Oceanic Near-Inertial Waves induced by atmospheric storms

a quantitative analysis of a coupled climate model

Author:
Søren Borg Nielsen

Supervisor:
Markus Jochum

Institute:
Niels Bohr Institutet - University of Copenhagen

Date:
2013-12-06

Abstract

15 strong ocean response events and 15 strong storm events from data of the model used by Jochum et al. (2013) are analysed to give a first assessment on the generated near-inertial waves in a coupled climate model. This is done by isolating the 5 strongest signals of the near inertial velocities of the ocean and the 5 strongest storms of three different regions. Analysis finds that for two of the regions, two different types of near-inertial waves account for those generated by atmospheric storms. One is characterised by a strong wind stress turning direction with a period similar to the near-inertial period at the given latitude. The other is characterised by the wind turning in phase with the already existing ocean oscillations at the given latitudes. These results are consistent with experimental results of the Ocean Storms Experiment, and show that storm movement rather than storm strength generates a strong ocean near-inertial response. The analysis finds that the combination of wind and ocean turning over the same time and with the same rotational respect locally is the driving mechanism in generating a large near-inertial response in the ocean.

Analysis carried out for the third region, the tropics, does not yield similar results, as wind stress turning is of small magnitude and incoherent with the ocean oscillations. The strong oscillation responses seem to be generated as a result of small wind stress adding a positive energy flux to the already existing oscillations over the long periods that are characteristic for the oscillations in the tropics.

Energy decay times of the ocean oscillations are calculated and it is found that most lie in the range of 5-15 hours, which is consistent with theory, although these results must be treated with caution due to uncertainties.

Contents

1 Introduction

In the upper ocean, several studies have shown energetic oscillations in the near-inertial frequency band, called near-inertial waves (NIWs). These are generated by the energy flux from wind stress doing work on the ocean surface (computed for instance by D'Asaro 1985). The inertial velocities of these waves can be separated into an eastward and northward component, u_i and v_i, respectively, that oscillate with the inertial frequency, equal to the local coriolis parameter.

The energy of an inertial oscillation is given as the sum of the square of the two velocity components:

$$E^i = (u^i)^2 + (v^i)^2, \tag{1}$$

where E^i is the inertial energy and u^i and v^i are the longitudinal and latitudinal velocities, respectively. The oscillation is initiated by the wind stress and is excited in several modes. Different modes have different phase speed, with the lowest modes travelling fastest (Simmons and Alford, 2012). These modes will, for the most part, travel equatorward (see for instance the description by Garrett 2001). Accordingly, the energy is suspected to propagate downwards away from the mixed layer, giving a total of two major contributions to the inertial energy decay of oscillations.

NIWs have been gathering oceanographers' attention over the past 30 years, especially in connection to the Ocean Storms Experiment of 1987-1988 (see for instance D'Asaro 1995). This collaboration resulted in several papers exploring the phenomenon of storm generated oceanic waves through an experiment with vast amount of data. Since, a number articles have emerged, leading to a better understanding of the phenomenon, in both a regional and in a global sense.

Recently, NIWs have been the topic of investigation in relation to the improvement of coupled atmospheric and oceanic circulation models. Instead of including them in a constant, background diffusivity, Jochum et al. (2013) attend to parameterize NIWs and investigate their global impact on climate. The results show that still much is to be gained from exploring the NIWs, as the parameterization for instance shows a change in precipitation in the tropics.

The present report goes into the data of Jochum et al. (2013) to investigate the NIWs in a more regional sense. The idea is to analyse possible linkages between the strength of the oceanic response and the storms creating them. The reason for this is to illuminate the dynamics that create a strong, near-inertial response and to give an assessment on possible different types of NIWs.

Dohan and Davis (2011) compared the upper-ocean response of two storms of the Ocean Storms Experiment that were similar in strength, and found that the turning of winds being coherent to the periods of the ocean oscillations, rather than the strength of the storm, generated large amplitude inertial oscillations in the upper-ocean. The same storm was analysed by Large and Crawford (1995) who found that significantly large cooling caused by large inertial ocean response was generated as a consequence of wind stress turning in phase with the pre-storm inertial currents.

The focus of this report is on two possible causes of the greatest NI ocean response.

(1) The strength of the wind stress, and (2) the possible resonance between the storm and the ocean oscillations, which is caused by storm turning times and movement. The basic idea of the project is to compare the periods of the storms and that of the ocean response in the generated data and to analyse if there is a connection between the two. Accordingly, the different ocean oscillations will be analysed as to see if large ocean oscillations originate under different conditions. NI ocean response during the strongest storms are also investigated to see what role storm strength plays in generating a strong response. Furthermore, the energy decay time of the ocean oscillations will be estimated.

To gain an overview of possible local differences, the oceans are separated into three regions and analysis is made within and between these. The following sections describes the data setup and the method of finding and isolating strong ocean response and strong storm events.

1.1   Data

For a full understanding of the data, see Jochum et al. (2013). The data consists of the global atmospheric and ocean surface velocity vectors, as well as filtered, inertial oceanic velocities. In the analysis, only the filtered ocean velocities are used. The focus is on three regions, or bands, of the ocean: The southern ocean, the northern tropics and the northern mid-latitudes. The southern ocean and northern mid-latitudes are constrained by latitudinal boundaries, whereas the tropics only consider the Pacific ocean. For each region, the data are searched for 5 of the strongest NI oceanic responses and 5 of the strongest atmospheric storms. For the ocean response, the storm field dynamics, storm path and how quickly winds turn from south to north or vice versa, are analysed, and for the storms the ocean response generated by the strong wind stress is investigated and compared to the strong ocean response events.

The data are organised as a time evolution. Every data point is two hours apart and all in all the series add up to a year. Ocean velocities and wind stress over mainland is set to a zero value.

Units of ocean velocities are cm s^{-1}, where as the wind stress has units of 10 dyne cm^{-2}. Note that the values of wind stress has been rounded to integer values. Velocity and stress components are positive for northward flow and negative for southward in the meridional components and for the zonal vectors, eastward is positive.

1.2   Method

When isolating different events to begin with, only the north-south component of wind stress vector and inertial velocities are used. The reason is that the point of interest is the change of direction of the wind and ocean movements, which is most clearly seen when using only one component of the velocities.

The different events are located by searching each region for the strongest northward signals, in both upper-ocean and atmosphere. First, the largest values within each

region are found for every longitude at one time step, giving 160 values of northward (positive) velocities. The largest value of these is then chosen and the value and corresponding coordinates are saved, and the process is repeated for each time step. Thus, for each time step, the largest northward value and the coordinates for this is stored. This leaves a time series of the strongest values of the region. The next step is to isolate the strongest of ocean velocities and wind stresses. This is done by simply finding the peaks of each time series. An amount of time steps between peaks is set to 100, which is 200 hours, in order eliminate possible peaks referring to the same event, leaving out only the strongest peak of each event. The peaks and their respective times of appearance and the coordinate of the event are then sorted, and the 5 strongest peaks are chosen.

When the strong signals are found, each peak's coordinates are held fixed, and the time evolution before and after the signal are found for that fixed coordinate. In other words, the analysis of the storms and oceans are held in an Eulerian reference frame.

The strongest peaks of both ocean velocities and wind stress of all three regions are found this way, and these are plotted together in a diagram. The periods of the oscillations now have to be determined. As the data are of discrete time and space, determining the exact period of the oscillations can be rather tricky, and it must be noted that the procedure has significant uncertainties (although the magnitude of these is difficult to estimate). Furthermore, some of the extreme events have little resemblance to an actual oscillation, which makes it more or less impossible to speak of an actual period (see for instance figure 2, event 2.1.1). The period is estimated as twice the time between the maximum of the event and the minimum that precedes it. The reason why this, and not the time from the maximum to the minimum following the maximum, is taken to represent the period is that the point of interest is whether the forcing that initiates a strong oscillation has a comparable period to that of the ocean. This has its problems as some events (especially in the northern mid-latitudes) are initiated in a southward direction half a period prior to the northward maximum of the events. For these events, this period is calculated and used. Given that the storm dynamics might vary considerably over just one period, only one half period is used to represent a period. Naturally this causes a rather large uncertainty, of at least ± 4 hr, which is significant for the periods in the southern ocean and the northern mid-latitudes, as we shall see later, and this fact should be kept in mind during the analysis of the different events.

When 15 strong ocean responses and 15 strong storms have been located (5 of each within each region), and the periods have been estimated, the storms are described and analysed to establish any similarities and differences.

The energy decay time for each strong ocean response event is defined as the characteristic time of an exponential decay of the oscillation, τ_d, defined in the usual way. τ_d is estimated through the decay of the inertial energy defined by eq. 1. The value is calculated from the maximum of the event and 40 time steps ahead, yielding a time evolution of the energy. An exponential decay is fitted to the energy values, and τ_d is taken as the decay parameter. The method has its flaws, as not all oscillations are just

excited by the wind and then left to decay, as will turn out to be the case of few events. Instead, wind stress continuously forces the ocean, either strengthening or dampening the oscillation. This means that, depending on the nature of the wind stress following the maximum of events, the exponential decay might either be too fast or too slow, and so, the estimation is very sensitive to the amount of time steps used. 40 has been used as a general value for all estimations, but this will show to lead to a collapse for some events. The short line is that nothing general can be said about the wrongness of the energy decay time, and the results are therefore just rough estimations used to compare if the energy decay is similar to previous findings.
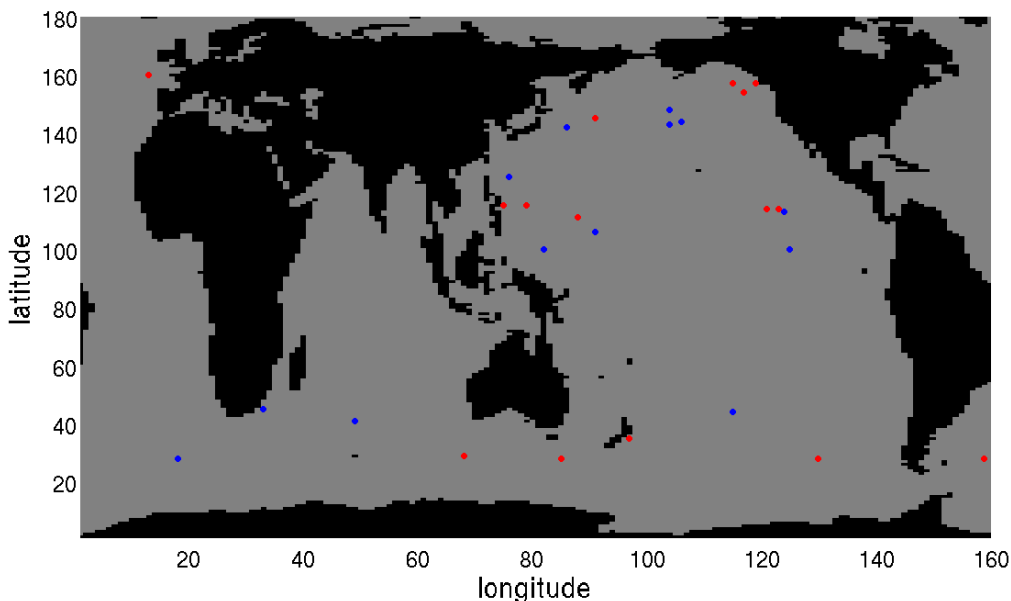

Figure 1: *Location of different events. Blue dots mark events with great ocean velocity response, red dots mark events with great wind stress. Note that two events happen on coordinate sets (100,125) and (45,33).*

2   Events

All 30 isolated events are plotted on a world map in figure 1. Blue dots refer to strong ocean response events, whereas red dots refer to strong storm events. Notice that two events in the tropics and two in the southern ocean occur at the same coordinates. Each event is labelled with a 3 digit number. The first digit refers to what kind of event it is. 1 means that it is a strong ocean response, whereas 2 refers to a strong storm event. The second digit refers to the region in which the event occurs. Here, the numbers 1, 2 and 3 refer to the southern ocean, the northern tropics and the northern mid-latitudes, respectively. The final digit simply lists the event after strength, going from the strongest, 1, to the weakest, 5.

For each region, periods of ocean oscillations, T_{ocean}, and winds, T_{wind}, are calculated and shown in tables along with the estimated energy decay time of the ocean oscillation, τ_d. In this section, events of the separate regions are described in general and in detail if necessary. This sets the grounds for the discussion and comparison of events and regions in the following section.

2.1 Region 1: The Southern Ocean

Let us first look at the events in the southern ocean. The ten events are all illustrated in figure 2. The graphs show the time evolution of northward ocean velocity (blue) and wind stress (red) before and after the maximum of the event, spanning 600 hours in total. The estimated periods of ocean and wind, along with decay times of the inertial energy, all in hours, are given in table 1.

