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FACULTY OF SCIENCE

BSc Report

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Solving the turbulence closure problem I

The tropical ocean mixed layer

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Abstract

The turbulent nature of the tropical mixed layer is hard to parameterize and connect to physical processes. One physical process that is suspected to maybe be the cause for a significant part of the eddy-kinetic energy (EKE) in this area are Near-inertial waves (NIW). In 2015 a cruise observed such a mixing event at 11°N, 23°W described in Hummels et al. 2020. In this project two things will be investigated. Firstly using an ocean only model the north Atlantic is modelled for different horizontal resolutions (1 degree, 0.25 degree and 0.1 degree) to try and see if the EKE and NIWs are resolution sensitive. A resolution sensitivity is found, most notably between the 0.25 degree run and the 0.1 degree run, however no set map of areas benefiting from a higher resolution can really be made due to computational requirements beyond the scope of this project. Secondly using the same model with a 1 degree horizontal resolution and different vertical resolutions (10 meters and 4 meters) the observed NIW event is recreated and a comparison with the observed data is done. A close match is found for the 10 meter resolution run, where the 4 meter run is shifted greatly. However the biggest difference between the 10 meter run and the observed data is found to be the EKE fall off rate with depth.

Contents

Introduction

The earth is dynamic and complex, so to describe the many systems quantitatively is quite the task. However scientists still work hard to do so. The ocean is no different and the theory describing the turbulent flow within has troubled many. The Navier-Stokes equations is a set of partial differential equations made to describe the flow of viscous fluids[1].

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\frac{\nabla P}{\rho} + \kappa \nabla^2 \vec{u} \tag{1}$$

The Navier-Stokes equations

These equations are however not something that can be solved analytically due to the complexity and non-linearity, which is what prompted the use time averaging. The Reynolds-averaged Navier-Stokes equations (RANS) treat the flow as two separate terms, one mean time averaged, and one fluctuating[1]. The problem here is that the RANS, which describes the mean flow, still contain a turbulence term, known as the Reynolds stress (τ_{ij}^R), due to the non-linearity of the Navier-stokes equations.

$$\tau_{ij}^R = -\overline{v_i' v_j'} \tag{2}$$

The Reynolds stress tensor

This means to model the mean flow, one need to describe the Reynolds stress as a function of the mean flow, meaning that the set of equations is not closed and a relation between these two parts needs to be devised to close the set[1]. This is, in short, the turbulence closure problem and what this project will try to help shed some light on, by studying resolution sensitivity and precision of an ocean only model.

In this project the north Atlantic will be simulated, using the ocean only model VEROS (will be discussed more in *methods*)[2].

This study will focus on the most turbulent area of the ocean: the mixed layer. The mixed layer is the layer between the surface and around a hundred meters down[3]. Here a quick response to the above wind field can be studied and the following turbulence can be quantified since the main driving force is the wind field. It is through this mixed layer that the energy from the wind is distributed to the interior of the ocean[3]. However in current ocean models some of the energy is not accounted for by any real physical processes[4].

The specific turbulent event this project will focus on is Near inertial waves (NIW). These are waves caused by strong, local winds and create large shear which induces a high mixing[5]. This may be, at least part of, what is missing in current ocean models. However NIW events are very local and the shear they induce is therefore believed to be resolution dependent, as a higher resolution would result in a bigger grid and in turn more shear is possible for these local events. a higher resolution, both Horizontally and vertically could therefore be a way to tie this energy with a physical process[4]. But there are limits. The wind field is usually at a higher resolution, but if a lower resolution is needed, the wind field may give a lower limit of what resolution is computational possible for the ocean. In this project the computational cost of a higher resolution will be touched upon, but this will not be a significant part. There could be other limits to the resolution. It is possible that at a certain resolution all processes are resolved (all significant processes that is, as turbulence non linearity requires an infinite amount of equations to solve precisely). Certain parameters are used in modeling of turbulence which are defined for certain length scales, so if the resolution reaches below this, some assumptions are no longer valid and need to be reevaluated. This resolution sensitivity of NIW events are one of the two major focus points of this project.

The other key aspect of the study is a comparison with the real world. Because NIW events are so local and quick it is very hard to measure them in the real world. A scientific cruise in mid September 2015 did however manage to observe such an event of the coast of Africa in the tropics[5]. The observational data that will be used is shown and discussed in detail in Hummels et al. from 2020. Doing this may lead to a more quantifiable difference between real world NIW events and the ones simulated, which could give a better understanding in what parameters are important for these events and how well they currently are being represented. The observations where done at 11°N, 23°W. This point will then be of central interest throughout this project since it is expected that a NIW event will happen here (fig. 1).

All Figures can be found in full size in the appendix.

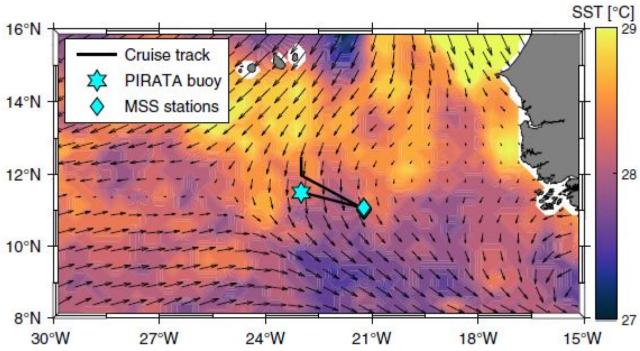


Figure 1: *The cruise track of the M119 expedition between 13 and 15 of September 2015 with the MSS station where the NIW event was observed, as well as the position of the PIRATA buoy is shown. The event is approximated to have taken place at 11°N and 23°W. Plotted against it is the local wind field and sea surface temperature. See Hummels et al. 2020 figure 1 for more details[5].*

Method

To simulate the ocean, the pure python ocean model Versatile Ocean simulation (VEROS) will be used. This model is running in pure python instead of the old norm FORTRAN[2]. The model is an ocean only model, meaning no atmosphere-ocean feedback and the wind field is predefined. The model Runs on a Arakawa C-grid (fig. 2)[6].

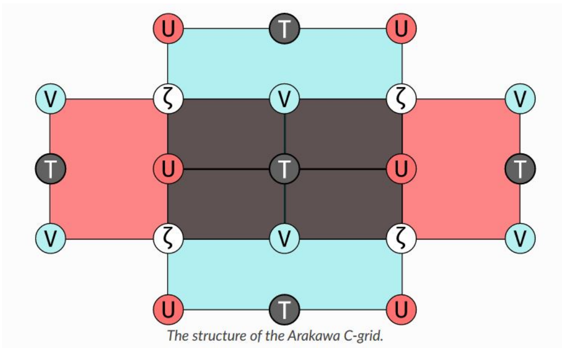


Figure 2: *A more intuitive way of describing the Arakawa C-grid. The different velocity and mass properties of the ocean are computed at different points of a box (shown unfolded here). This grid system is used to represent orthogonal variables.*

At all points, using the C-grid, the Navier-Stokes equation for momentum is solved to best simulate the ocean dynamics. The specific setup of the model is discussed in the next subsection, but for a more detailed description of VEROS and the model see Häfner et al. 2018[1].

Model Setup

For this project a realistic model of the north Atlantic is used. This is chosen so the model output can be compared with the observational data at 11° North and 23° West[5]. The zonal model boundary is at 98°W and 17°E, and the meridonal boundary is at 18°S and 70°N. Within this basin there is a lot of coast which works as boundaries. The specific topography for this setup is predefined in VEROS (inspired by Smith et al. 2000).
To make sure the Courant–Friedrichs–Lewy criterion (CFL criterion) is met the time step is changed to fit the

[1]Or see https://veros.readthedocs.io

different resolutions, but starts at 30 minutes for the 1 degree setup[7].

$$\Delta t(\sum_{i=1}^{n} \frac{u_{x_i}}{\Delta x_i}) \leq 1 \quad (3)$$

n-dimensional CFL criterion

The output used from the model is snapshots taken every 3 hours of the model run, with the following variables: zonal ocean velocities u, meridonal ocean velocities v, vertical ocean velocities w, temperature T, vertical viscosity κ_M, vertical diffusivity κ_H, the interpolated wind stress τ_x and τ_y and some model parameters containing the specific coordinates and such. The model is simulated for two months, specifically August and September, of 2015.
The model is run for four different resolution, three different horizontally and one different vertically. The standard setup is a one degree horizontal resolution with a vertical stratification every 10 meters. This model setup is run with a time step of 30 minutes. The second run is done with a quarter degree resolution and 10 meter vertical stratification with a time step of 7.5 minutes to meet the CFL criterion. The last Horizontal resolution run is a tenth degree resolution, again with a 10 meter vertical stratification. The time step here is 3 minutes.
For the vertical resolution change, the horizontal resolution is one degree and the vertical stratification is 4 meters, with a time step of 12 minutes.
The rest of the model physics and parameters are from a predefined VEROS model of a realistic north Atlantic (inspired by Smith et al. 2000)[2].
Due to time constrains the tenth degree model was only run for five days, since the runtime was close to real time. This do pose challenges later in the project, but certain arguments can be made to, at least somewhat, circumvent these. This model is more specifically run from the 12 of September to the 16 of September.

Wind field

It was stated earlier that the wind field for VEROS models are predefined, so for this project data from ECMWFs ERA5 is used[8]. This wind field has a quarter degree resolution and is therefore linearly interpolated to the right resolution for the different setups used. The wind data used is tri-hourly measurements at 10 meters height from the 1 of August to the 30 of September 2015.

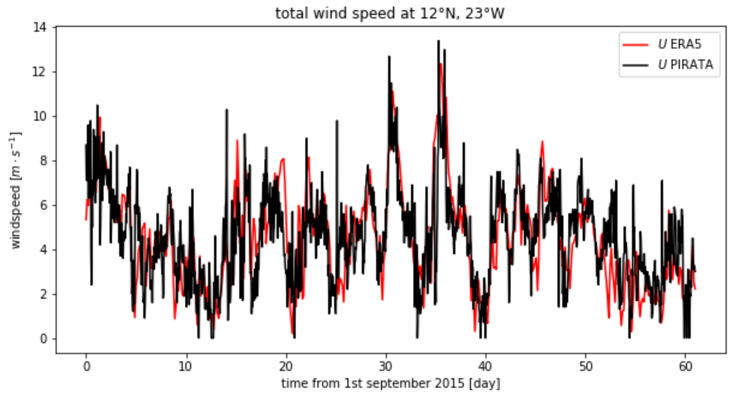


Figure 3: *The total wind speed during August and September of 2015 at 11°N and 23°W from both the ERA5 database and the PIRATA buoy located at 11°N and 23°W. The winds are largely in agreement, with small differences. The timing of the large wind burst are very close and so is the magnitude.*

A quick comparison between the wind stress used in this project and from a PIRATA mooring at 12°N and 23°W shows that the data represent the real world well, at least at the point of interest (fig. 3). This means it can safely be assumed that the wind forcing used in the simulation will accurately describe the wind forcing where the observational data was taken[9]. Early problems did however arise with the wind field. Due to inexperience working with ERA5 data the wind is mirrored around 26°N for the Horizontal resolution experiment. (fig. 4).

[2]The specific setup can be found at https://veros.readthedocs.io/en/latest/reference/setups/north-atlantic.html

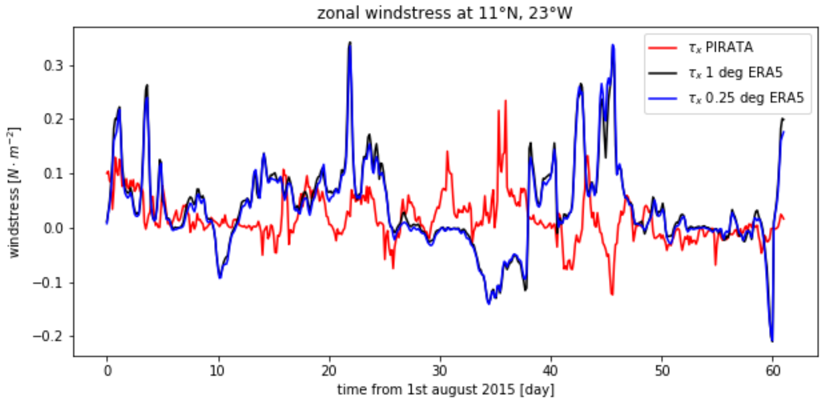


Figure 4: *The zonal wind stress used for the 1 degree and 0.25 degree run for the horizontal resolution study and the wind stress from the PIRATA buoy. A large difference in both magnitude and form is seen. This large difference is due to an unfortunate mirroring of the wind field.*

Due to time constraint these three simulations were not rerun. A new one degree run was however made for the vertical resolution study and the comparison with the observational data. Nevertheless the unfortunate error does not compromise the result from the horizontal resolution study. First of, all three runs were with the same wind field which is still of the right order of magnitude and secondly the study is about the amount of turbulent processes resolved for different resolution for which a precise copy of the real world wind field is not needed.

Observational data used

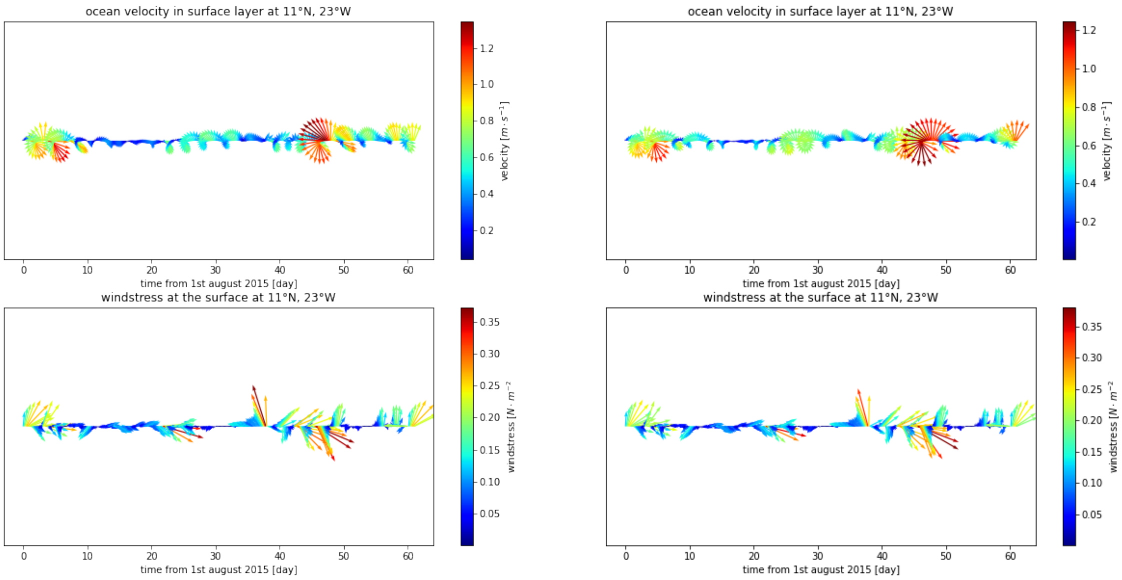
The observational data used in this project to compare to an ocean only model is described and analysed in detail in the 2020 paper: *Surface cooling caused by rare but intense near-inertial wave induced mixing in the tropical Atlantic* by Hummels et al[5]. The data was taken on the M119 cruise around 11 ° N, 21 ° W in mid September 2015. For the data analysis done in the paper, the wind field (and other variables) were taken from the PIRATA buoy at 11 ° N, 23 ° W, were the paper then approximate the event to have happened[5]. The paper focuses on the upper 80 meters of the mixed layer, which is then also taken as the area of interest in this study.

Results

In this section the relevant raw data gathered from the different simulation setups will be shown. Firstly the three simulations for the horizontal resolution sensitivity will be shown and explained. Afterwards the one degree models with the wind field correctly mirrored will be shown, one with 10 meters vertical resolution and one with 4 meters. The vertical resolution part of the study is put under the comparison with the observed NIW event since it is done with the right wind field, so there is no confusion about this.
The data will be shown and explained in this section but the analysis and discussion of the data is done in later sections. The data here does therefore also include the mean flow and not just the high frequency band were the NIWs are[5].

Resolution sensitivity

The main focus of the Horizontal resolution study, is to see how much energy is resolved and if any NIW events are created. Firstly a look at the surface wind stress and the ocean surface velocities will give some insight whether or not any NIWs are observed. Secondly a look at the zonal and meridional ocean velocities versus depth, will give some understanding of the amount of energy is resolved.



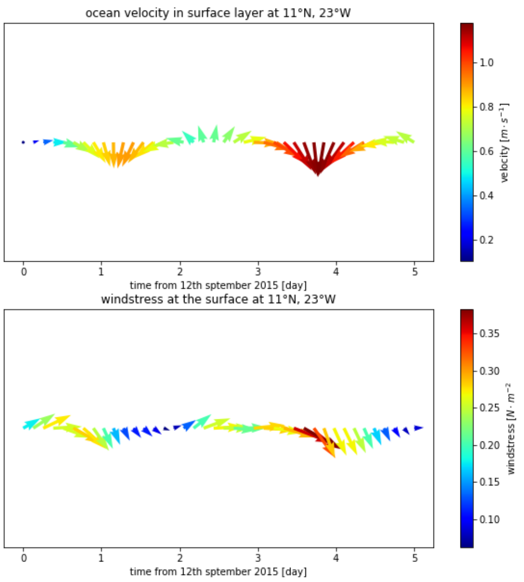
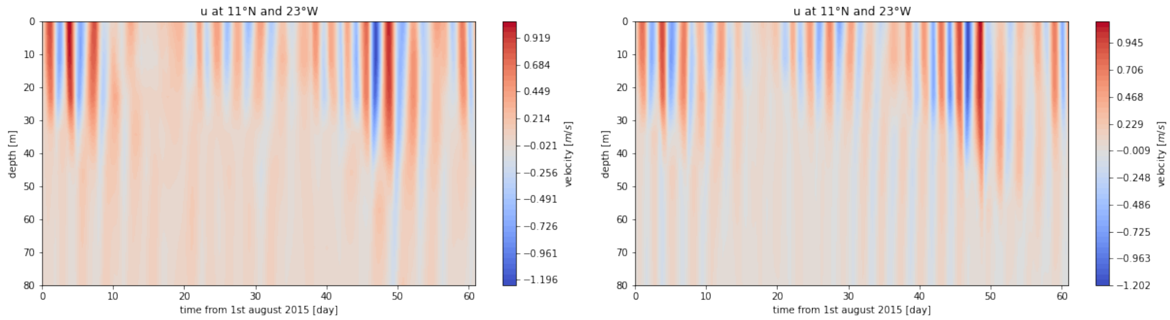


Figure 5: *Vector plots of the wind stress (lower in each sub-figure) and ocean surface velocity (upper in each sub-figure) at 11°N and 23°W over time for the different horizontal resolutions.*
upper left: 1 degree resolution.
Upper right: 0.25 degree resolution.
lower left: 0.1 degree resolution.
in all plots strong wind burst can be seen followed by rotations of strong ocean velocities.

As stated a NIW event is signified by a large shear and therefore also a large spike in ocean velocities[5]. For all three resolutions a large spike in ocean velocities can be seen around the 16 of September (fig. 5). Further more it is clearly visible that the spike in ocean velocity changes direction in the horizontal plane, which would induce a high shear effect (fig. 5). Even for the only five day long data series of the tenth degree resolution this rotation of direction is visible. The surface wind stress around the same time can also be seen spiking. The magnitude of the ocean velocity is around $1.2\frac{m}{s}$ for all three resolution, however the time duration of this peak seems to grow with resolution.



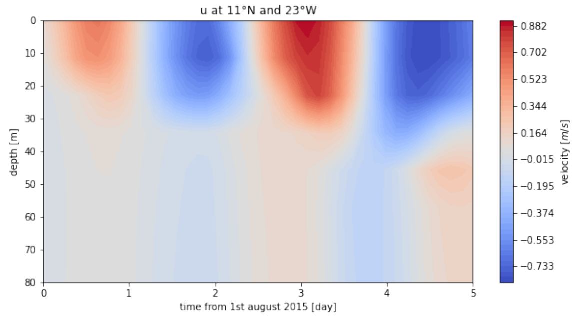
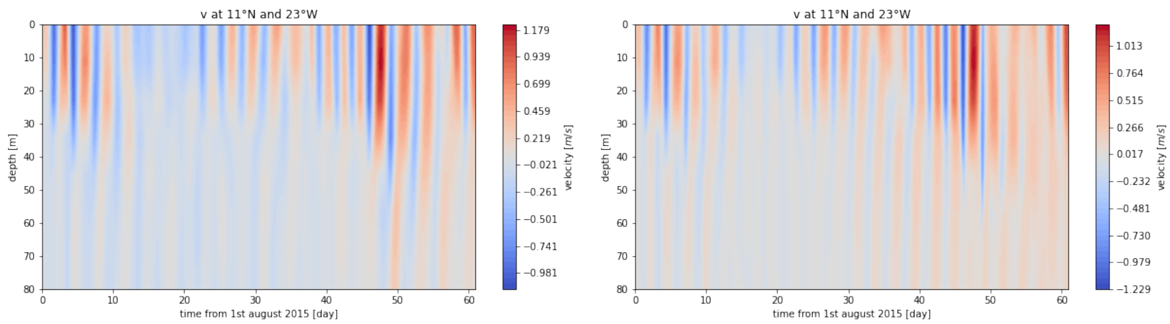


Figure 6: *Zonal ocean velocities at 11°N and 23°W over time for the upper 80 meters of the mixed layer. In each sub-figure strong peaks can be see at around the 15 September, reaching depths of 30 meters and oscillating in direction around every 24 hours.*
upper left: 1 degree resolution.
Upper right: 0.25 degree resolution.
lower right: 0.1 degree resolution.

The large spikes in ocean velocities do not only happen at the surface, but in the upper 40 meters or so of the mixed layer (figs. 6 and 7). It can be seen that the velocity spikes oscillates in direction around every day for all resolutions, and that the zonal and meridonal ocean velocities are phase shifted almost a complete half rotation (this is most clear looking at the tenth degree resolution of figs. 6 and 7). Again an interesting thing is the time duration of the NIWs which seems to be larger for the higher resolution simulations.
The strength of the sharp peaks of both u and v do quickly fall after 30-40 meters. deeper than this, the ocean velocities does not seem to be affected by the large wind stress spikes.



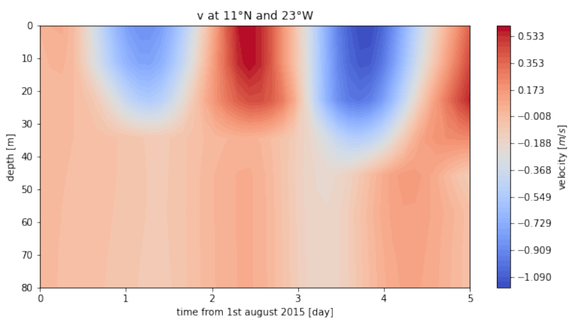


Figure 7: *Meridional ocean velocities at 11°N and 23°W over time for the upper 80 meters of the mixed layer. In each sub-figure strong peaks can be see at around the 15 September, reaching depths of 30 meters and oscillating in direction around each 24 hours.*
upper left: 1 degree resolution.
Upper right: 0.25 degree resolution.
lower left: 0.1 degree resolution.

Comparison of NIW events

In this subsection the data that will be used for the comparison with the observational data and the vertical resolution sensitivity will be shown and described, but the actual comparison will be in the *Discussion* section. These results are for a one degree horizontal resolution and a 10 meter and 4 meter vertical resolution. Again, the wind field for these simulations are rightly placed.

10 meter vertical resolution

Like in the horizontal resolution data, a good place to start is looking at a vector plot of the wind stress and ocean velocities at the surface. For this simulation there are four sharp wind burst (fig. 8). These short but large bursts reach magnitudes of around $0.12\frac{N}{m^2}$, which is over twice the size of the normal wind stress in this area. Around the time of these wind bursts large rotating peaks is seen in the ocean surface velocities. These rotations are the NIW events and reach a size of around $0.6\frac{m}{s}$. The time length of these events do vary greatly within the simulation data (fig. 8). The rotation around the 15 of September is the NIW event measured and shown in the Hummels et al. paper[5].

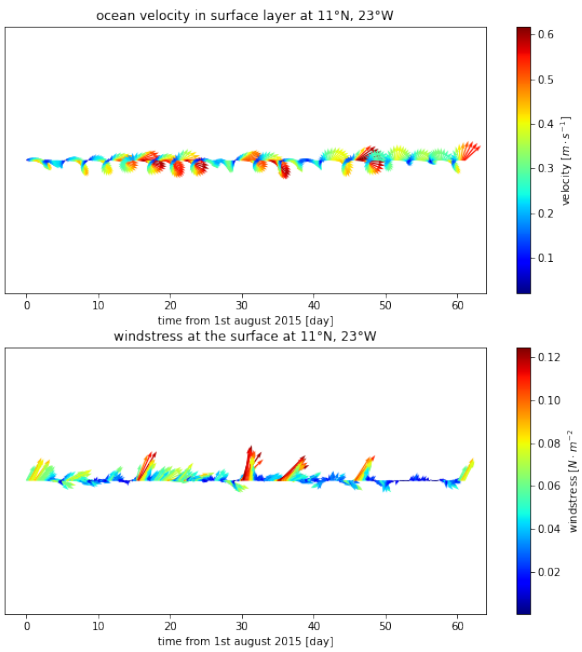


Figure 8: *upper: the ocean velocity of the 1 degree horizontal resolution with 10 meter vertical resolution run at 11°N and 23°W.*
lower: Wind stress at the surface for the model run at 11°N and 23°W.
Multiple wind burst are seen, most notably around the 14 September which is the wind burst before the observed NIW event. This event is also visible in ocean velocity around the 15 of September.

