figure 3: Energy density and the respective contribution of KE and APE during El Nino priod for left) mode 1 and right) mode 2.

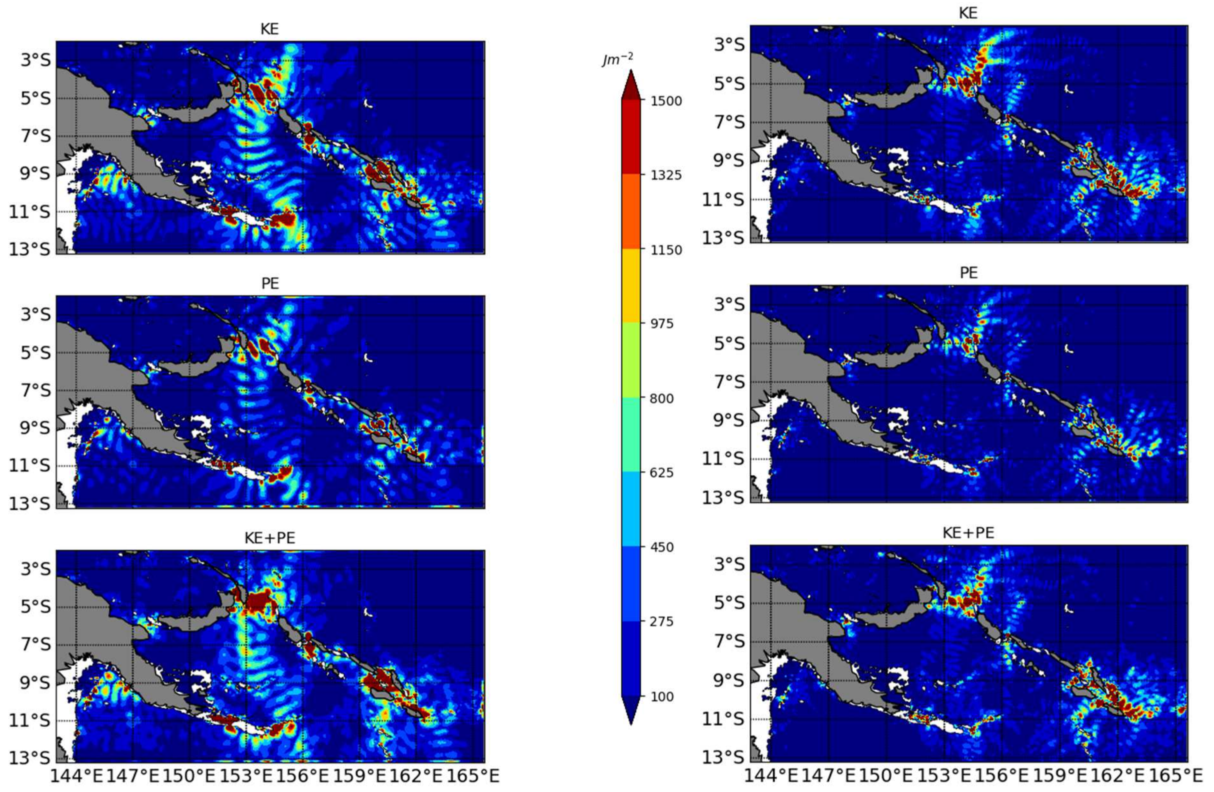


Figure 4: Energy density and the respective contribution of KE and APE during La Nina priod for left) mode 1 and right) mode 2.

670 - This describes energy flux. If you wish to better see the contribution by higher modes, energy density is a helpful scalar. Flux = Energy x c. Fluxes emphasize mode1 because c_1 is about 2 x c_2.

Fluxes near the source regions may be confusinge. g., 2 oppositely directed fluxes give flux = 0 even though there is plenty of energy.

Yes, the discussion is on energy flux. We agree that energy density is well suited to discuss on high modes. This is of particular interest near the source regions where most the energy of the high modes is supposed to locally dissipated. We show above the figures for the modal partition of energy density for modes 1 and 2 during El Nino and La Nina conditions. But we chose not to add this figure in the paper because it doesn't bring new information with regard to Figure 10 (which has been improved to be more readable). Compared to La Nina, we clearly the propagation of mode 2 inside the Solomon Sea during El Nino.

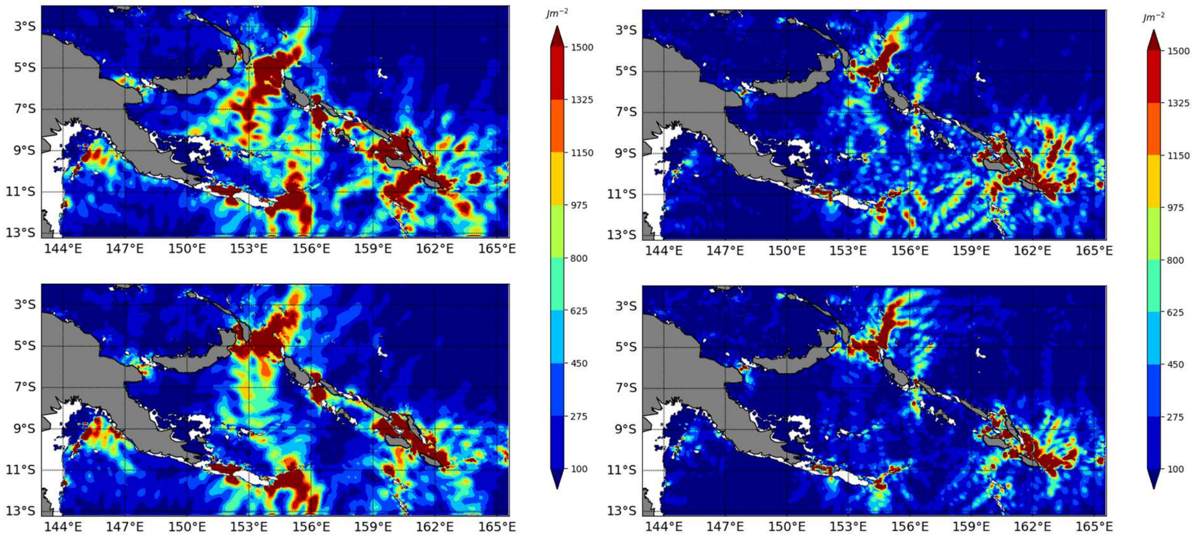


Figure: Energy density maps for mode 1 (left) and mode 2 (right) during El Nino (top) and La Nina (bottom) conditions.