					Southern Ocean					
Event	1.1.1	1.1.2	1.1.3	1.1.4	1.1.5	2.1.1	2.1.2	2.1.3	2.1.4	2.1.5
T_{ocean}	16	16	24	24	24	40	20	16	16	36
T_{wind}	16	16	40	24	24	52	32	24	24	24
τ_d	8.6	582.1	14.6	23.2	8.2	16.9	0.7	0.9	6.8	8.6

Table 1: *Periods of the ocean, T_{ocean}, and wind, T_{wind}, during the maximum of events of the southern ocean, and energy decay times, τ_d, of the ocean oscillations, τ_d. All units are in hours.*

Inspecting events 1.1.1-5, the first thing to notice is that the four strongest ocean responses (1.1.1-4) all reach inertial velocities greater than 50 cm s^{-1} in magnitude. Standing out is 1.1.5 that has a maximum inertial velocity of 47 cm s^{-1}. Corresponding wind stresses during the maximum of events vary from a magnitude of 420 dyne cm^{-2} (1.1.4) to 880 dyne cm^{-2} (1.1.1). Event 1.1.1-4 all occur while the winds turn from strong northward stress to similar magnitude southward stress. Note that events 1.1.2-4 occur as winds excite the ocean while the amplitude of north-southward ocean velocities are already of significant magnitude compared to the maximum. These relatively large amplitude oscillations seem to be caused days earlier by wind stresses of comparable magnitude to the ones exciting the waves to their maximum velocities. Events 1.1.1 and 1.1.5, on the contrary, seem to be rather spontaneously excited. All ocean oscillations of events 1.1.1-5 seem to persist for several periods. Some seem to be continuously excited by the winds even past the maximum of the events.
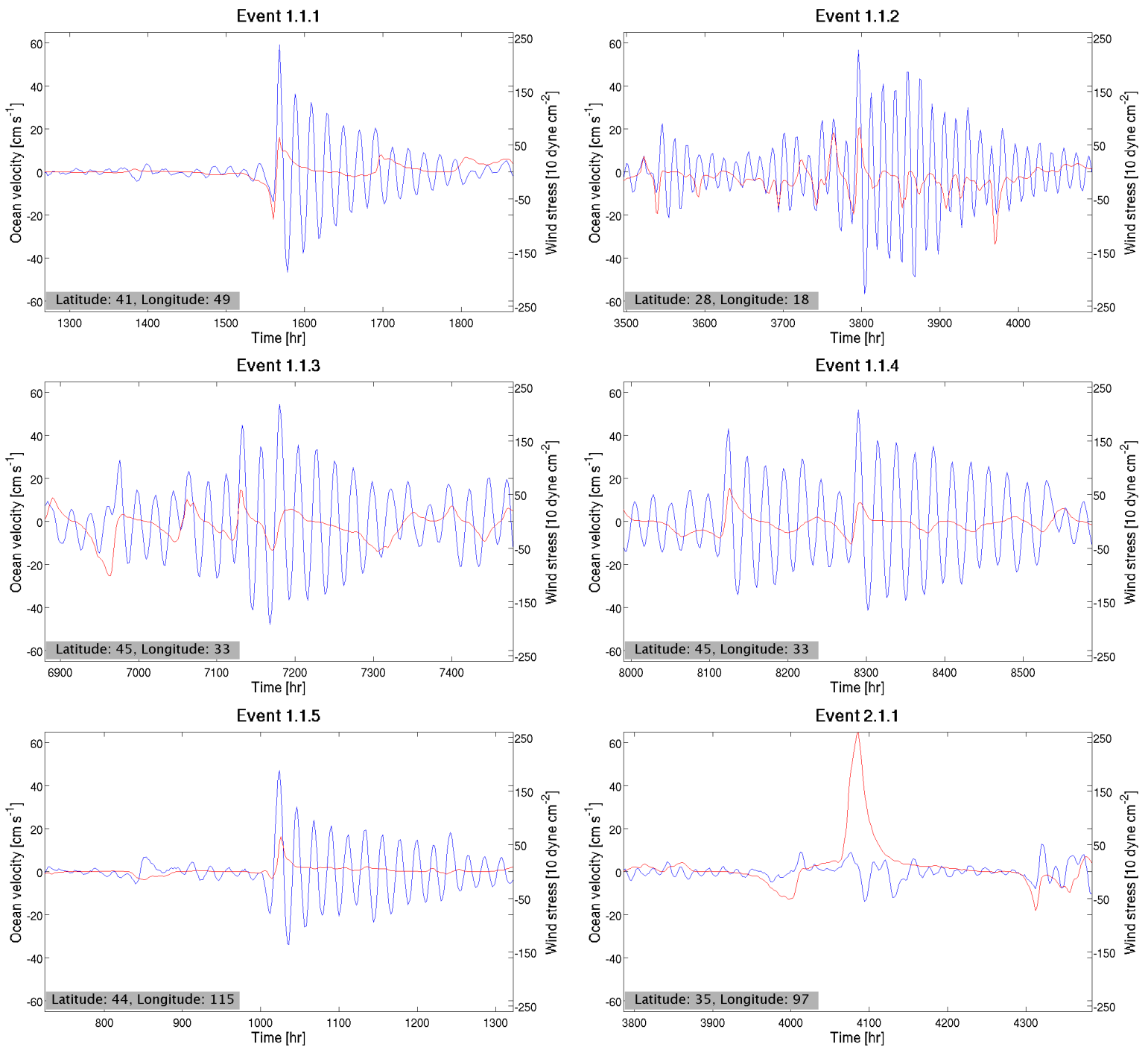
Figure 2: *The ten events of the Southern Ocean. Blue lines refer to ocean velocities, red lines wind stress.*
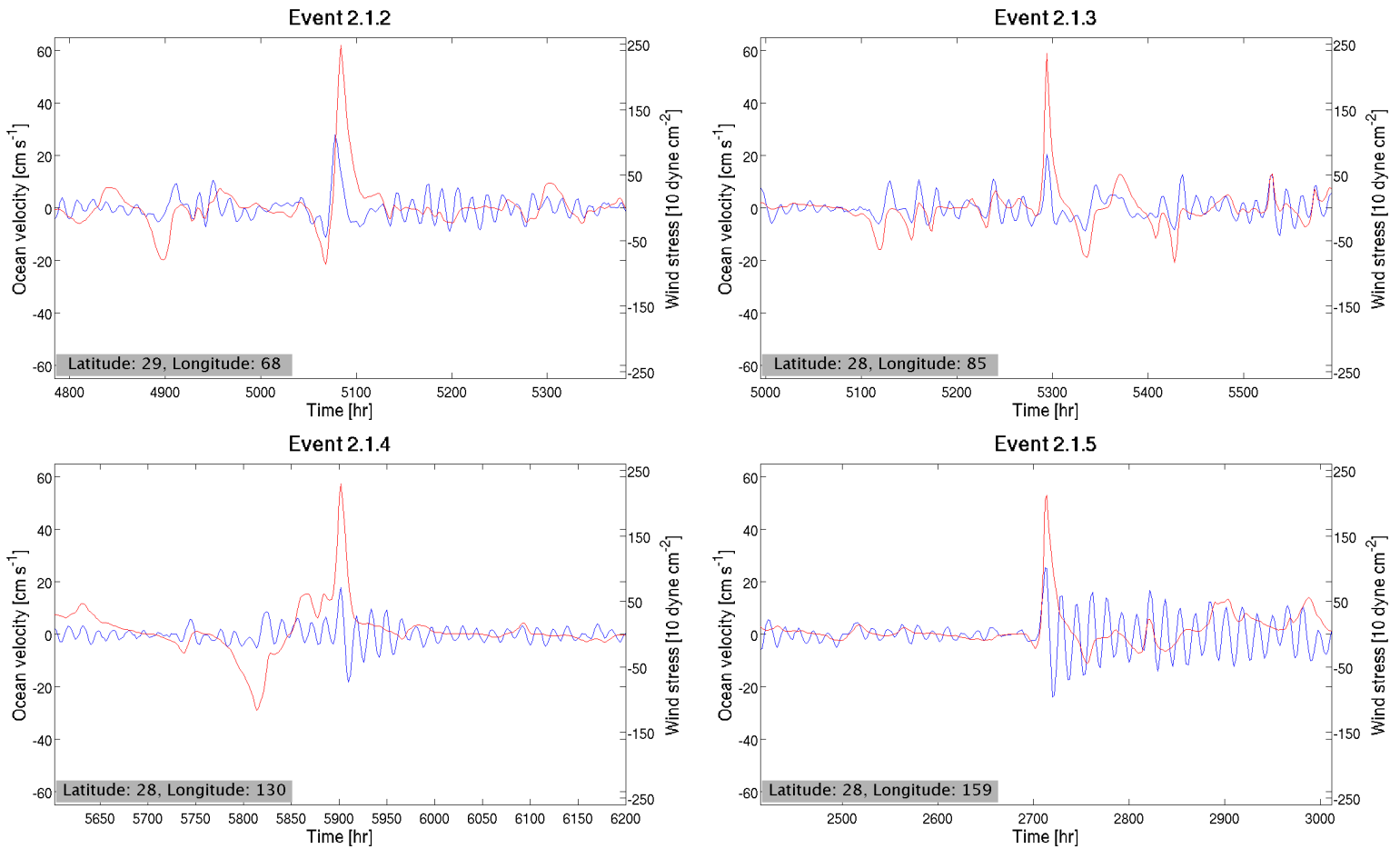
Figure 2: *continued*

As seen in table 1, the turning time of the winds are, for 4 of the 5 events, comparable to the period of the ocean oscillations. Only 1.1.3 seems to differ in turning time from the ocean period, but notice that the maximum of the event is reached as the winds turn from northward to comparable southward magnitude over only a little more than 1.5 oscillations of the ocean. Thus, wind stress and ocean velocities have northward and southward extrema almost synchronously, prior to the maximum of the ocean response. Energy decay times of events 1.1.1-5 vary from 8 to 25 hours, with the exception of the decay time of event 1.1.2 that is of almost 600 hours. This extremely large number is the result of the incompleteness of the calculation of decay times, as the calculations involve time steps up to the time that the oscillations are re-forced by the wind (see figure 2, event 1.1.2).

Turning our attention to the storm events 2.1.1-5, all storms reach a maximum stress greater than 2000 dyne cm^{-2}, in the range between 2000 and 2500 dyne cm^{-2}. None of the storms, however, excite the ocean velocities any greater than 30 cm s^{-1}. It is very characteristic for these events that except for 2.1.4, none of the events have wind stress that turns northward to southward or vice versa in similar strength, and even for 2.1.4,

the northward stress reaches a magnitude of twice the southward stress. Note also how the turning or strengthening of the winds also for all events 2.1.1-5 have longer periods than the oscillation periods of the ocean (table 1).

Energy decay times of oscillations caused by strong storms range from below 1 hour to 17 hours, with a general faster decay than the strong ocean responses.

2.2 Region 2: The Northern Tropics

The 10 events of the Northern Tropics can be seen in figure 3. The corresponding periods of both ocean and winds, in hours, are given in table 2, along with energy decay times.

