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Response of the UK Met Office wave model when forced with tropical cyclone winds.

by

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Abstract

This paper describes a model which has been developed to calculate the surface wind field within a tropical cyclone. It also presents the results from two sensitivity studies which investigated the impact of spatial and direction resolution.

The results indicate that the spatial resolution of the tropical cyclone wind field has greatest impact in the centre of the storm. They also indicate that the UK Met Office wave model should be run with at least 24 direction components for operational use and with at least 32 direction components for consultancy hindcast studies.

Response of the UK Met Office wave model when forced with tropical cyclone winds

1. Introduction

The aim of this report is two fold. Firstly, it describes a model which has been developed to calculate the surface wind field within a tropical cyclone. This wind field can then be used in the UK Met Office wave model to simulate the effect of a tropical cyclone on an area of sea. Secondly, it presents the results from two hindcast sensitivity studies. These studies were designed to analyse the impact of spatial and direction resolution.

2. The tropical cyclone wind model

Tropical cyclones have small spatial dimensions in comparison with mid-latitude weather systems. Therefore, to model the effect of a tropical cyclone on an area of sea to a reasonable degree of accuracy, the wave model must be run with a high spatial resolution over the area of interest. Ideally, it must also be driven with a high resolution surface wind field. However, the only wind fields currently available for use in the wave model are those produced by the Met Office atmospheric NWP global and limited area models. The resolution of the winds produced by these models, shown in Table 1, is not fine enough to represent tropical cyclone winds to a reasonable degree of accuracy. In addition, the NWP limited area model does not cover regions where tropical cyclones occur.

	Degrees latitude	Degrees longitude	km
Global	0.8333	1.25	90
Limited Area	0.4425	0.4425	50

Table 1. Resolution of wind fields produced from the Met Office atmospheric NWP global and limited area models.

To overcome this problem, a model has been developed which will calculate the surface wind field within a tropical cyclone area to a required resolution. This wind field can then be merged with the background global wind field for wave model runs. For input, the model requires the latitude and longitude of the centre of the storm, the atmospheric pressure at the centre of the storm, the maximum wind speed, the radius of maximum winds (i.e. the distance from the centre of the storm at which the maximum wind speed occurs), and the ambient atmospheric pressure far from the storm. It also requires details of the grid resolution.

The surface wind model adopts the algorithm described by Holland (1980) to calculate the wind speed. This algorithm assumes that the wind field within a tropical cyclone can be represented in a relatively simple parametric form. The effects of friction are assumed to be negligible, so the surface wind speed is equal to the gradient wind speed, V_G. The gradient wind speed at a distance r from the centre of the storm is calculated using the equation

$$V_G = [\, AB(p_N - p_C) \exp(-A/r^B) \,/\, \rho r^B + r^2 f^2/4]^{1/2} \qquad (1)$$

where f is the Coriolis parameter, ρ is the air density (assumed constant at 1.15 kg m^{-3}), p_C is the pressure at the centre of the tropical cyclone, and p_N is the ambient pressure far from the storm. The scaling parameter A determines the location of the pressure or wind profile relative to the origin and B defines the shape of the profile. The model calculates these parameters from the maximum wind speed, V_M, and the radius of maximum winds, R_W, using the expressions

$$B = (\rho e V_M)/(p_N - p_C) \qquad (2)$$
$$A = R_W{}^B \qquad (3)$$

The model calculates the initial wind direction from the geostrophic wind direction. Following Shea and Gray (1973), the wind direction is then turned by a constant factor of 25°, so that the surface wind spirals in towards the centre of the storm.

3. The sensitivity hindcast studies

3.1 The impact of spatial resolution

The first sensitivity test was designed to analyse the impact of spatial resolution on the performance of the wind model. The surface wind model was run with data taken from Holland (1980). This data corresponds to Hurricane Joan which affected the coast of northwest Australia in December 1975. The wind model was run over the area extending between 5°S to 25°S, 110°E to 130°E, from 00Z 3rd December 1975, until 00Z 8th December 1975. Figure 1a illustrates the track of Hurricane Joan over this period. Initially, the wind model was run at the standard global wave model grid resolution, 0.833° latitude by 1.25° longitude. It was then run again at the increased resolution of 0.25° latitude by 0.25° longitude. Figure 1b illustrates the wind field calculated by the wind model at 0.25° latitude by 0.25° longitude resolution between 00Z 3rd December 1975 and 00Z 7th December 1975.