697 - It's noted that local dissipation is considerable, while for other topography (Hawaii) very little energy is dissipated. Even in the Solomon Sea area there are some ridges that are dissipative and others that are far less dissipative. Explanation is not really provided as to why.

The low modes (especially the first one) show stronger far propagation capabilities. Also interaction of internal tides with local topography conditions (especially for higher modes as their horizontal scales are much shorter) will modulate the rate of energy that will be dissipated near generation location, and symmetrically the rate of energy available for far propagation. Depending on the topographic features, most of baroclinic energy propagate (low modes) or is locally dissipated (high modes) from the generation sites. By example, Hawaii is the location where internal tides energy propagates far away from the source, whereas the mid-Atlantic ridge is more favorable for local dissipation of the internal tides (Vic et al., 2018). Such variations are function of different parameters such as the ratio of the topographic slope to the slope of the internal characteristic, the Froud Number (Legg et al., 2008)… We don't investigate this point in the paper because it is far from the main motivation of the paper that is to illustrate internal tides in two contrasted ENSO conditions.

736 - Kida & Wijffels (2012) doi: 10.1029/2012JC008162 also note surface cooling in the Maritime Continent on a fortnightly cycle.

Yes, we add this reference

Fig 11- I'm not sure this makes sense. Flux is of the same sign on both sides of the topography. Either the figure does not go deep enough or the meridional direction is not really suitable to show what the authors intend. Perhaps a more NE orientation? Or deeper coverage?

This comment looks like the comment at l.323. See the corresponding response.

Interactive comment on "Internal tides in the Solomon Sea in contrasted ENSO conditions" by Michel Tchilibou et al.

Response to reviewer 2

Billy Kessler's referee 2

This is useful work that will be of interest to the community. The authors use simulations with and without tidal forcing, following and progressing from previous such work. They have advanced the understanding of the role of tides, and the modeling of tides, in the Solomon Sea. The results might have implications for ENSO effects, and also be of interest for other such partly-confined seas.
I recommend MINOR REVISION.

We are pleased that our work has been well received. We try to address the different comments as best we can, especially the main remark.
Thank to your remark on the possible role of the seasonal cycle in the interpretation of our results, we have redone some calculations that highlight two points:

- First there was some problems with the files used to do the last Figure (Fig. 14). It drastically changes our conclusion on the ENSO tidal effect at the surface
- Second, we will show below that the variations described between the two ENSO periods used are mainly due to interannual variability and not to the different phases of the seasonal cycle.

So to take account of these points, the section 5 has been rewritten and some conclusions have been revisited.

Major point:

- *The authors consider the periods JFM 1998 (El Nino) and AMJ 1999 (La Nina). They should emphasize that these are truly extreme periods, likely to exemplify the very maximum possible effects of ENSO variations.*

Yes, we are conscious that the period chosen corresponds to extreme periods. This is mentioned in the discussion/conclusion (l. 657-659), and we agree that it needs to be mention earlier. We report this point earlier in the text by explicitly citing the year and the phase of the seasonal cycle corresponding at each El Nino and La Nina events and the extreme character of such events. By example:
l. 140-141:
Old:"… , that have been performed during a 3 year period including an El Niño and a La Niña event."
→
New:" We will also consider case studies for two extreme periods: the summer 1998 El Niño and the fall 1999 La Niña that exhibits different stratification and mesoscale activity.

l. 258-260:
Old: "this section is motivated by a presentation of the Solomon Sea circulation, its variability, and its vertical stratification for two distinct ENSO periods: the 1998 El Niño and the 1999 La Niña. All of these dynamical elements may influence the internal tide fields from its generation to its propagation and dissipation."
→
New: "This section presents the Solomon Sea circulation, its variability, and its vertical stratification for the three year daily simulations, and for the two extreme ENSO periods: The January- March 1998 El Niño and the April-June 1999 La Niña."

- *In that light, the rectified anomalies due to tides are quite small: about 0.08psu in the surface layer, and 0.06psu in the upper thermocline (lines 568-583, and Fig.13). These small signals, given that* *extreme-opposite situations are compared, are not particularly convincing that ENSO-related tidal mixing is an important part of the observed erosion of thermocline properties that has been shown in several publications. In effect they are an upper limit of tidal effect variation, and the values given really aren't that impressive.*

Yes, we agree, and this is especially true once results have been revisited as mentioned above. The section 5 has been rewritten. The new version of this section is added at the end of the review.

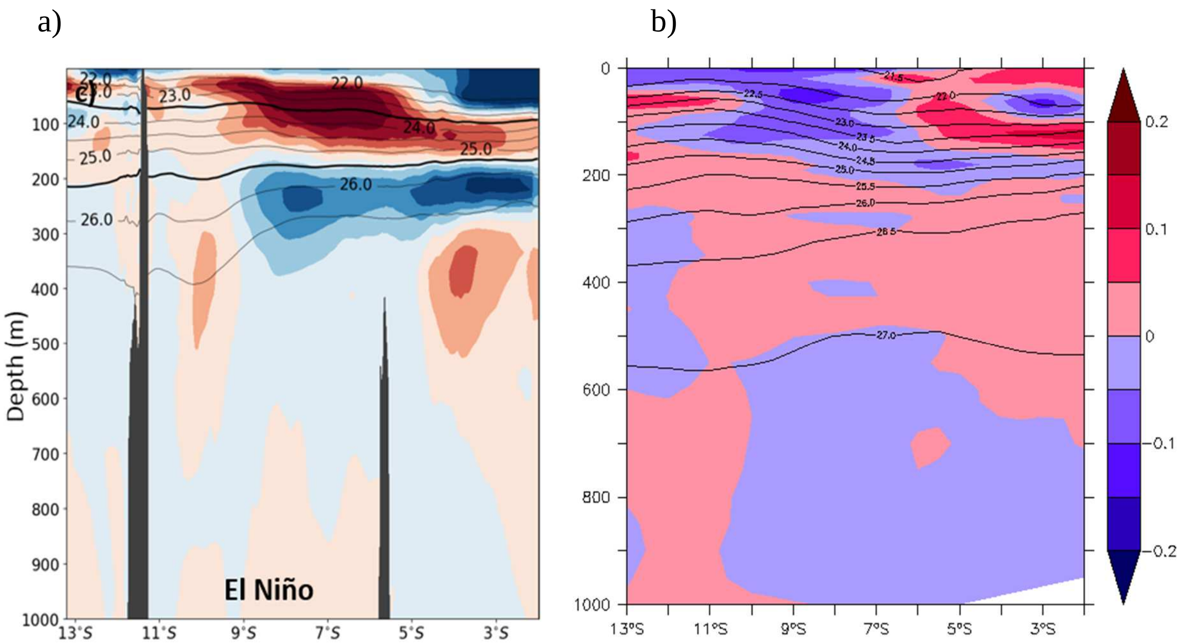
- *In addition, there may be tidal-effect anomalies due to the study periods being in different phases of the seasonal cycle. These are not brought out, but they should be since we can't tell if the rectified tidal difference signals are due to ENSO or to seasonality.*