	Northern Tropics									
Event	1.2.1	1.2.2	1.2.3	1.2.4	1.2.5	2.2.1	2.2.2	2.2.3	2.2.4	2.2.5
T_{ocean}	96	180	120	56	92	32	52	44	36	32
T_{wind}	80	136	52	32	72	56	48	56	36	32
τ_d	25.6	6.7	8.3	11.6	12.7	35.6	127.4	60.2	-162.3	19.5

Table 2: *Periods of the ocean, T_{ocean}, and wind, T_{wind}, during the maximum of events of the northern tropics, and energy decay times, τ_d, of the ocean oscillations. All units are in hours. Note that the negative τ_d of event 2.2.4 is a consequence of the uncertainty in estimating τ_d.*

The strong ocean response events, 1.2.1-5, are characterised by considerably longer periods than those of the two other regions. This is also what theory predicts, as the period depends on the coriolis parameter. Maximum ocean velocities excited range from 40 to 50 cm s^{-1}. The oscillations are, however, not as well defined as those of the other two regions, except for the ones of 1.2.4 and partially that of 1.2.1. The three most peculiar events are 1.2.2, 1.2.3 and 1.2.5. The oscillations seem to be the sum of two oscillations, one with large amplitude and period and one with small amplitude and period. The oscillations of long periods are not well-defined, as their structure is more similar to the storm events of the other regions than the strong ocean response events.
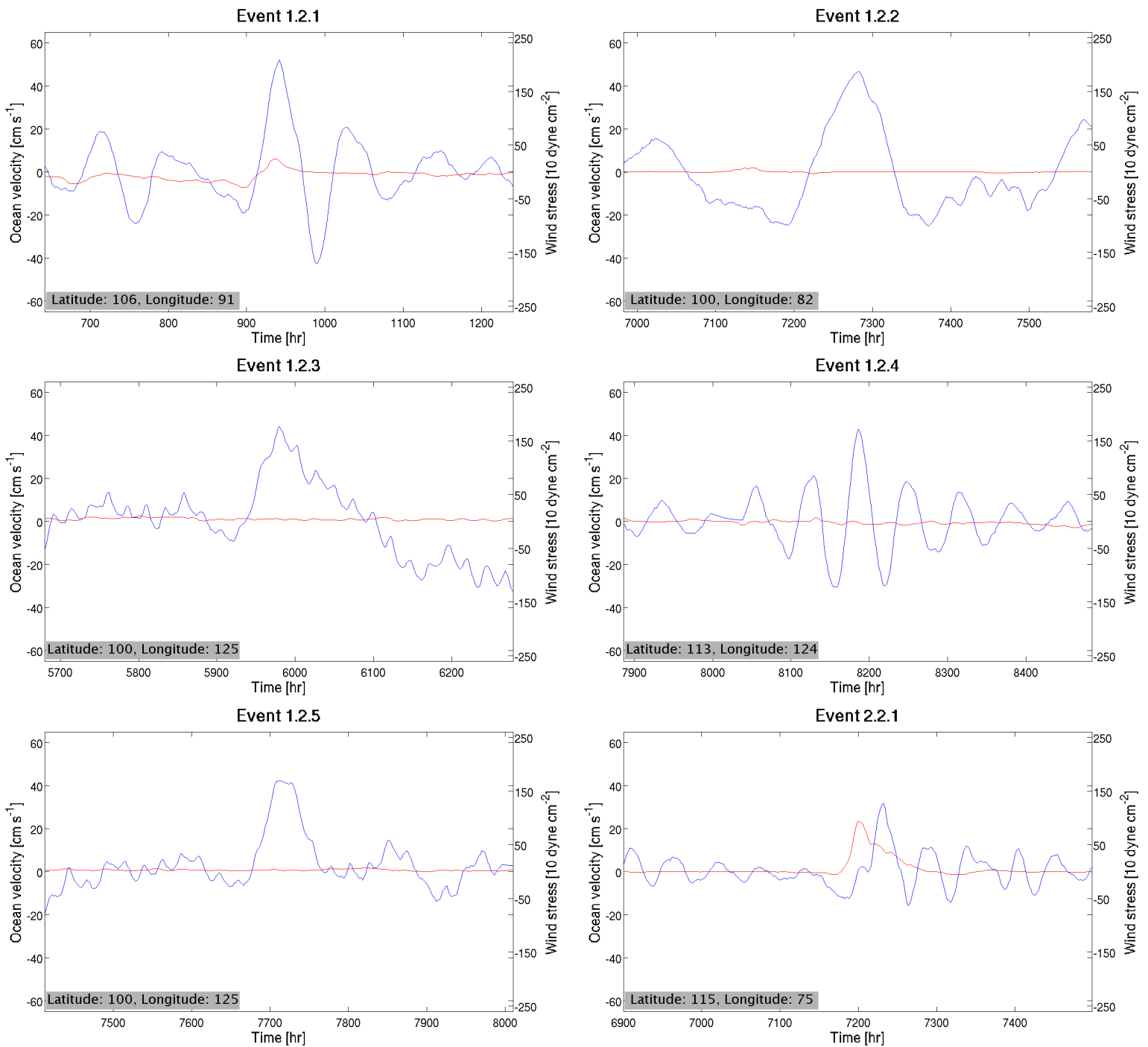
Figure 3: *The ten events of the northern tropics. Blue lines refer to ocean velocities, red lines wind stress.*
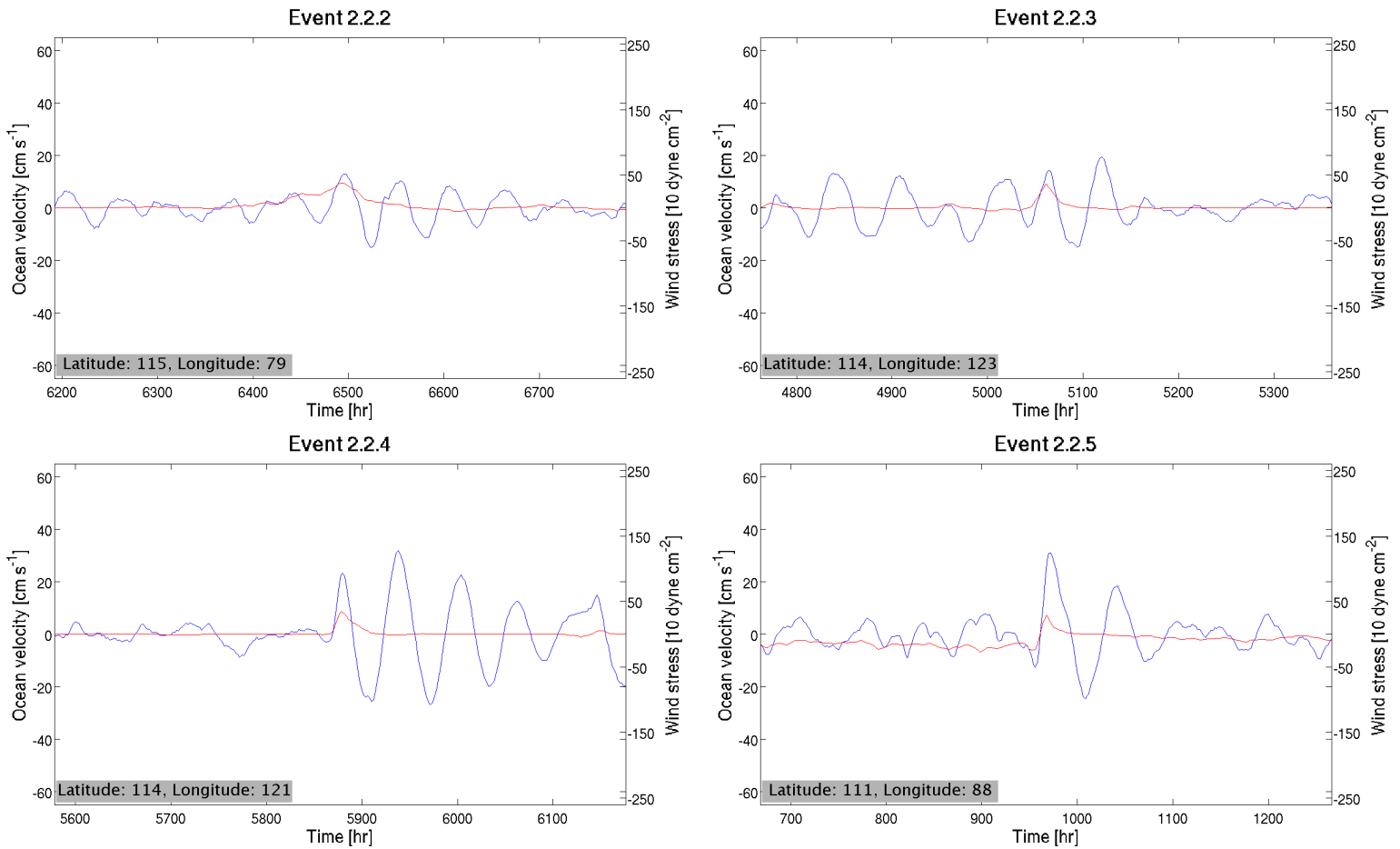
Figure 3: *continued*

The periods of wind and ocean differ considerably, and concerning the structure of the events, only 1.2.1 has a wind turning from a southward direction to a northward of similar strength, and even more notable is the fact that of all events 1.2.1-5, only the wind stress of 1.2.1 has magnitude greater than 150 dyne cm^{-2}, which is well below that found in the southern ocean, at any time. Another peculiar observation of the events is how the winds in events 1.2.2-5 are constant during long time spans. The explanation is to be find in that the wind stress over time is very low varying. As the stress have been rounded to integers, very little variation will not be seen. This does not, on the other hand, change the fact that the winds are remarkably weak during the strong ocean response events.

The strong ocean responses have decay times ranging between 6 and 26 hours, which is quite similar to the decay times of the southern ocean. Of the tropic events, events 1.2.2-5 have decay times less than 15 hours.

The strong storm events of the northern tropics have the weakest wind stress of the three regions. The maximum wind stress of events 2.2.1-5 range between just below 300 dyne cm^{-2} to almost 1000 dyne cm^{-2}, making the strongest storm peak at a maximum

magnitude of half the strength gained by the fifth strongest storm of the southern ocean. The ocean response velocities excited reach a magnitude of 20-35 cm s^{-1}, which is, however, similar to the velocities excited by the storm events of the southern ocean. The storm structures are similar to the ones of region 1, despite the comparably weaker wind stress. Weak wind stress is increased to a northward maximum strength, and weaken after peaking, without reaching a similar southward strength. Only event 2.2.5 differs from this structure, as a southward wind stress of 250 dyne cm^{-2} turn to a northward of 290 dyne cm^{-2}. This happens with a turning period of 32 hours, which is equal to the period of the oscillating ocean, as seen in table 2, and it also excites a fairly strong NI response.

The decay times of the ocean oscillation energies range between 20 hours and 130 hours. One event, 2.2.4, has a negative decay time, obviously caused by the problems of estimating the decay time. The ocean oscillation peaks one period following the wind forcing, resulting in a positive energy flux to the oscillation during calculation of energy decay time, causing the exponential fit to be positive.

2.3   Region 3: The Northern Mid-Latitudes

The events occurring in the final region, the northern mid-latitudes, are shown graphically in figure 4. The periods of ocean oscillations and the turning of the winds prior to the maximum of the events are shown in table 3, along with energy decay times. As with previous tables, all units are in hours.

The strong ocean response events of the northern mid-latitudes, 1.3.1-5, are more similar to the southern ocean events than the tropic ones. Ocean velocities are excited to a maximum velocity of between 45 and 65 cm s^{-1}, which is the greatest velocities of all regions, by winds of strength ranging from 1000 to 1500 dyne cm^{-2}, with the exception of event 1.3.2, where wind stress has a maximum strength of only 670 dyne cm^{-2} around the peak of ocean velocities.

	Northern mid-latitudes									
Event	1.3.1	1.3.2	1.3.3	1.3.4	1.3.5	2.3.1	2.3.2	2.3.3	2.3.4	2.3.5
T_{ocean}	64	16	20	16	24	24	8	12	20	8
T_{wind}	124	16	24	12	24	56	24	16	28	48
τ_d	5.4	11.8	14.7	12.3	16.3	4.2	19.2	15.7	7.2	13.3

Table 3: *Periods of the ocean, T_{ocean}, and wind, T_{wind}, during the maximum of events of the northern mid-latitudes, and energy decay times, τ_d, of the ocean oscillations. All units are in hours.*

Yet, unlike events 1.1.1-5, the storms of events 1.3.1-5 do not turn from either southward to northward direction or vice versa (except for 1.3.2), but rather occur as the winds gain strong velocity in one direction and then weaken, as in the typical storm events of 2.1.1-5. Especially event 1.3.1 and 1.3.3 are good examples of this, as the wind gains maximum strength southward and northward, respectively, and then more or less weaken to small strength compared to the peak of the storm. This leaves the oscillation of the ocean to decay rather unforced by the winds. Especially the decay of 1.3.3 seems unforced and shows a long lasting velocity amplitude decay, whereas the southward winds of 1.3.1 seem to oppose the ocean oscillation during the first period of the strong response, dampening the ocean oscillations significantly.
Event 1.3.2 has a similar structure as most of events of the southern ocean, whereas the events of 1.3.4-5 happen as northward winds excite an already existing oscillation in the ocean to double the amplitude of the speed.
Energy decay times of the strong ocean events range between 5 and 16 hours, which is much like the events of the southern ocean and the northern tropics.

The strong storms of the northern mid-latitudes have a very similar structure as those of events 2.1.1-5 in the southern ocean. The storms reach a maximum northward strength in the range of 1500-2000 dyne cm^{-2} and then weaken over time, not gaining any southward strength of comparable magnitude. The ocean velocities are excited to values in the range of 10-30 cm s^{-1}, meaning velocities somewhat smaller than the 45-60 cm s^{-1} found in the strongest of the ocean responses of events 1.3.1-5.
Energy decay times of the oscillations caused by these storm events range between 5 and 20 hours.

