Reply to reviewer's comments for "**Impact of swell waves on atmospheric surface turbulence: Wave-turbulence decomposition methods**"

Reviewer comments are presented in black text using the "Calibri" font format with a size of 12. My responses are displayed in blue text using the "Calibri" font format with a size of 13. The text in the paper are shown as orange text in the "Calibri" font format with a size of 13.

Comments

its actual state reads quite unorganized and it needs some organization to make the readers follow precisely the main innovations, goals and the validation/evaluation of what you propose. Therefore, I think the manuscript still needs several major revisions. My comments are based on the annotated/trach changes version of your manuscript.

1. As commented before, the paper lacks some clear organization and is difficult to follow. The results section, as an example, appears as an intermittent provider of results and evaluations.

I appreciate the reviewer for dedicating time to provide insightful comments, and I largely see them helping better clarity of the work. I have tried to address each comment.

In the results section, I added a brief introductory phrase and have included headings to categorize the results based on different methods, as given, to some extent, in the methods section.

4 Results

In this section, I utilize three-dimensional wind speed for calculating measured turbulence and wave-induced stresses. For clarity and brevity, the vertical wind component is used to study the performance of the wave-turbulence decomposition techniques. This further provides insights into vertical motion relevant for studying vertical momentum transport, vertical coherence, and turbulence variation with height. I initiate this section with idealized examples, based on the proposed coherence model, to establish a foundational understanding of the developed techniques under controlled parametric conditions.

The results section has been divided into 4 subsection to assure clarity and clear structure: 4.1 Theoretical coherence; 4.2 Measured wind-wave spectra; 4.3 Spectral and coherence analyses; and 4.4 Momentum flux estimation

1.1 Even at the abstract level it is difficult to see the organization of the work: "The primary goal of this study…" sentence, as an example, appears kind of suddenly. Maybe this should be further up in the abstract?

This part has been fully revisited to avoid any potential confusion as follows:

"To study turbulence properties, specifically vertical momentum fluxes during swell wave conditions, we investigate the impact of waves on the power spectrum and spectral coherence of turbulent wind across various spatial and temporal scales. Using a theoretical model derived from sonic anemometer measurements at heights of 15 m and 20 m above the mean sea level, …"

1.2 Also in line 11 you stated "two days of sonic anemometers" which gives the impression you analyzed two full days of high frequency sonic measurements: however, you show in many plots (Figs. 2, 5, 6 and 8) more than two days of measurements, but you also focused on two episodes/events on one single day (as far as I understood), i.e. two ten minutes (are they actually two 10-min events only?) in June 24th. So, is it really just two events that are analyzed, I mean in terms of velocity spectra and coherence? If so this should just be clearer from the start (Abstract and Section 3:Data).

I utilized nearly two days evaluating the overall performance of the methods, more specifically both wave decomposition from wind and the estimation of wave-induced momentum. I have also focused on selected episodes within the study period to highlight the performance and efficiency of the decomposition method alone. The initial section illustrates the method's application over two days, as depicted in Figures 2, 5, 6, and 8. Corresponding changes have been made in the abstract to highlight this.

Using a few days of sonic anemometer wind measurements at 15 m height from June 20 to 26, 2015, the upward momentum transfer could be observed during high-steady (~ 7 m/s) and decaying wind conditions. During the high and decaying winds, the atmospheric stability changes between unstable and stable conditions, blurring the wave signals due to the thermally/mechanically generated turbulence.

Here, I elaborate on the selected cases, serving as benchmarks, to offer additional insights into the spectral characteristics and the effectiveness of the proposed decomposition technique.

“The vertical wind spectra from selected episodes within the study period, serving as benchmarks, provide insights into the nature of impacts on energy elevation within the wave band during low winds, old sea, and stable boundary layer conditions. These spectra also facilitate an effective performance assessment of the proposed decomposition method. “

1.3 Further, in Fig. 4 you analyze two other events?

This is addressed in my previous response. The selected episodes during the study period are utilized to explore the spectral nature of this interaction in more detail.

2. Line 10 and the implications of this: don't you need information on the three velocity components together with (at least) a coherence model to generate turbulent time series?

It is noted that this method is equally applicable to all three wind velocity components, and we are relying on observed data. Generating 3D synthetic turbulence goes beyond the scope of this study, which may (or may not depending on the selected) require the three velocity components. Here, 1D turbulence time series generator is sufficient to address the main objective as we are not generating a turbulence box for the structural load analysis. A forthcoming manuscript, to be submitted soon, will utilize the theoretical model to generate a time series of turbulence for all three wind components using NREL TurbSIM (constraint turbulence). These time series will then be fed into the openFAST model to examine aerodynamics and structural responses of both bottom-fixed and floating turbines. In the outlined procedure, observational data is utilized, and prior to applying the constrained turbulence tool, we incorporate a decomposition step. It's important to emphasize that the turbulence box, particularly the constrained synthetic turbulence box, is not the focus of this paper.

The sentence reads as you only need a coherence model (which can be independent from velocity spectra models).