This comment refers to section 5.b and Figure 13 where we discuss results on tidal effect at the surface between El Nino and La Nina. As mentioned at the beginning of the review, this discussion was wrong because of the use of a wrong file, and section 5 has been rewritten (we add it at the end of the review).

But the reviewer is right that there may be tidal-effect anomalies due to the study periods being in different phases of the seasonal cycle. So, we illustrate below that the anomalies as described in Figure 4 of the paper are mainly due interannual variability rather than to the different phases of the seasonal cycle (Figure 1). The January-March 1998 and the April-June 1999 salinity anomalies (Fig. 4 of the paper) are compared to the corresponding seasonal anomalies from CARS. It illustrates how the effect of the vertical heaving due to the interannual conditions dominate the effect of the seasonal cycle. This point is now mentioned in the new version of the manuscript. By example:

Section 2.1:" For these two periods the interannual conditions dominate the effect of the mean seasonal cycle (not shown)."

Section 3: ' We verified that most of the circulation and stratification changes between these two periods are not due to the different phases of the mean seasonal cycle (not shown)."



c) d)

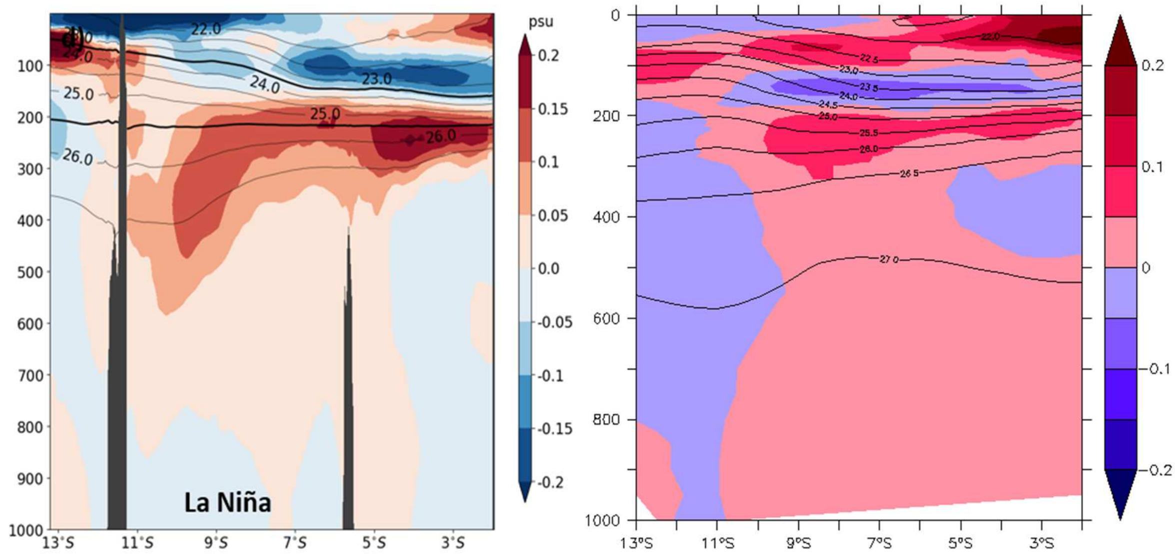


Figure 1: Section at 154°E of salinity anomalies relative to the long term mean (shading) and density (contours) for a) the January-March 1998 El Nino period, b) the January-March seasonal cycle, c) the April-June 1999 La Nina period and d) the April-June seasonal cycle.

Because one file was corrupt, the last figure of the paper has been redone. After corrections, the ENSO-tidal effect anomalies are relatively limited. I present below the TIDE-NOTIDE temperature anomalies for the SW waters (each temperature are relative to their long term mean) during the El Nino and La Nina period phase locked on the seasonal cycle (Figure 2). The temperature anomaly due to the ENSO-tidal effect is only of 0.15°c and is limited in areas characterized by a drastic change of the mean circulation that is along the LLWBCs during El Nino (increase of the LLWBCs), and along the Solomon archipelago during La Nina (increase of the SSI). The positive temperature anomalies damp the cooling of the surface layer induced by the tides as illustrated on figure 12 of the paper. So, more the circulation is intense, less the tidal effect is visible. In consequence, the section has been rewritten (see at the end of the reply).

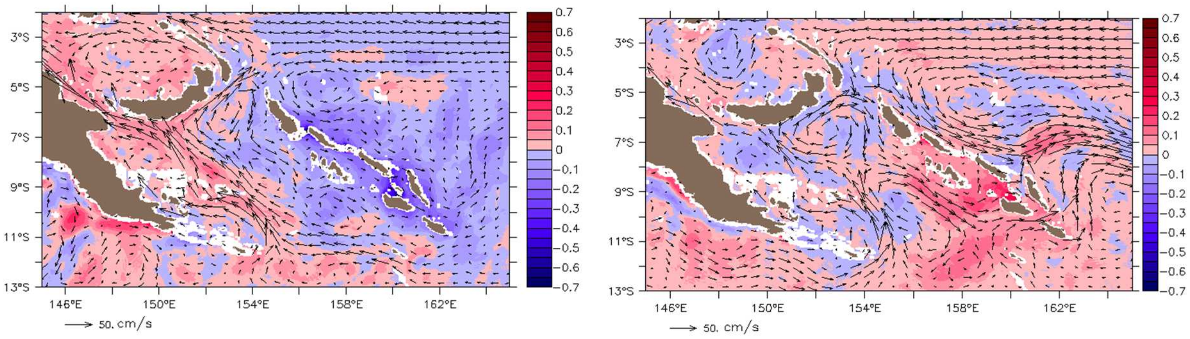


Figure 2: Temperature differences between the TIDE-NOTIDE simulations during El Nino (left) and La Nina (right) conditions. The TIDE (NOTIDE) temperature are anomalised relative to the 3 years mean TIDE (NOTIDE) temperature. The mean SW circulation over the El Nino and La Nina period is superimposed.