This ends the review of the events of the different regions. In the following section I will discuss the differences and similarities of events across regions and draw parallels to the experimental results found by Dohan and Davis (2011) and Large and Crawford (1995).

3 Comparison analysis

In this section I will discuss events within and across regions and compare the overall results between the three regions. Initially I will discuss the different regions to point out potential trends that seem characteristic for each, if any, starting with the southern ocean.

The strong ocean response and strong storm events of the southern ocean seem to differ considerably. Whereas events 1.1.1-4 all gain ocean velocities greater than 50 cm s^{-1} at the maximum, the strongest ocean velocities excited by the strong storms reach a value of almost 28 cm s^{-1}, about half the strongest velocities in events 1.1.1-4. There are other notable differences in the strong ocean and storm events.

First of all, events 1.1.1-4 all seem to occur while the winds turn from a significant southward velocity to a similar magnitude northward velocity or vice versa. The only event of 2.1.1-5 that has a similar characteristic is event 2.1.2, which is also the storm
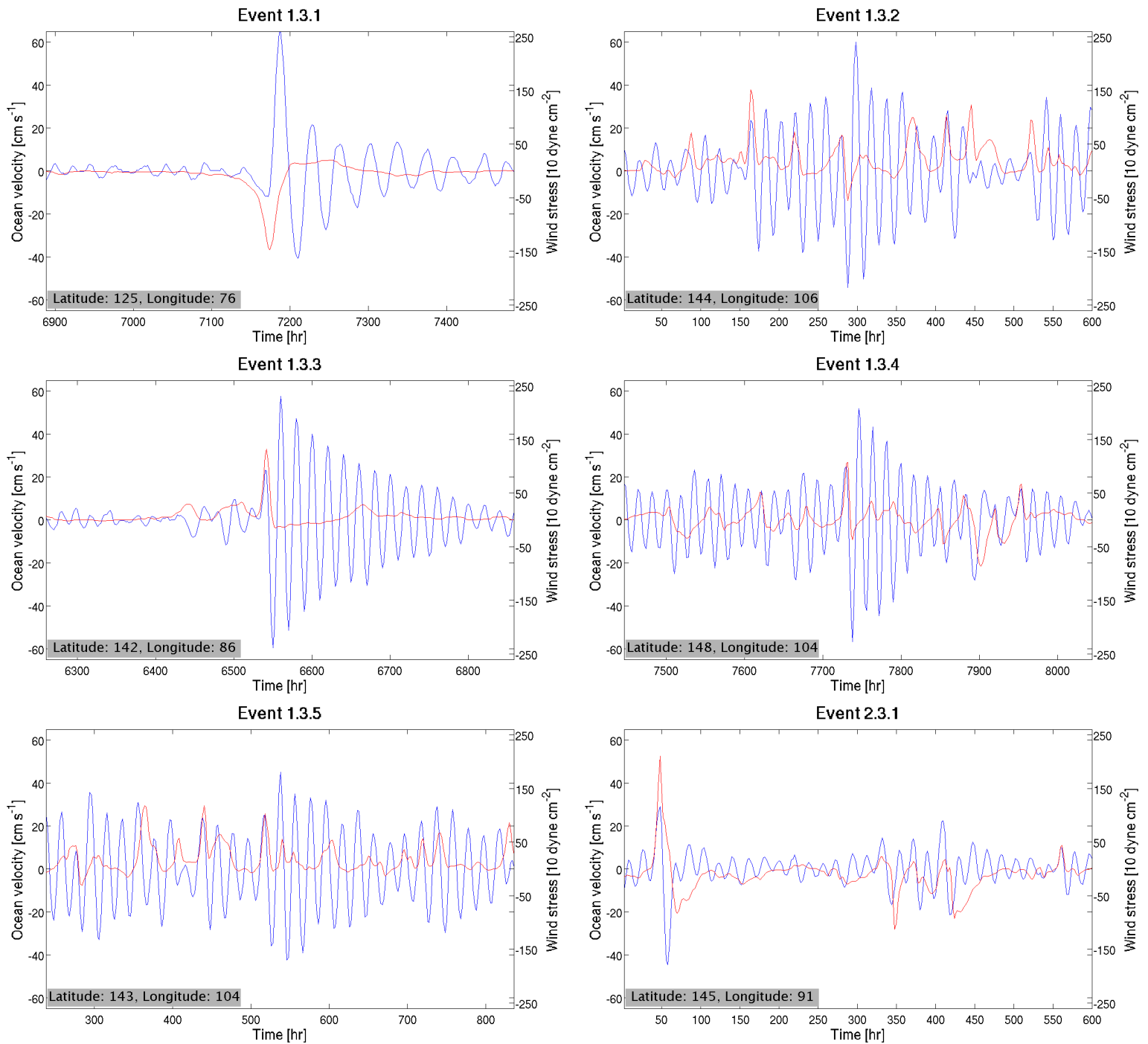
Figure 4: *The ten events of the Northern Mid-Latitudes. Blue lines refer to ocean velocities, red lines wind stress.*
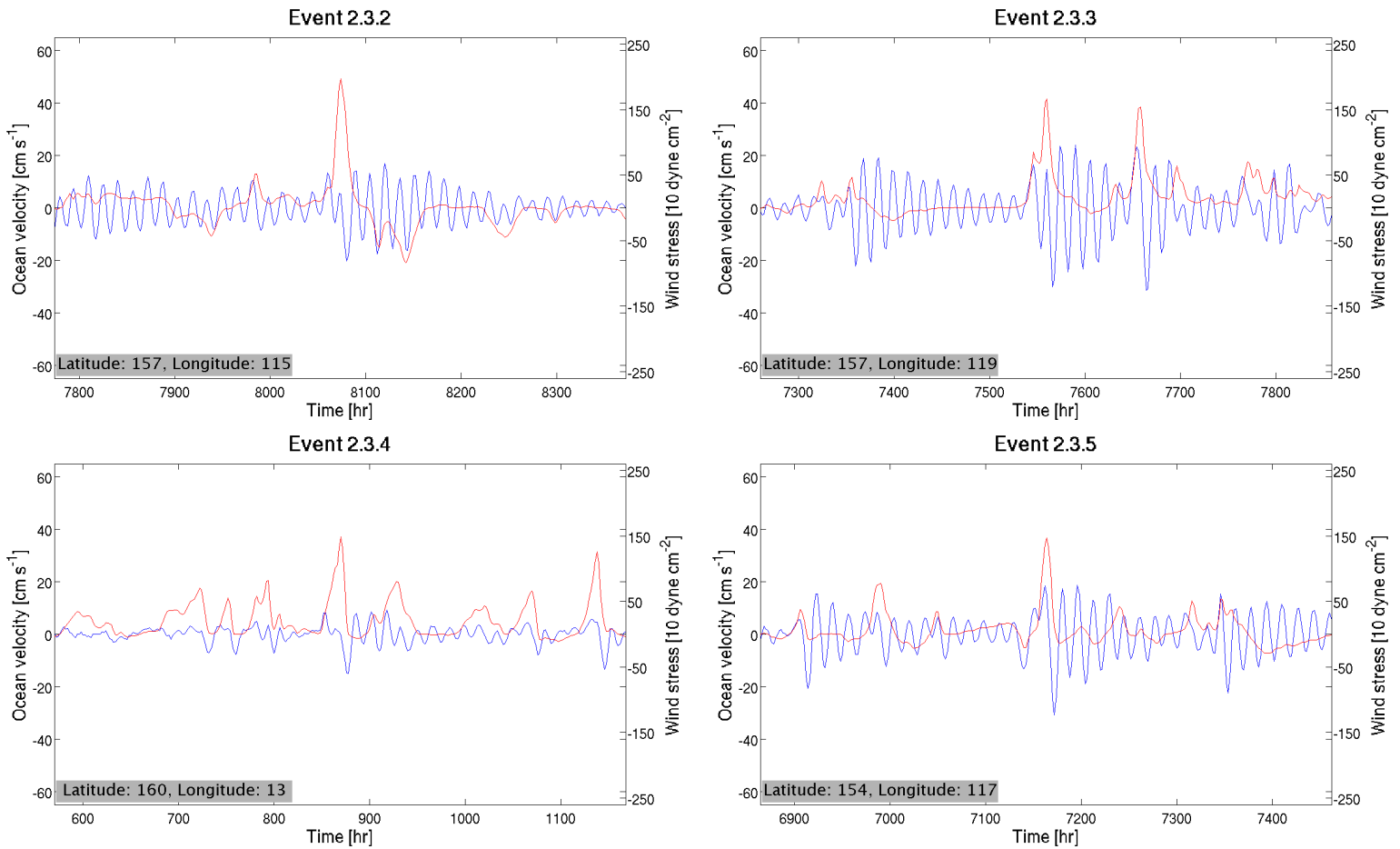
Figure 4: *continued*

event that excites the largest ocean velocities of those five. The other four storms turn from weak southward velocities to strong northward velocities, and all of them over longer times than the NI oscillations. Keep in mind that no storm of weak northward wind stress and strong southward are present, as the storms are defined by their strong northward response.

There is an interesting difference between the events 1.1.1-4 and 1.1.5: The former ones occur when the winds turn northward to southward or vice versa, where the latter is excited only by a 600 dyne cm^{-2} strong northward wind stress, following rather weak peak in southward stress. This creates a strong ocean response, but with velocities of magnitude 20 % less than the 4 greatest ocean response events of the same region.

Another trend of the strong ocean response events is that 4 of these events occur when ocean periods and turning of the winds are equal at the build-up of the maximum northward velocities (as seen in table 1), whereas none of the storms turn with periods similar to the NIWs. That the periods of the wind and ocean are of similar magnitude, and phase, is in agreement with the results of Dohan and Davis (2011), who argue that the similar turning of wind and ocean is an important element in creating a strong

near-inertial response. Event 1.1.3 stands out from this, as the period of the wind is significantly longer than that of the ocean. However, when going into detail of the structure of the event it is found that the ocean oscillations are forced more than once by the wind: as the wind turns from northward to southward velocities over the span of 1.5 periods of the ocean oscillation, and then again turn northward, over a period somewhat longer than that of the ocean oscillation. The first forcing suggests that an approximate 1:3 period relation between storm and ocean might resonate the ocean to great NI velocities on a similar scale as a 1:1 period would. This seems reasonable, as long as the wind stress turns in a way so that it does not stress the ocean surface in the opposite direction of existing NI currents.

Event 1.1.1 and 1.1.5 are generated as weak ocean oscillations are excited by one event of strong wind stress, where events 1.1.2-4 occur while the ocean oscillations are already of relatively great amplitudes, as they previously to the maximum are excited by strong wind events. This gives rise for a separation of two different types of strong NI ocean oscillation responses: one type of events occur as small amplitude oscillations are forced by strong winds (1.1.1 and 1.1.5), creating large magnitude ocean velocities, and the other type consists of driven oscillations, where several wind forcing continuously drive the oscillation to strong velocities (1.1.2-4). The latter is the type of response described by Large and Crawford (1995).

The tropics seem to stand out from the two other regions. The NI response velocities generated are on the overall comparable to those of the other regions, yet the evolution of the great velocity amplitudes is for most events considerably different from those of the southern ocean and the northern mid-latitudes. The wind forcing during the events is of significantly smaller magnitude than of other region ocean response events. Accordingly, of the five events, only 1.2.1 seems to be excited as a result of changing winds, or wind behaviour in general. Notable is it also that it is the only strong ocean event of the tropics where wind stress exceeds 100 dyne cm^{-2}, gaining a maximum stress of just below 300 dyne cm^{-2}.

This is quite different from the southern ocean and is inconsistent with the findings of Dohan and Davis (2011), as it seems the winds play very little role in generating the strongest NI velocities in the tropics. Curiously, the winds of the tropics seem extremely weak in events 1.2.2-5, especially considering how, as an example, the winds of event 1.2.2 are extremely weak for a time span of at least 200 hours. The constant value wind stress is, as mentioned earlier, a result of the wind stress matrix being in integers, meaning that small changes are not visible. Nevertheless, it is remarkable that wind stress of greater magnitude is not obtained in this region. One might expect that the oscillations are instead generated by zonal wind stress bursts, but this shows not to be the explanation, as seen in figure 5. This is a curious result.