The ocean velocity peaks fall off at around 20 meters depth in both zonal and meridonal direction (fig. 9). These peaks are around $0.6\frac{m}{s}$ magnitude. A shift in direction happens around every 24 hours for both zonal and meridonal velocities. The meridonal velocities are phase shifted approximately a half rotation with regards to the zonal velocities.
Another very important variable for these NIW events is the induced mixing because of the high shear. The vertical diffusivity, κ_H, and the vertical viscosity, κ_M, are the two parameters used in this simulation to quantify and study the mixing (fig. 9). Very sharp peaks can be seen for both mixing terms at the time of the high velocity peaks. These peaks of mixing are of the magnitude $1.7 \cdot 10^{-2}\frac{m^2}{s}$ for both diffusivity and viscosity. These peaks fall of at around 20 meters depth like u and v. The viscosity peaks start at the very surface, where the diffusivity peaks around 10 meters and fall of both towards the surface and towards the 20 meters depth. Mixing can be seen at the time of the observational event, this is however the smallest mixing event in the simulation.

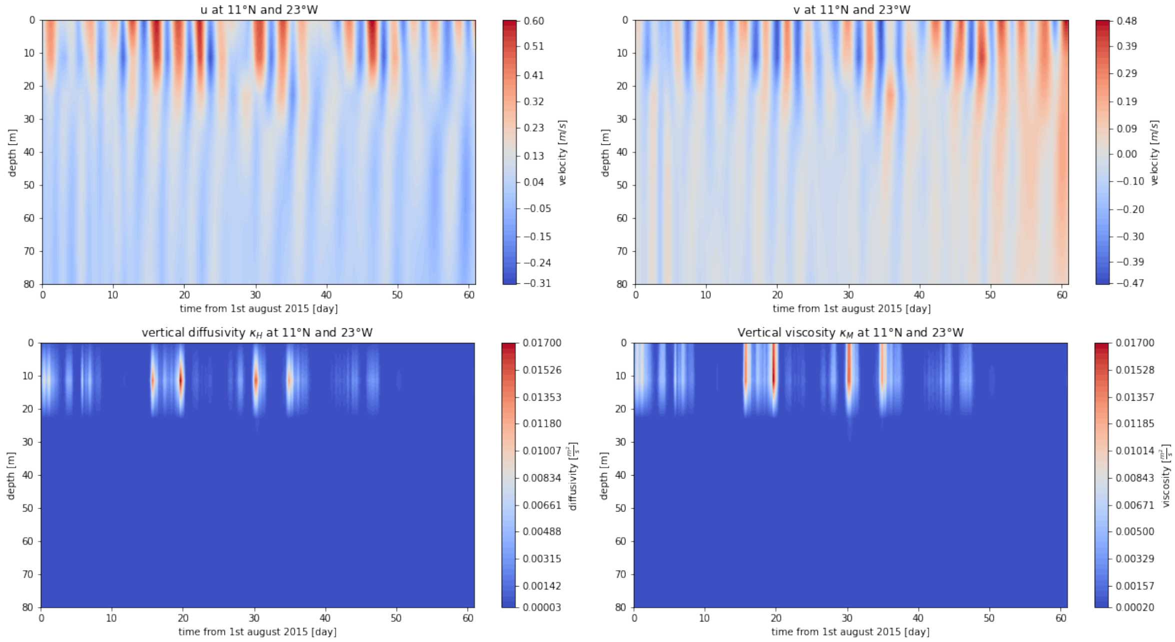


Figure 9: *Ocean properties of the upper 80 meters over time for the 10 meter vertical resolution run. The values are from 11°N and 23°W. Clear peaks can be seen in all sub-figures, both velocities and mixing, at the time of the NIW events. Upper left: The zonal ocean velocities. Upper right: The meridonal ocean velocities. Lower left: The vertical diffusivity. Lower right: The vertical viscosity*

4 meter vertical resolution

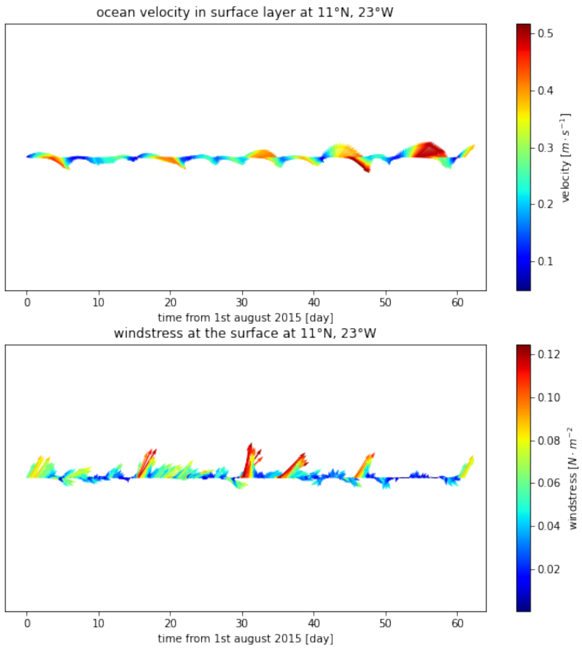


Figure 10: *upper: the ocean velocity of the 1 degree horizontal resolution with 4 meter vertical resolution run at 11°N and 23°W.*
lower: Wind stress at the surface for the model run at 11°N and 23°W.
Multiple wind burst are seen, most notably around the 14 September which is the wind burst before the observed NIW event. The resulting ocean response is at the 24 of September.

The wind field is identical to the above described, so the wind stress form, magnitude and timing is the same as for the 10 meter vertical resolution. The ocean surface velocities are however different. The peaks are almost of the same magnitude at around $0.5\frac{m}{s}$, however the timing and form is different for the 4 meter resolution (fig. 10). The peaks of the ocean velocities are smaller in both magnitude and duration at the start and grow as time goes. The form of these NIW events are not as round, but more dragged out over time.
As seen from the vector plot, the ocean velocity peaks are longer in time duration, but the magnitude does not compensate to keep the circular form as seen for the 10 meter vertical resolution. u and v drop of at around 20 meters depth (fig. 11). The width of these peaks are around 2-3 days, and do not oscillate between equally strong positive and negative peaks. The meridonal velocities do still have about a half rotation of phase shift compared with the zonal velocities.
The mixing terms, κ_M and κ_H, peaks at around 5 meters depth, and falls of towards the surface and around 10 meters depth. both terms peak at around $2.55 \cdot 10^{-2}\frac{m^2}{s}$. Many small peaks can be seen through out the simulation run time. A mixing event can be seen at around 15 of September, which is around the time of the cruise[5].

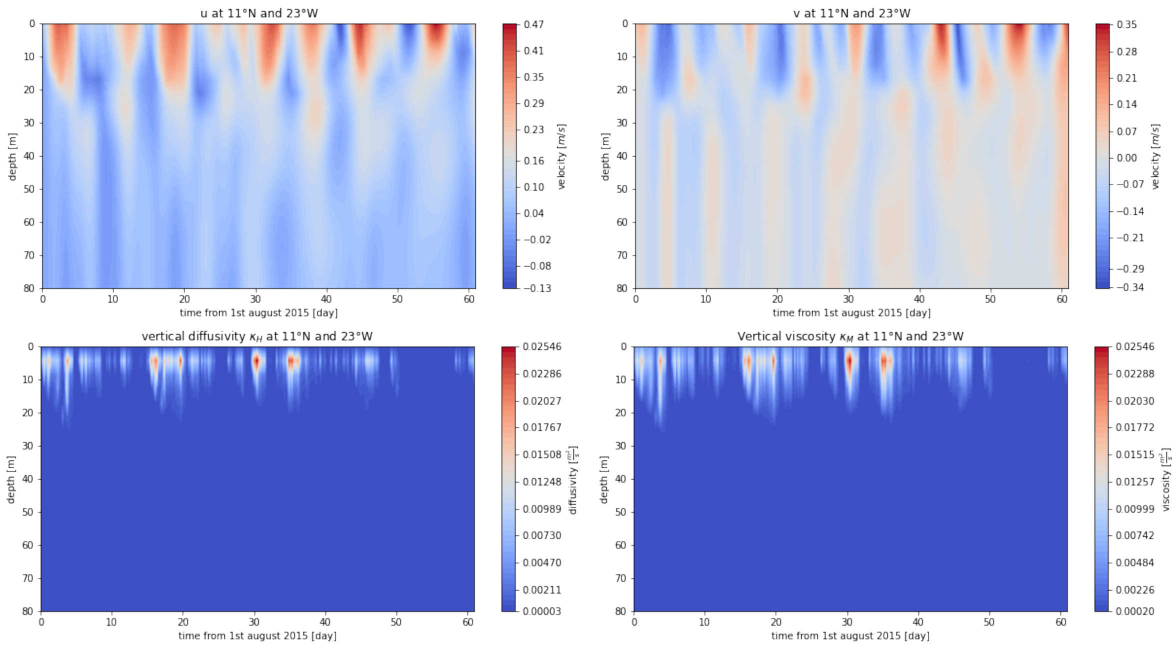


Figure 11: *Ocean properties of the upper 80 meters over time for the 4 meter vertical resolution run. The values are from 11°N and 23°W. Clear peaks can be seen in all sub-figures, both velocities and mixing, at the time of the NIW events. Upper left: The zonal ocean velocities. Upper right: The meridonal ocean velocities. Lower left: The vertical diffusivity. Lower right: The vertical viscosity*

Analysis

In this section the data gathered from the simulations will be analysed, the discussion is left for the next chapter. Firstly as this project focuses on NIW events which are in the high frequency band a simple inverse boxcar filter is used to filter the mean flow away[10]. The simple boxcar filter is a type of convolution of the following form and is used as a moving average to isolate the mean flow, which is then subtracted from the original data to get the noise.

$$A_k = \frac{1}{k}\sum_{i=n-k+1}^{n} p_i$$
$$A_{k+1} = A_k + \frac{1}{k}(p_{n+1} - p_{n-k+1}) \tag{4}$$
Simple moving average (Boxcar)

This method will work similarly to a high pass filter and remove the mean flow of the data. The boxcar will have a size of 8 days to make sure all mean flow is captured here. This is of course not possible for the 5 day run for the tenth degree resolution, a different method is therefore used for this.
Again to keep the section as readable as possible, the two main focus points, the horizontal resolution and the comparison with observational data with different vertical resolutions, will be analysed separately.

Resolution sensitivity

Using the boxcar filter the velocity signals can be split into a mean flow part and the wanted high frequency part (fig. 12). Doing this the NIW can be extracted from the original signal. The boxcar of 8 days is used to get the high frequency band of the variables for both the 1 degree resolution and the 0.25 degree resolution (since both are run for 2 month this is fine). The 0.1 degree resolution can however not be filtered, due to the short running time.

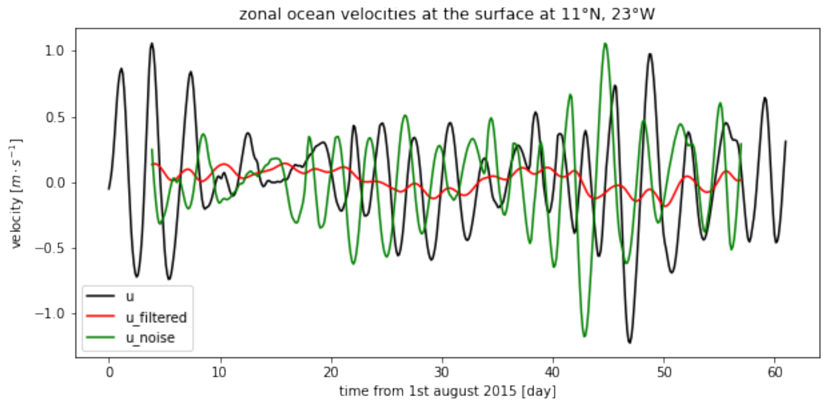


Figure 12: *Example of the boxcar filter. Zonal velocity at the surface at 11°N and 23°W. A boxcar filter is used to split the high frequency noise from the mean flow. The noise is the signal used as this is the frequency band where NIWs are.*

The focus point here is, as stated, to check for a correlation between horizontal resolution and the amount of turbulent processes resolved, specifically the NIWs. One way to do this is by looking at the variance of the zonal and meridonal velocities within the high frequency band, since the velocities are proportional to the eddy kinetic energy (EKE) in the system[11]. The variance will tell how sharp these peaks are within the high frequency band, and therefore how much shear is possible and how much mixing can occur.
A higher variance of the ocean velocities (and therefore the EKE) will mean a larger amount of turbulent processes are resolved by the model and more energy is being mixed down by the NIWs.
The place with the highest variance of the high frequency band of the zonal ocean velocity is around the tropics, more specifically the equator (fig. 13). Along the east coast of North America some strong larger values can also be seen due to the western boundary current (the gulf stream) and the resulting turbulent eddies[11]. Most of the interior is steady in both the 1 degree setup and the 0.25 degree setup. The lack of a steady mean flow in the tenth degree is most likely a direct result of the short running time (discussed more in *Discussion*).

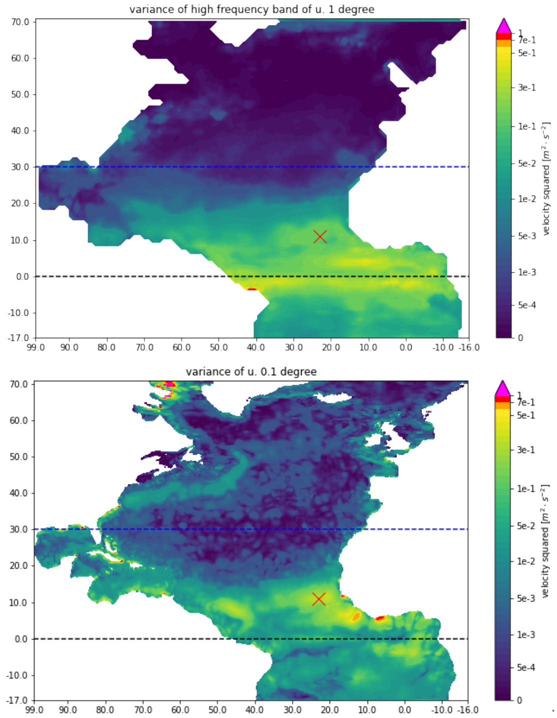


Figure 13: *The variance of the high frequency band of of the zonal ocean velocities (for the 0.1 degree run it is the variance of u). Shown also is the equator, the position of interest (11°N,23°W) and the 30°N line. Upper left:the 1 degree horizontal resolution. Upper right: the 0.25 degree horizontal resolution. Lower left: 0.1 degree horizontal resolution.*

From an initial look at the variance of the high frequency band of the zonal velocities, it seems to rise in the interior of the ocean (fig. 13). However This is mostly due to the tenth degree variance, which is of the whole signal and not just the high frequency part, meaning there is still the mean flow. In theory this should however not matter as the interior mean flow is thought to be in a steady state, so there should not be any variance in time[1]. To back this argument up, a ratio between the variance of the high frequency band of u and the variance of u is taken for the 0.25 degree resolution (fig. 14).

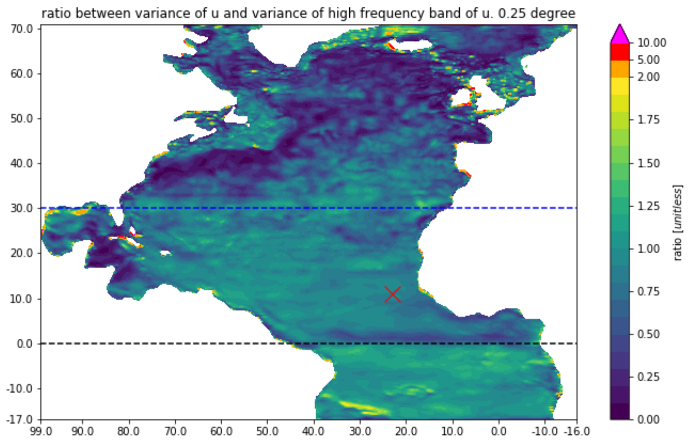


Figure 14: *A ratio between the variance of the high frequency band of the zonal velocity from the 1 degree run and variance of the zonal velocity from the 1 degree run. This shows how much of the EKE is in the mean flow. Along boundaries sharp peaks can be seen, these are not due to a sizable contribution to the mixed layer EKE, but by both variance values being close to zero.*

for the quarter degree resolution most of the north Atlantic follow the statement of a steady state for the mean flow, especially in the tropics this ratio is close to one. when looking at the north, past 30 degrees north, the statement begins to break down, and more energy is found in the entire signal than in just the high frequency

band (fig. 14). This study does however focus on the tropics so using the variance of u for the tenth degree resolution is an acceptable approximation, but results gathered using this should be discussed more carefully.
The variance of the meridonal ocean velocities follow the same structure as the zonal (see appendix). The Tropics have the highest variances of the high frequency band, with the turbulence around the gulf stream also being visible. Again the tenth degree resolution looks more turbulent in general, which may be caused by the mean flow not being filtered away, and the run time not being long enough for it to enter a steady state.

For good measure a ratio between the variance of v and the variance of the high frequency band of v is also done (see appendix). For the meridonal velocities, the statement also holds well for most of the north Atlantic below 30 degrees north, where the variance of the high frequency band of v begins to fall of compared to v.
The best way to check for a correlation between turbulence resolved and resolution is to compare these variances a bit more quantitatively. This is done by taking the ratio between the variance of the high frequency band of the ocean velocities of the lower resolution and the higher resolution. So a ratio between 1 degree and 0.25 degree and a ratio between 0.25 degree and 0.1 degree, of course for all points in the simulation.
To get the data of the same size the higher resolution data is interpolated to the lower resolution, using linear interpolation[12].

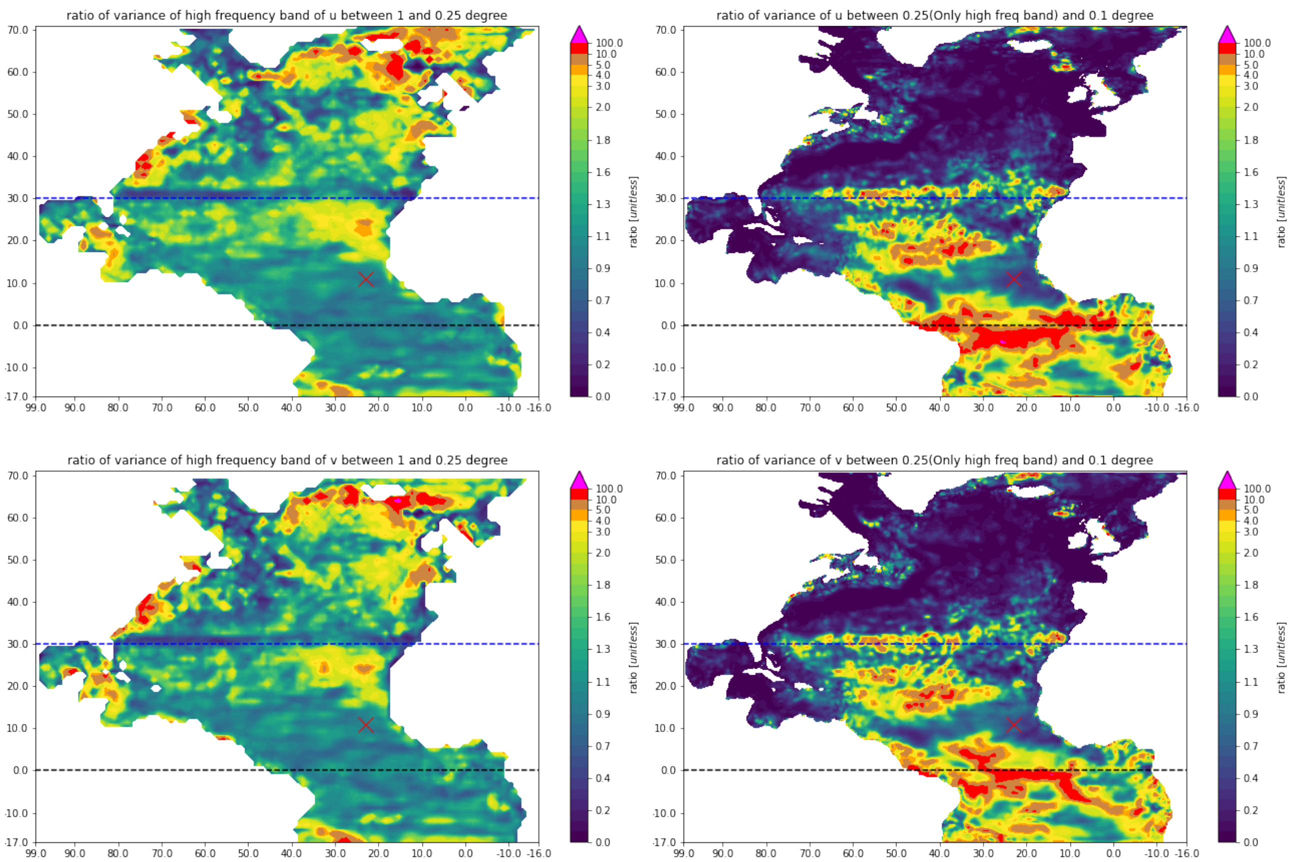


Figure 15: *Upper left: A ratio between the variance of the high frequency band of the zonal velocity from the 1 degree run and the 0.25 degree run. Upper right: A ratio between the variance of the high frequency band of the zonal velocity from the 0.25 degree run and the 0.1 degree run. Lower left: A ratio between the variance of the high frequency band of the meridonal velocity from the 1 degree run and the 0.25 degree run. Lower right: A ratio between the variance of the high frequency band of the meridonal velocity from the 0.25 degree run and the 0.1 degree run. Again the sharp peaks along boundaries are due to both values being close to zero.*

The general trend in the ratio between the one degree resolution and the quarter degree resolution lies between 3 and 0.5 with a middle of around 1 for both u and v (fig 15). This means that the variance of the high frequency band of the ocean velocities does not change significantly for a lot of the tested ocean basin between these two resolution. However some places, especially in the north, the ration is three or above meaning more resolved turbulence for the lower resolution. Then at around 30 degrees north a strip of around 0.5 can be seen meaning that here the quarter degree resolution resolves more. in the tropics and around the equator the general value is around 1.

Looking at the ratio between the variance of the high frequency band of u and v of the quarter degree and the variance of u and v of the tenth degree, it tells a different story. Here most of the north, past the 30 degree north mark, is very low, meaning a large difference between the two resolution with much more resolved by the tenth degree resolution. again at 30 degrees north there is a band, this time being of larger values than the general trend around. For the tropics and around the equator the ratio is mostly below 1, but some areas have sharp peaks reaching values of over 10, especially around the equator. This suggest that the quarter degree resolution resolves more around the equator.

These steep ratio spots in both cases, should however be taken with a grain of salt, as the variances are not normalized. This means that, yes one resolution may resolve more at one point but both resolutions have a very low variance at this point. An example can be seen of the coast of Iceland in the ratio between the 1 degree and 0.25 degree, where it seems that the 1 degree resolves much more, but by looking at the variance alone of these resolutions at this point shows that both values are very small compared to the tropics, or the coast of north America.

Comparison of NIW events

In this subsection the data will be processed, analysed and showed so it can directly be compared with the observed event, the comparison will however take place in the next section.

The observational data that the simulation will be compared to is of course the whole data and not just the high frequency part, so the inverse boxcar filter will not be used to the same extend here.

Besides the magnitudes that can be seen from the different figures, an important factor is the timing. It is interesting to see the time interval between these wind bursts and the NIW events. This is done by finding the middle of the NIW events, since they span a longer time duration, compared to the wind burst.