- *It would therefore help to expand the work to include a comparison of the phases of the seasonal cycle (say by compositing an annual cycle from the many years of the NEMO simulation). That* *might explain part of the differences found. (It might even be that the ENSO anomalies are _larger_ in the context of the seasonal cycle).*

This remark is in the continuity of the precedent remark. The reviewer suggests to expand the work to include a comparison of the phases of the seasonal cycle. It will allow to illustrate seasonal-tidal effect. To do that we need a robust annual cycle based on many years of the Nemo simulation, but our simulations is only 3 years long and include two strong ENSO events. We have looked at the relative importance of the seasonal variability against interannual variability by the use of the CARS climatology (see above). It seems that the impact of the seasonal cycle is relatively small compared to ENSO.

- *Given the above, some of the results are over-claimed. Examples would be the last, and 3rd-last, sentences of the abstract, and the paragraph in lines 640-645.*

Yes, we agree. This remark is also declined on points 5,6 below. According to the reviewer, we have rewritten the section 5 and some sentences in the manuscript. See the corresponding answers.

Other comments:

1) The boundaries of the nested region should be stated in the text, and ideally shown on a map (probably Fig.1). The crucial tidal forcing is specified as a boundary condition at these edges, so this is an important point that should be stated precisely (section 2.1).

Yes, you are right: We have forbidden to mention the domain of the nested region. We add this information in section 2.1 and in the legend of Fig. 1:

l.155:

Old: "It is a 1/36° horizontal resolution model originally developed by Djath et al. (2014)."

→

New:"It is a 1/36° horizontal resolution model originally developed by Djath et al. (2014) that encompasses the Solomon Sea from 143°E to 165.5°E in longitude and from 13°S to 2°S in latitude."

Figure 1:

Old: Bathymetry of the Solomon Sea (in color, unit in m)…

→

New: Bathymetry of the Solomon Sea over the domain of the regional simulation (in color, unit in m)…

2) The explanation/definition(s) of barotropic and baroclinic components is explained very nicely in section 2.2a. This was especially clear and helpful to this non-specialist. Bravo!

Thank you

- *However, one point remains to be explained, possibly reflecting my ignorance: I am familiar with a Sturm-Liouville mode decomposition, but only by assuming a complete separation of z from (x,y,t). In that case the vertical structure cannot vary in (x,y,t), but here it apparently is computed locally (according to the topography) and therefore does so vary. That means that the vertical mode structures differ by location; presumably the modes would then disperse in hard-to-understand ways, and their propagation becomes unclear.*

Yes, you are right. The modes are computed at every grid cell as classically done in other publications on tidal analysis (Merrifield and Holloway, 2002; Zaron and Egbert, 2014….). This is particularly crucial to analyze the propagation of the mode 1 energy flux within the thermocline.

Sloping topography is mostly an issue for w-modes (bottom boundary condition), but not really for u-modes and p-modes (which are the base modes for tidal energy budget). In addition, the w bottom boundary condition (w-BBC) fails only if significant internal tide currents meet a sloping topography, which occurs only on some locations. Finally, the w-BBC does not fundamentally alter the w-mode profiles. So, despite its limitation, the vertical mode approach remains the most efficient ones to separate barotropic and baroclinic dynamics.

- *On a related point, lines 504-506 assert a mode change due to the near-surface T/S ENSO variability. This could be verified by doing the S-L decomposition for these two periods. Do the modes in fact change?*

Yes, we have done the S-L decomposition for the two periods. Yes, the modes change, this is highlighted by the Fig. 5 of the paper that shows the difference of the N^2 profiles.

3) (nearly a "Major comment") Lines 336-341 describe large-scale water mass changes during the ENSO cycle. But I think this might be confusing "heaving" of the thermocline (vertical motion of the entire T/S structure) with water mass changes. This is apparently the cause of the anomalies in Fig.4c/d. It is easy to be misled as these might appear to be T/S variations if measured at a particular depth. But if what is really happening is heaving, then no water mass changes are implied. Please clarify this point, perhaps by plotting on isopycnals instead of depth. This is a crucial point because the paper argues that differences in tidal effects across the ENSO cycle have implications for mixing and downstream impacts.
The reviewer is right that most of the anomalies in Fig. 4c/d are due to heaving of the thermocline. The objective here is not to describe large-scale water mass changes during the ENSO cycle but to illustrate how the thermocline is pulled up and down during El Nino and La Nina and change the vertical stratification discussed on Fig. 5.
The misunderstanding here comes from the first sentence (l. 329) that introduces the paragraph:
"To illustrate the changes in the properties of water masses with the ENSO cycle…"
This sentence is wrong in this context and is rewritten:
"To illustrate the role of the ENSO cycle in the vertical heaving of this mean structure, the salinity anomalies for El Niño and La Niña periods from R36Td are calculated with reference to the complete period (Fig. 4c, d)."

4) Lines 479-495: This paragraph reads like an incoherent list of information. It jumps topic from sentence to sentence. I found it very difficult to read. Please improve it, perhaps by making an outline of the points to be made, and then probably separating into several paragraphs, each with a clear topic.
This remark was also done by the other reviewver. We try to rewritten the summary to be more readable:
Old:
"In summary, there are three areas where a large part of the barotropic flux energy is converted into baroclinic energy (63 to 79%), and a considerable fraction of the excited baroclinic energy is dissipated locally (46 to 80%). The two main generation sites radiating baroclinic tidal energy into the Solomon Sea are at Solomon strait and at the Southeast extremity of PNG. The generation box at Solomon strait radiates most of the baroclinic energy, especially during the La Ni.a state with a 27% increase of the energy flux compared to El Ni.o. There is a strong modification of the circulation at this site between the two periods, since the strong northward LLWBC current exiting the Solomon Sea during El Ni.o is replaced by the southward SSI current during the La Ni.a period that favors the advection of the tidal baroclinic energy inside the Solomon Sea. Most of this baroclinic energy is dissipated in the northern Solomon Sea as illustrated by Figure 9f, showing higher dissipation in the northern Solomon Sea during La Ni.a compared to El Ni.o. Indeed, the higher EKE level during La Ni.a than during El Ni.o (Fig. 2) favors stronger interactions between eddies and internal tides. This appears to render the internal tide more incoherent (e.g. Fig. 3gh) and to increase the tidal dissipation. The impact of ENSO is particularly visible at the southern Solomon Sea with a 70% increase of the baroclinic flux radiating away from this generation site during El Ni.o compared to the La Ni.a period. The EKE is strongest in this area duringLa Ni.a with higher dissipation and in consequence, there is a lower baroclinic energy flux radiating away."
→
New:
"In summary, there are three areas where a large part of the barotropic flux energy is converted into