The decomposition method employed in this study allows for individual application to each wind speed component—thereby eliminating the necessity to concurrently process all three-dimensional components (because we are going to apply it to our sonic measurements and not generating turbulence box synthetic data for the load problem). This flexibility enables a focused and efficient analysis of turbulence and wave characteristics in specific directions. In section 2.2, I have however applied the decomposition separately to all three components of wind speed.

Note that the theoretical model was fitted to the measured coherence spectrum to distinguish the velocity spectrum into its wave and turbulent components, as depicted in Fig. 6, and Appendix C. It can be independently applied to both horizontal (for u- and v-component) and vertical components of wind.

And the synthetic generation of turbulent fields is an important part of your method and so it should be mentioned in the abstract just after you state that you fit the suggested velocity spectrum to the observed one over the range of wave-affected frequencies: so lines 8—11 should be rephrased to reflect this

The primary objectives, as highlighted in the initial lines of the abstract, center around investigating the influence of waves on the power spectrum and spectral coherence of turbulence.

"….we investigate the impact of waves on the power spectrum and spectral coherence of turbulent wind across various spatial and temporal scales …"

While the generation of 3D turbulence is intricately linked to its applications in load analysis, this section specifically emphasizes the method's representation. It's noteworthy that, for calculating the observed wave-induced momentum flux, the decomposition is applied to all three velocity components. This addition is outlined in line 268.

"... Moreover, we apply the decomposition methods outlined in Section 2.1 to all three components of measured wind velocities to estimate the observed wave-induced $\tilde \tau$. …."

where E^o_{ww} and E^m_{ww} are the sonic based energy spectrum and the model spectrum of the vertical wind speed given by Eq. (3), respectively. Figure 8a shows a measure to assess the strength of wavy structures in the observed velocity spectra. I apply the decomposed turbulence time series when $R > \bar{R}$ (i.e. when there exists a well-pronounced energy elevation around f_p). Here, $\bar{R}$ represents the average value of R. In Fig. 8b, I compare the total wind stress at the surface obtained from Eq. (13), black curve, with the bulk estimation (red curve) derived from COARE3.6 algorithm (see Eq. 2). The two stress estimates align consistently when $R < \bar{R}$. Additionally, it is noteworthy that the wave-induced form stress at the surface, shown by blue markers, undergoes transitions from positive to negative for swells moving opposite to the wind direction (i.e., when $R > \bar{R}$). Figure 8c shows that the estimated form stress at $z = 15$ m according to Eq. (14) is approximately in acceptable agreement with the measured $|\tilde{\tau}|$ from the sonic data, using eddy covariance technique according to Eq. (2). In estimated form stress at 15 m height, the dimensionless function for the vertical decay, i.e. Eq. (14), plays a significant role in vertical distribution of the wave-induced momentum flux. Moreover, the decomposition methods outlined in Section 2.1 have been applied to all three components of measured wind velocities to estimate the observed wave-induced stress $|\tilde{\tau}|$ represented in Eq. (2). Figure 8d illustrates that the ratio of wave-induced (turbulence) intensity (the standard deviation of $\tilde{w}$ over the mean wind speed) to corrected turbulence intensity (the standard deviation of the corrected w over the mean wind speed) is most pronounced when wave elevations are clearly visible around the peak frequency f_p (in agreement with Fig. 8a).

I modified very briefly the methodology section as follows to highlight further where I use three dimensional wind components.

at the flow speed from those traveling at the wave speed (Ayet and Chapron, 2022). This multiscale wind-wave coupling, mediated by wave-coherent motions, is a responsible mechanism for variations of turbulent characteristics over the swell waves. For instance using Eq. (1), the total wind stress vector over the wavy surface is given as follows

$$\boldsymbol{\tau} = \boldsymbol{\tau}' + \tilde{\boldsymbol{\tau}}, \tag{2}$$

where $\boldsymbol{\tau}' = -\rho_a(\overline{u'w'}, \overline{v'w'})$ is the turbulent stress and $\tilde{\boldsymbol{\tau}} = -\rho_a(\overline{\tilde{u}\tilde{w}}, \overline{\tilde{v}\tilde{w}})$ denotes the wave-induced stress. Here, ρ_a indicates the air density. The total wind stress in Eq. (2) can be determined either through high-frequency measurements using the eddy covariance technique, to calculate the observed $\boldsymbol{\tau}'$ and $\tilde{\boldsymbol{\tau}}$, or by employing a bulk formula such as the one provided by COARE3.6 (Edson et al., 2013).

2.1 Wind-wave decomposition

3. Following on point 1, I wonder whether section 2.2 (which tells the reader the procedure to separate wind spectrum from wave spectrum) should be before section 2.1 (which introduces a coherence function and the synthetic fields). Then, you could somehow include the time series generation you describe in lines 132-140 in the section with the synthetic generation.

Reviewer’s comment has been addressed.

4. Line 123: do you actually need this? I mean can you not just use the relation f S(f) = k F(k)? is the dispersion relation (which you do not describe) really need it?