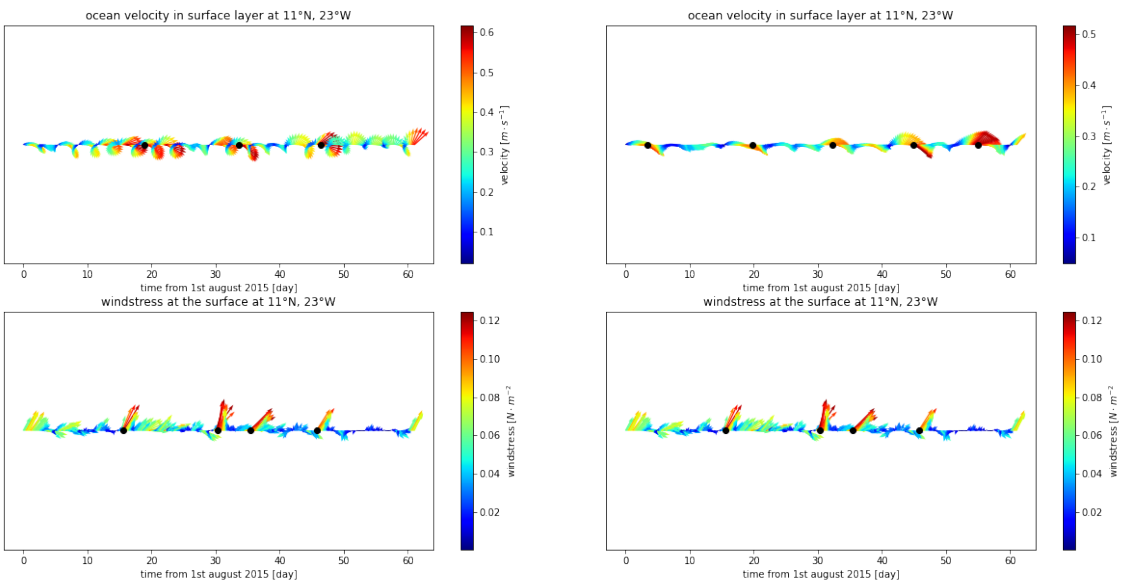


Figure 16: *Centers for the wind bursts and the NIW events in the ocean surface is plotted against fig. 8 and fig. 10. For a more detailed description of the vector plots see them.*

In the two months analysed, 4 significant wind bursts are seen at around: noon on the 15 of August, 9am on the 30 of August, 9am on the 4 of September and 6pm on the 14 of September (fig. 16). This is the case for both vertical resolutions, as they use the same wind field. The NIWs are however quite different, and so is the timing of them. The 10 meter vertical resolution have 3 visible NIWs at the point of observation, where the first happens for a long duration, and could possible be treated as multiple events but is simplified in this study to one. These events happen at: 11pm on the 18 of August, 1pm on the 2 of September and 9am on the 15 of September. In this comparison the third wind burst is not used. This is due to the fact that between that wind burst and the next NIW event another wind burst happens, and this next wind burst is therefore taken as the cause. The time intervals between these wind bursts and and the resulting NIW event are: 82 hours, 76 hours and 15 hours. This last event is the one that was observed.
Now for the 4 meter vertical resolution 4 significant spikes is seen in for the ocean velocities. These NIWs happened at around: 7pm on the 19 of August, 7am on the 1 of September, 11pm on the 13 of September and 00am on the 24 of September. The Time intervals between these events and the wind burst are then: 102 hours, 47 hours, 230 hours and 221 hours.

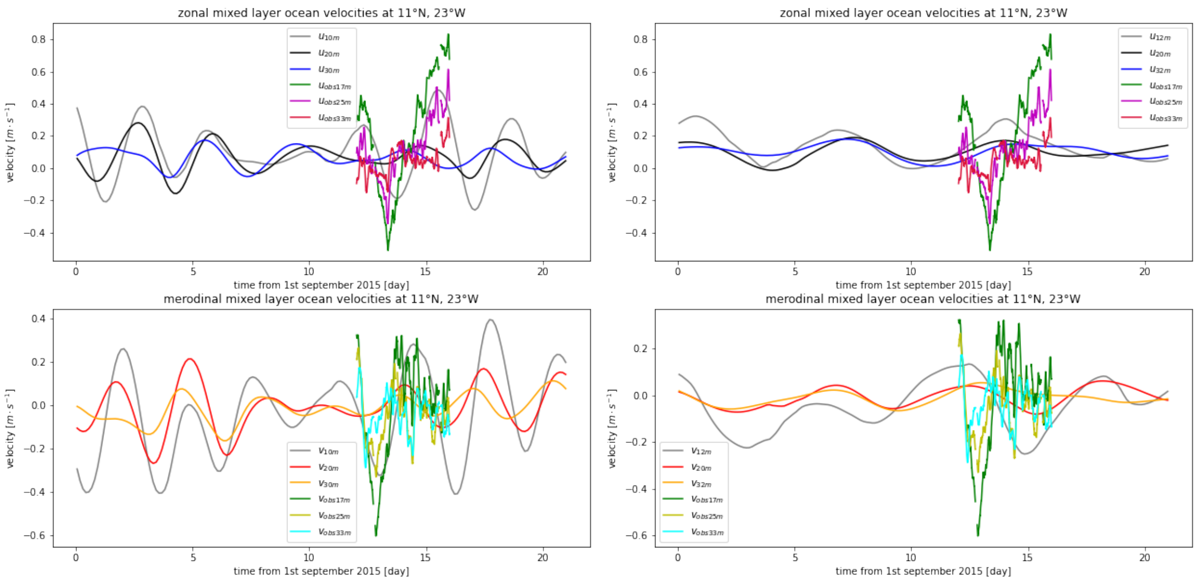


__Figure 17:__ Upper left: Comparison between the observed zonal ocean velocities in the mixed layer and the zonal ocean velocities from the 10 meter vertical resolution run. Upper right: Comparison between the observed zonal ocean velocities in the mixed layer and the zonal ocean velocities from the 4 meter vertical resolution run. Lower left: Comparison between the observed meridonal ocean velocities in the mixed layer and the meridonal ocean velocities from the 10 meter vertical resolution run. Lower right: Comparison between the observed meridonal ocean velocities in the mixed layer and the meridonal ocean velocities from the 4 meter vertical resolution run.

The observed NIW event is estimated to be from the 12 September to the 17 September in thew paper[5]. The ocean velocities for the 10 meter vertical resolution follow the same trend as the observed for both zonal and meridonal (fig. 17). The fall off in velocity is however much faster for the simulated than in the real world. This is the case for both u and v. At around 10 meter depth they do however follow the observed values quite close.
The 4 meter vertical resolution is another story. The zonal ocean velocities does not have a significant peaks at the time of the observed event and both the zonal and meridonal velocities fall of quite drastically.

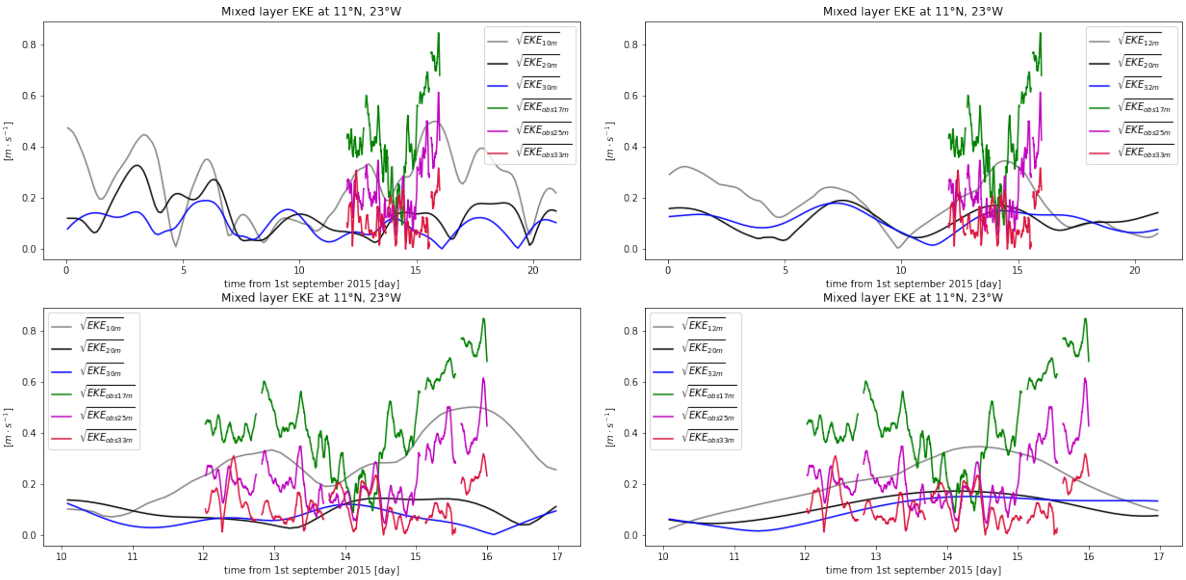


Figure 18: *Upper left: comparison between observed mixed layer EKE and mixed layer EKE gathered from the 10 meter vertical resolution run. Upper right: comparison between observed mixed layer EKE and mixed layer EKE gathered from the 4 meter vertical resolution run. Lower left: Closer look at the 10 to 17 of September of upper left. Lower right: Closer look at the 10 to 17 of September of upper right.*

The eddy kinetic energy of the system at the observed point will give a good idea of the whole trend of the system. For the 10 meter vertical resolution The EKE of the simulation follows the trend and phase of the observed data. The form is very close to the observed, however the magnitude is lower. The fall off of the simulated EKE is much quicker than the observed value, but around 30 meters depth they are of the same size. The 4 meter vertical resolution run almost follows an inverse trend as it is phase shifted around 180 degrees. The magnitude of the simulation is much smaller than that of the observed, and again it fall of much faster.

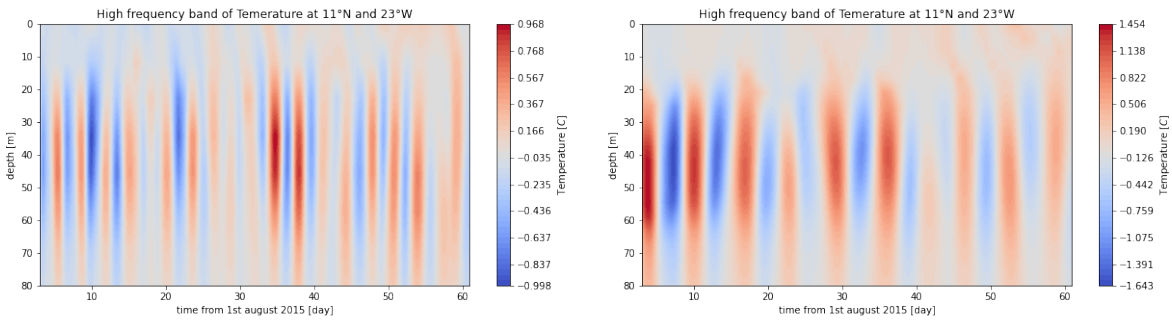


Figure 19: *The high frequency band of the temperature over time at versus depth. Left: 10 meter vertical resolution run. right: 4 meter vertical resolution run.*

Using the inverse boxcar filter, the temperature spikes that are caused by the NIWs mixing can be shown (fig. 19). For both vertical resolutions strong temperature gradients are created at the time of the NIW events. These temperature gradients peak at around 40 meters depth and fall off both upwards and downwards. The time duration of these peaks closely resembles the peaks of the ocean velocities for both resolutions. This shows that strong vertical mixing does occur at these events.

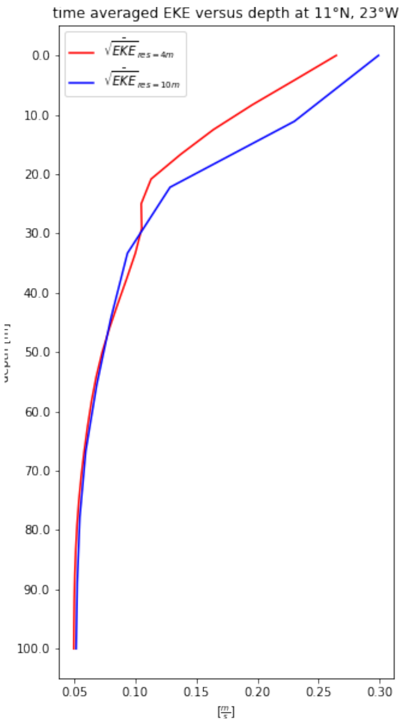


Figure 20: The time averaged EKE versus depth at 11°N and 23°W. Here the time averaged EKE is plotted for both the 10 meter vertical resolution run and the 4 meter vertical resolution run.

Since the 4 meter resolution has is phase shifted it is helpful to see if the energy shift is due to a change downward or upward change in energy(fig. 20). A change is however not apparent, and both simulations fall off exponentially between the surface and around 30 meters depth.

Discussion

In this section the results from the simulations and the findings ind the data analysis will be discussed as will their implication and meaning. The original questions will be tried to answered or at least some argumentation towards possible solutions will be given. Problems, limitations and further work will also be discussed.
For the resolution sensitivity the discussion will mostly focus on how the different resolutions compare to each other with regards to energy resolved. It will also discuss what the possible optimal resolution could be for different parts of the north Atlantic, among other things. It is also in this section that a clear comparison with the observed NIW event will be done, with focus on timing, strength, form and more. The implication of the vertical resolution will also be discussed.

Resolution sensitivity

The main question of this part of the study was: Is there a resolution sensitivity in the amount of turbulent processes resolved? The answer is unfortunately not as straightforward. When looking at the variance of the high frequency band of the ocean velocities for the different resolution, the general trend is upwards with resolution(fig. 13). In this study the variance of the high frequency band is used instead of the actual EKE, but the two are proportional[11]. This means that in general our model resolved a higher amount of energy for the models with a higher resolution. This difference is however very small for a resolution change from 1 degree to 0.25 degree (fig. 15). When looking at this ratio one should keep in mind that the data is not normalized, so the high ratios around coasts and in the northern sea are due to both values being close to zero. In the tropics there is close to no change between these to resolutions. At around 30 ° N the quarter degree has more EKE, but this is a special case as generally the energy resolved is the same for the two resolutions, with it being higher for

one in some area and higher for the other in some other areas, these differences and areas are however not large enough for a change in resolution would be justified.
A change to 0.1 degree do however change the amount of energy in the system quite drastically. For this resolution the energy is not as strongly confined to the tropics as it is for the two other resolutions (fig. 13). The gulf stream is much more visible and the energy distribution in the tropics is less uniform around the equator.
The ratio between the 0.25 degree and the 0.1 degree is for most of the interior around 0.2, meaning around 5 times more EKE is resolved for the 0.1 degree compared to the 0.25 or 1 degree (fig. 15). The tenth degree resolution is however the whole signal and not only the high frequency band, and it is shown that the difference between these for the 0.25 degree resolution generally is around 1.25 (fig. 14). This means that the amount of EKE resolved is more around 4 times higher for the 0.1 degree. There are also large areas in the model were this ratio is very different. Most notably around the equator, 18 ° N and 30 ° N (fig. 15). around the equator this ratio is between 2 and 20, meaning that a lot of energy is missing in the 0.1 degree setup that was resolved for the 1 and 0.25 degree setups. This is not due to all values being small, as the tropics is where most of the energy is for all three models. For the two other sections, the ratio is between 2 and 10, again meaning less energy resolved for the tenth degree setup.
These large differences between the tenth degree and the other resolutions may be effected by the short running time. This model was only run for 5 days compared to the 2 months the others were run. In 5 days the general trend of the different regions of the north Atlantic is not resolved yet and in this can create some variance in the model output as the ocean interior has not settled into a steady state. The mean flow simply is not resolved properly. This can however not take away from the general larger amount of energy in the tenth degree system.
The change between 1 degree and 0.25 degree horizontal resolution is very local and the general trend in EKE is the same. The 0.1 degree horizontal resolution does generally have more energy, but because of the short running time the more local differences of the different sections of the north Atlantic is not possible to quantify.

Comparison of NIW events

Now it is time to look at the whole picture, all the data and the analysis, and see if the simulated NIW event actually look anything like the observed. This has been discussed in some sense when the different results were shown, however it will now be done all together, and with the observed data shown for a closer comparison.
Firstly it has been shown that the wind field used for the simulation is close to the wind field observed at the buoy, the time of the strong wind burst are assumed to be a fair representation of the real world (fig. 3). The observed event take place between the 12 September and the 17 September. The simulation run with a vertical resolution of 10 meters was found to have a NIW event around the 15 September, which spanned multiple days (15 September is the middle of the event). The timing and span of the 10 meter vertical resolution model therefore compares very well with the observed. The 4 meter vertical resolution run had a NIW event around the 13 which also spanned multiple days. This change in vertical resolution, changed the time response of the ocean to the wind stress.
The form of the NIW events from the simulation compare well with the observed data, showing these rotating patterns (fig. 21). The 10 meter resolution do however keep the circular form better, than the 4 meter resolution. This may be caused by the fact that for a lower vertical resolution the shear in the ocean can happen quicker, due to more points were it can happen so the energy is dissipated quicker.
The magnitude and oscillation of the zonal and meridonal ocean currents are well represented in the simulations. The observed u and v reaches peaks of $0.5\frac{m}{s}$ and changes direction about every 24 hours (fig. 21)[5]. This compares well with the 10 meter vertical resolution ocean simulation which reaches peaks of $0.6\frac{m}{s}$ in the zonal direction and $0.48\frac{m}{s}$ in the meridonal direction. As stated earlier this model also oscillates in direction around every day, where the 4 meter vertical resolution run oscillates every 2-3 days. The magnitudes of this run are $0.47\frac{m}{s}$ in the zonal direction, and $0.35\frac{m}{s}$ in the meridonal direction.
The strength of the ocean velocities are very close to the observed event, at least for the surface. A comparison of the EKE (and ocean velocities) at different depths between the models and the observed event, shows that there is a large difference in fall off rates (figs. 17 and 18).

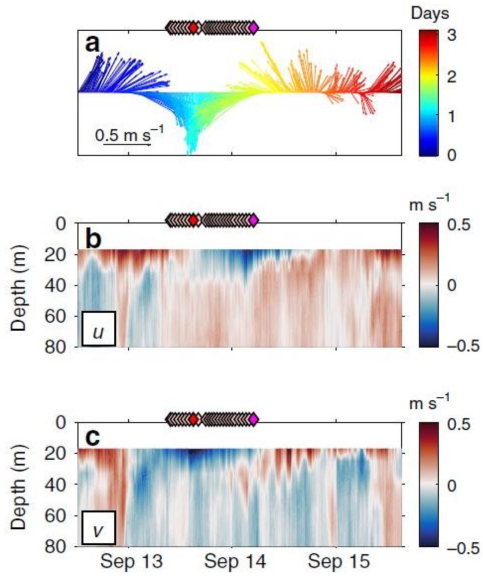


Figure 21: *a: vector plot of the surface ocean velocities of the observed data over time. b: the zonal ocean velocities of the upper 80 meters over time of the observed NIW event. c: the meridonal ocean velocities of the upper 80 meters over time of the observed NIW event. See Hummels et al. 2020 figure 3 for more details[5].*

The 10 meter vertical resolution run fall off to a third of the surface velocities at around 20 meters depth at the time of the observed event. The general fall off of both runs is very fast through out the upper 20-30 meters (fig. 20). This is relatively fast compared to the observed event, that does not fall off significantly until a sharp gradient around 20 meters depth[5]. This fall off issue is the same for both vertical resolutions (fig. 20). However due to the timing shift in the 4 meter vertical resolution, the ocean velocities at the time of the observed NIW event is very different. The 10 meter vertical resolution run compares very well in form and timing with the observed event, except for the quick fall off (fig. 18). The 10 meter vertical resolution run is in almost perfect phase with the observed event, in both meridonal and zonal ocean velocities, and therefore also EKE[5]. The 4 meter vertical resolution run is in a almost 180 degree phase shift from the observed event. The vertical resolutions effect on the timing could therefore be quantifiable in future projects.

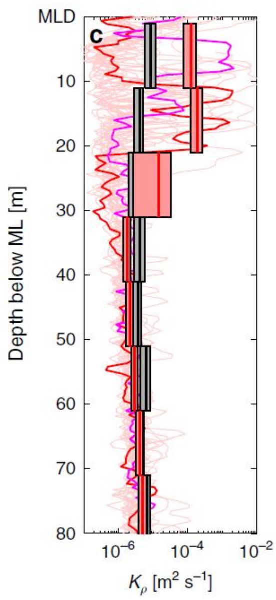


Figure 22: *The eddy diffusivity of the observed data versus depth. See Hummels et al. 2020 figure 4 for more details.*

Another important part of the NIW event to compare is the mixing. As stated earlier vertical mixing was seen from both simulations at the time of the EKE peaks. This happened in the upper 20 meters for the 10 meter vertical resolution run, and the upper 10 meters for the 4 meter vertical resolution run (figs. 9 and 11). The vertical mixing of the observed NIW event drops after 20 meters depth much like the 10 meter resolution run (fig. 22)[5]. The observed vertical mixing peaks at around $1 \cdot 10^{-2} \frac{m^2}{s}$. The 10 meter vertical resolution run peaks at $1.7 \cdot 10^{-2} \frac{m^2}{s}$ and the 4 meter vertical resolution run peaks at $2.5 \cdot 10^{-2} \frac{m^2}{s}$. The vertical mixing in the 4 meter vertical resolution run is much larger than the observed, were the 10 meter vertical resolution run is closer, but is still almost a factor of 2 larger. As discussed earlier a larger vertical resolution will increase the available shear and in turn the vertical mixing.

For most of the comparison the 10 meter vertical resolution is relatively close to the observed event, were for the 4 meter vertical resolution a lot of things were different, most notably the timing and phase. The most notable difference between the 10 meter vertical resolution run and the observed event is the energy fall off rate[5]. The observed have a quick fall off around 20 meters, where as the simulation falls off exponentially over the first 20 meters starting from the surface. A change in the parameterization of the mixed layer could be a possible solution to this, as well as the unexpected changes due to a higher vertical resolution. But for this limited study the 10 meter vertical resolution made a good representation of the observed event with few differences.

Computational problems and further study

There were some problems doing this project that hindered it some what. Firstly do to the lack of experience working with ERA5 data, the problem with the mirrored wind data occurred. In future studies this can of course be avoided. For this project this meant that the horizontal resolution part of the project needed to be treated separately from the rest, and the results and data analysis could not be compared with the observational data. A future study in how the horizontal resolution sensitivity found in this study could help replicate observed event, could be interesting.

Furthermore due to time limitations two things happened. Firstly the 0.1 degree could only be run for 5 days and not the preferred 2 months, so such a run would be great for a better comparison between the resolutions. Also the models could not be rerun for the right wind field. A more in depth study of the horizontal resolution sensitivity could be done with more resolutions and all run for the same time.

Conclusion

The mixing caused by NIW events is, in this study, shown to be horizontal resolution sensitive. However not straight forward, as there is a difference between going from 1 degree to 0.25 degree and going from 0.25 degree to 0.1 degree resolution. However there still is a sensitivity, and quite a large one, if the results gathered in this project is to be believed. There is however some uncertainties regarding the results due to computational constraints. Nevertheless the data can still be used to argue for a more detailed look at the horizontal resolution sensitivity of the mixed layer, as such a sensitivity is found, and for a more qualitative map of areas benefiting from a greater resolution.

The current VEROS model can be used to quite accurately model NIW events in the tropical north Atlantic. It is shown that with a 1 degree horizontal resolution and a 10 meter vertical resolution, the form, magnitude, phase and timing of an observed NIW event can be accurately modelled. There is however a large difference in the fall off rate of the mixing energy. doing a 4 meter vertical resolution run showed that this fall off rate is not changed significantly with a higher vertical resolution, but a lot of other aspect of the mixed layer is. The timing, magnitude and phase are all changed significantly from the observed when the vertical resolution is changed. Further study into why the vertical resolution changes this and which parameters could be optimized to prevent this would be very useful for further improvements on the 10 meter vertical resolution run and the very different fall off rate.