baroclinic energy (63 to 79%). Most of the excited baroclinic energy is dissipated locally (46 to 80%), and only two generation sites at Solomon Strait and at the Southeast extremity of PNG radiate significant baroclinic tidal energy into the Solomon Sea.

Solomon Strait radiates most of the baroclinic energy into the Solomon Sea, especially during the La Niña state with a 27% increase of the energy flux compared to El Niño. Most of this baroclinic energy is dissipated in the northern Solomon Sea as illustrated by Figure 9f, with higher dissipation here during La Niña compared to El Niño. This is likely to be impacted by the contrasted circulation and mesoscale activity in this area between the El Niño and La Niña periods. The strong northward LLWBC current exiting the Solomon Sea during El Niño is replaced by the southward SSI current during the La Niña period (see Fig. 2) that favors the advection of the tidal baroclinic energy inside the Solomon Sea. Also, the higher EKE level during La Niña than during El Niño (Fig. 2) favors stronger interactions between eddies and internal tides. This appears to render the internal tide more incoherent (e.g. Fig. 3gh) and to increase the tidal dissipation (Fig. 9f).

At the Southeast extremity of PNG (Fig. 9f, blue) crossed by the strong NGCU the tidal baroclinic energy exhibits no contrasted situations between the two ENSO phases."

5) *The analysis of potential effects on SST - and thus on air-sea fluxes - is intriguing but not developed enough (lines 610-624). The idea seems plausible but with the short description here the conclusion is not well established. Since this is mentioned in the abstract and several other places (e.g. L642-645) the conclusion needs to be clearer and more confident. Otherwise it is could be mentioned in the discussion but not highlighted as much as done here.*

This remark and other main remarks concern the section 5.b. We have already respond on this point in the main remarks. This part is no more valid and the new results bring new conclusion. In consequence the section 5 has been rewritten (see this new section at the end of the report)

- *Worth noting here (line 621) is that anomalies don't mix, only total properties do. Please rephrase this sentence.*

The text has been suppressed (see above), so this remark is no more relevant.

6) Line 641: As noted in the major comment above "greatly" is much too strong for the small rectified changes described, given the extreme forcing differences.

This part has been suppressed, so this remark is no more relevant.

7) I have spent a great deal of time along coasts of the Solomon Sea in several locations on both sides of the sea, and consistently observe a very predominantly diurnal (24-hr) sea level tide. This phenomenon appears in Fig.6a. Why is this paper almost entirely focused on the M2 tide? Why doesn't the diurnal tide also produce a baroclinic component worth analyzing? If there is a straightforward answer it would be useful to say it.

The reviewer is right: the diurnal barotropic tides is dominant in the Solomon Sea but not the diurnal baroclinic tides (Fig. 3). But the main forcing of the baroclinic tides is the M2 barotropic component as highlighted by the SSH amplitude of the baroclinic components (Fig. 4). This is the raison why the paper focuses on the M2 tide.

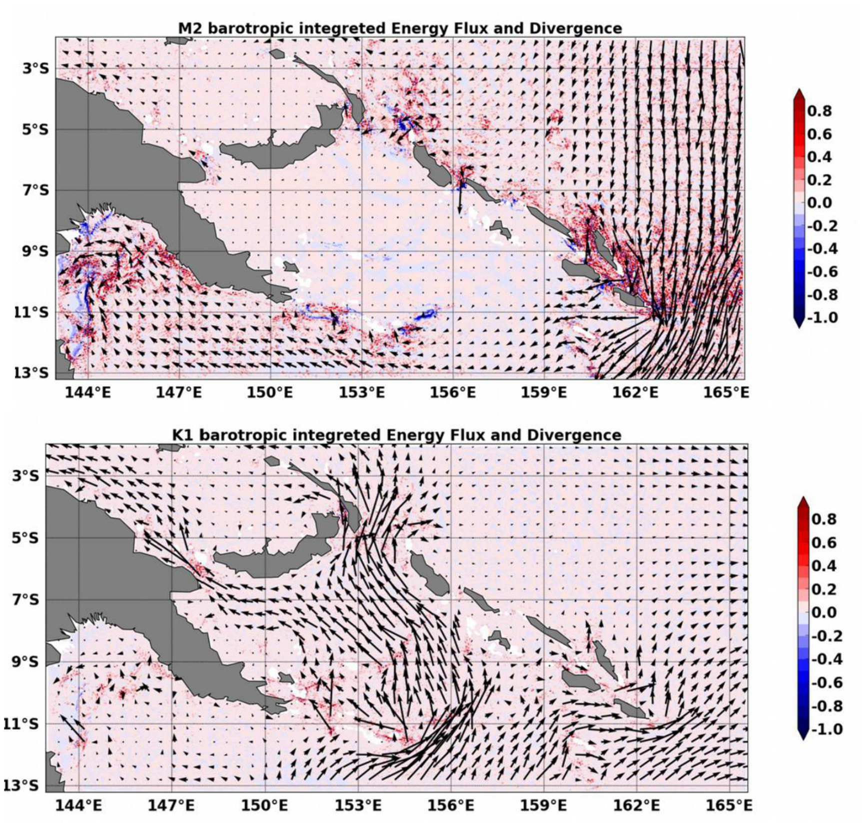


Figure 3: barotropic integrated energy flux (arrows) for the M2 (top) and K1 (bottom) components