As for the northern mid-latitudes, only event 1.3.2 occurs while winds turn from northern velocities to southern of similar magnitude. Event 1.3.1 and 1.3.3-5 occur during strong wind stress in only one direction. This contrasts the findings of the close relationship between the turning of the winds and the ocean response in the southern ocean. Yet, the period of which the winds gain and lose strength are within uncertainties
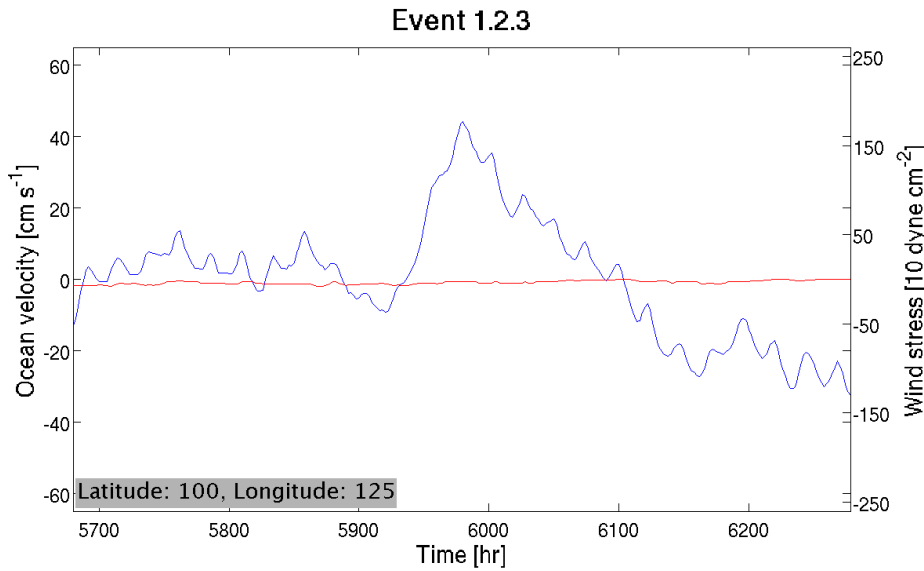
Figure 5: *Meridional ocean velocity (blue) and zonal wind stress (red) for event 1.2.3. This example shows that the ocean oscillations in the tropics are not seemingly generated by zonal wind stress.*

equal to the periods of and in phase with the NI oscillations, although the relation is not as clear as is the case with the southern ocean. This is not the case for event 1.3.1, but note that the wind stress have very little similarity to an actual oscillation.

Thereby, although they do not turn direction rather than weaken, the time scales of the behaviour of the winds are similar to that of the ocean oscillation, suggesting that winds closely in phase and with similar period with the ocean is a main driving mechanism for generating a strong NI response in the ocean. It appears from events 1.1.3 and 1.3.1 that when wind stress peaks close to the peak of the NIWs, without necessarily changing over the same time span of the ocean, it will excite the NI oscillations significantly.

This agrees with the argument by Large and Crawford (1995). If storms and ocean change in phase, we would expect a resonance as the winds will keep forcing the ocean in the same direction as the movement of the ocean oscillations. The opposite should show to dampen NI oscillations. This fact is verified by event 1.3.1, where the storm persists while the ocean current is turning, dampening the oscillation by 50 % within just one period. Several of the storm events similarly indicate that this in fact the case, take for example events 2.1.2, 2.3.1.

The strong ocean oscillation responses seem to be of the same two forms as in the southern ocean, events 1.3.1 and 1.3.3 being forced without any significant oscillation prior to the wind stress forcing, where as the rest are more similar to driven oscillations.

Considering the storm events, it is interesting to notice how the winds of event 2.3.1 force ocean response velocities of almost same magnitude as event 1.3.5, the latter having wind stress strength of approximately half the stress of 2.3.1. The oscillation of event 2.3.1 is however quickly damped by almost 75 %, as the wind period following the
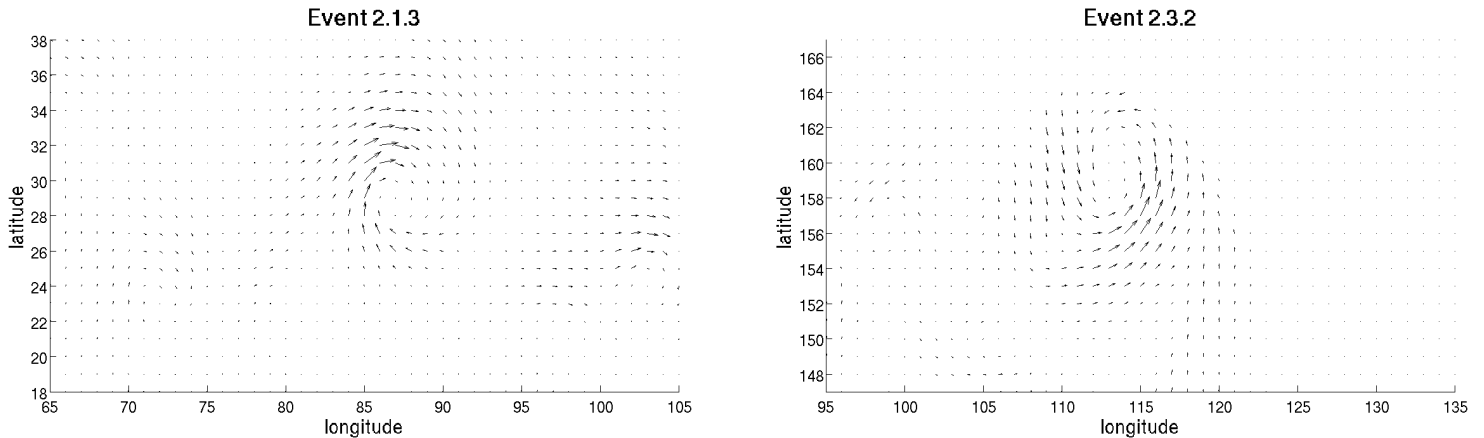
Figure 6: *The wind stress vector field at the peak of event 2.1.3 (left) and event 2.3.2 (right) shows that storms in the southern hemisphere turn clockwise whereas northern hemisphere storms turn counter clockwise.*

oscillation is almost twice that of the ocean, resulting in opposite forcing to the ocean velocities following just one NI oscillation. As the period of the wind is rather large compared to that of the ocean leading up to the event (as seen in table 3), at a first glance it does not seem that this has any connection to the large response of the ocean. Notice, however, that the winds prior to the storm are very weak compared to the maximum strength, with a minimum long before the initiation of the strong meridional burst. This example illustrates that the periods of the winds are tricky to deal with as there may not be no well defined period. Sure, the time from the strongest southward wind to the strongest northward is considerably longer than that of the ocean period, but the calculation of this period neglects the fact that the winds have been very slow varying, almost constant, for 8 hours prior to the build-up of the storm, blurring the definition of a well defined turning period.

Seen in figure 6 is the wind stress vector field over the ocean during two storm events, one in the southern hemisphere (left) and one in the northern hemisphere (right). These show that the storms of the southern hemispheres turn clockwise, as would also be expected from theory, whereas northern hemisphere storms turn counter clockwise. Despite the difference in the storm structure of the different hemispheres, the NI response of the strong storm events in both hemisphere are very similar.

Considering the above discussion, it is not immediately clear that anything can be said in general about the generated NIWs, as especially the tropics suggest different results than the two other regions. Yet, something seems to be characteristic for at least the southern ocean and the northern mid-latitudes, and that is that two different types of strong oscillations seem to occur as a result of wind forcing. One type is characterised by 'sudden excitations'. These are generated by a strong wind forcing of small amplitude oscillations, exciting the ocean to great velocities compared to those prior to the wind forcing. Examples of this kind of NIWs are events 1.1.1 and 1.3.3.

One trait that is characteristic for these oscillations is that they are generated over a short time scale, of half an ocean oscillation. The winds creating oscillations of this type seem to need to have a considerable strength. Wind stresses generating the strongest events found here are all of magnitude greater than 600 dyne cm^{-2}.

The other type of oscillations could be called 'driven oscillations' as they are the result of several wind stresses exciting the oscillations one after another. The effect is that the winds over several events provide a positive energy flux to the oscillation, making a series of energy flux contributions to an already oscillating wave. Particularly different from the other type of strong ocean oscillations is that these are generated over a long time, of several periods. This means that the wind forcing needed to cause these oscillations may not need to be quite as strong as the first type of oscillations, although most events found are of comparable wind stress strength. The weakest wind stress in for instance the southern ocean is found for event 1.1.4, which has wind stress of magnitude just 420 dyne cm^{-2}. This type of oscillation is of the same characteristic as the strong storm analysed by Large and Crawford (1995). Their result found that the wind stress turning in phase with the pre-existing inertial oscillations forced significantly strong ocean response, and through that mixed layer cooling. This is similar to the events described here, as it is characteristic that most events are found to have comparable periods for wind and ocean. One event, 1.1.3, however, suggests that an approximate 1:3 relationship between wind and ocean periods can also strengthen existing oscillations, as long as the northward and southward peaks fall coherently.

3.1 Storm turning

Something that the two types of oscillations have in common is the apparent connection between the change in wind stress and the oscillation period of the ocean. Figure 7 shows the relation between periods of the turning of the wind and the period of the ocean oscillations for the different events. Each colour and marker type represents a region. Crosses represent southern ocean events, diamonds represent the northern tropics and circles the northern mid-latitudes. Only the strong ocean response events are presented. As should be apparent from figure 7, the southern ocean and the northern mid-latitudes are characterised by a close to 1:1 relationship between ocean and wind periods. Note that of the southern ocean, 4 events fall in two different points. The relationship is seemingly not complete, as it breaks down for the tropics, and one event in each of the southern ocean and the northern mid-latitudes.

The event in the southern ocean is event 1.1.3, and that of the northern mid-latitudes is event 1.3.1. As has been noted earlier, event 1.1.3 is characteristic due to its almost 1:3 relation between wind and ocean periods, giving two positive energy flux contributions to the NIWs within 40 hours. As for the event 1.3.1, this is indeed an event that is remarkably different from all other events, as the storm both excites and opposes the ocean velocities, and thereby dampens the oscillations, within just one oscillation period. The event does not quite fall into the category of either of the two types of oscillations mentioned, although in structure it is like those initiated by a 'sudden
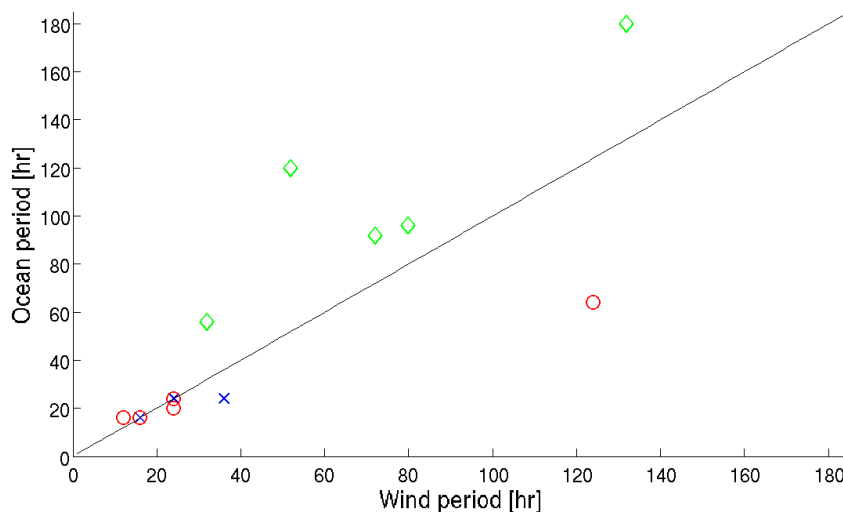
Figure 7: *The relation between periods of ocean oscillation and wind turning for the three regions. Crosses refer to the southern ocean, diamonds to the northern tropics and circles refer to the northern mid-latitudes. Note that two marks of the southern ocean lie in each of the (16,16) and (24,24) coordinates. The black line indicates a 1:1 relation. All units are in hours.*

excitation'. This is seen as a single strong wind stress initiates strong ocean oscillations following otherwise small magnitude ocean velocities.

As for the tropics, the ocean periods are all considerably longer than the corresponding wind periods, and no connection seems apparent. This calls for an explanation, yet none seems obvious. One might be that winds do not play a big role in forcing the tropic oscillations. This seems implausible compared to the two other regions, where the relation between wind and ocean seems to play a very important role in generating NIWs (as seen in figure 7), and as event 1.2.1 similarly indicates a connection between turning of winds and ocean oscillations. Accordingly, events 2.2.1 and 2.2.5 indicate that strong wind forcing alone might excite oscillations of considerable magnitude. Another explanation might be that wind forcing is not the only mechanism in resonating the NIWs. This is contradicted by the other regions, as none of the oscillations in these seem to be created without significant forcing by the wind. One possibility, however, is that this other mechanism is only significant near the tropics. One possible explanation is that the generation of strong NI ocean velocities in the tropics lie in the nature of the low frequency that is characteristic for the tropics. As velocities may be northward for a very long time span, a small magnitude wind stress in the same direction will provide a positive energy flux. While the flux is small, the long timespan makes the total energy input significant, possibly increasing the NI velocities.