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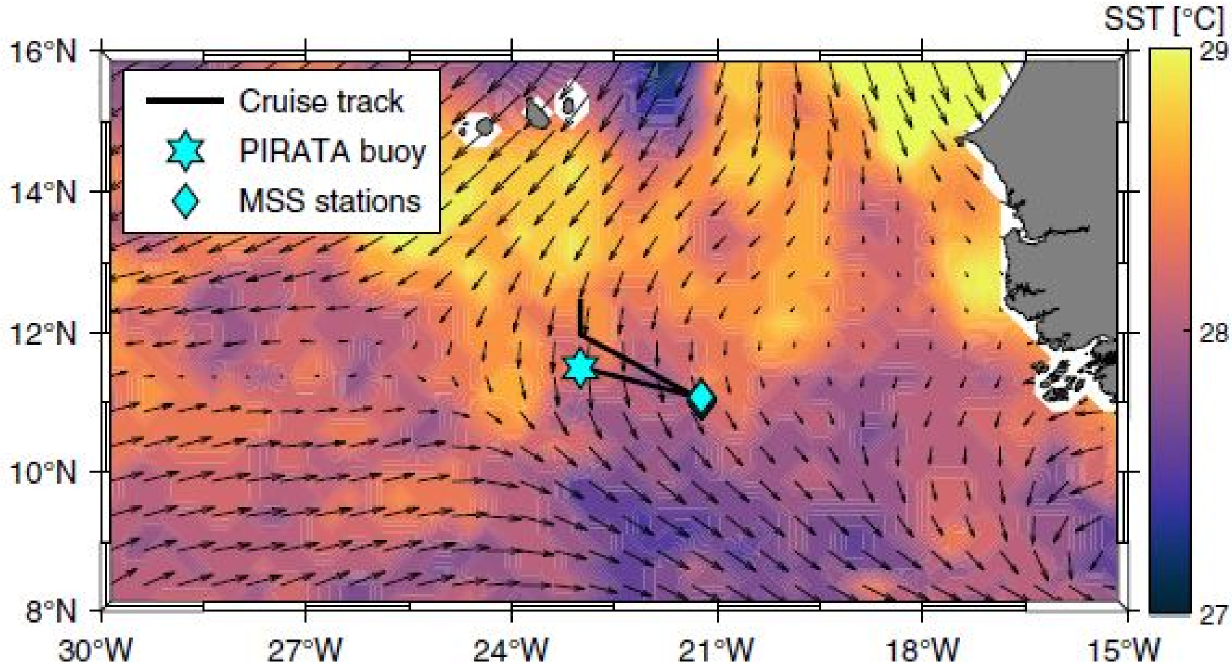
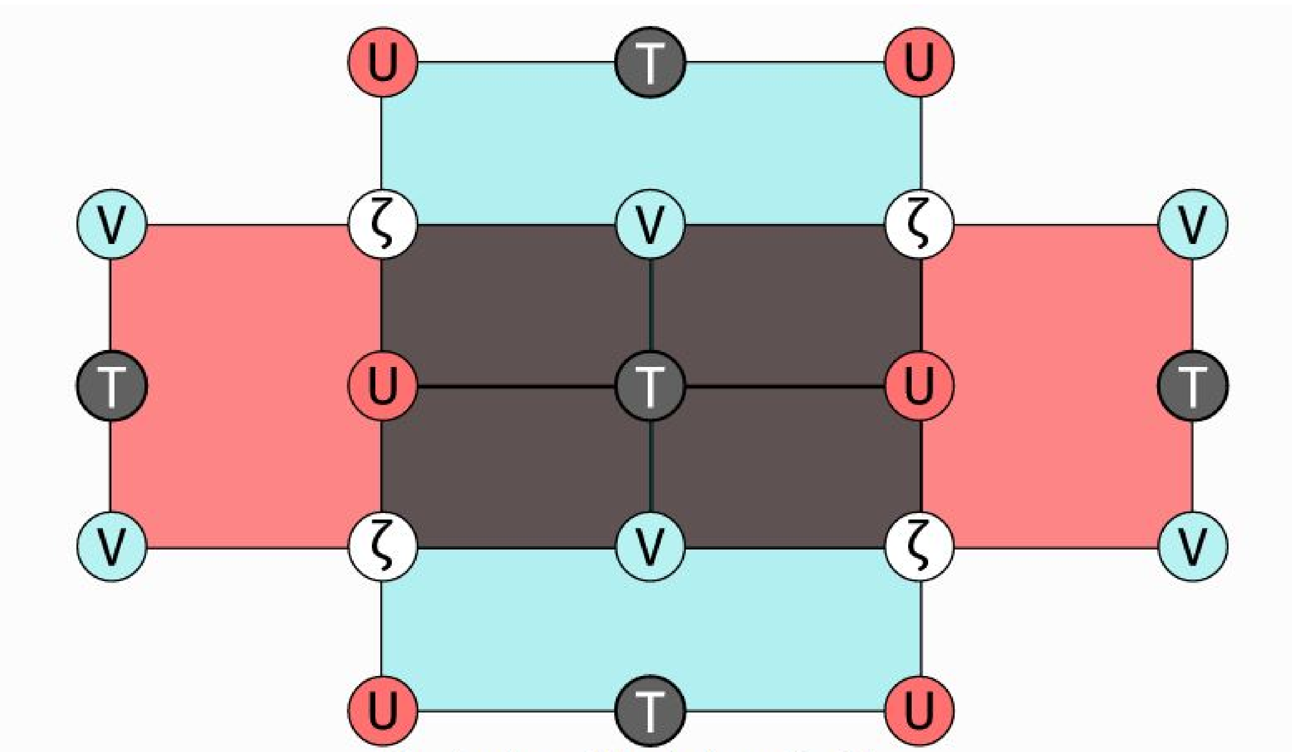
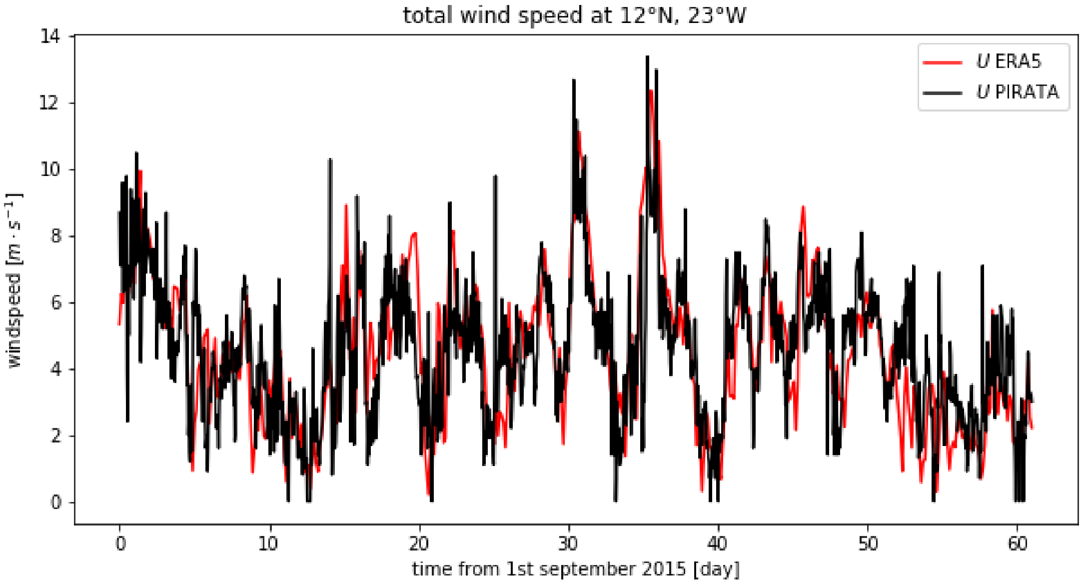
Appendix





The structure of the Arakawa C-grid.


total wind speed at 12°N, 23°W
U ERA5
U PIRATA
windspeed [m · s^-1]
time from 1st september 2015 [day]
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2
4
6
8
10
12
14
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10
20
30
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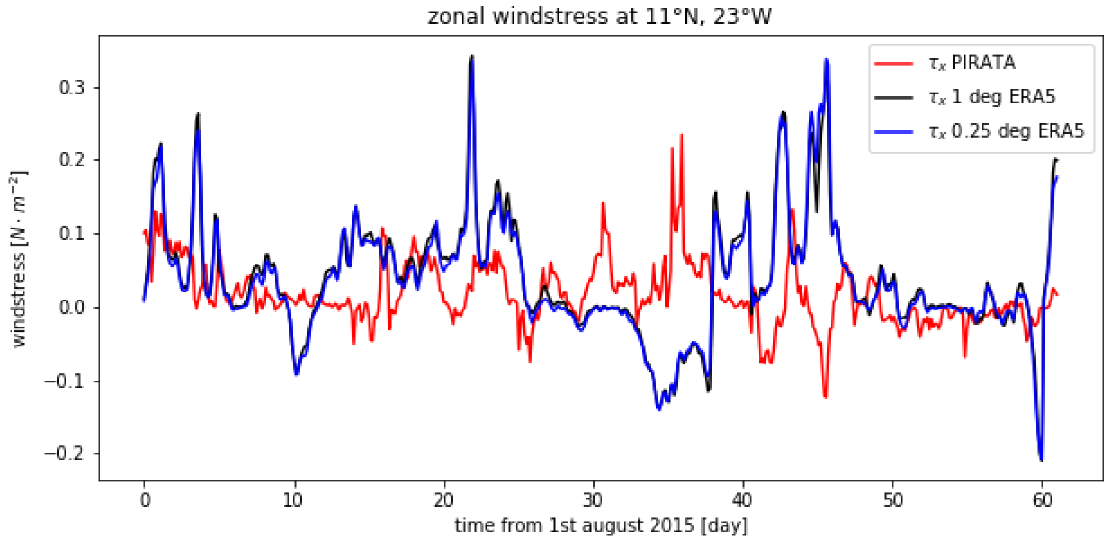
50
60


zonal windstress at 11°N, 23°W
windstress [N · m⁻²]
time from 1st august 2015 [day]
τx PIRATA
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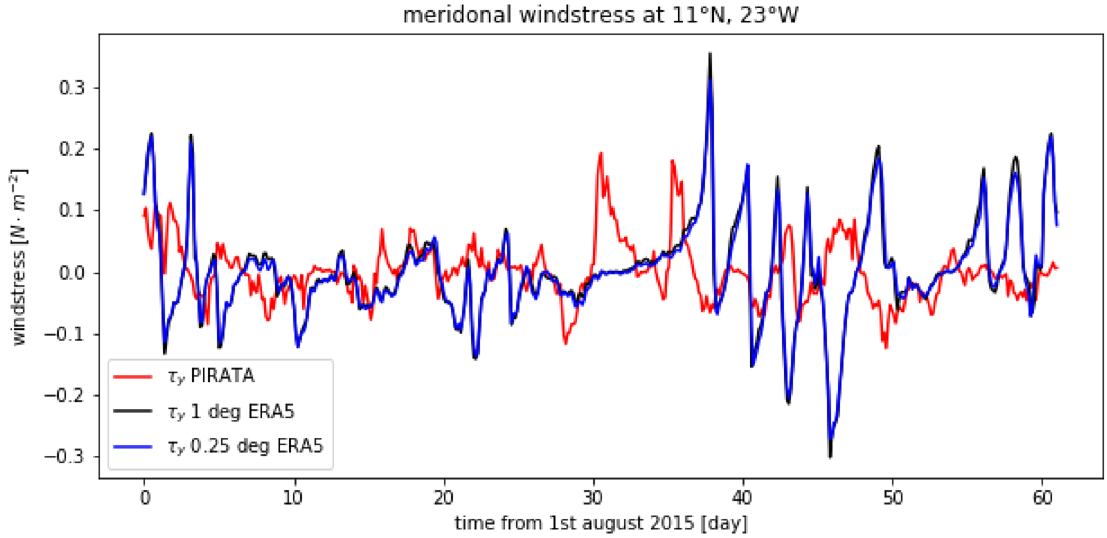
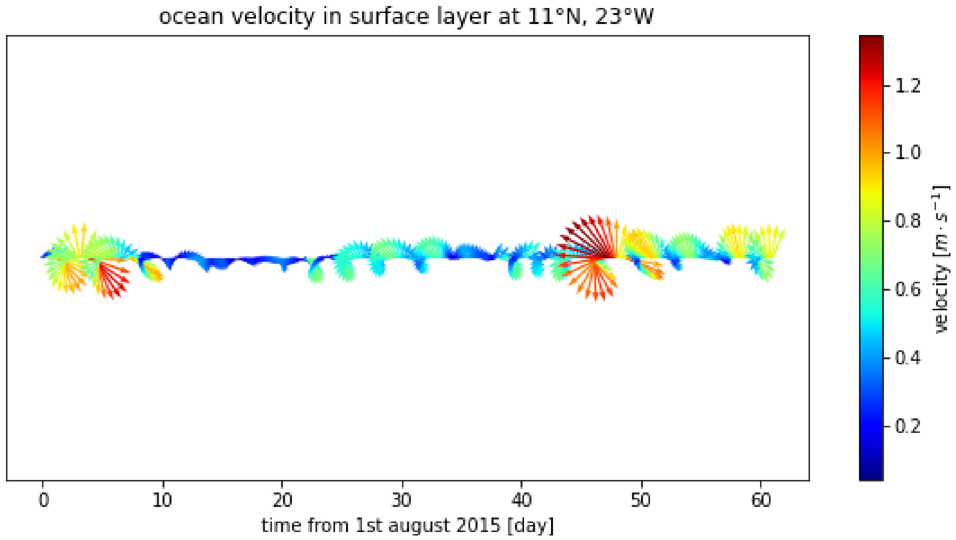

meridonal windstress at 11°N, 23°W
windstress [N · m⁻²]
time from 1st august 2015 [day]
τy PIRATA
τy 1 deg ERA5
τy 0.25 deg ERA5


ocean velocity in surface layer at 11°N, 23°W
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time from 1st august 2015 [day]
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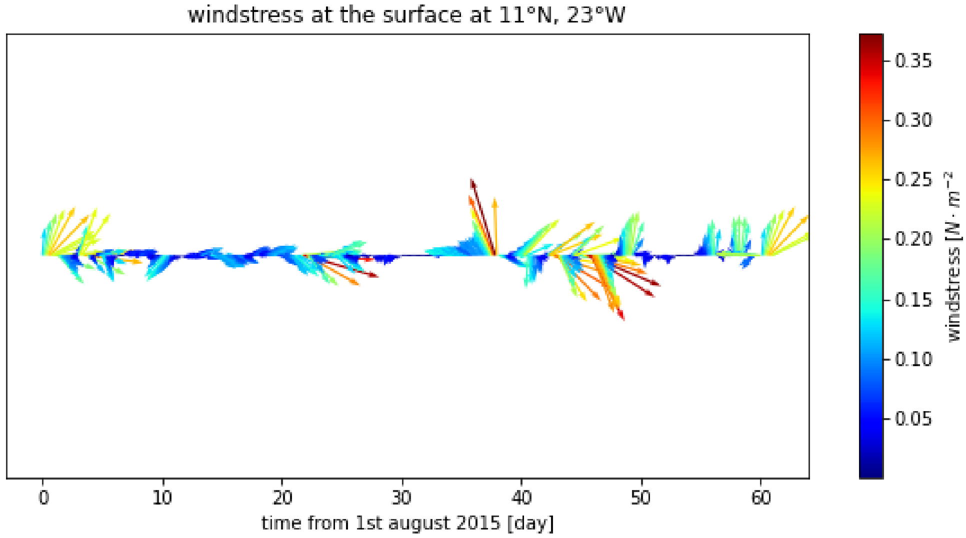
velocity [$m \cdot s^{-1}$]


windstress at the surface at 11°N, 23°W
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40
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time from 1st august 2015 [day]
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0.30
0.25
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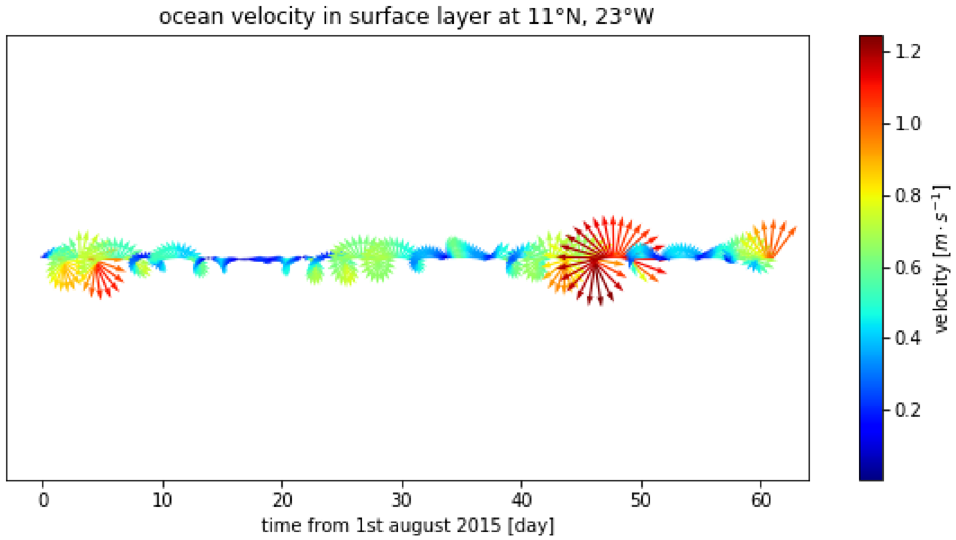
0.10
0.05
windstress [$N \cdot m^{-2}$]


ocean velocity in surface layer at 11°N, 23°W
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time from 1st august 2015 [day]
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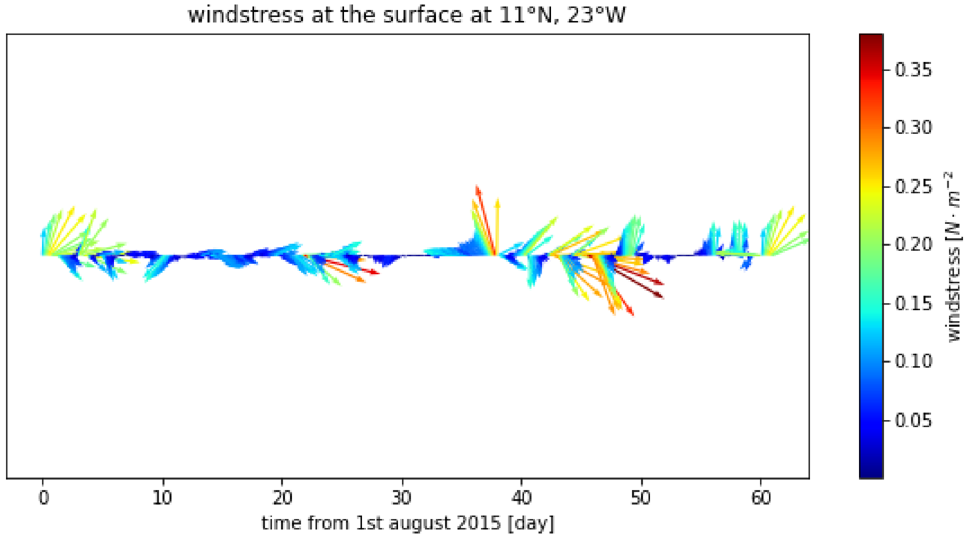
velocity [$m \cdot s^{-1}$]


windstress at the surface at 11°N, 23°W
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time from 1st august 2015 [day]
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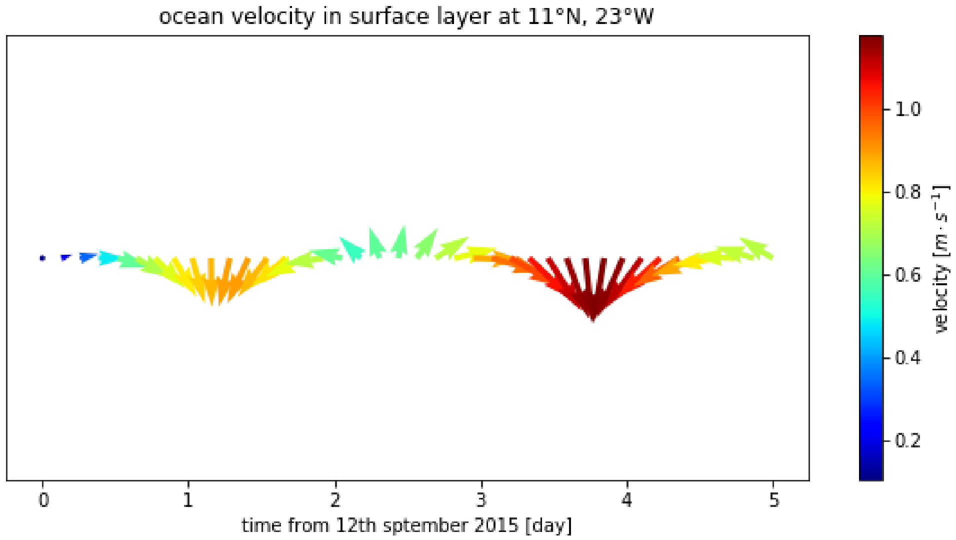
windstress [$N \cdot m^{-2}$]


ocean velocity in surface layer at 11°N, 23°W
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time from 12th sptember 2015 [day]
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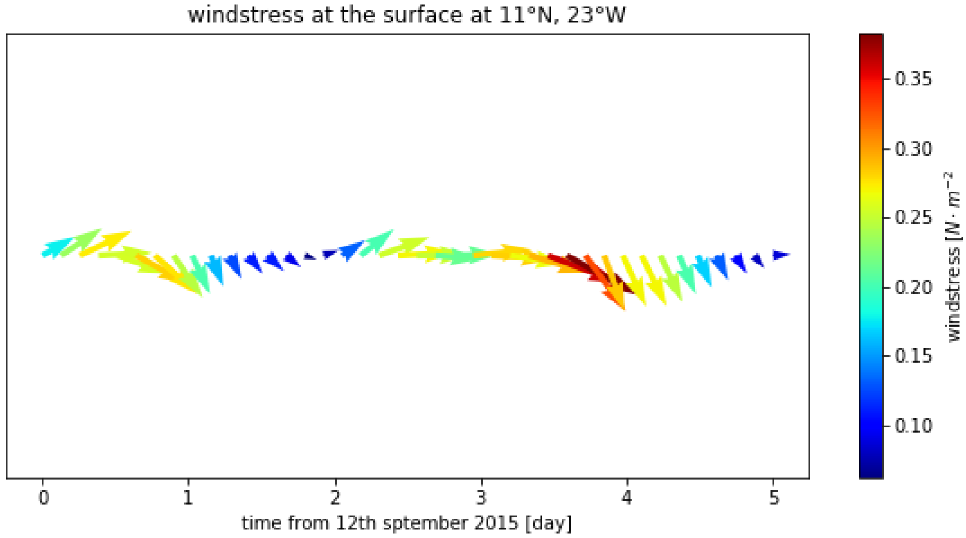
0.8
0.6
0.4
0.2
velocity [$m \cdot s^{-1}$]