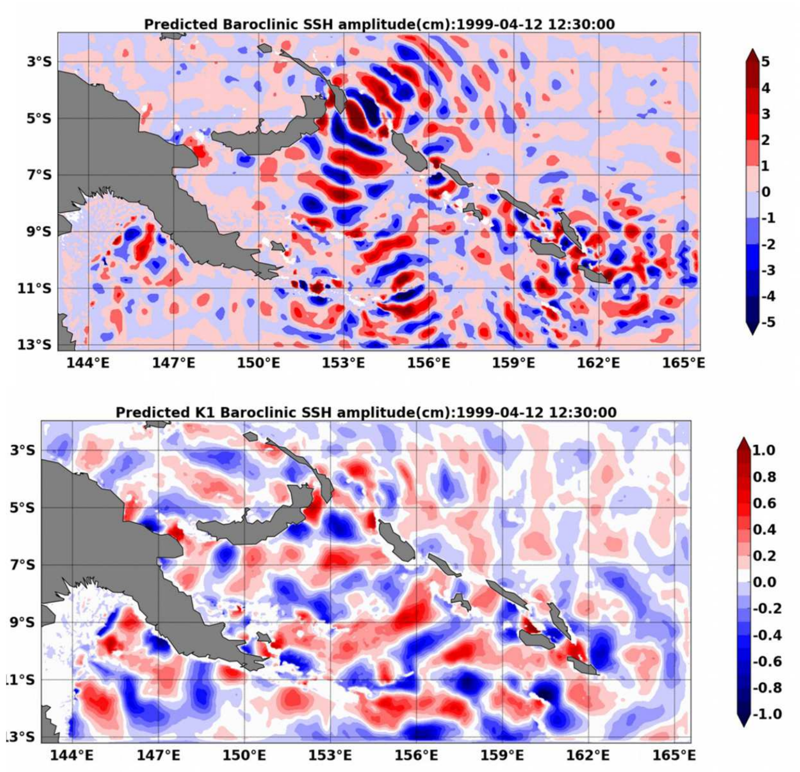


Figure 4: SSH signature of the baroclinic tides (shaded) for the M2 (top) and K1 (bottom) components (look at the different shading scales)

8) *Considering the small rectified changes noted in the major comment above, it might be worth noting that there is a different hypothesis for the mixing that apparently occurs in the Solomon Sea. Kessler et*

al (2019) show very large changes of velocity structure between their two glider lines, one just outside the sea, the other just inside (e.g their Figs.1 and 6 or 11). The two inflows (SEC and NGCU) merge (and presumably mix) just at the southern entrance to the sea. They speculated that the property differences between entrance and exits noted in several papers could be due to this non-tidal effect.
Yes, we agree. We add such hypothesis in the text for the discussion, see the new section 5 at the end of the reply. We also point this hypothesis in the abstract.

Abstract: "However, when averaged over the Solomon Sea, the tidal effect on water mass transformation is an order of magnitude less than that observed at the entrance and exits of the Solomon Sea. These localized sites appear crucial for diapycnal mixing, since most of the baroclinic tidal energy is generated and dissipated locally here, and the different currents entering/exiting the Solomon Sea merge and mix. Finally, the extreme ENSO condition case studies highlight the dominant role of local circulation changes that modify the internal tides more than the vertical stratification changes."

9) *The figures need a good deal of improvement:*
a) Many (most) of the figures have information that is too small to see. These include:
- Teeny-tiny axis labels (Fig.4 is the worst, but 3, 6b, 10, 11, 13, 14 are also very hard to read).
- Some fine contours are impossible to read and are thus useless. E.g. phase lines in Fig.7 and EKE contours in Fig.14.
- I strained to see the "isobathymetric lines" referred to in many figures. I still don't know what this refers to; is it just the reef edge? (In any case I would call these "isobaths").
- Teeny vectors and color blotches in Figs.9 and 10. These figures thus do not convey the information desired. Perhaps use fewer, larger vectors and simplify the color shading?
b) It is hard to see the difference between the green and blue lines in Fig.5. Then these colors change meaning in Fig.6. These should be more distinct, and use consistent colors (for El Nino/La Nina) between these figures.
Yes, We hope that now the new figures are readable.

Minor comments:
1) *The English is quite good throughout, with the exception of the Introduction which is sprinkled with distracting small errors. Since one of the authors is a native English speaker (let's accept for the moment that Australian is a close-enough dialect of English ;-), it would be worth going over this section.*
The English has been revised.

2) *Line 323: I think this should be "154E" (not 154S).*
Yes!

3) *The citation for Kessler et al (2019) is wrong (author list as published is different).*
Ok, the citation has been suppressed.

The section 5 has been rewritten:

5. Tidal effect on water mass transformation

Here, we take advantage of our twin simulations, forced with tides (TIDE) and without tides (NOTIDE), to analyze the impact of internal tides on the Solomon Sea's water mass modification. Most of the transformation occurs in the SW (σ_θ <23.3), UTW (23.3< σ_θ <25.7), and IW (26.7< σ_θ <27.5) water masses. We recall that the salinity maximum of the SPTW waters in the UTW is the key variable that impacts on the T–S modifications on the EUC. Whereas the SWs, which feed into the west Pacific warm pool, can modulate the critical air-sea interactions there. At depth, the IW influence the water mass properties of the cross-equatorial intrusion, in turn impacting on the North and equatorial Pacific's overturning circulation (Qu and Lindstrom, 2004).

This section will firstly address the long-term impacts of internal tides on the SW, UTW and IW, based on the daily outputs from the 3-year simulations. Also, the transit time for the SW waters are short enough (e.g. Melet et al., 2013) to allow us to investigate any sensitivity of the internal tide on the SW properties during our contrasting ENSO conditions.

a) Long term changes between TIDE and NOTIDE simulations

Salinity is a key parameter defining the water mass extrema. The mean salinity distribution of UTW waters shows the intrusion of the high salinity SPTW water in the Solomon Sea on Figure 12 for the 3-year NOTIDE and TIDE simulations compared to the CARS climatology. This high salinity tongue is firstly advected westward by the NVJ at 11°S before joining the NGCU around 155°E. As it continues to be carried northward into the Solomon Seas, it is eroded along its route. Interactions between the NGCU and the bathymetry, as well as the merging of the different currents, and the effects of tides are components that can erode the salinity maximum. The models with and without tides and the CARS data all show a strong erosion at the entrance of the Solomon Sea with a 0.06 freshening between the southeastern extremity of PNG and the Woodlark archipelago at 9°S. The salinity erosion is enhanced in the TIDE simulation compared to the NOTIDE simulation, and erosion is also visible in the northern Solomon Sea along the NGCU pathway. We note that the mean N^2 profile along the axis of this high salinity tongue at 154°E (Fig.5) had already highlighted the close resemblance of the UTW in the CARS and TIDES simulations compared to the NOTIDES simulation.