The fact that the storm period being closely equal to the local ocean oscillation period is a central mechanism for both types of strong ocean responses found for the southern ocean and northern mid-latitudes suggest that the generation of strong NIWs

is in these regions related to one of the following two courses: either the winds turn over a calm ocean in a time scale close to the local ocean oscillation period, initiating a strong response, or the wind stress turns over a similar time scale and in phase with an already existing near inertial oscillation.

3.2   Storm strength and movement - comparing 2 similar events

A first inspection of the strong storm events indicates that great ocean response is not a result of strong wind forcing alone. The strong storms of the southern ocean, with a magnitude of more than 2000 dyne cm^{-2} fail to produce ocean oscillations with velocities close to those found in strong ocean response events. Inspecting the strong ocean response events generated over short periods, as 1.1.1, does suggest, however, that strong winds has a considerable role in causing strong oceanic NI circulation, although comparing these events with the strong storm events indicate that it is not the dominating mechanism. Comparing events 1.1.5 and 2.1.3 one finds that the structure of these has significant similar traits: small amplitude oscillations are excited by a sudden wind forcing, the wind stress peaks around the same time as the ocean northward velocity, and the winds then weaken. Yet, the response of event 2.1.3, which is generated by a significantly stronger wind stress than event 1.1.5, is much weaker than that of event 1.1.5. The energy decay time is also almost an order of 10 smaller than the strong ocean response event. It is curious that such two events of comparable structure has considerable differences in ocean velocity magnitudes, especially considering that the strong storm is the one creating the weakest response.

Not surprisingly, the answer to this appears to be the movement of the storm in the Eulerian reference frame of the event coordinate. The two events are both taken from the southern ocean. Inertial oscillations are anticyclonic, the coriolis force acting to the left of movement on the southern hemisphere. This means that when measuring near inertial wave velocities in the Eulerian reference frame, one would measure the velocities turning counter clockwise. If we now turn to the events 1.1.5 and 2.1.3 and plot the corresponding wind forcings, seen in figure 8, we see that although the ocean velocities and wind stress of the two events turn from southward to northward in a comparable amount of time, the wind of event 1.1.5 turns counter clockwise, whereas the strong storm of event 2.1.3 turns clockwise, resulting in a much weaker NI response to the wind forcing. This is similar to the two storms from the Ocean Storms Experiment analysed by Dohan and Davis (2011), where two storms of comparable magnitude show to have different effects on the upper ocean. Their examples also showed that the storm initiating a weak NI response was turning opposite to the ocean oscillations, locally. The example at hand shows that although wind stress is significantly stronger in one event, and turning from southward to northward velocities is of comparable periods, the orientation of the rotation of the winds plays a significant role in generating a near-inertial response.

This means that in order for strong inertial oscillations to be generated by storms, not only turning meridional wind stress over the same time as the ocean is significant, but
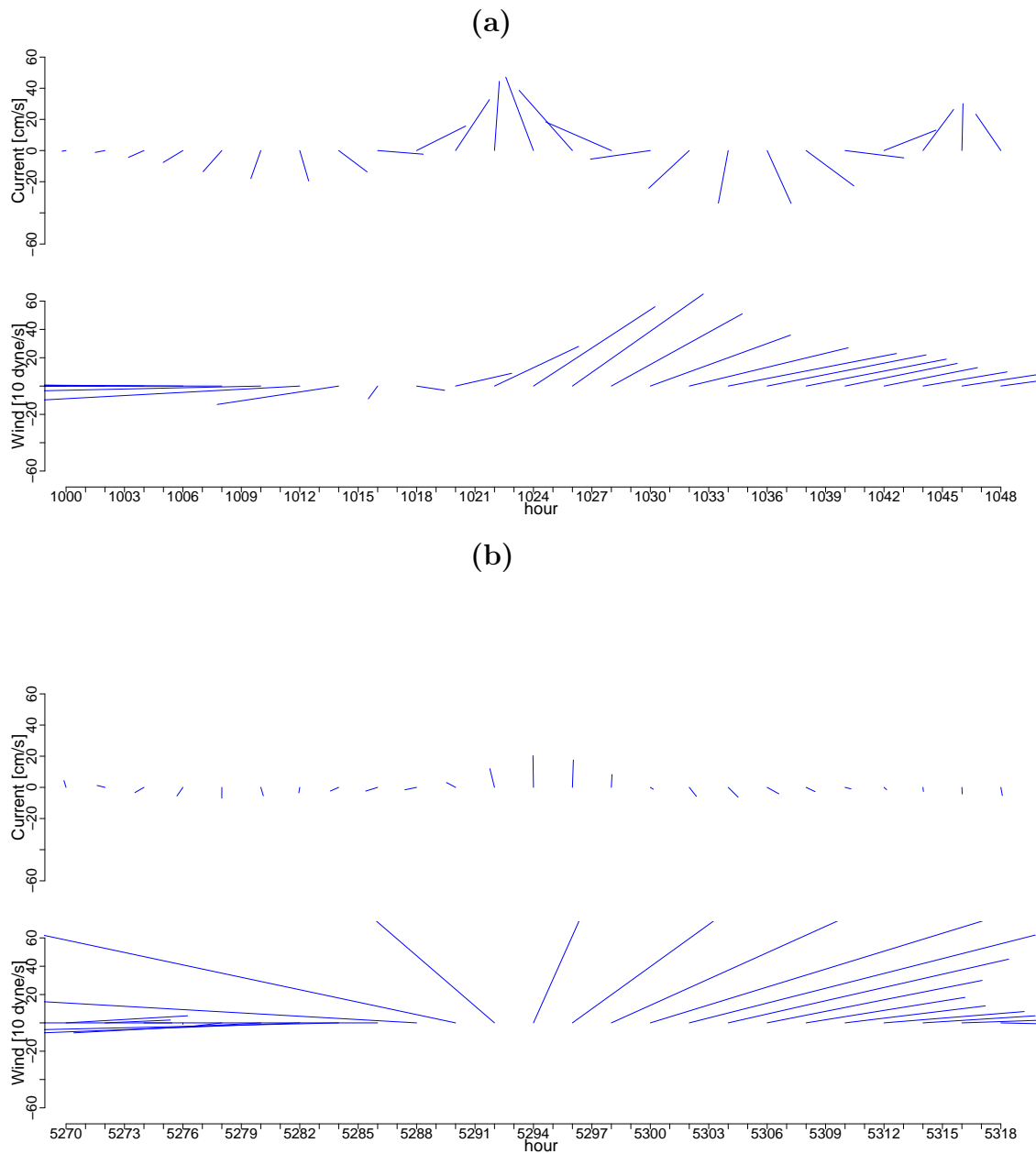
Figure 8: *Turning of ocean velocities and wind stress at events 1.1.5 (a) and 2.1.3 (b) show that orientation of rotation plays a role in generating a strong ocean response.*

also the orientation of the rotation of the storm plays an important role. In theory, this means that two storms of equal strength and group speed will have great different ocean responses depending on the path of the storm, as Dohan and Davis (2011) points out. In effect, two different storms, although of exact structure, will likely generate completely different upper ocean responses depending on their movement.

When comparing the role of the three mechanisms of interest in investigating the generation of NIWs, we find that the two most important are that the period of the turning of winds and the ocean oscillations are similar and that the wind and inertial oscillations turn in the same direction. Of less importance is the strength of the storm, although one might expect that a very strong storm that also turns in the same direction and over the same time as the ocean will in general generate the strongest ocean responses. Such event is, however, not seen in the data set of this survey.

The strength (and orientation) of the existing ocean oscillations prior to any wind forcing also seems to play an important role, as seen for those events that seem driven by different wind stress events. This makes sense when comparing the scenario to other physical examples of oscillations, such as a swing, and is supported by the results of Large and Crawford (1995).

Both the results from the southern ocean and the northern mid-latitudes suggest that two different types of NIWs are dominating as the strong ocean response to wind forcing, and both depend significantly on the movement and turning time of the storm, and not as much on the storm strength. The tropics tells a different story, as the NIWs here do not seem to be generated by strong wind forcing bursts, as described earlier.

3.3   Energy decay times

The calculation of energy decay times breaks down for some events, as presented in the results. When correcting for this, the energy decay times for all regions lie in the range of 1 to 30 hours for the strong ocean response events, whereas strong storm events are more spread out. The latter is explained by the diversity of the structure of the storm events. Some, e.g. 2.1.1, 2.3.1, strongly force the ocean, but has a much longer period than the oscillations, resulting in a negative energy flux as the ocean velocities turn southward, causing the energy decay time to be short. Other storms, e.g. 2.2.2, 2.3.3, force the ocean and then weakens, leaving the oscillations weakly forced, resulting in longer energy decay periods. Other storms act uniquely, either strengthening or weakening the oscillations.

The energy decay of the strong ocean response events are for the greatest part in the range between 5 and 15 hours. The energy of the oscillations is primarily radiated downward and southward, and is distributed between the normal modes. These travel at different phase velocity, and the decay time depends on the energy distribution of these different modes. According to Simmons and Alford (2012), the two lowest modes travel at velocities of 3 m s^{-1} and 1.5 m s^{-1}. At a very rough estimate, ignoring latitudinal variation that is significant, the latitude dimension of one grid point in the data set is 110 km. This means that crossing one latitude section takes 10 and 20

hours for the two lowest modes, respectively, for the velocities of Simmons and Alford (2012). Given that the primary amount of energy is stored in these two modes, this corresponds well with the estimated energy decay times. Remember though, that these are influenced by further wind stress following the maximum of the oscillation, giving rise for considerable uncertainties in the estimates.

4   Conclusion

The analysis of the computed data of Jochum et al. (2013) of the strong ocean response events in the southern ocean and the northern mid-latitudes indicate that especially two types of strong NI oscillations account for most strong NI responses in the ocean. One type is characterised by being initiated by one strong wind stress over a short time, whereas the other type is characterised as being generated through multiple wind forcing over a much longer time scale, as with a driven oscillation in a spring.

The investigation of the three mechanisms that might generate strong NIWs - storm strength, turning period and storm path - shows that a strong wind stress alone is not the driving mechanism in generating a strong NI response. This is seen as the 15 strong storm events that have been analysed find that the strongest magnitude wind stress events in some cases generates strong ocean velocities of magnitude of less than 25 % of the strongest velocities otherwise observed in the ocean.

Instead, the two other mechanisms seem of significantly greater importance in the generation of strong NIWs. Analysis shows that for the southern ocean and the northern mid-latitudes, all events are generated as the ocean velocity and wind stress vectors rotate in the same direction in an Eulerian reference frame, and over the same time, as seen in figure 7. These results agree with the findings of Dohan and Davis (2011), meaning that two identical storms can generate significantly different upper ocean responses depending on the path of the storm. Accordingly, the in-phase turning of the wind and pre-existing ocean oscillations shown for the events of the southern ocean and the northern mid-latitudes agree with the analysis by Large and Crawford (1995). Thus, the combination of ocean and wind turning in the same rotational direction and over a comparable amount of time show to generate the strongest NIWs.

The tropics are found to be in less agreement with these results. Here, low frequency oscillations seem to be strengthened by very weak wind forcing acting the same direction as the ocean velocity over a long time. Thus, the generation of strong ocean oscillations here appear not in general to be created by the turning of wind stress, but rather as a result of the nature of the low frequency oscillations. This result is contradicting what would be predicted, and needs further analysis.

   Energy decay times for the NIWs have been calculated to lie primarily in the range between 5 and 15 hours. This is, as a rough estimation, in agreement with the values of Simmons and Alford (2012), although a deeper analysis of these values might be of further interest. Improvement of the method can be made, as one event (2.2.4) shows a negative decay time. This is a result of the decay time calculating too many time

steps, including a further positive energy flux to the event. Choosing the right amount of time steps is a matter of balance, as too few will give too few data points to fit to.

The approach used is not without problems. First of all, the strong storm and ocean events have been chosen solely on their northward velocity, leaving out events with a strong southward or zonal velocity or stress. The possible loss caused by this selection should not be significant, as events of the northern mid-latitudes show stronger southward velocities than northward, as seen in figure 4, but a possible loss cannot be ruled out completely.