windstress at the surface at 11°N, 23°W
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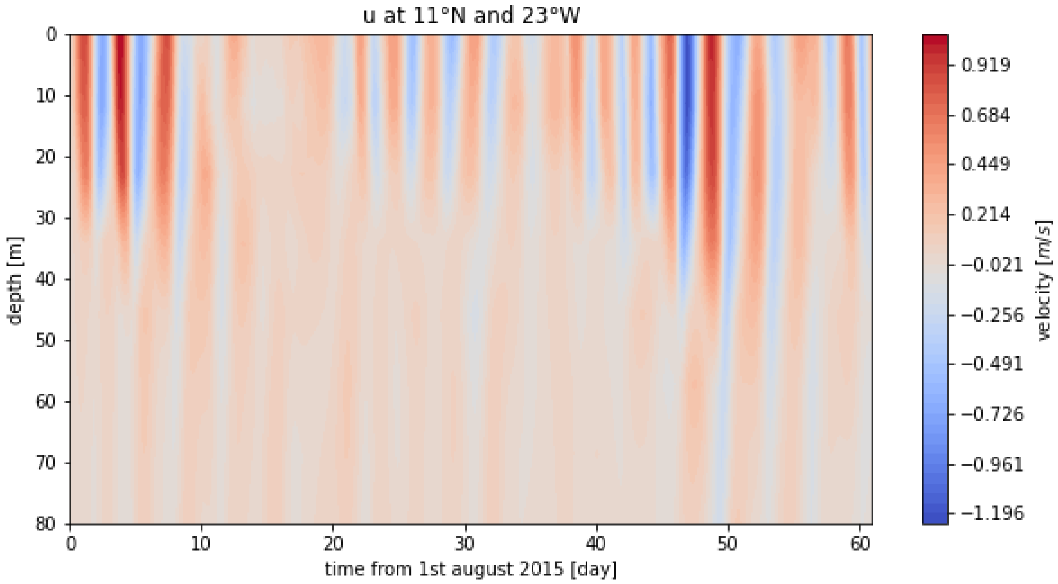
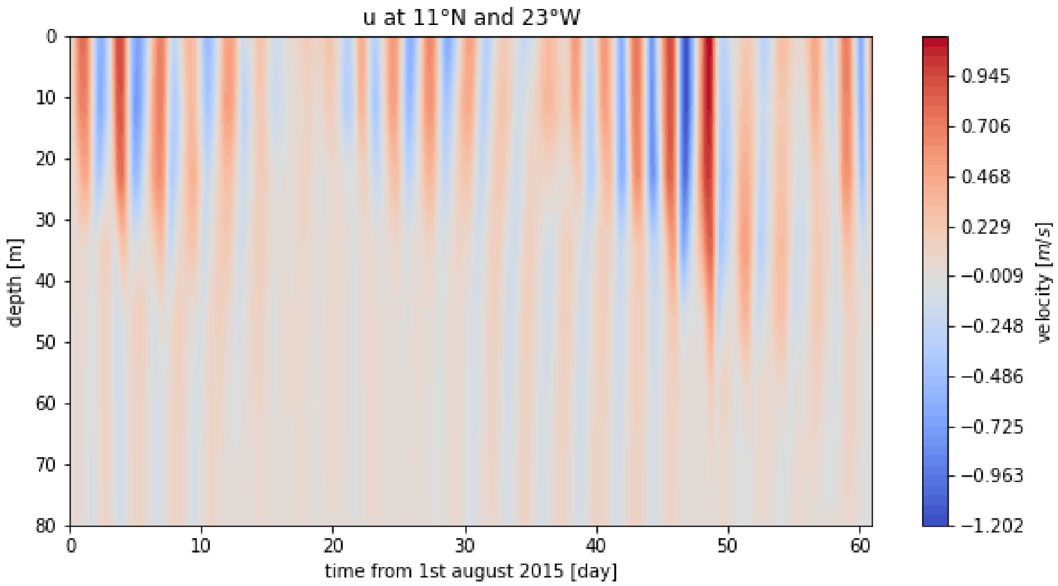
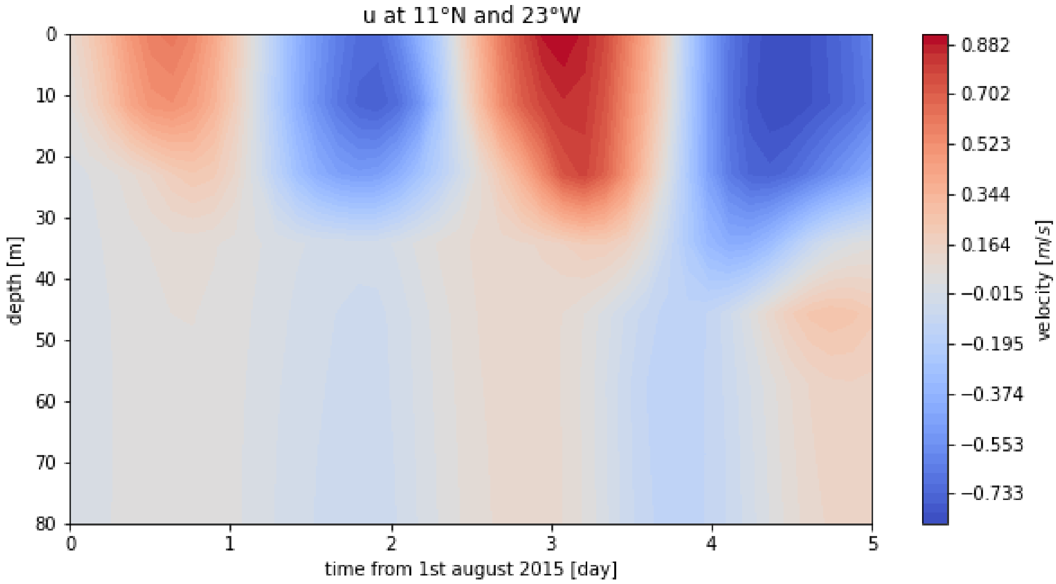
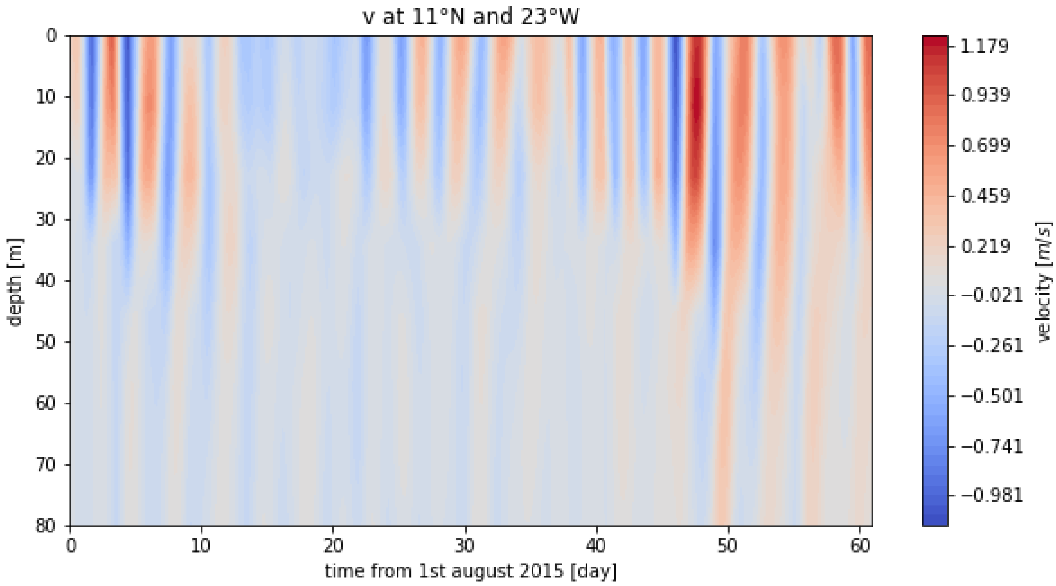
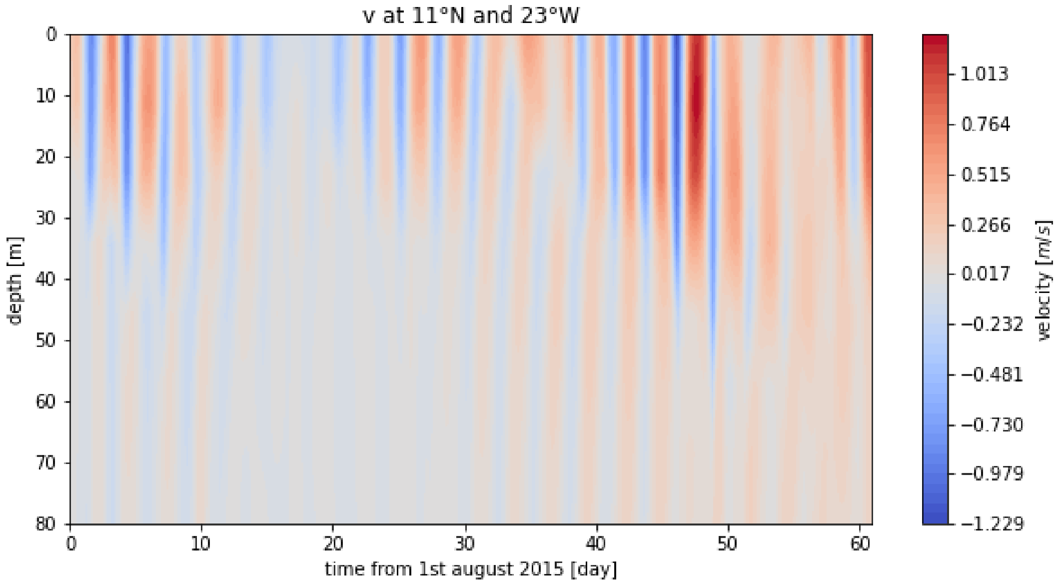
3
4
5
time from 12th sptember 2015 [day]
0.35
0.30
0.25
0.20
0.15
0.10
windstress [$N \cdot m^{-2}$]

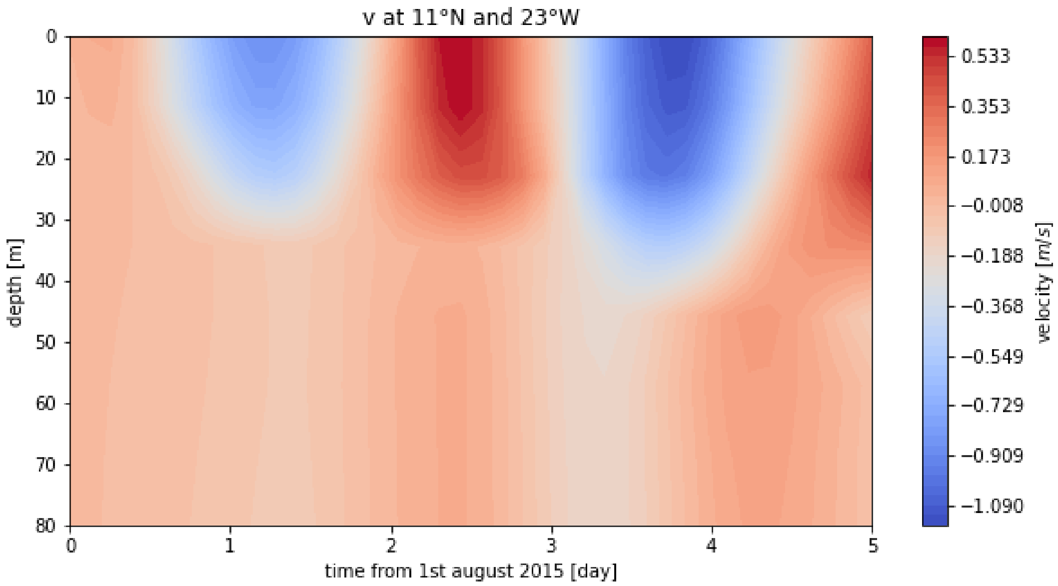

u at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0.919
0.684
0.449
0.214
−0.021
−0.256
−0.491
−0.726
−0.961
−1.196

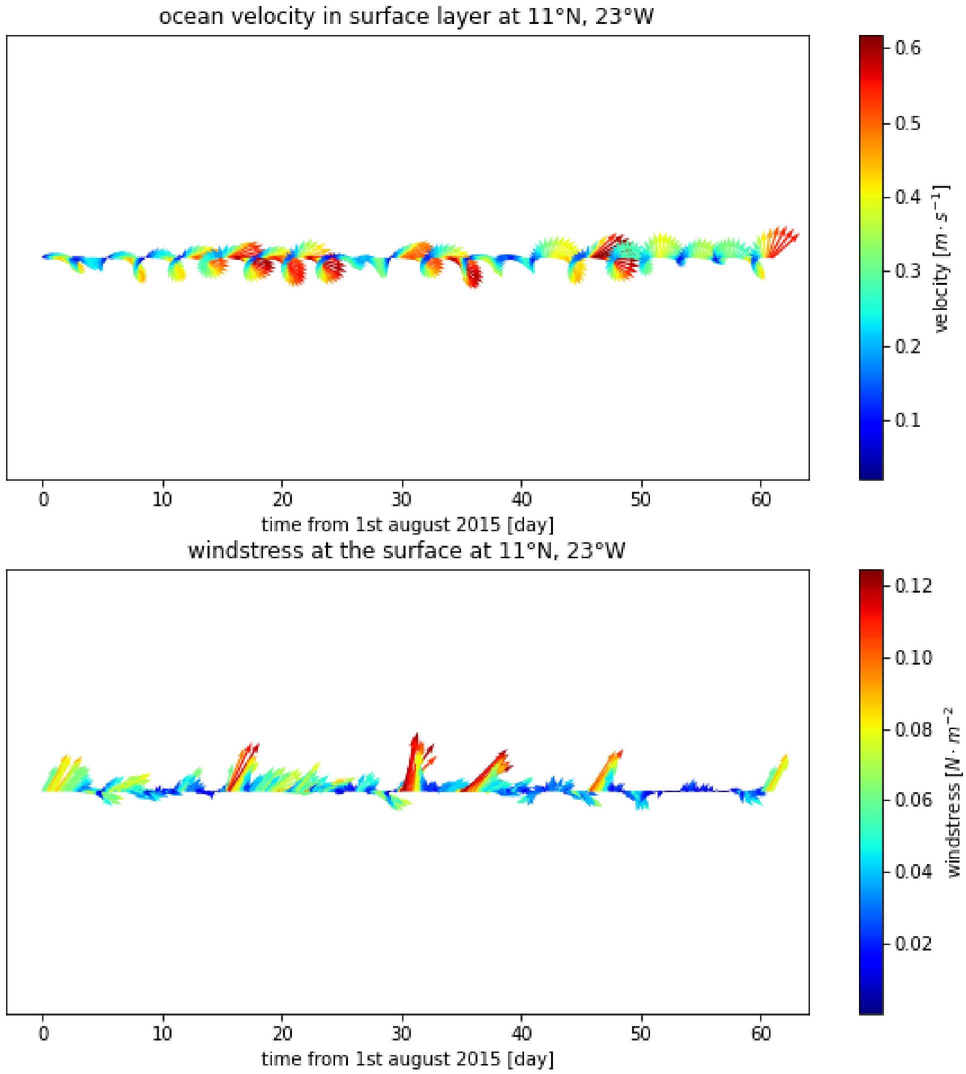

u at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0.945
0.706
0.468
0.229
−0.009
−0.248
−0.486
−0.725
−0.963
−1.202

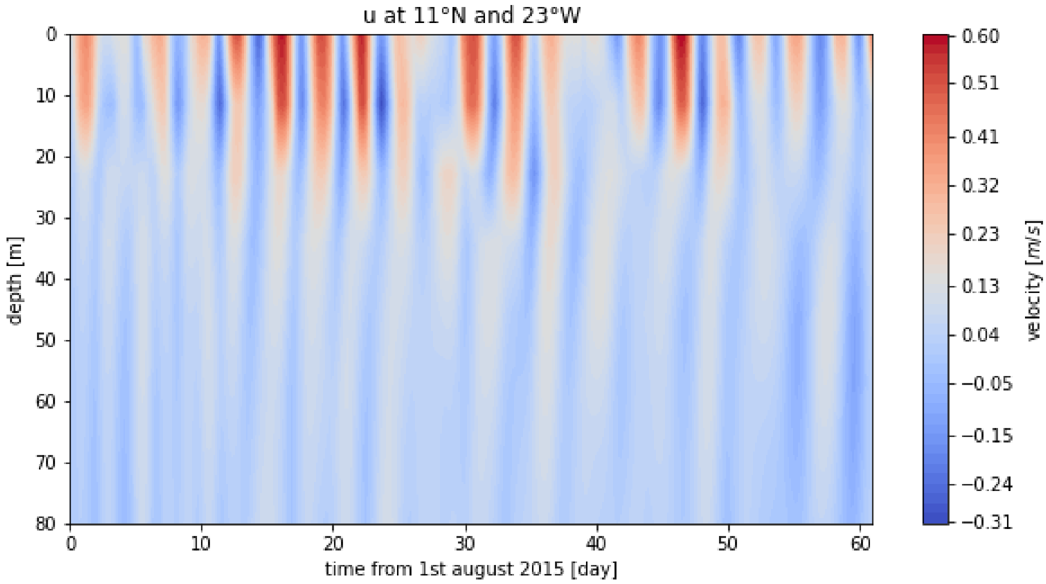

u at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0.882
0.702
0.523
0.344
0.164
−0.015
−0.195
−0.374
−0.553
−0.733

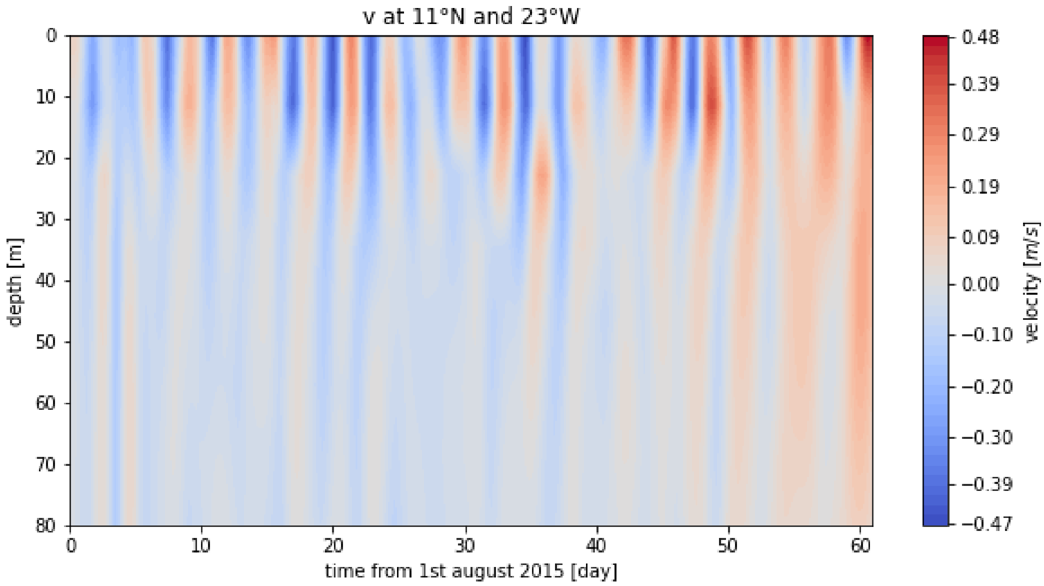

v at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
1.179
0.939
0.699
0.459
0.219
−0.021
−0.261
−0.501
−0.741
−0.981

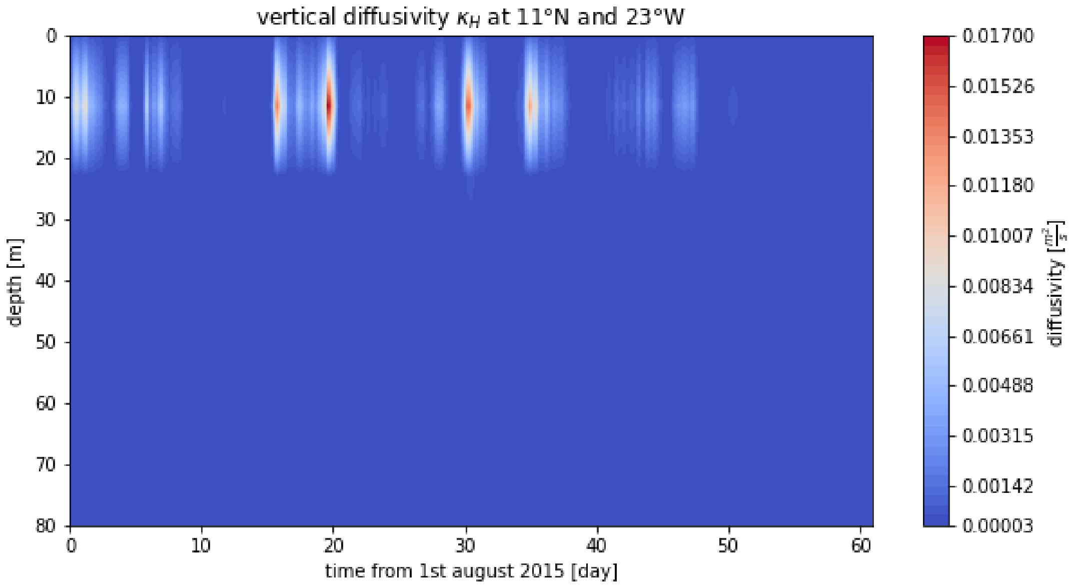

v at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0
10
20
30
40
50
60
70
80
0
10
20
30
40
50
60
1.013
0.764
0.515
0.266
0.017
−0.232
−0.481
−0.730
−0.979
−1.229

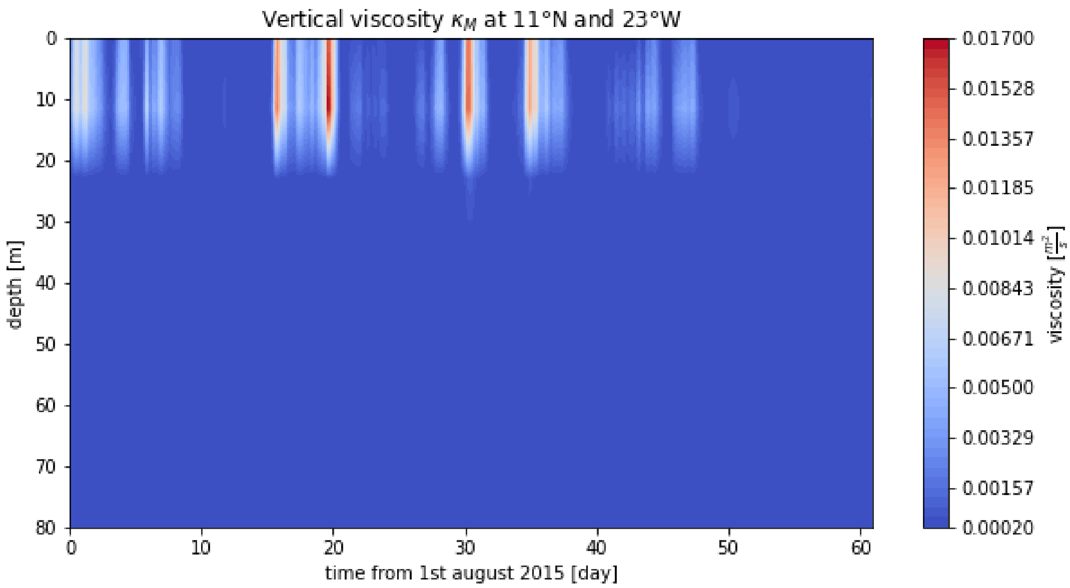

v at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
0.533
0.353
0.173
−0.008
−0.188
−0.368
−0.549
−0.729
−0.909
−1.090

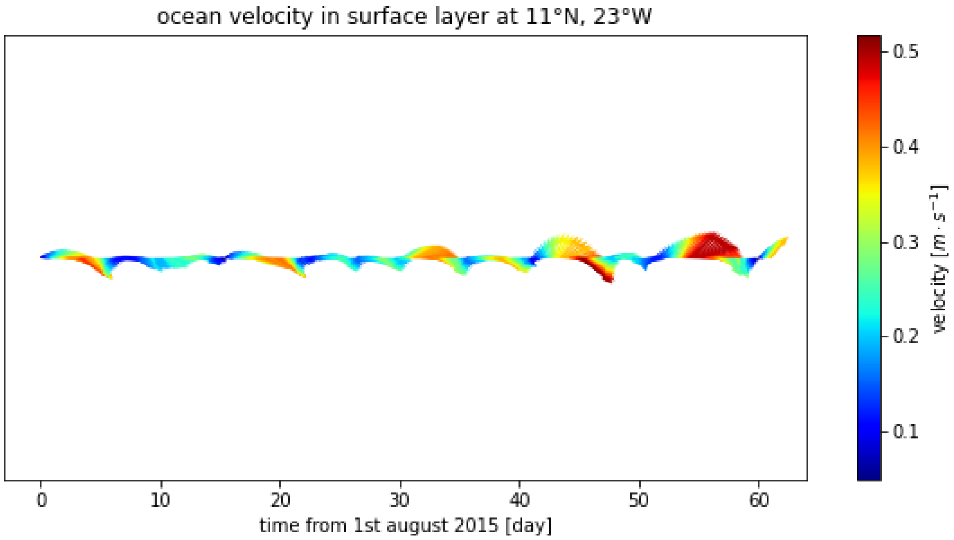

ocean velocity in surface layer at 11°N, 23°W
time from 1st august 2015 [day]
0
10
20
30
40
50
60
velocity [$m \cdot s^{-1}$]
0.1
0.2
0.3
0.4
0.5
0.6
windstress at the surface at 11°N, 23°W
time from 1st august 2015 [day]
0
10
20
30
40
50
60
windstress [$N \cdot m^{-2}$]
0.02
0.04
0.06
0.08
0.10
0.12

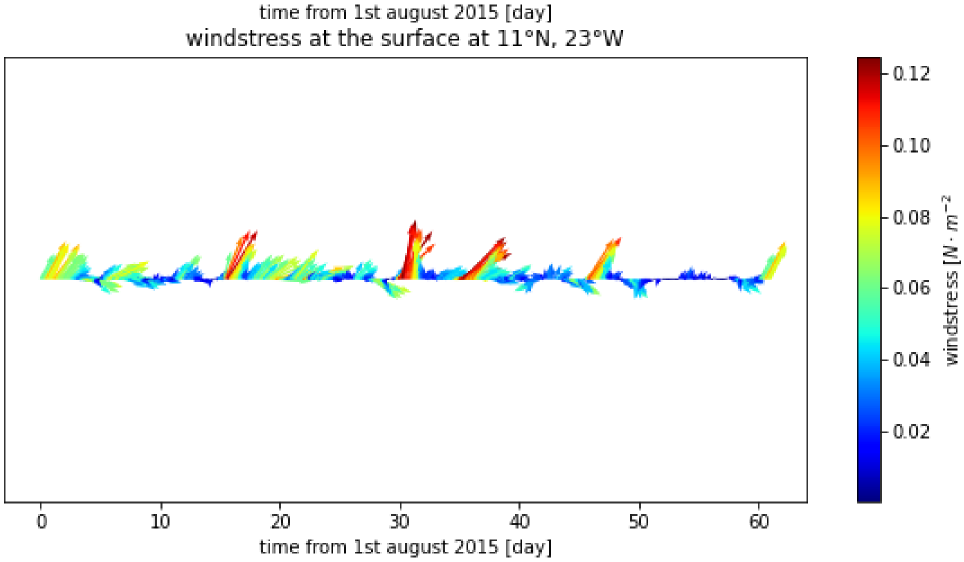

u at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0.60
0.51
0.41
0.32
0.23
0.13
0.04
−0.05
−0.15
−0.24
−0.31

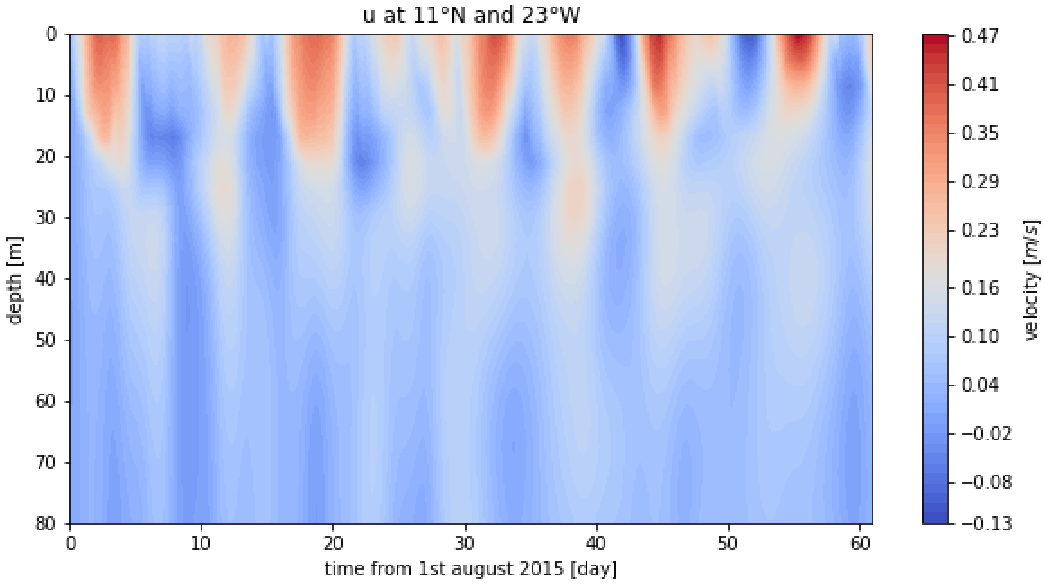

v at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0.48
0.39
0.29
0.19
0.09
0.00
−0.10
−0.20
−0.30
−0.39
−0.47