Another discrepancy between the TIDE and NOTIDE simulations concerns the zonal salinity gradient between the salinity tongue carried by the LLWBCs and the lower UTW salinity along the Solomon Islands. This zonal salinity gradient is enhanced in the TIDE simulation, suggesting that tides induce diapycnal mixing that is particularly efficient in the eastern and northern parts of the Solomon Sea. These regions where mean currents and EKE are relatively low (eastern Solomon Sea) and where strong recirculation exists (northern Solomon Sea) could be favorable to tidal mixing because of longer transit time for particles here.

The strong zonal salinity gradient in the TIDE simulation is also visible in the CARS climatology, although a fresh bias of about 0.02 psu may be noted in the TIDE simulation compared to CARS. This comparison with the long-term CARS climatology has some limitations with regard to the particular conditions of our 3-year simulation including strong El Niño and La Niña events. We note that CARS shows a strong salinity maximum around 5°S outside and to the east of the Solomon Sea that does not match our 3-year period simulations, where this salinity maximum in the open ocean is shifted to the south around 11°S. We have verified that the UTW salinity averaged over the same period as our simulations based on a monthly gridded T-S data (CORA05; Cabanes et al., 2013), also exhibits such a southward shift (not shown). Unfortunately, CORA05 has few observations available inside the Solomon Sea, since it is based mainly on ARGO data. So we can perform interannual validations outside the Solomon Sea, but only long-term climatological comparisons inside.

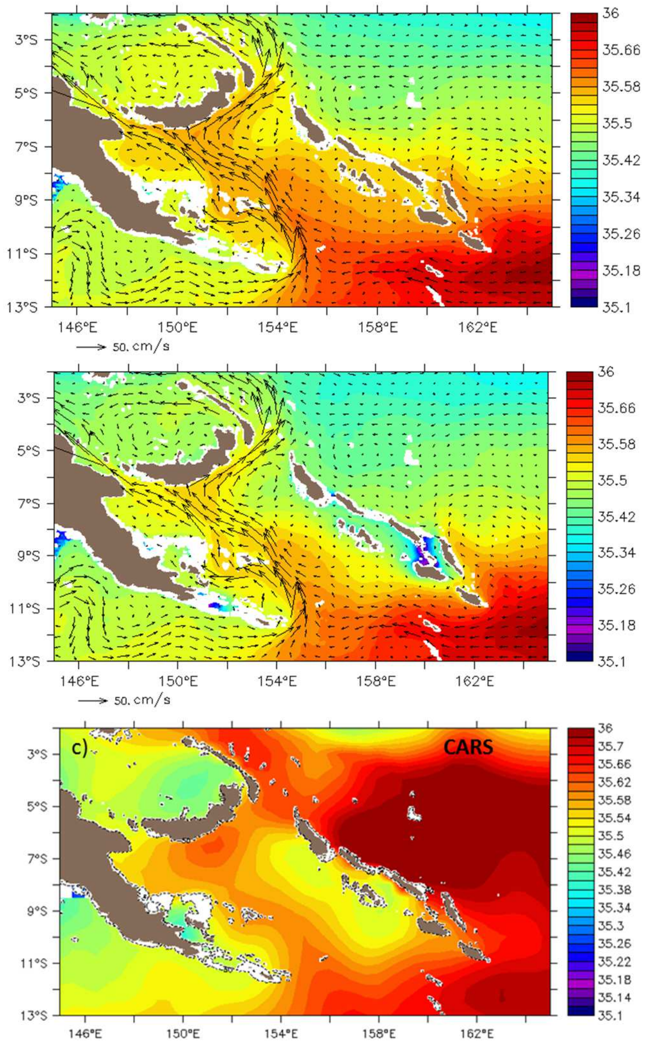


Figure 12. Mean salinity of the UTW waters for NOTIDE (top), TIDE (middles) simulations and the CARS climatology. The mean modelled circulation at the UTW level is plotted for the NOTIDE and TIDE simulation (arrows).

Temperature and salinity changes between the NOTIDE and TIDE simulations are presented on Figure 13 for the different water masses. The difference between these 3-year simulations shows that tidal mixing reduces the T/S extrema, and induces cooler and saltier SW, cooler and fresher UTW, and warmer and saltier IW. It means that the corresponding salt flux is transferred downward to IW, and upward to SW. In the same way, the diapycnal mixing from tides at the thermocline level induces a heat flux that cools the UTW and SW, and warms the IW. This results in a weaker stratification at the thermocline level in the TIDE simulation compared to the NOTIDE simulation (e.g. Fig. 5).

The largest impact of the tides is for the UTW, and the tide effect is strongest along the Solomon Islands with fresher salinity up to -0.08 psu and colder temperature up to -0.3°C for the TIDE simulation. But when averaged over the Solomon Sea, the rectified anomalies due to the tides are only of -0.04 for salinity and -0.1°C for temperature. The salt and heat fluxes in the TIDE simulation impact the SW and IW waters to a lesser effect, again with the highest differences along the Solomon Islands. Once again, when averaged over the Solomon Sea, the rectified anomalies due to the tides are only of -0.06°C (0.08°C) for temperature and of 0.01 for salinity for IW and SW, respectively, although locally the differences may reach 0.9°C and 0.15 psu (Fig. 13).

At the surface, the cooling of SW by the tides could affect the SST field that in return affects the latent heat flux and the corresponding net heat flux (Qnet). This corresponds to a positive Qnet anomaly between the simulation with and without tides (not shown) that acts to reduce the SST cooling induced by internal tides. Averaged over the Solomon Sea, the SST cooling due to the tides is of -0.06°C for SW, and only -0.04°C at the surface. This is an order of magnitude less that the SST cooling in the Indonesian Seas that drastically affects the overlying deep atmospheric convection when modeled in a coupled ocean-atmosphere model including a tidal parameterization (Koch-Larrouy et al. , 2010).