The estimation of periods also has significant uncertainties. As the resolution of time is of 2 hours, determining the exact time of a peak of an event complicating the determination of an exact maximum. Improvement of this is rather unrealistic if the sole purpose is to decrease the uncertainty of determining the periods of ocean and storms, when such climate model already comes with significant uncertainties in several other aspects. One thing that could improve the calculations would be to compare the estimated periods to the periods predicted by theory, calculating the periods directly by the NIWs' latitudinal coordinate. Such comparison would give information about the correctness of the periods found, at least for the ocean oscillations. Storm periods are a different matter, as these for several events are not well defined as oscillations at all. This gives a huge disadvantage in illuminating a possible connection between ocean oscillations and winds, and there is no obvious way to deal with this problem easily.

5   Acknowledgements

References

D'Asaro, E. A. (1985). The energy flux from the wind to near-inertial motions in the surface mixed layer. *J. Phys. Oceanogr. 15*, 1043–1059.

D'Asaro, E. A. (1995). A collection of papers on the ocean storms experiment - an introduction. *J. Phys. Oceanogr. 25*, 2817–2818.

Dohan, K. and R. E. Davis (2011). Mixing in the transition layer during two storm events. *J. Phys. Oceanogr. 41*, 42–66.

Garrett, C. (2001). What is the near-inertial band and why is it different from the rest of the internal wave spectrum? *J. Phys. Oceanogr. 31*, 962–971.

Jochum, M., G. Danabasoglu, W. G. Large, N. J. Norton, S. R. Jayne, M. H. Alford, and F. O. Bryan (2013). The impact of oceanic near-inertial waves on climate. *Journal of Climate 26*, 2833–2844.

Large, W. G. and G. B. Crawford (1995). Observations and simulations of upper-ocean response to wind events during the ocean storms experiment. *J. Phys. Oceanogr. 25*, 2831–2852.

Simmons, H. L. and M. H. Alford (2012). Simulating the long-range swell of internal waves generated by ocean storms. *Oceanography 25(2)*, 30–41.