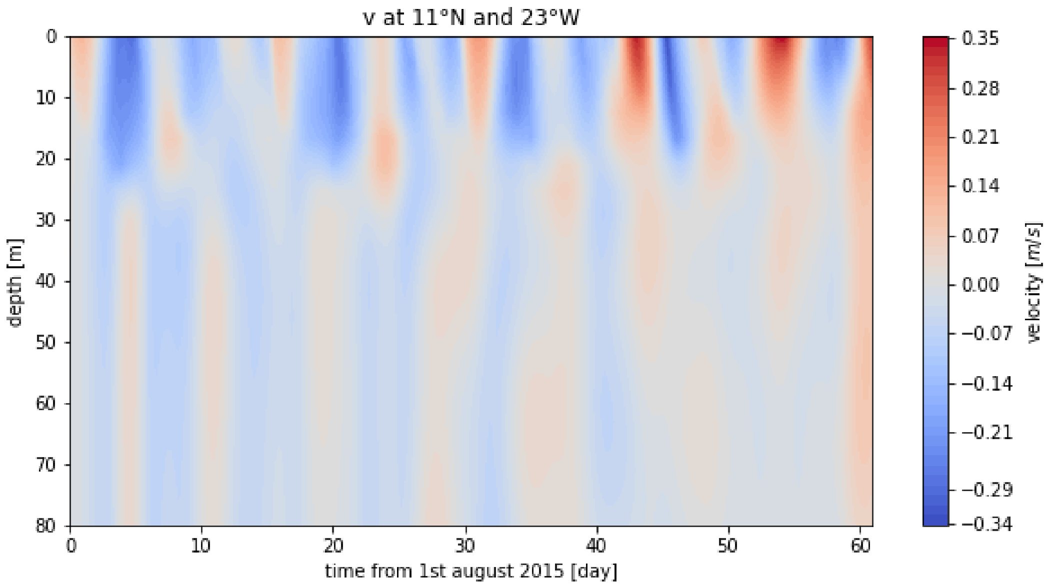

vertical diffusivity κ_H at 11°N and 23°W
depth [m]
0
10
20
30
40
50
60
70
80
time from 1st august 2015 [day]
0
10
20
30
40
50
60
diffusivity [$\frac{m^2}{s}$]
0.01700
0.01526
0.01353
0.01180
0.01007
0.00834
0.00661
0.00488
0.00315
0.00142
0.00003

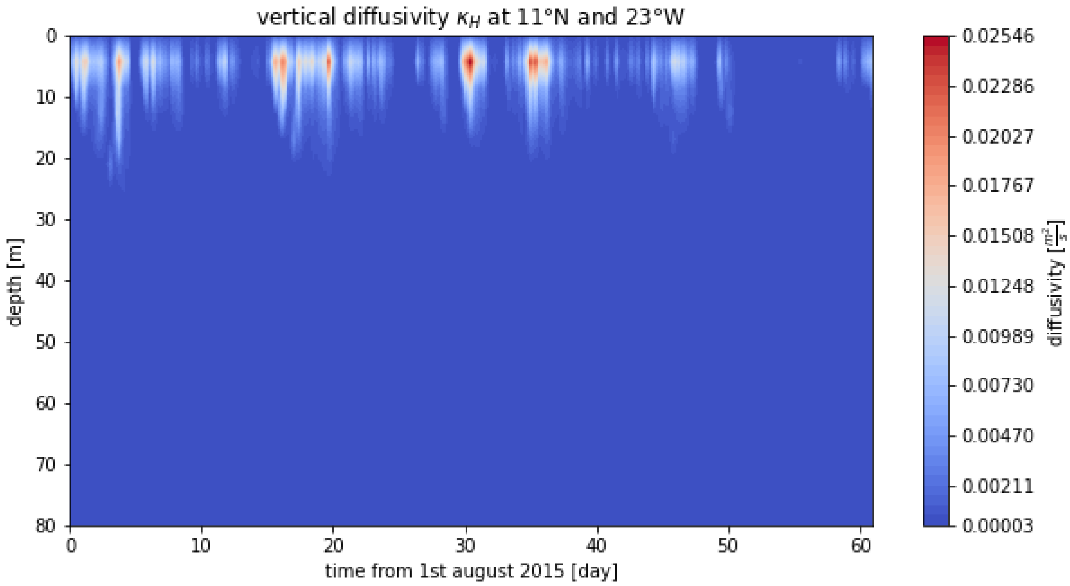

Vertical viscosity κ_M at 11°N and 23°W
depth [m]
0
10
20
30
40
50
60
70
80
time from 1st august 2015 [day]
0
10
20
30
40
50
60
viscosity [$\frac{m^2}{s}$]
0.01700
0.01528
0.01357
0.01185
0.01014
0.00843
0.00671
0.00500
0.00329
0.00157
0.00020

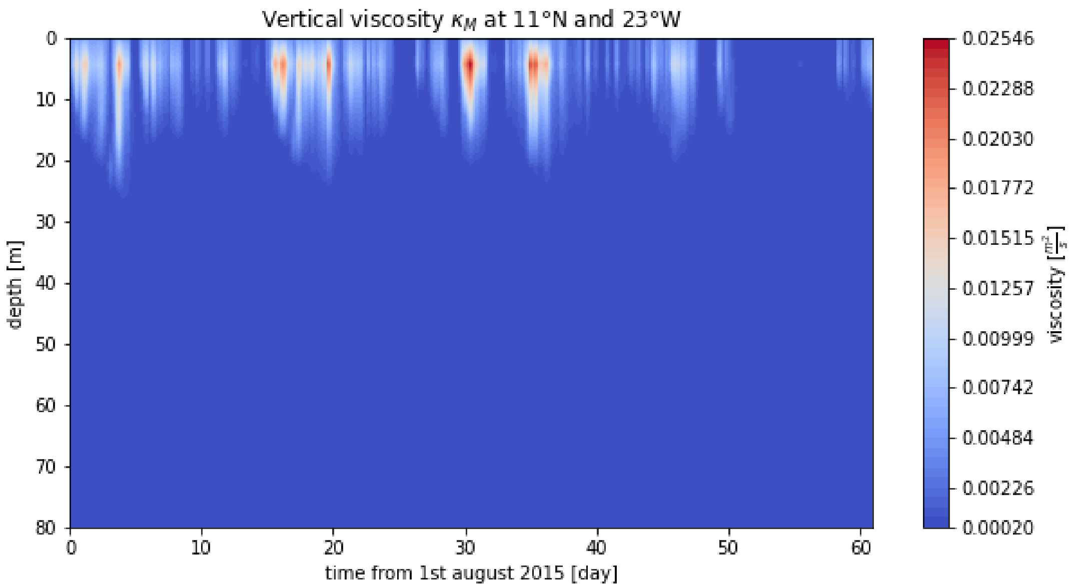

ocean velocity in surface layer at 11°N, 23°W
0
10
20
30
40
50
60
time from 1st august 2015 [day]
0.5
0.4
0.3
0.2
0.1
velocity [$m \cdot s^{-1}$]

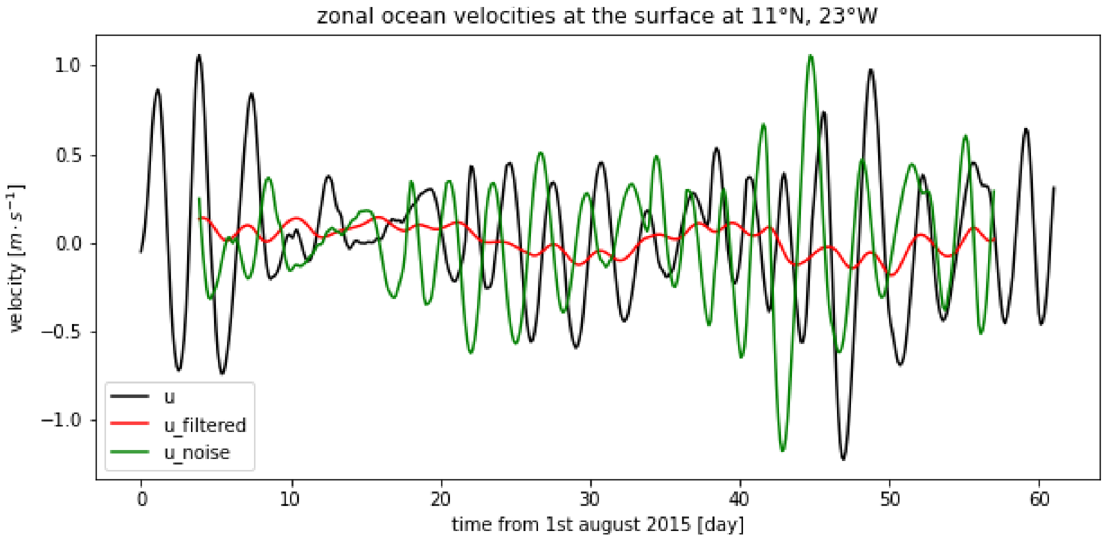

windstress at the surface at 11°N, 23°W
0
10
20
30
40
50
60
time from 1st august 2015 [day]
0.12
0.10
0.08
0.06
0.04
0.02
windstress [$N \cdot m^{-2}$]

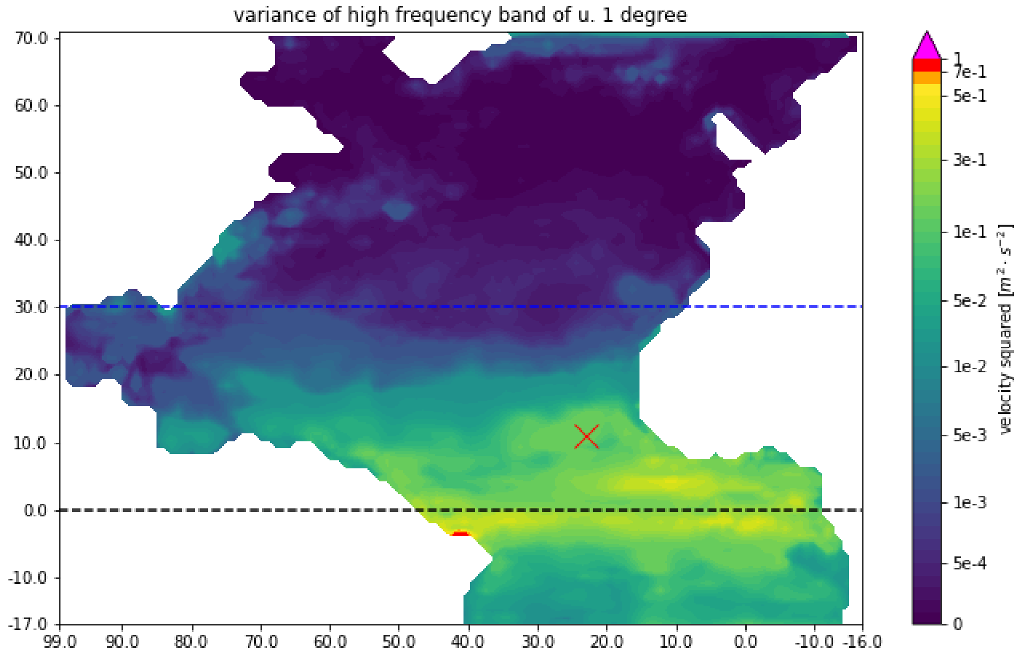

u at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0
10
20
30
40
50
60
70
80
0.47
0.41
0.35
0.29
0.23
0.16
0.10
0.04
−0.02
−0.08
−0.13

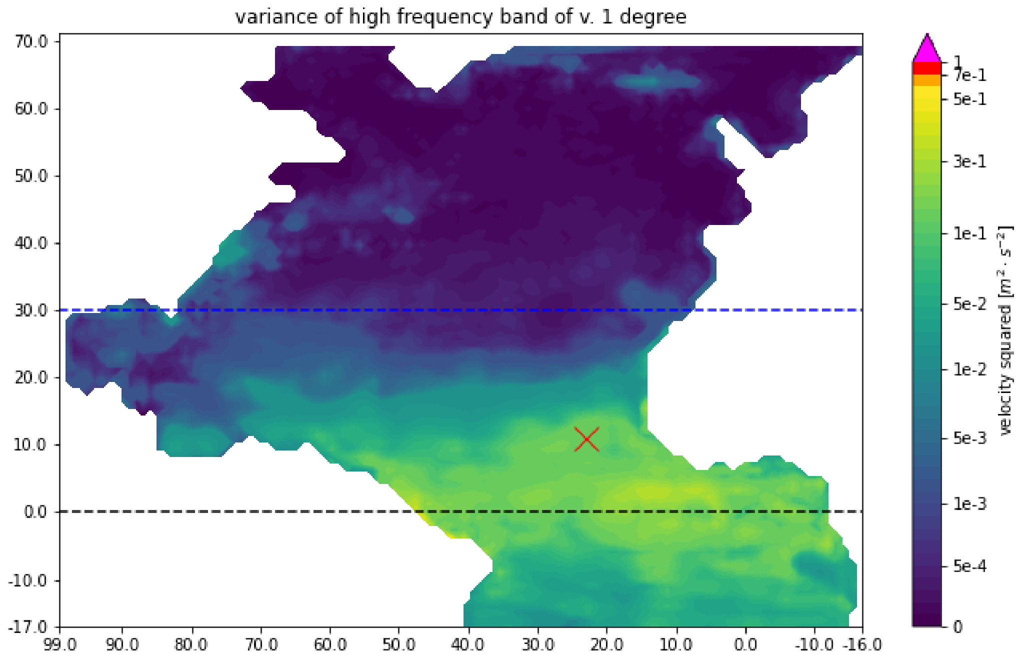

v at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
velocity [m/s]
0
10
20
30
40
50
60
70
80
0.35
0.28
0.21
0.14
0.07
0.00
−0.07
−0.14
−0.21
−0.29
−0.34

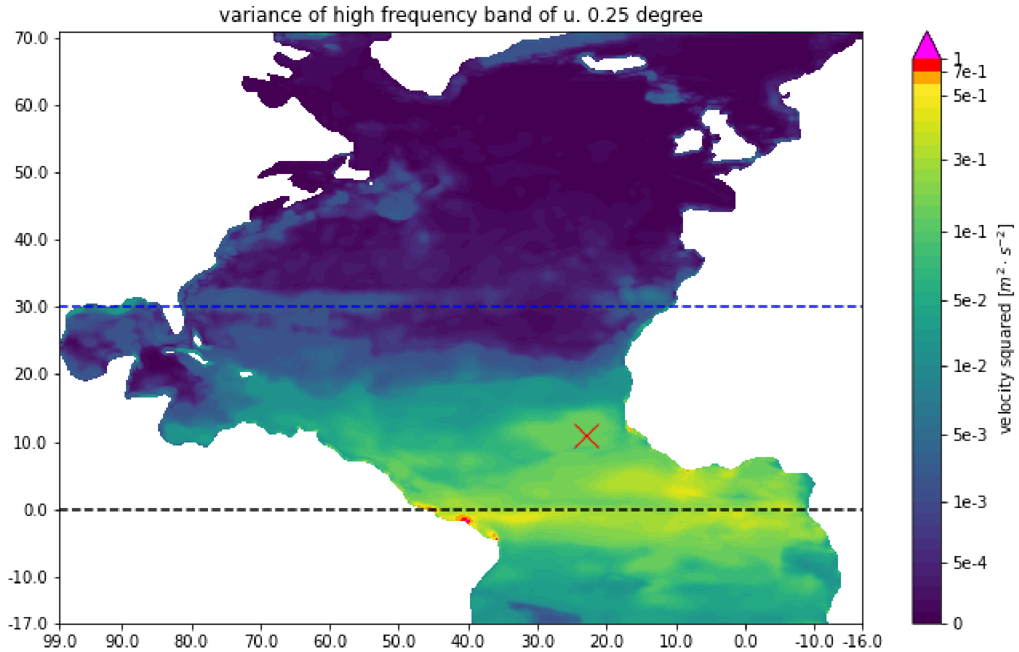

vertical diffusivity κ_H at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
diffusivity [$\frac{m^2}{s}$]
0.02546
0.02286
0.02027
0.01767
0.01508
0.01248
0.00989
0.00730
0.00470
0.00211
0.00003

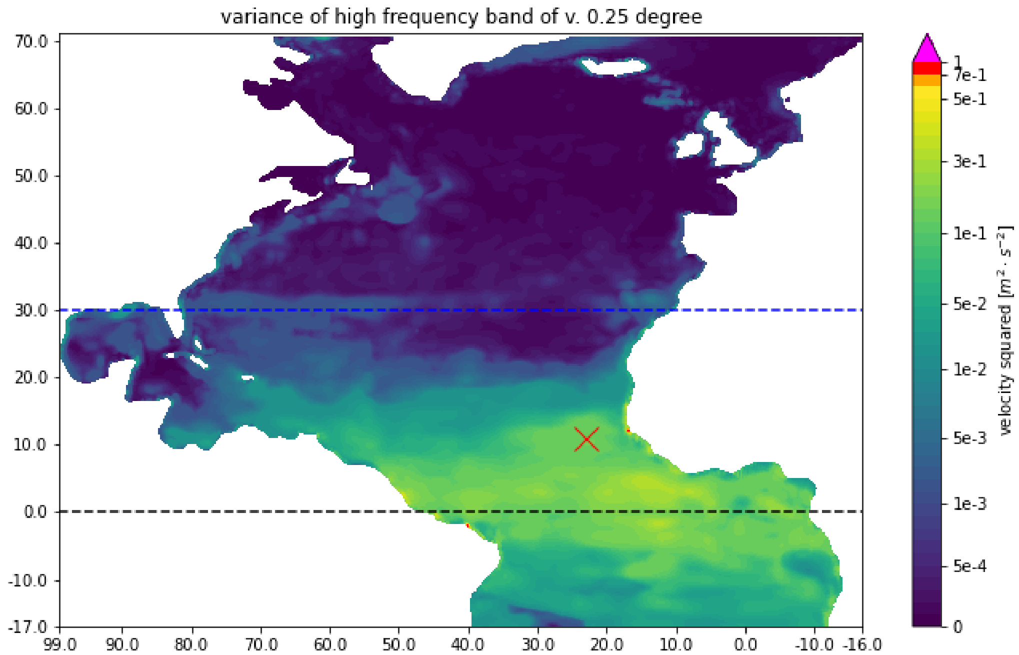

Vertical viscosity κ_M at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
viscosity [$\frac{m^2}{s}$]
0.02546
0.02288
0.02030
0.01772
0.01515
0.01257
0.00999
0.00742
0.00484
0.00226
0.00020

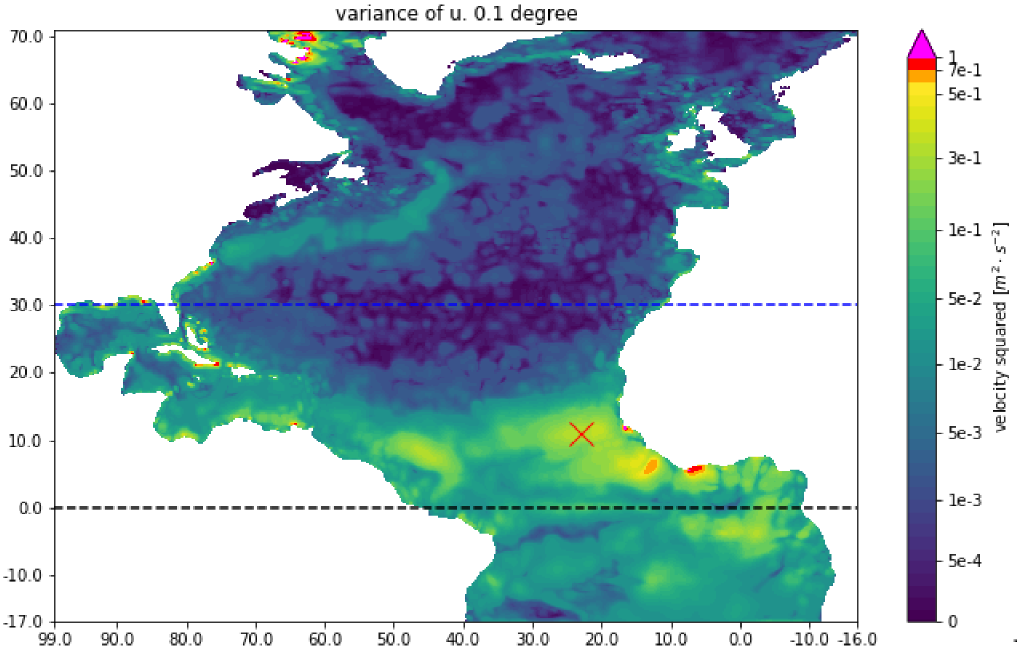

zonal ocean velocities at the surface at 11°N, 23°W
velocity [$m \cdot s^{-1}$]
time from 1st august 2015 [day]
u
u_filtered
u_noise
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50
60

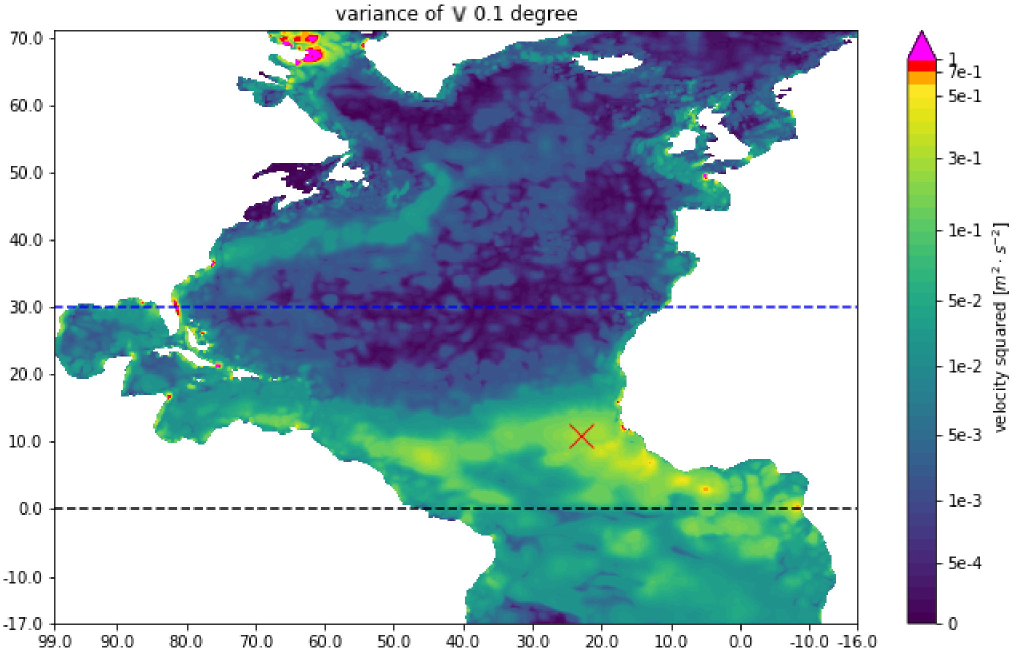

variance of high frequency band of u. 1 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
1
7e-1
5e-1
3e-1
1e-1
5e-2
1e-2
5e-3
1e-3
5e-4
0
velocity squared [$m^2 \cdot s^{-2}$]

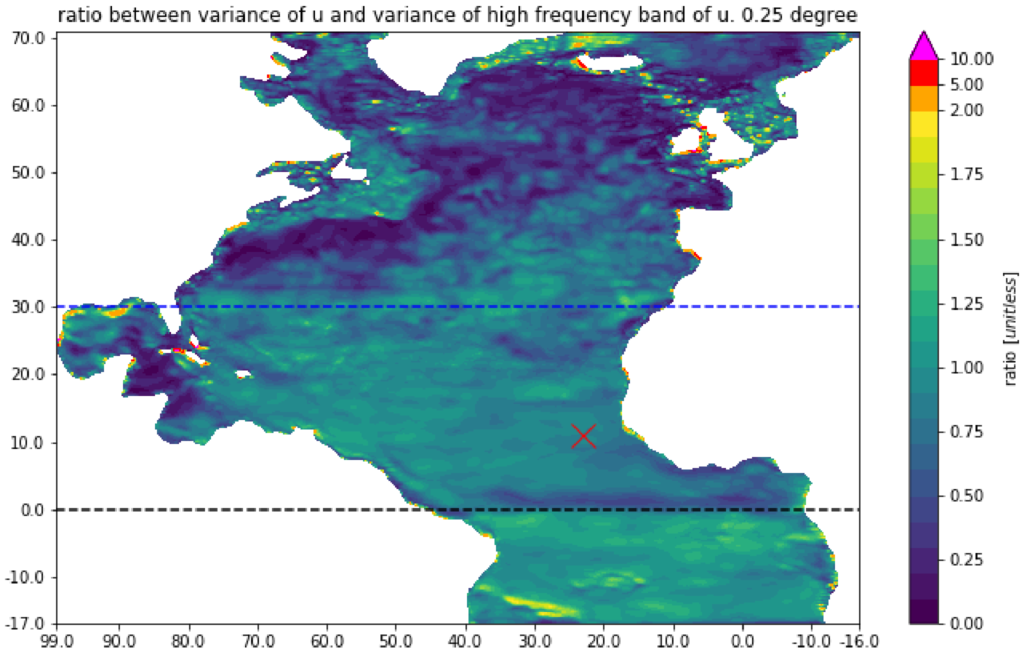

variance of high frequency band of v. 1 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
1
7e-1
5e-1
3e-1
1e-1
5e-2
1e-2
5e-3
1e-3
5e-4
0
velocity squared [$m^2 \cdot s^{-2}$]