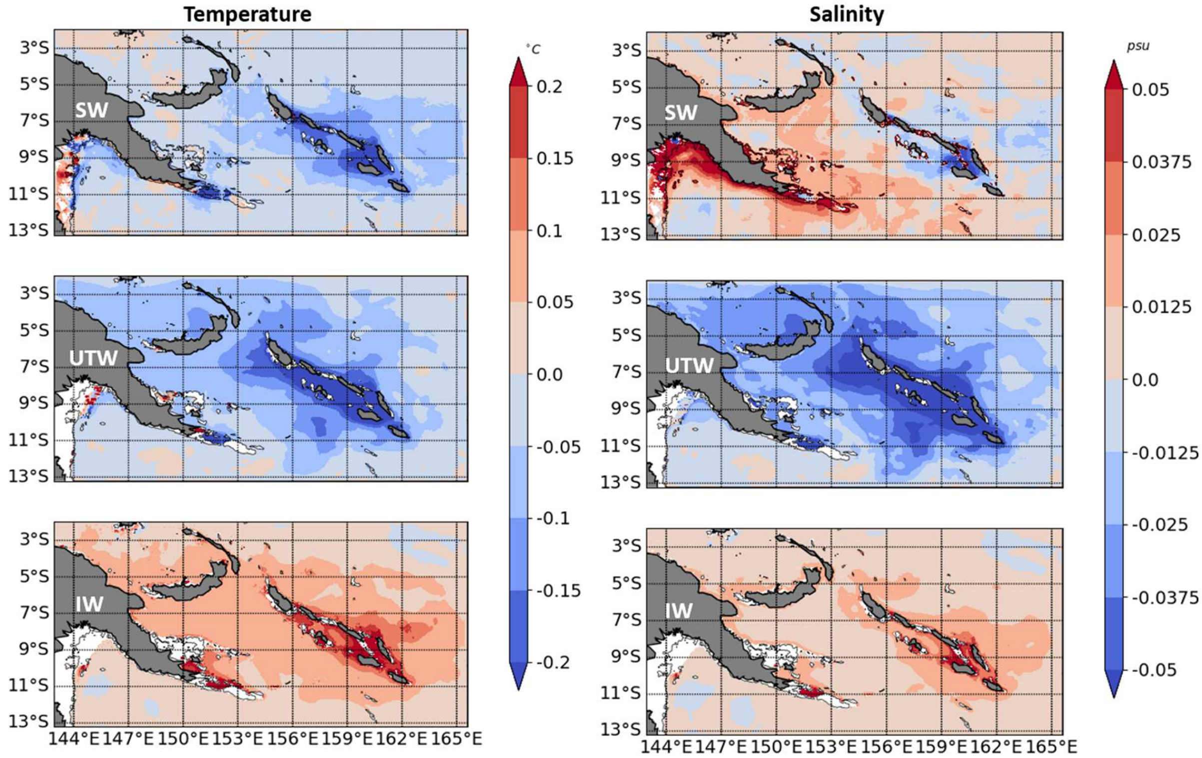


Figure 13: Mean temperature (left) and salinity (right) differences between the TIDE – NOTIDE simulations for the SW (top), UTW (middle), and IW (bottom) waters.

b) Sensitivity to extremes conditions

The mean tidal effect on water mass transformation is rather modest, but we can ask if extreme conditions like ENSO events impact on the role of tides on water mass transformation because internal tides are sensitive to contrasted ENSO periods (e.g. section 4). To illustrate this point, we focus on the 3-month periods of El Niño and La Niña, and we concentrate on SW waters since the transit time of SW waters is short enough to be influenced by these extreme conditions. Fig. 14 shows the temperature differences of SW between the TIDE-NOTIDE simulations for the two ENSO periods, calculated relative to their 3-year mean. The tidal impact on SWs during the ENSO period is quite small, with maximum differences within the Solomon Seas of +/- 0.15°C between the TIDE and NOTIDE simulations. But it is notable that the differences are strongly related to the circulation anomalies. During El Niño, the LLWBC strongly increases and we observe maximum positive temperature differences due to the tides along its pathway (Fig. 14a). In the same way, during La Niña maximum positive differences are present along the Solomon Islands where the SSI increases strongly southward (Fig. 14b). Since these positive temperature anomalies are relative to the 3-year mean cooling of SWs (Fig. 13) by the tides, they highlight that the intense circulation changes during the ENSO periods lead to a reduced effect of the tides on the SW waters. In other words, the tidal effect will be more efficient when the circulation has lower energy. When averaged over the Solomon Sea, the tidal differences compare to the 3-year mean are weaker in the La Niña condition with a temperature difference of 0.018°C compared to 0.05°C for El Niño, and these values are of same order as the mean tidal effect.

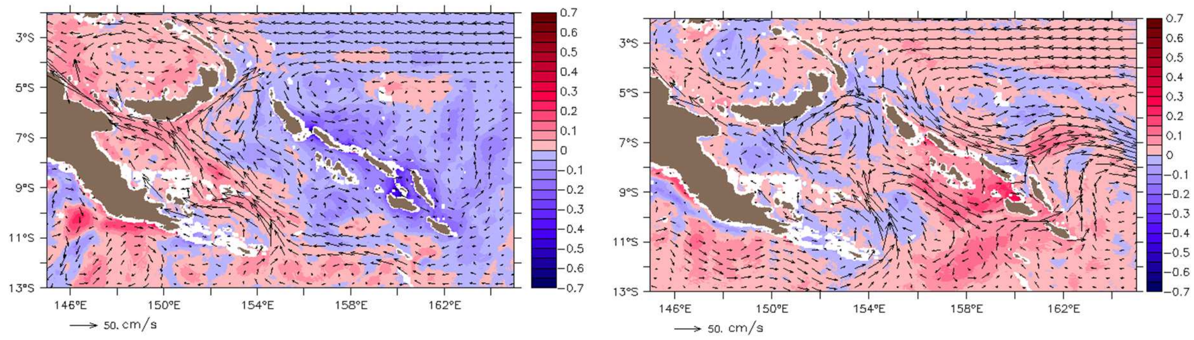


Figure 14: Temperature differences between the TIDE-NOTIDE simulations during El Nino (left) and La Nina (right) conditions. The TIDE (NOTIDE) temperature are anomalised relative to the 3 years mean TIDE (NOTIDE) temperature. The mean SW circulation over the El Nino and La Nina period is superimposed.