Yes. I added a new appendix to clarify this

Appendix A: Calculation of df/dk based on linear dispersion relation

The wavenumber and frequency spectra are interrelated through the dispersion relation (I assume here the linear dispersion relation):

$$\omega^2 = gk\tanh(kd),$$

where ω is the angular frequency, and d denotes the water depth. The spectral variance, whether expressed in frequency or wavenumber spectra, can be determined accordingly:

$$\sigma^2 = \int F(k)dk = \int E(f)df,$$

where $E(f)$ and $F(k)$ are the frequency and wavenumber spectra respectively. Assuming linear dispersion, we can estimate dk/df, essential for the transformation between these two spectra as

$$\frac{df}{dk} = \frac{g}{4\pi\omega}\left[\tanh(kd) + \mathrm{sech}^2(kd)kd\right].$$

5. Following on point 1, I wonder if it helps to have a first subsection in Section 4 where you show the results for the "ideal setup", i.e., Fig. 3a (and somehow it is weird that in the same figure you also have what appears as results from the two episodes you analyzed).

Reviewer's comment has been addressed.

Minor comments

1. The use of “we” should be replaced by “I” since I think you did the study alone (at least you wrote “my knowledge” under conclusions)

I tried to address this for the entire paper!

2. Line 24: delete the parenthesis and add “with” before “low”

Reviewer’s comment has been addressed.

….Within the WBL, particularly under the influence of swell waves with low to moderate wind speeds, MOST or the logarithmic law …

3. Line 32: you already introduced “MOST” so use instead of “Monin…”

In line 32, I am using “Monin-Obukhov scaling” that cannot be replaced by MOST

4. Line 61 and maybe others: you already introduced WBL so use the acronym

Reviewer’s comment has been addressed.

… in this section the WBL through …

5. Lines 67-68: something is grammatically wrong with this sentence… kind of reads as incomplete

The old version is as follows:

As discussed, the undulating ocean surface generates wave-coherent perturbations in the velocity (and pressure) fields, potentially exerting a dominant influence on turbulent properties within the WBL…

I could not identify any apparent grammatical issues. However, for the sake of ensuring clarity for the readers and appreciate reviewer's comment, I have made enhancements to the sentence as follows:

"The undulating surface of the ocean, as previously discussed, produces wave-coherent perturbations in the velocity (and pressure) fields. This has the potential to exert a dominant influence on turbulent properties within the WBL."

6. Line 124: last sentence of that page was already mentioned

Thanks anyway for this reviewer's comment. I prefer to retain this sentence as it emphasizes that curve fitting is conducted both below and above the wave-affected band, enhancing overall clarity.

7. Line 140 "Eqs. 11 and 11"?

I could not identify any issue here, as I mean exactly Eq. (1).

8. Lines 159 and 160 what medium and large waves mean? What are the sizes?

I agree the terms "medium waves" and "large waves" are relative descriptions, and their specific sizes can vary based on the classification system used. Here large waves generally refer to waves that exceed 4m in height and medium waves may fall within a range of approximately between 2-4m in height. I found these representation in line 41 and clarified as follows:

"For medium waves (approximately 2 to 4 m in height), the typical WBL height is a few meters, while for larger waves (more than 4 m in height), it can extend up to say 20 m."

9. Line 161 you are sure you meant Eq. (1)?

Yes, if you mean line 141.

10. Line 167 do you really mean the wave variance spectrum or just the wave spectrum?

I think of the wave variance spectrum as a specific type of wave spectrum focusing on the variance (or energy content) across frequencies. But the term "wave spectrum" is used in a more general form containing various types of spectral representations used to analyze wave characteristics in different domains (frequency, wavenumber, etc.).

11. Line 174 sentences on form drag should be after Eq. (15) is introduced

I could not identify any issue and think the order of equations sounds ok to me after checking.

12. Line 210 L has units of m I guess

Yes. I modified as follows
“denotes the Obukhov length scale (in meter) …”

13. Eq. (16) should be moved where appropriate under methods

Addressed! It has moved to the end of Section 2.2.

The observed coherence of vertical velocities is determined using the following relationship:

$$\gamma(z_1, z_2, f) = \frac{|\mathrm{Co}_{z_1 z_2}(f)|}{\sqrt{E^{z_1}_{w'w'}(f) E^{z_2}_{w'w'}(f)}}, \tag{12}$$

where $E^{z_1}_{w'w'}(f)$ and $E^{z_2}_{w'w'}(f)$ are the the power spectral density at heights z_1 and z_2, respectively. $\mathrm{Co}_{z_1 z_2}(f)$ denotes the two-point cross-power spectral density at heights z_1 and z_2.

2.3 Air-sea momentum flux

14. The words “physics-informed” and “learning solely” are very much machine learning jargon. You do not really use machine learning so I would rephrased these sentences to reflect that

I just simply removed this.

15. Line 319 “discussed in a separate independent study” if you cannot reference this then rephrase otherwise why mentioning this at all.

I prefer to keep it as it is and.

16. Fig.1b it looks like both Eww/Euu and Evv/Euu approach the black line of 3/4 but in line 329 3/4 should be the inverse ratio

I think this line is correct and 4/3 is just for better representation.

“It’s evident that the non-corrected ratios in Fig. B1b approach a value of 3/4 for frequencies larger that …”