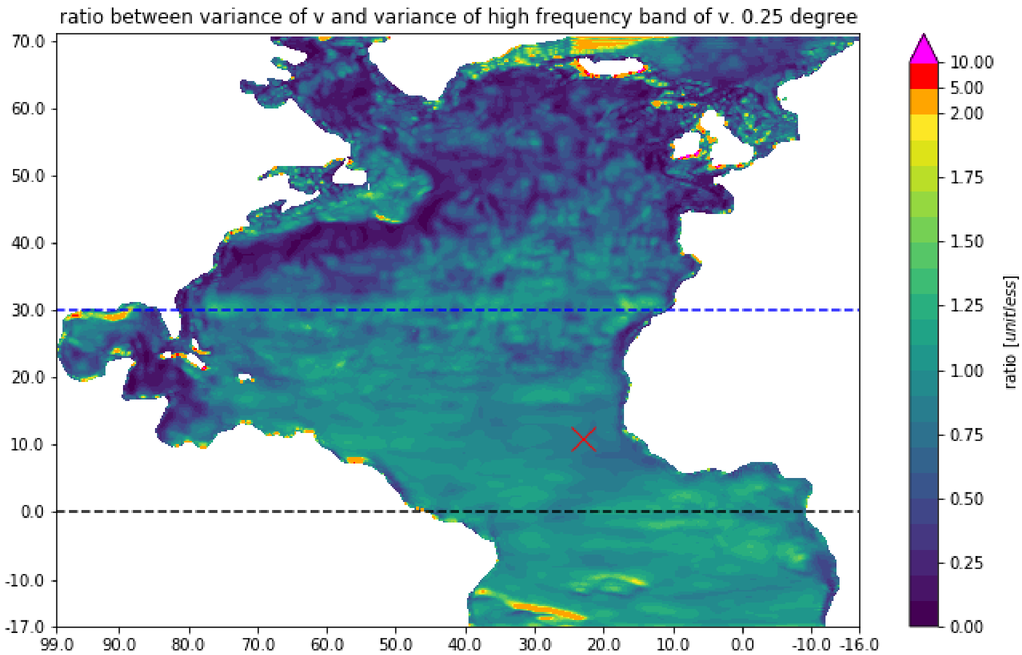

variance of high frequency band of u. 0.25 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
1
7e-1
5e-1
3e-1
1e-1
5e-2
1e-2
5e-3
1e-3
5e-4
0
velocity squared $[m^2 \cdot s^{-2}]$

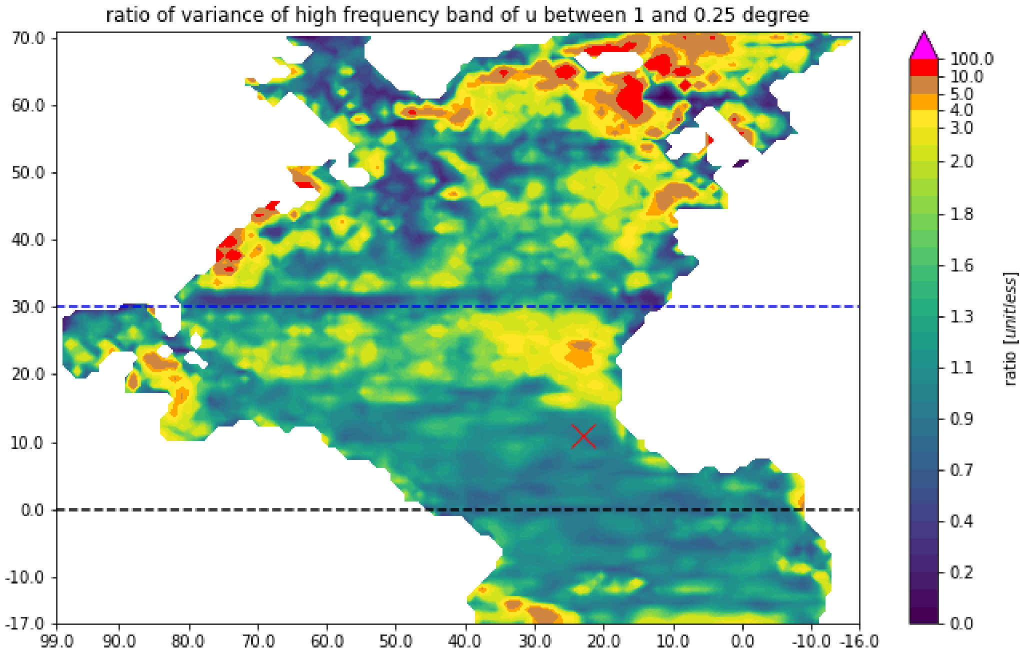

variance of high frequency band of v. 0.25 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
1
7e-1
5e-1
3e-1
1e-1
5e-2
1e-2
5e-3
1e-3
5e-4
0
velocity squared $[m^2 \cdot s^{-2}]$

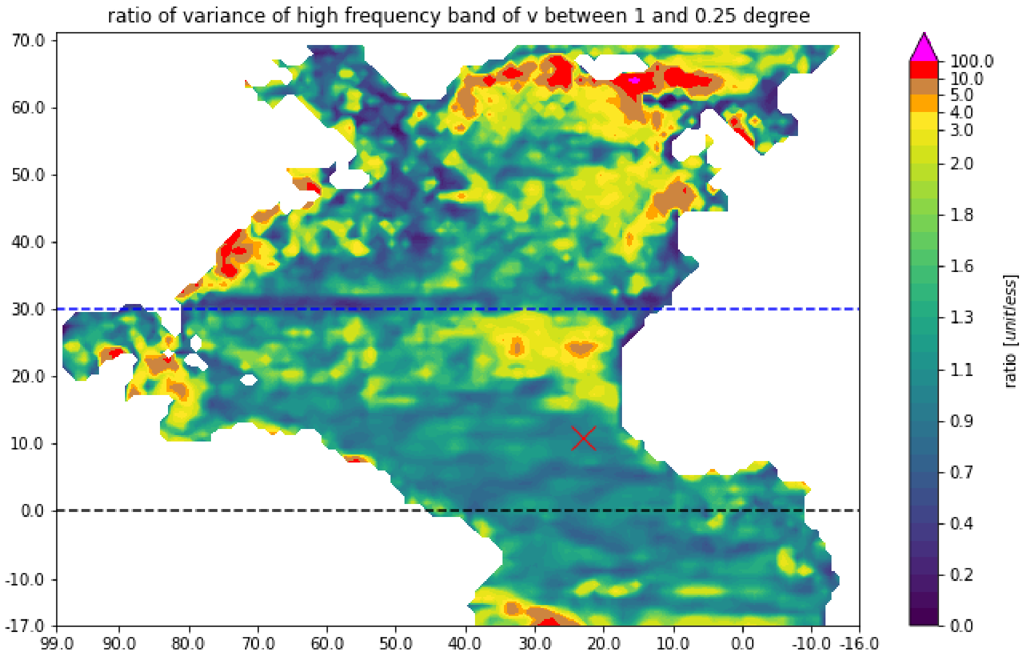

variance of u. 0.1 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0 90.0 80.0 70.0 60.0 50.0 40.0 30.0 20.0 10.0 0.0 -10.0 -16.0
1
7e-1
5e-1
3e-1
1e-1
5e-2
1e-2
5e-3
1e-3
5e-4
0
velocity squared [$m^2 \cdot s^{-2}$]

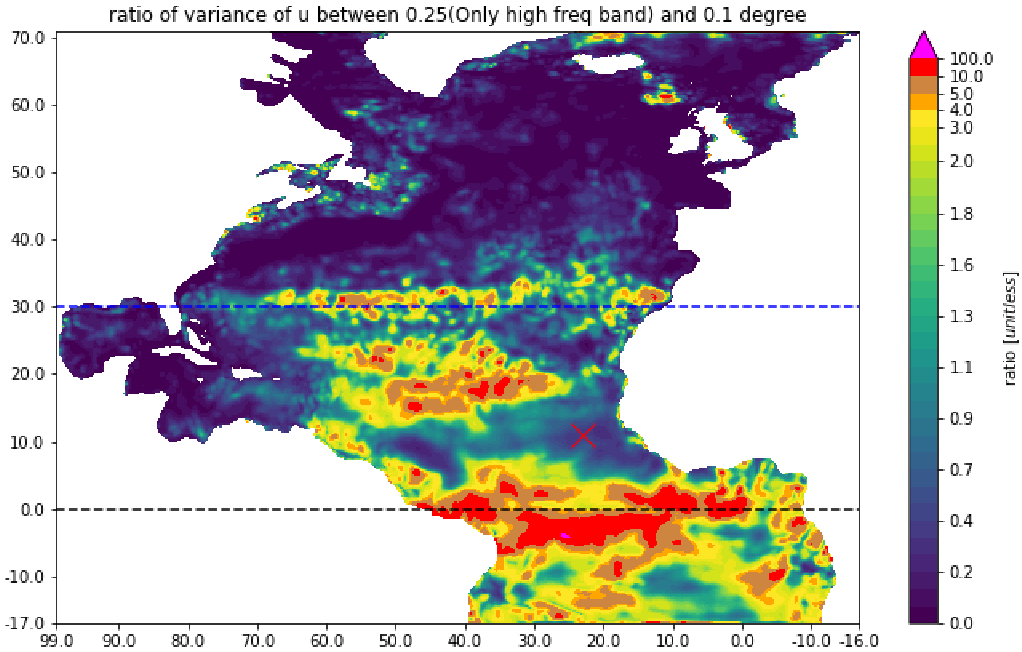

variance of v 0.1 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0 90.0 80.0 70.0 60.0 50.0 40.0 30.0 20.0 10.0 0.0 -10.0 -16.0
1
7e-1
5e-1
3e-1
1e-1
5e-2
1e-2
5e-3
1e-3
5e-4
0
velocity squared [$m^2 \cdot s^{-2}$]


ratio between variance of u and variance of high frequency band of u. 0.25 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
10.00
5.00
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
ratio [unitless]

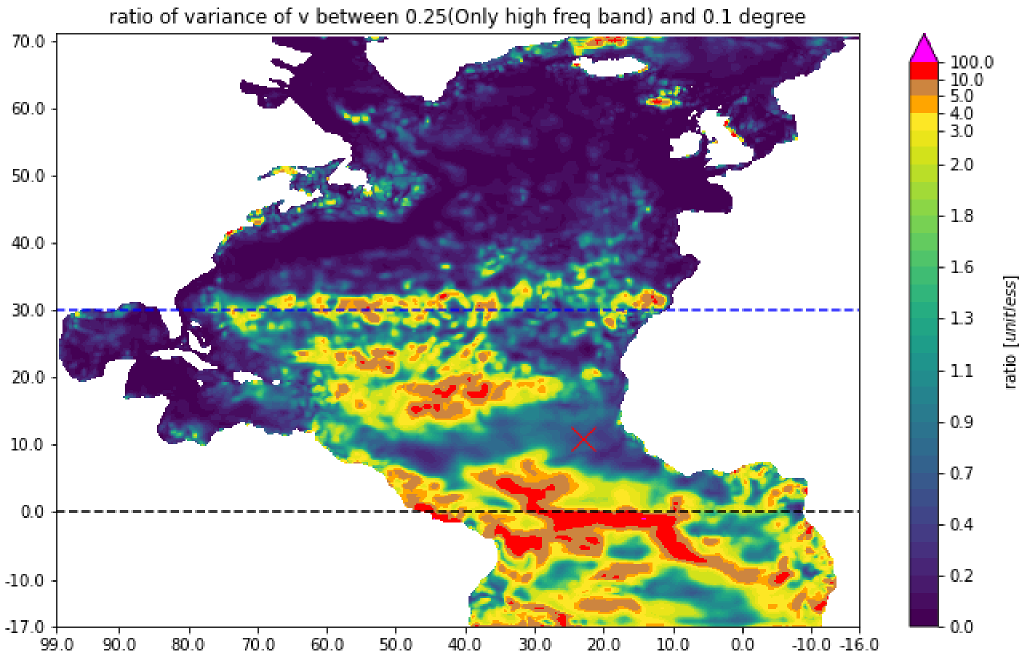

ratio between variance of v and variance of high frequency band of v. 0.25 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
10.00
5.00
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
ratio [unitless]


ratio of variance of high frequency band of u between 1 and 0.25 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
100.0
10.0
5.0
4.0
3.0
2.0
1.8
1.6
1.3
1.1
0.9
0.7
0.4
0.2
0.0
ratio [unitless]

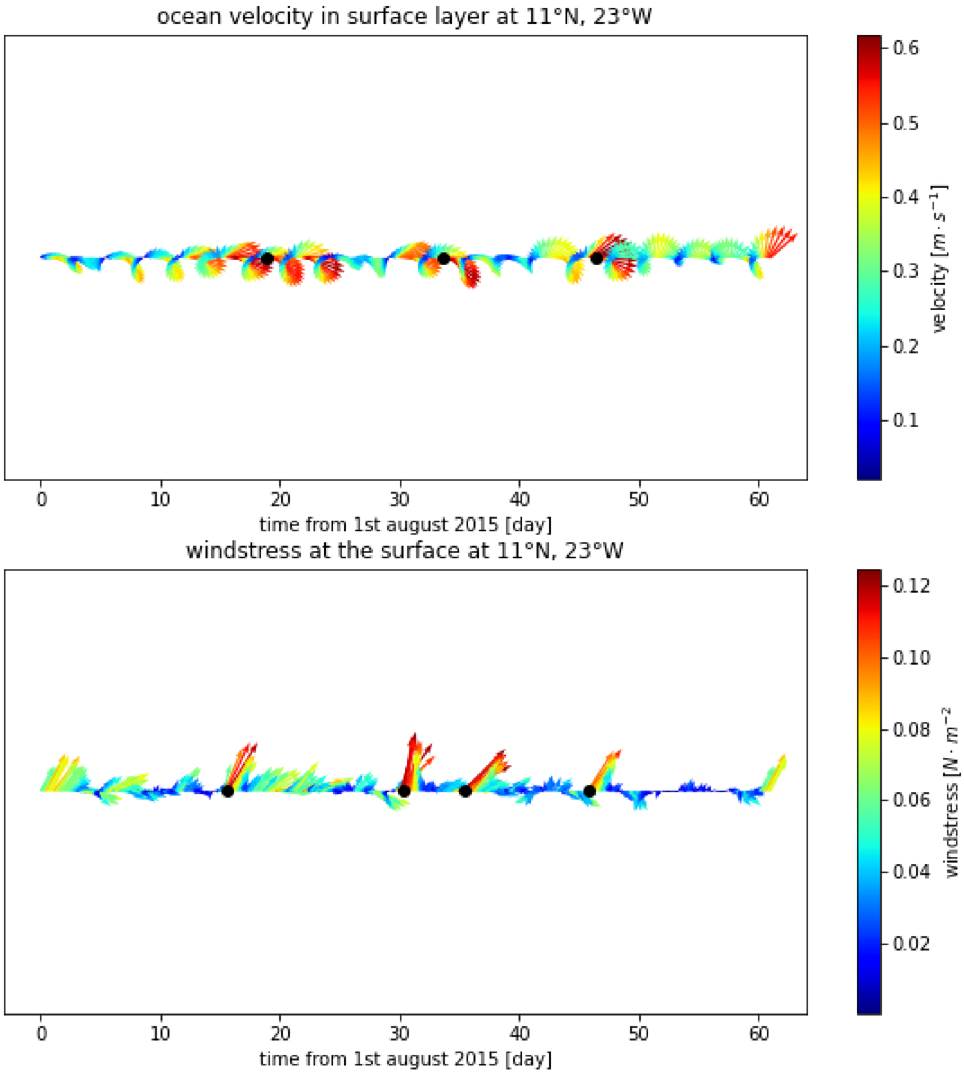

ratio of variance of high frequency band of v between 1 and 0.25 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
100.0
10.0
5.0
4.0
3.0
2.0
1.8
1.6
1.3
1.1
0.9
0.7
0.4
0.2
0.0
ratio [unitless]

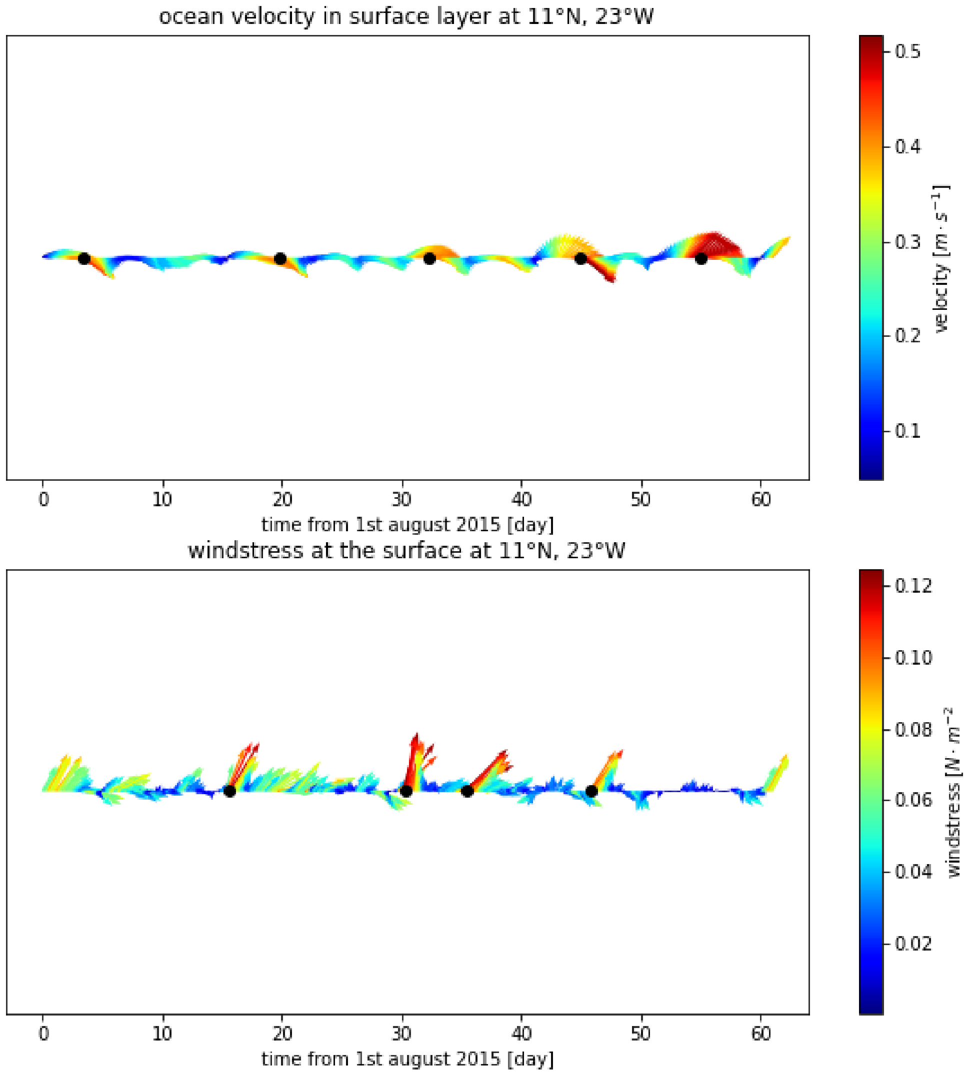


ratio of variance of u between 0.25(Only high freq band) and 0.1 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
100.0
10.0
5.0
4.0
3.0
2.0
1.8
1.6
1.3
1.1
0.9
0.7
0.4
0.2
0.0
ratio [unitless]

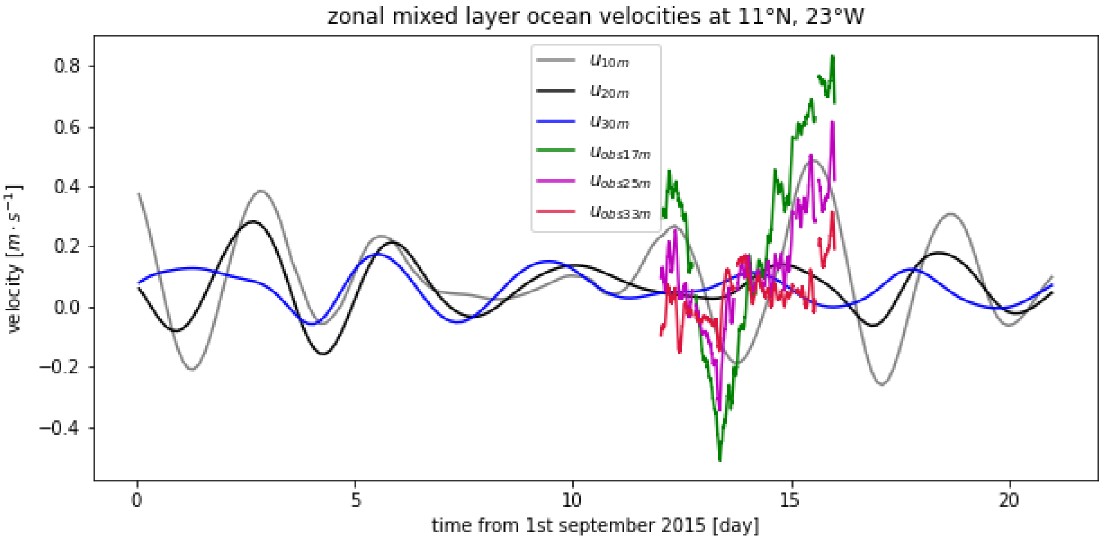


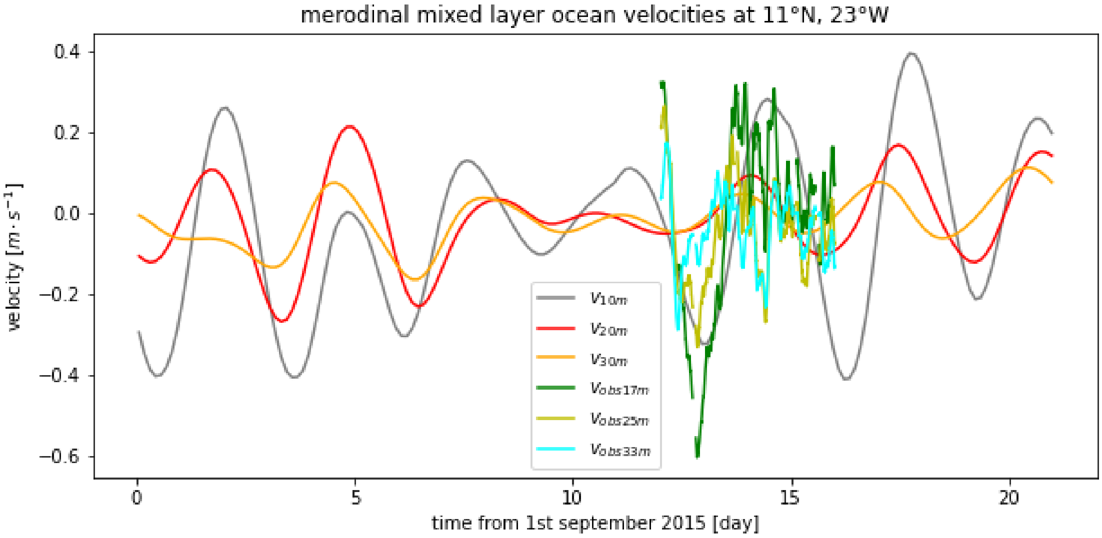
ratio of variance of v between 0.25(Only high freq band) and 0.1 degree
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-17.0
99.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-16.0
100.0
10.0
5.0
4.0
3.0
2.0
1.8
1.6
1.3
1.1
0.9
0.7
0.4
0.2
0.0
ratio [unitless]