A Appendix - code

```matlab
1  clc
2  close all
3  clear all
4  %% Defining
5  NIV=load('nivvel.mat');%opens the nivvel file, ocean velocity
       in v-direction. This is a struct.
6  NIU=load('niuvel.mat');%loads niuvel file, ocean velocity in u
       -direction
7  TAUY=load('ntauy.mat');%loads wind stress in x-direction
8  TAUX=load('ntaux.mat');%loads wind stress in y-direction
9  [a b c] = size(NIV.nivvel);%saves dimensions of niuvel matrix
       for organizing the data
10 n=1;%parameter for defining time step if not all data series
       are wanted
11 %Following switches are for desired plots and/or calculations.
        '0' means
12 %turned off, '1' means turned on.
13 energy_switch=1;%if energy decay times should be calculated
14 map_switch=1;%for scatter plot on world map of events
15 period_switch=1;%for scatter plot of period relations
16 plot_switch1=1;%for plots of region 1
17 plot_switch2=1;%for plots of region 2
18 plot_switch3=1;%for plots in region 3
19 storm_switch=1;%plot of storm evolution
20 zonal_switch=1;%plots of zonal wind stress in tropics
21
22 A=zeros(b,c,a);%creates matrix for organized data of v-
       velocities
23 B=A;%initializing for wind stress v-direction
24 C=A;%for u-direction
25 D=A;%ocean u-direction velocities
26 k=1;%counter for figures
27 %the following loop organizes data in bxcxa matrix
28 % b denotes latitude, c longitude and a are time steps
29 for j=1:n:a
30     for i=1:c
31         A(:,i,j)=NIV.nivvel(j,:,i);%ocean respons y-direction
32         B(:,i,j)=TAUY.ntauy(j,:,i);%wind stress y-direction
33         C(:,i,j)=TAUX.ntaux(j,:,i);%wind stress x-direction
34         D(:,i,j)=NIU.niuvel(j,:,i);%ocean response x-direction
35     end
```

```matlab
36 end
37
38 %% Find maximums of regions
39 %This finds maximum values of the entire ocean, split in three
      regions.
40 %The function outputs are maximum velocity/stress in the
      region and the
41 %coordinates of the maximum for each time step
42 region1=reg_maker(A,a,20,45,1,1);%these find maximum ocean
      responses
43 region2=reg_maker(A,a,100,115,75,140);
44 region3=reg_maker(A,a,125,160,1,1);
45
46 wind_reg1=reg_maker(B,a,20,45,1,1);%these find maximum wind
      stress
47 wind_reg2=reg_maker(B,a,100,115,75,140);
48 wind_reg3=reg_maker(B,a,125,160,1,1);
49
50 %Next lines orders the velocities in strength in 2 different
      ways. First 2
51 %lines use all data, line 3−6 sorts away peaks which should
      rule out cases
52 %where the same storm appears more than one time.
53 order1=ord_maker(region1,a,100);
54 order2=ord_maker(region2,a,100);
55 order3=ord_maker(region3,a,100);
56
57 %The next routine for the wind maxima
58 w_order1=ord_maker(wind_reg1,a,100);
59 w_order2=ord_maker(wind_reg2,a,150);
60 w_order3=ord_maker(wind_reg3,a,150);
61
62 %sc_x and sc_y are used for scatter plots of the storms. sc_x
      gives
63 %longitude coordinates and sc_y gives latitude
64 sc_x1=zeros(1,15);%digit 1 gives strong ocean response events
65 sc_y1=sc_x1;
66 sc_x2=sc_x1;%digit 2 gives strong storm events
67 sc_y2=sc_x1;
68 for i=1:5;
69     sc_x1((i−1)*3+1)=order1(3,i);
70     sc_x1((i−1)*3+2)=order2(3,i);
71     sc_x1((i−1)*3+3)=order3(3,i);
```

```matlab
72        sc_y1((i-1)*3+1)=order1(2,i);
73        sc_y1((i-1)*3+2)=order2(2,i);
74        sc_y1((i-1)*3+3)=order3(2,i);
75        sc_x2((i-1)*3+1)=w_order1(3,i);
76        sc_x2((i-1)*3+2)=w_order2(3,i);
77        sc_x2((i-1)*3+3)=w_order3(3,i);
78        sc_y2((i-1)*3+1)=w_order1(2,i);
79        sc_y2((i-1)*3+2)=w_order2(2,i);
80        sc_y2((i-1)*3+3)=w_order3(2,i);
81    end
82    %% colormaps
83    %the following switch gives a world scatter plot of events.
          First three
84    %lines create the world map to be black, making room for
          events.
85    if map_switch==1;
86        continents=A(:,:,1)+A(:,:,2)+A(:,:,3)+A(:,:,999)+A
              (:,:,1000);
87        continents(continents==0)=nan;
88        continents=continents-continents;
89        figure(k)
90        set(gca,'color',[0 0 0]);
91        hold on
92        colormap gray
93        imagesc(continents)%plots continents
94        axis([1 160 1 180])
95        set(gca,'fontsize',20)
96        xlabel('longitude','fontsize',24)
97        ylabel('latitude','fontsize',24)
98        scatter(sc_x1,sc_y1,'fill','blue')%ocean events
99        scatter(sc_x2,sc_y2,'fill','red')%storm events
100       hold off
101       k=k+1;
102   end
103   %% Wind & Ocean response plots
104   %Next part identifies the time evolution before, during and
          after the
105   %storms in both windstress and ocean response.
106   o_res1=time_ev(A,order1); %one digit refers to the biggest
          ocean responses
107   w_stress1=time_ev(B,order1);
108   o_res2=time_ev(A,order2);
109   w_stress2=time_ev(B,order2);
```

```
110  o_res3=time_ev(A,order3);
111  w_stress3=time_ev(B,order3);
112
113  o_res11=time_ev(A,w_order1); %two digits refer to the biggest
         wind stress
114  w_stress11=time_ev(B,w_order1);
115  o_res22=time_ev(A,w_order2);
116  w_stress22=time_ev(B,w_order2);
117  o_res33=time_ev(A,w_order3);
118  w_stress33=time_ev(B,w_order3);
119
120  %% Period estimator
121  %Following matrices gives the estimated periods of ocean and
         wind. Number
122  %labels are the same as for the orders.
123  P1=p_find(o_res1,w_stress1);
124  P2=p_find(o_res2,w_stress2);
125  P3=p_find(o_res3,w_stress3);
126  P11=p_find(w_stress11,o_res11);
127  P22=p_find(w_stress22,o_res22);
128  P33=p_find(w_stress33,o_res33);
129  if period_switch==1;%For a scatterplot of wind vs ocean
         periods.
130      figure(k)
131      scatter(P1(4,:),P1(2,:),'x')
132      hold on
133      scatter(P2(4,:),P2(2,:),'x')
134      scatter(P3(4,:),P3(2,:),'x')
135      plot(1:180,1:180,'Color','black')
136      set(gca,'fontsize',20)
137      xlabel('Wind period','fontsize',24)
138      ylabel('Ocean period','fontsize',24)
139      hold off
140  end
141
142  %% Energy decay times
143  %This switch calculates energy decay times and gives energy
         evolution
144  %matrices in case these are wanted for further analysis.
145  if energy_switch==1;
146      [E1,d_t1]=e_decay(A,D,order1);
147      [E2,d_t2]=e_decay(A,D,order2);
148      [E3,d_t3]=e_decay(A,D,order3);
```

```matlab
149         [E4,d_t4]=e_decay(A,D,w_order1);
150         [E5,d_t5]=e_decay(A,D,w_order2);
151         [E6,d_t6]=e_decay(A,D,w_order3);
152     end
153     %%
154     %plotting time evolution of ocean and wind for the 5 events of
            region 1
155     if plot_switch1==1;
156     for j=1:5
157         k=k+1;
158         X1=order1(4*j)*2-150*2:2:order1(4*j)*2+149*2;
159         if X1(1)<1
160             X1=2:2:600;
161         end
162         figure(k)
163         hold on
164         [AX,H1,H2]=plotyy(X1,o_res1(j,:),X1,w_stress1(j,:));
165         title(['Event 1.1.',num2str(j)],'fontsize',28,'fontweight'
                ,'b')
166         xlabel('Time [hr]','fontsize',24,'Color','black')
167         set(get(AX(1),'Ylabel'),'String','Ocean velocity [cm s
                ^{-1}]','fontsize',24,'Color','black')
168         set(get(AX(2),'Ylabel'),'String','Wind stress [10 dyne cm
                ^{-2}]','fontsize',24,'Color','black')
169         set(AX(1),'xlim',[min(X1) max(X1)],'ylim',[-65 65],'ytick'
                ,-60:20:60,'fontsize',20,'ycolor','black')
170         set(AX(2),'xlim',[min(X1) max(X1)],'ylim',[-260 260],'
                ytick',-250:100:250,'fontsize',20,'ycolor','black')
171         set(H1,'Color','b')
172         set(H2,'Color','r')
173         uicontrol('Style','text','String',['Latitude: ',num2str(
                order1(2+4*(j-1))),', Longitude: ',num2str(order1(3+4*(j
                -1)))],'fontsize',22,'Position',[170 85 410 38])
174
175
176         hold off
177
178         k=k+1;
179         X1=w_order1(4*j)*2-150*2:2:w_order1(4*j)*2+149*2;
180         if X1(1)<1
181             X1=2:2:600;
182         end
183         figure(k)
```

```matlab
184         hold on
185         [AX,H1,H2]=plotyy(X1,o_res11(j,:),X1,w_stress11(j,:));
186         title(['Event 2.1.',num2str(j)],'fontsize',28,'fontweight'
                ,'b')
187         xlabel('Time [hr]','fontsize',24,'Color','black')
188         set(get(AX(1),'Ylabel'),'String','Ocean velocity [cm s
                ^{-1}]','fontsize',24,'Color','black')
189         set(get(AX(2),'Ylabel'),'String','Wind stress [10 dyne cm
                ^{-2}]','fontsize',24,'Color','black')
190         set(AX(1),'xlim',[min(X1) max(X1)],'ylim',[-65 65],'ytick'
                ,-60:20:60,'fontsize',20,'ycolor','black')
191         set(AX(2),'xlim',[min(X1) max(X1)],'ylim',[-260 260],'
                ytick',-250:100:250,'fontsize',20,'ycolor','black')
192         set(H1,'Color','b')
193         set(H2,'Color','r')
194         uicontrol('Style','text','String',['Latitude: ',num2str(
                w_order1(2+4*(j-1))),', Longitude: ',num2str(w_order1
                (3+4*(j-1)))],'fontsize',22,'Position',[170 85 410 38])
195
196         hold off
197     end
198     end
199     %% Region 2 plots
200     %plotting for region 2
201     if plot_switch2==1;
202     for j=1:5
203         k=k+1;
204         X1=order2(4*j)*2-150*2:2:order2(4*j)*2+149*2;
205         if X1(1)<1
206             X1=2:2:600;
207         end
208         figure(k)
209         hold on
210         [AX,H1,H2]=plotyy(X1,o_res2(j,:),X1,w_stress2(j,:));
211         title(['Event 1.2.',num2str(j)],'fontsize',28,'fontweight'
                ,'b')
212         xlabel('Time [hr]','fontsize',24,'Color','black')
213         set(get(AX(1),'Ylabel'),'String','Ocean velocity [cm s
                ^{-1}]','fontsize',24,'Color','black')
214         set(get(AX(2),'Ylabel'),'String','Wind stress [10 dyne cm
                ^{-2}]','fontsize',24,'Color','black')
215         set(AX(1),'xlim',[min(X1) max(X1)],'ylim',[-65 65],'ytick'
                ,-60:20:60,'fontsize',20,'ycolor','black')
```

```matlab
216         set(AX(2),'xlim',[min(X1) max(X1)],'ylim',[-260 260],'
                ytick',-250:100:250,'fontsize',20,'ycolor','black')
217         set(H1,'Color','b')
218         set(H2,'Color','r')
219         uicontrol('Style','text','String',['Latitude: ',num2str(
                order2(2+4*(j-1))),', Longitude: ',num2str(order2(3+4*(j
                -1)))],'fontsize',22,'Position',[170 85 410 38])
220
221
222         hold off
223
224         k=k+1;
225         X1=w_order2(4*j)*2-150*2:2:w_order2(4*j)*2+149*2;
226         if X1(1)<2
227             X1=2:2:600;
228         end
229         figure(k)
230         hold on
231         [AX,H1,H2]=plotyy(X1,o_res22(j,:),X1,w_stress22(j,:));
232         title(['Event 2.2. ',num2str(j)],'fontsize',28,'fontweight'
                ,'b')
233         xlabel('Time [hr]','fontsize',24,'Color','black')
234         set(get(AX(1),'Ylabel'),'String','Ocean velocity [cm s
                ^{-1}]','fontsize',24,'Color','black')
235         set(get(AX(2),'Ylabel'),'String','Wind stress [10 dyne cm
                ^{-2}]','fontsize',24,'Color','black')
236         set(AX(1),'xlim',[min(X1) max(X1)],'ylim',[-65 65],'ytick'
                ,-60:20:60,'fontsize',20,'ycolor','black')
237         set(AX(2),'xlim',[min(X1) max(X1)],'ylim',[-260 260],'
                ytick',-250:100:250,'fontsize',20,'ycolor','black')
238         set(H1,'Color','b')
239         set(H2,'Color','r')
240         uicontrol('Style','text','String',['Latitude: ',num2str(
                w_order2(2+4*(j-1))),', Longitude: ',num2str(w_order2
                (3+4*(j-1)))],'fontsize',22,'Position',[170 85 410 38])
241
242         hold off
243     end
244 end
245 %% Region 3 plots
246 %plotting for region 3
247 if plot_switch3==1;
248 for j=1:5
```

```matlab
249        k=k+1;
250        X1=order3(4*j)*2−150*2:2:order3(4*j)*2+149*2;
251        if X1(1)<1
252            X1=2:2:600;
253        end
254        figure(k)
255        hold on
256        [AX,H1,H2]=plotyy(X1,o_res3(j,:),X1,w_stress3(j,:));
257        title(['Event 1.3.',num2str(j)],'fontsize',28,'fontweight'
               ,'b')
258        xlabel('Time [hr]','fontsize',24,'Color','black')
259        set(get(AX(1),'Ylabel'),'String','Ocean velocity [cm s
               ^{−1}]','fontsize',24,'Color','black')
260        set(get(AX(2),'Ylabel'),'String','Wind stress [10 dyne cm
               ^{−2}]','fontsize',24,'Color','black')
261        set(AX(1),'xlim',[min(X1) max(X1)],'ylim',[−65 65],'ytick'
               ,−60:20:60,'fontsize',20,'ycolor','black')
262        set(AX(2),'xlim',[min(X1) max(X1)],'ylim',[−260 260],'
               ytick',−250:100:250,'fontsize',20,'ycolor','black')
263        set(H1,'Color','b')
264        set(H2,'Color','r')
265        uicontrol('Style','text','String',['Latitude: ',num2str(
               order3(2+4*(j−1))),', Longitude: ',num2str(order3(3+4*(j
               −1)))],'fontsize',22,'Position',[170 85 410 38])
266
267        hold off
268
269        k=k+1;
270        X1=w_order3(4*j)*2−150*2:2:w_order3(4*j)*2+149*2;
271        if X1(1)<1
272            X1=2:2:600;
273        end
274        figure(k)
275        hold on
276        [AX,H1,H2]=plotyy(X1,o_res33(j,:),X1,w_stress33(j,:));
277        title(['Event 2.3.',num2str(j)],'fontsize',28,'fontweight'
               ,'b')
278        xlabel('Time [hr]','fontsize',24,'Color','black')
279        set(get(AX(1),'Ylabel'),'String','Ocean velocity [cm s
               ^{−1}]','fontsize',24,'Color','black')
280        set(get(AX(2),'Ylabel'),'String','Wind stress [10 dyne cm
               ^{−2}]','fontsize',24,'Color','black')
```

```matlab
281        set(AX(1),'xlim',[min(X1) max(X1)],'ylim',[-65 65],'ytick'
               ,-60:20:60,'fontsize',20,'ycolor','black')
282        set(AX(2),'xlim',[min(X1) max(X1)],'ylim',[-260 260],'
               ytick',-250:100:250,'fontsize',20,'ycolor','black')
283        set(H1,'Color','b')
284        set(H2,'Color','r')
285        uicontrol('Style','text','String',['Latitude: ',num2str(
               w_order3(2+4*(j-1)),', Longitude: ',num2str(w_order3
               (3+4*(j-1)))],'fontsize',22,'Position',[170 85 410 38])
286
287     hold off
288  end
289  end
290  %% Plotting ocean response and wind stress vector
291  %this section plots ocean response (absolute value) contour vs
         wind stress
292  %vectors.
293  if storm_switch==1
294  for i=1:11
295  k=k+1;
296  figure(k)
297  hold on
298  %contour(80:129,30:55,A(30:55,80:129,order1(20)+(i-6)*2),8)
299  quiver(60:109,15:40,C(15:40,60:109,order1(20)-6+i),B
         (15:40,60:109,w_order1(12)+(i-6)))
300  quiver(60:109,15:40,D(15:40,60:109,order1(20)-6+i),A
         (15:40,60:109,w_order1(12)+(i-6)))
301  title(['storm in the Northern Pacific at ',num2str(2*w_order1
         (12)+(i-6)*2),' hour'],'fontsize',13)
302  xlabel('longitude')
303  ylabel('latitude')
304  caxis([-40 40])
305  contourcbar
306  hold off
307
308  end
309  %% zonal wind
310  if zonal_plot==1;
311      z_stress2=time_ev(C,order2);
312      for j=1:5
313      k=k+1;
314      X1=order2(4*j)*2-150*2:2:order2(4*j)*2+149*2;
315          if X1(1)<1
```

```
316            X1=2:2:600;
317        end
318          figure(k)
319          hold on
320          [AX,H1,H2]=plotyy(X1,o_res2(j,:),X1,z_stress2(j,:));
321          title(['Event 1.2.',num2str(j)],'fontsize',28,'fontweight'
                 ,'b')
322          xlabel('Time [hr]','fontsize',24,'Color','black')
323          set(get(AX(1),'Ylabel'),'String','Ocean velocity [cm s
                 ^{-1}]','fontsize',24,'Color','black')
324          set(get(AX(2),'Ylabel'),'String','Wind stress [10 dyne cm
                 ^{-2}]','fontsize',24,'Color','black')
325          set(AX(1),'xlim',[min(X1) max(X1)],'ylim',[-65 65],'ytick'
                 ,-60:20:60,'fontsize',20,'ycolor','black')
326          set(AX(2),'xlim',[min(X1) max(X1)],'ylim',[-260 260],'
                 ytick',-250:100:250,'fontsize',20,'ycolor','black')
327          set(H1,'Color','b')
328          set(H2,'Color','r')
329          uicontrol('Style','text','String',['Latitude: ',num2str(
                 order2(2+4*(j-1))),', Longitude: ',num2str(order2(3+4*(j
                 -1)))],'fontsize',22,'Position',[170 85 410 38])
330
331
332        hold off
333        end
334   end
335
336   %% functions
337   function reg=reg_maker(A,a,n,m,n2,m2);
338   %this function finds all maximum values of a specified region.
             Output is a matrix with maximum value and coordinate for
           each time step
339   %n2 and m2 gives a difference in longitude. These should be
           set ==1 if the
340   %entiere band around the earth is wished. The primary reason
             for their use
341   %is in the tropics, where storms are found too close to land.
342   reg=zeros(4,a);
343   for i=1:a
344        if n2~=1;
345            [Q,I]=max(A(n:m,n2:m2,i));%defines all maximums along
                     region and indicies where they are on longitude
```

```
346        [E,F]=max(max(A(n:m,n2:m2,i)));%defines maximum value
                   and its latitude
347      else
348      [Q,I]=max(A(n:m,:,i));%defines all maximums along region
             and indicies where they are on longitude
349      [E,F]=max(max(A(n:m,:,i)));%defines maximum value and its
             latitude
350      end
351      reg(1,i)=E;%stores maximum value
352      reg(2,i)=I(F)+n-1;%stores latitude
353      reg(3,i)=F+n2-1;%stores longitude
354      reg(4,i)=i;%stores time
355   end
356   end
357
358   function ord=ord_maker(region1,a,n)%Function finds storm peaks
          with time separation n. Input matrix is then ordered for
        these maxima. parameter a is the number of time steps
359
360   [peaks1,locs1]=findpeaks(region1(1,1:a-150),'minpeakdistance',
         n);%Clears all data except peaks. Peak distance is
         arbitrarily chosen. DISCUSS THIS WITH MARKUS
361   region11=region1(:,locs1);%Clears all data from matrix except
          the storm peaks and their coordinates
362   [d1,d2]=sort(peaks1,'descend');%Sorts storm peaks
363   ord=region11(:,d2);%Orders data including coordinates and time
364   end
365
366   function locs=p_find(A,B)
367   %This function is designed to calculate the periods (in hours)
           of the storm or ocean
368   %oscillations. The function finds the difference between the
          storm maximum
369   %and the minimum and times it with the time step (2 h) and
          doubles as it is
370   %only half a period. Note that for region 3 the calculations
          collapse for
371   %the period because the event is created in norhtward to
          southward change,
372   %unlike the other regions.
373   [a b]=size(A);%initiating for different sized matrices
374   locs=zeros(8,a);
375   E=-fliplr(A);%for calculation of period before max
```

```matlab
376  F=-fliplr(B);
377  for i=1:a;
378      [e1,e]=min(E(i,:));%Starting point to calculate periods
379      [g1,g]=min(F(i,e-4:e+4));%in case the other function has
              max at another time than "e".
380
381      e=e+1;
382      [d1,l]=findpeaks(E(i,e:end),'npeaks',1);%gives peak from
              minimum to maximum(matrix has been mirrored)
383      [d1,l2]=findpeaks(-E(i,e+l:end),'npeaks',1);%gives ocean
              period from peak before to min (for north mid-lats)
384      [d1,h]=findpeaks(F(i,e-(5-g):end),'npeaks',1);%Gives wind
              period from min to peak
385      [d1,h2]=findpeaks(-F(i,e-(5-g)+h:end),'npeaks',1);%gives
              period before (for north. mid-lats)
386
387
388
389  locs(1,i)=l;%period of ocean from min to peak
390  locs(2,i)=h;%Period calculated from minimum to peak
391  locs(3,i)=l2;%The ocean period of peak before to minimum (used
          for reg 3)
392  locs(4,i)=h2;%Wind period of peak before, to minimum. Used for
          reg 3
393  end
394  locs=2.*2.*locs;%calculates resulting period of oscillation in
          hours
395  end
396
397  function [E,d_t] = e_decay(A,D,order)%this function calculates
          the energy decay time at which E = 1/3*E_initial from a
      fitted curve
398  m=40;%how many data points should be included
399  d_t=zeros(1,5);
400  E=zeros(m,5);
401  x=(0:m-1)';
402  for i=1:5;
403      for j=1:m;
404          E(j,i)=A(order(2,i),order(3,i),order(4,i)-1+j)^2 + D(
                  order(2,i),order(3,i),order(4,i)-1+j)^2;%time
                  evolution of energy
405      end
406      e_fit=fit(x,E(:,i),'exp1');%gets exponential fit
```

```matlab
407        vals=coeffvalues(e_fit);%gets coefficients
408        d_t(i)=(vals(2)*-2)^-1;%calculates characteristic time.
409 end
```