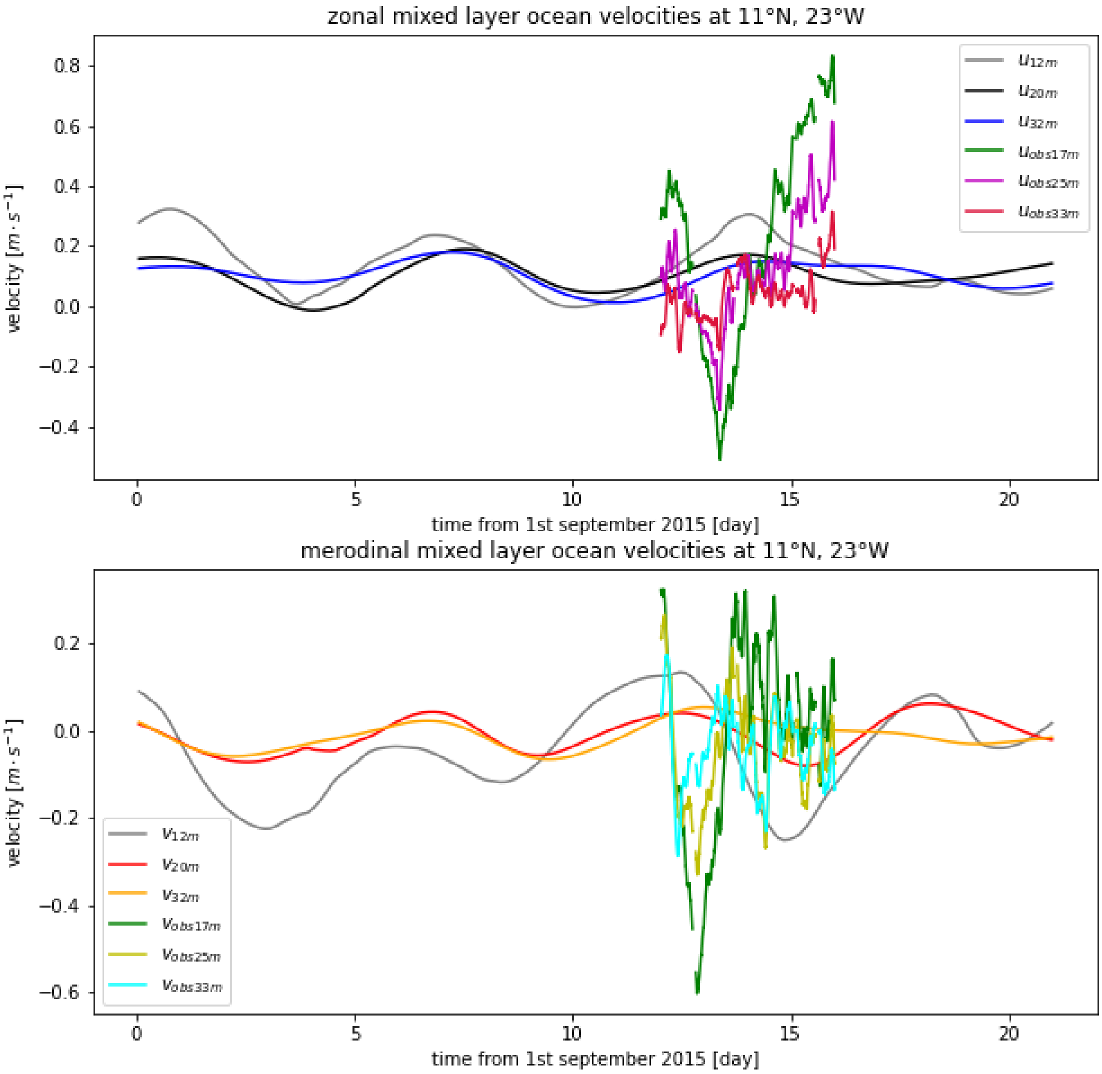

ocean velocity in surface layer at 11°N, 23°W
0
10
20
30
40
50
60
time from 1st august 2015 [day]
0.6
0.5
0.4
0.3
0.2
0.1
velocity [$m \cdot s^{-1}$]
windstress at the surface at 11°N, 23°W
0
10
20
30
40
50
60
time from 1st august 2015 [day]
0.12
0.10
0.08
0.06
0.04
0.02
windstress [$N \cdot m^{-2}$]

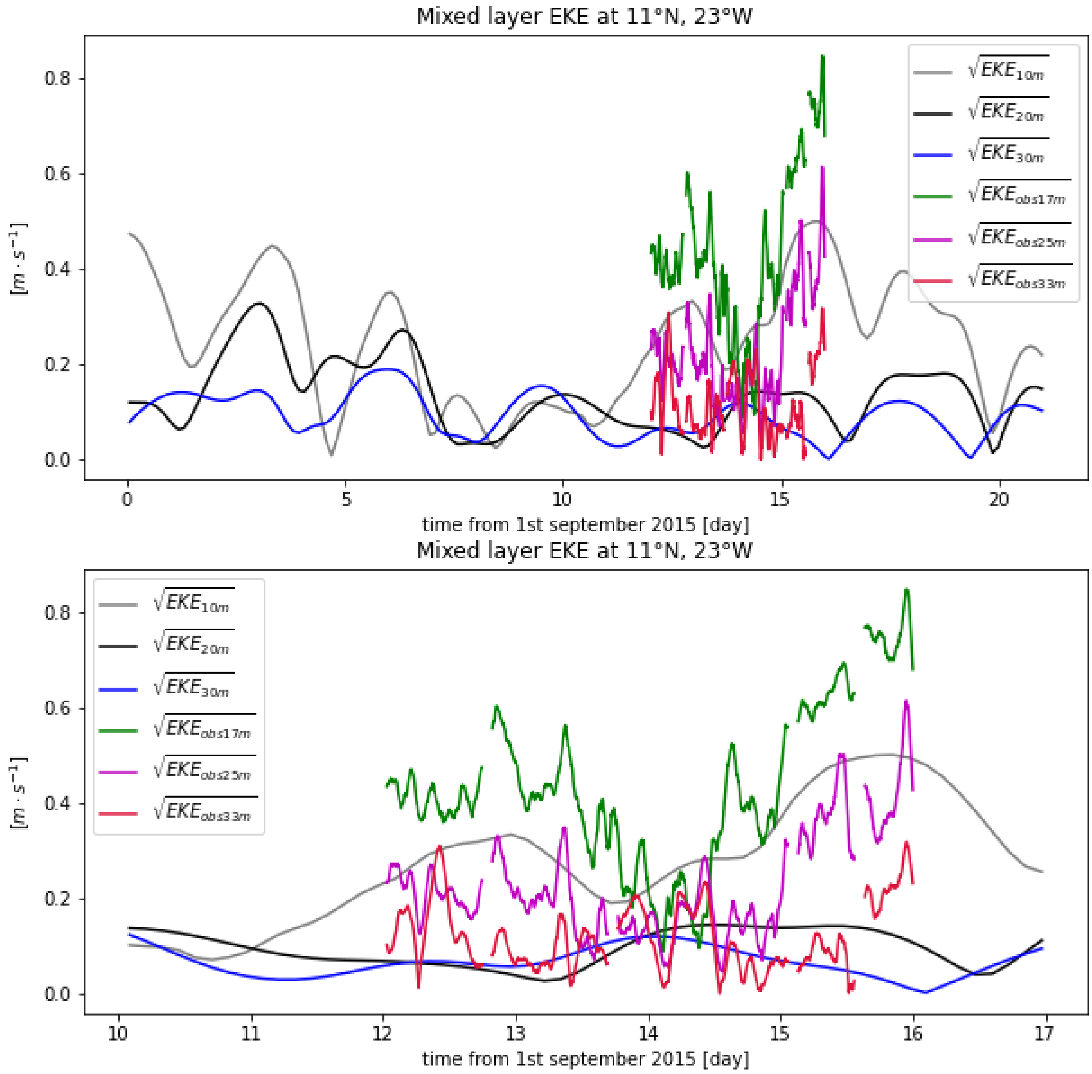


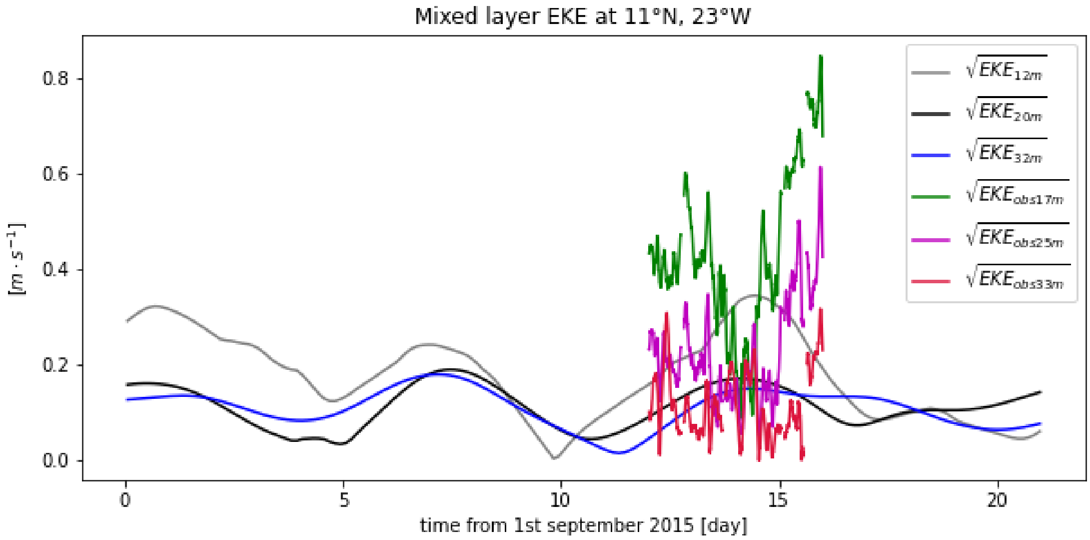
ocean velocity in surface layer at 11°N, 23°W
0
10
20
30
40
50
60
time from 1st august 2015 [day]
velocity [$m \cdot s^{-1}$]
0.1
0.2
0.3
0.4
0.5
windstress at the surface at 11°N, 23°W
0
10
20
30
40
50
60
time from 1st august 2015 [day]
windstress [$N \cdot m^{-2}$]
0.02
0.04
0.06
0.08
0.10
0.12

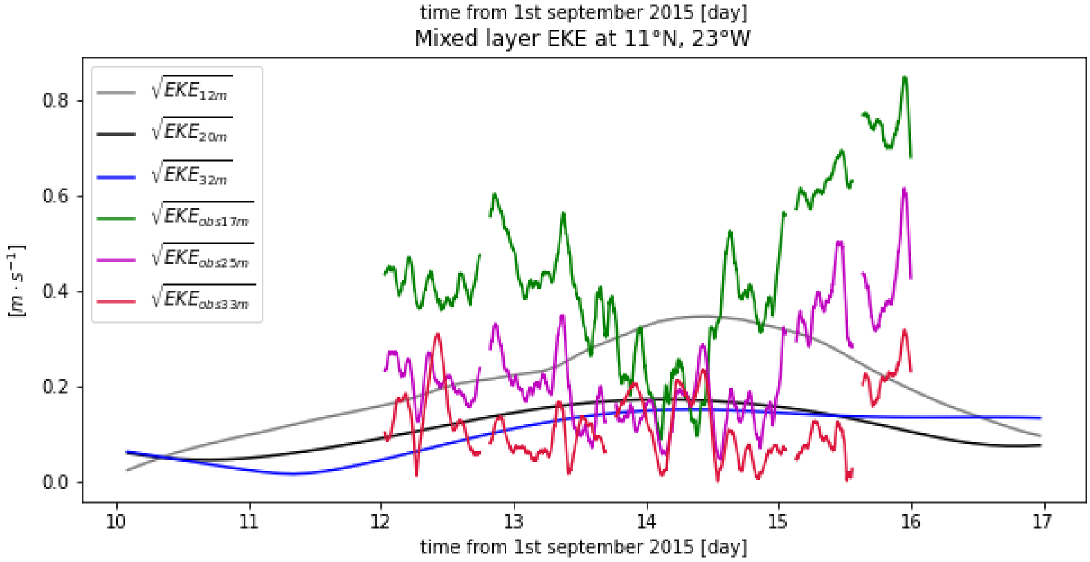

zonal mixed layer ocean velocities at 11°N, 23°W
velocity [$m \cdot s^{-1}$]
time from 1st september 2015 [day]
u_{10m}
u_{20m}
u_{30m}
u_{obs17m}
u_{obs25m}
u_{obs33m}

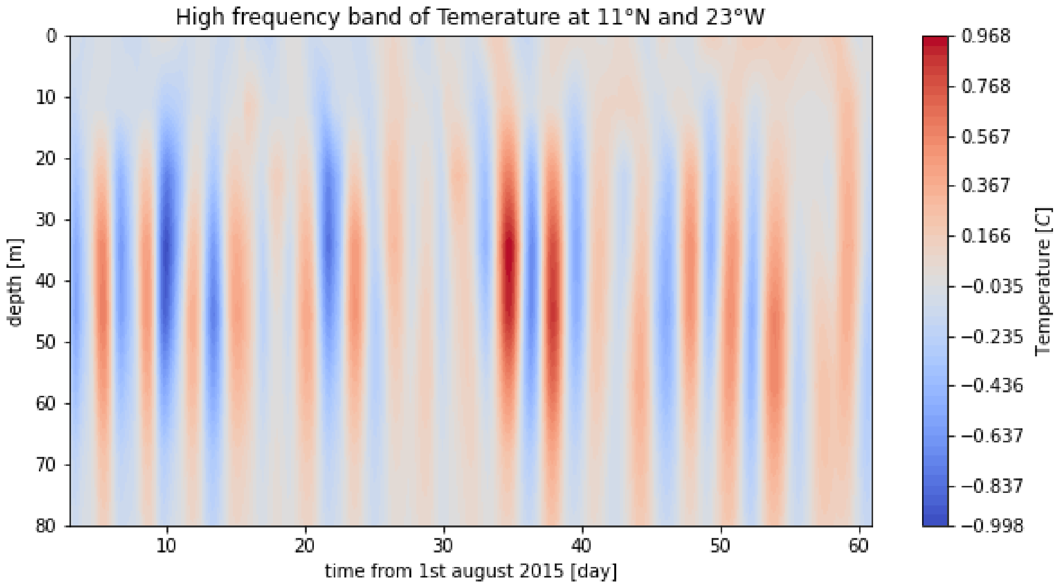

merodinal mixed layer ocean velocities at 11°N, 23°W
velocity [$m \cdot s^{-1}$]
time from 1st september 2015 [day]
v_{10m}
v_{20m}
v_{30m}
v_{obs17m}
v_{obs25m}
v_{obs33m}

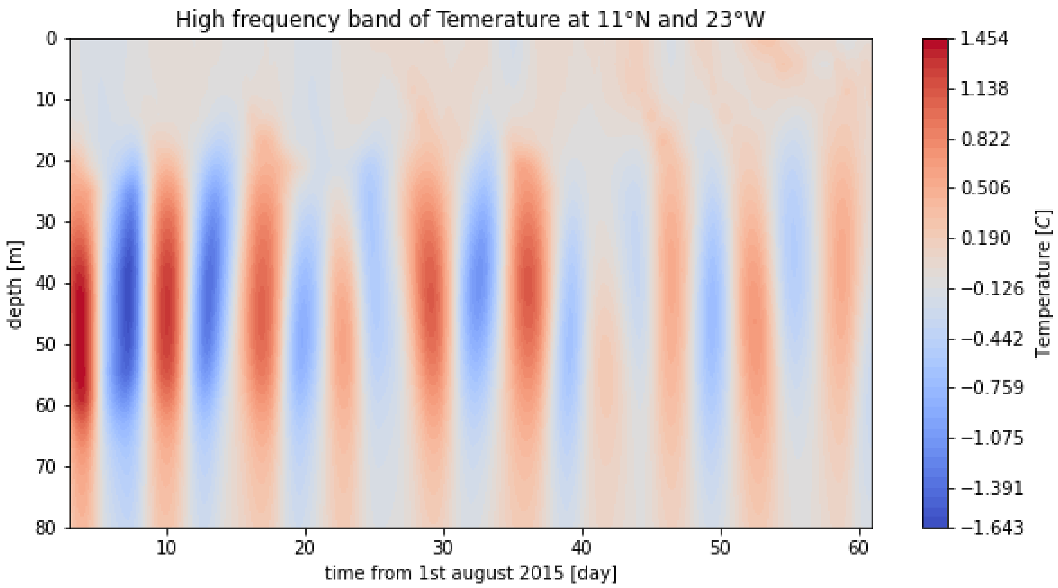

zonal mixed layer ocean velocities at 11°N, 23°W
velocity $[m \cdot s^{-1}]$
time from 1st september 2015 [day]
u_{12m}
u_{20m}
u_{32m}
u_{obs17m}
u_{obs25m}
u_{obs33m}
merodinal mixed layer ocean velocities at 11°N, 23°W
velocity $[m \cdot s^{-1}]$
time from 1st september 2015 [day]
v_{12m}
v_{20m}
v_{32m}
v_{obs17m}
v_{obs25m}
v_{obs33m}

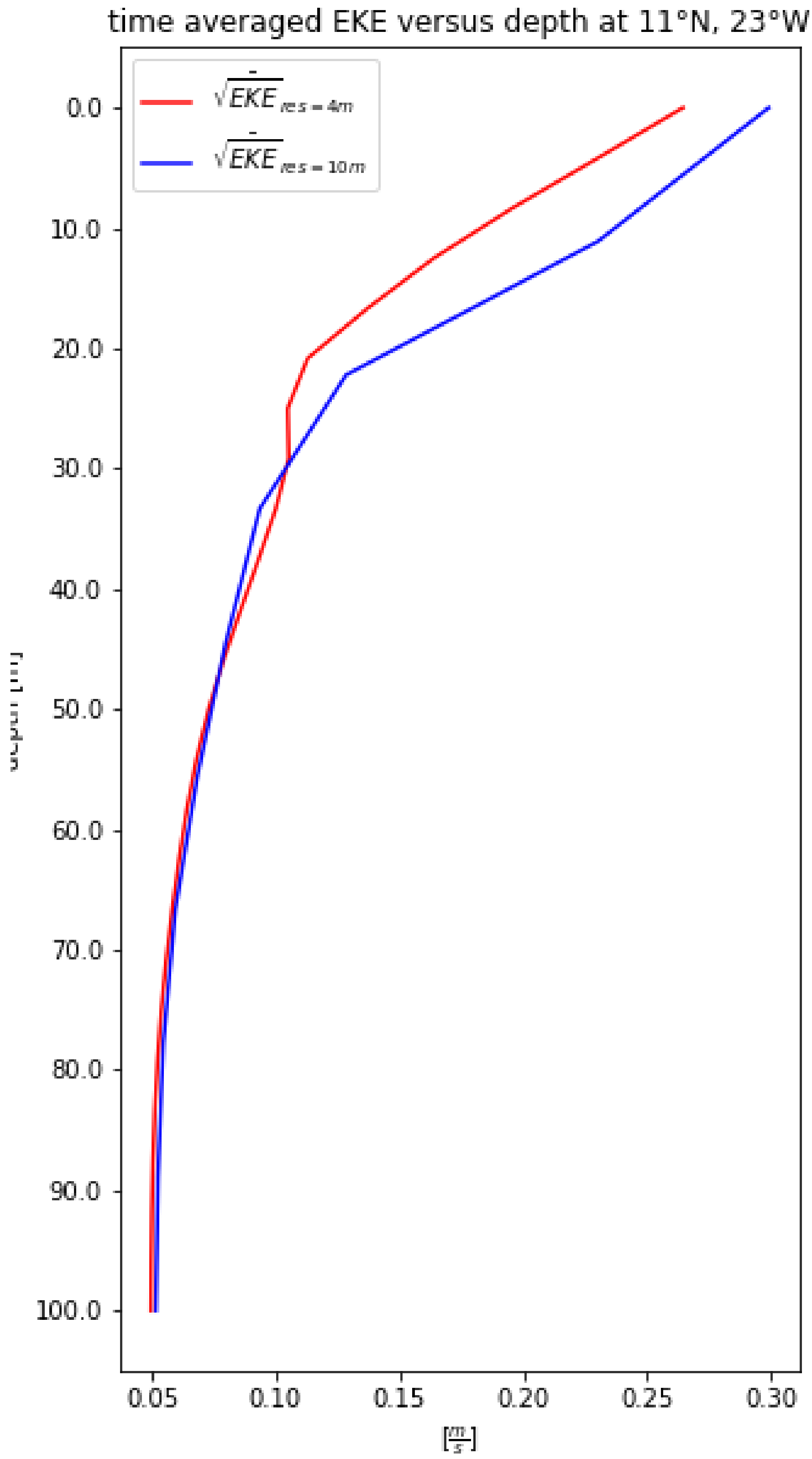

Mixed layer EKE at 11°N, 23°W
$\sqrt{EKE_{10m}}$
$\sqrt{EKE_{20m}}$
$\sqrt{EKE_{30m}}$
$\sqrt{EKE_{obs17m}}$
$\sqrt{EKE_{obs25m}}$
$\sqrt{EKE_{obs33m}}$
$[m \cdot s^{-1}]$
time from 1st september 2015 [day]
Mixed layer EKE at 11°N, 23°W
time from 1st september 2015 [day]


Mixed layer EKE at 11°N, 23°W
$\sqrt{EKE_{12m}}$
$\sqrt{EKE_{20m}}$
$\sqrt{EKE_{32m}}$
$\sqrt{EKE_{obs17m}}$
$\sqrt{EKE_{obs25m}}$
$\sqrt{EKE_{obs33m}}$
$[m \cdot s^{-1}]$
0.0
0.2
0.4
0.6
0.8
0
5
10
15
20
time from 1st september 2015 [day]

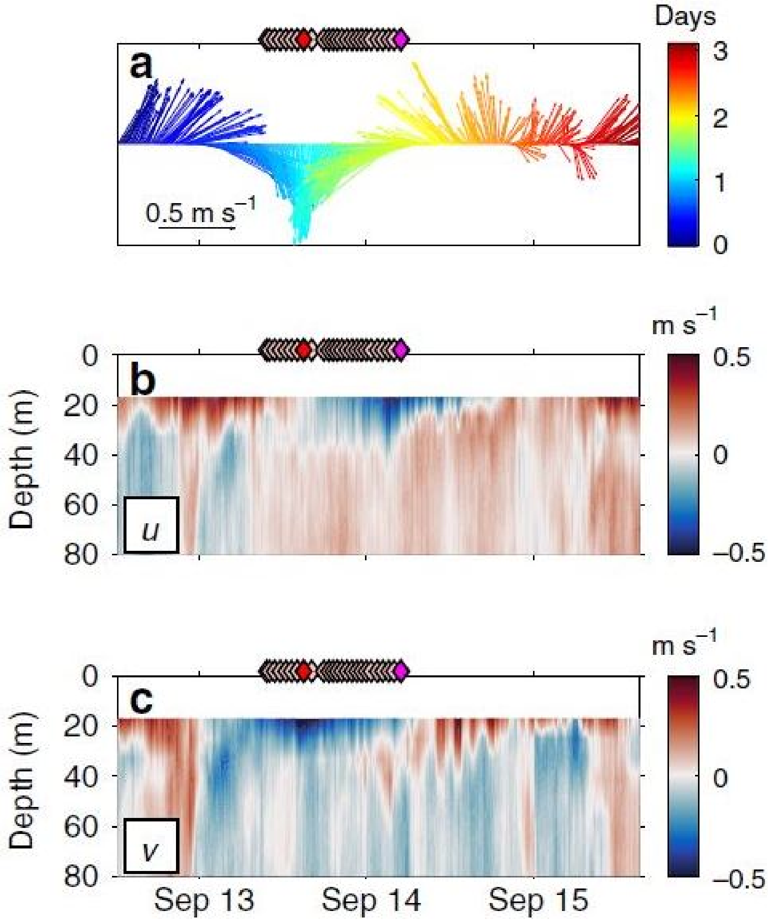

Mixed layer EKE at 11°N, 23°W
$\sqrt{EKE_{12m}}$
$\sqrt{EKE_{20m}}$
$\sqrt{EKE_{32m}}$
$\sqrt{EKE_{obs17m}}$
$\sqrt{EKE_{obs25m}}$
$\sqrt{EKE_{obs33m}}$
$[m \cdot s^{-1}]$
0.0
0.2
0.4
0.6
0.8
10
11
12
13
14
15
16
17
time from 1st september 2015 [day]


High frequency band of Temerature at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
Temperature [C]
0.968
0.768
0.567
0.367
0.166
−0.035
−0.235
−0.436
−0.637
−0.837
−0.998

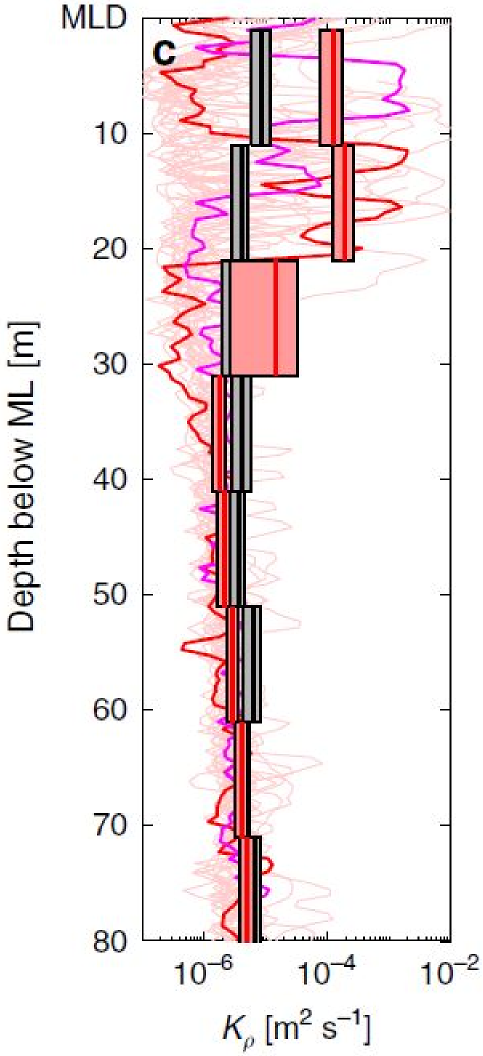

High frequency band of Temerature at 11°N and 23°W
depth [m]
time from 1st august 2015 [day]
Temperature [C]
1.454
1.138
0.822
0.506
0.190
−0.126
−0.442
−0.759
−1.075
−1.391
−1.643



time averaged EKE versus depth at 11°N, 23°W
$\sqrt{\bar{EKE}}_{res=4m}$
$\sqrt{\bar{EKE}}_{res=10m}$
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
0.05
0.10
0.15
0.20
0.25
0.30
$[\frac{m}{s}]$



a
b
c
Days
0.5 m s^{-1}
m s^{-1}
Depth (m)
u
v
Sep 13
Sep 14
Sep 15


MLD
c
Depth below ML [m]
10
20
30
40
50
60
70
80
10^{-6}
10^{-4}
10^{-2}
K_ρ [m^2 s^{-1}]