Two wave model runs were then performed over the region extending between 5°S to 25°S, 110°E to 130°E. In the first, the wave model was run at global grid resolution, with the global grid resolution wind field produced by the tropical cyclone wind model. In the second, the wave model was run at the resolution of 0.25° latitude by 0.25° longitude with the 0.25° latitude by 0.25° longitude resolution wind field produced from the tropical cyclone wind model. Both wave model simulations were started from rest at midnight on the 3rd December 1975, and were allowed to spin up for 3 days using the wind fields produced by the tropical cyclone wind model. The wave model ran with its standard frequency resolution and with 16 direction components in both simulations.

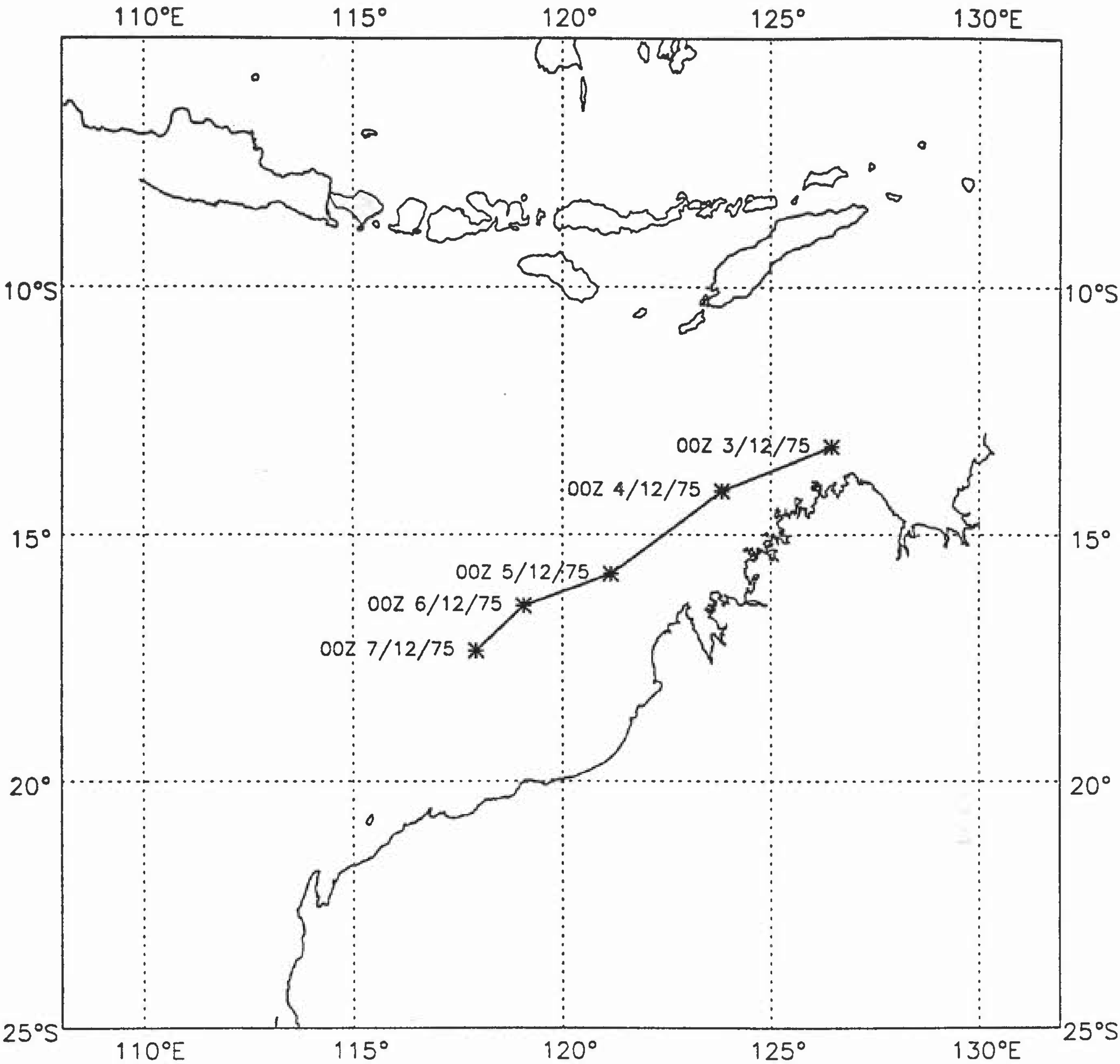

Figure 1a. Track of Hurricane Joan.

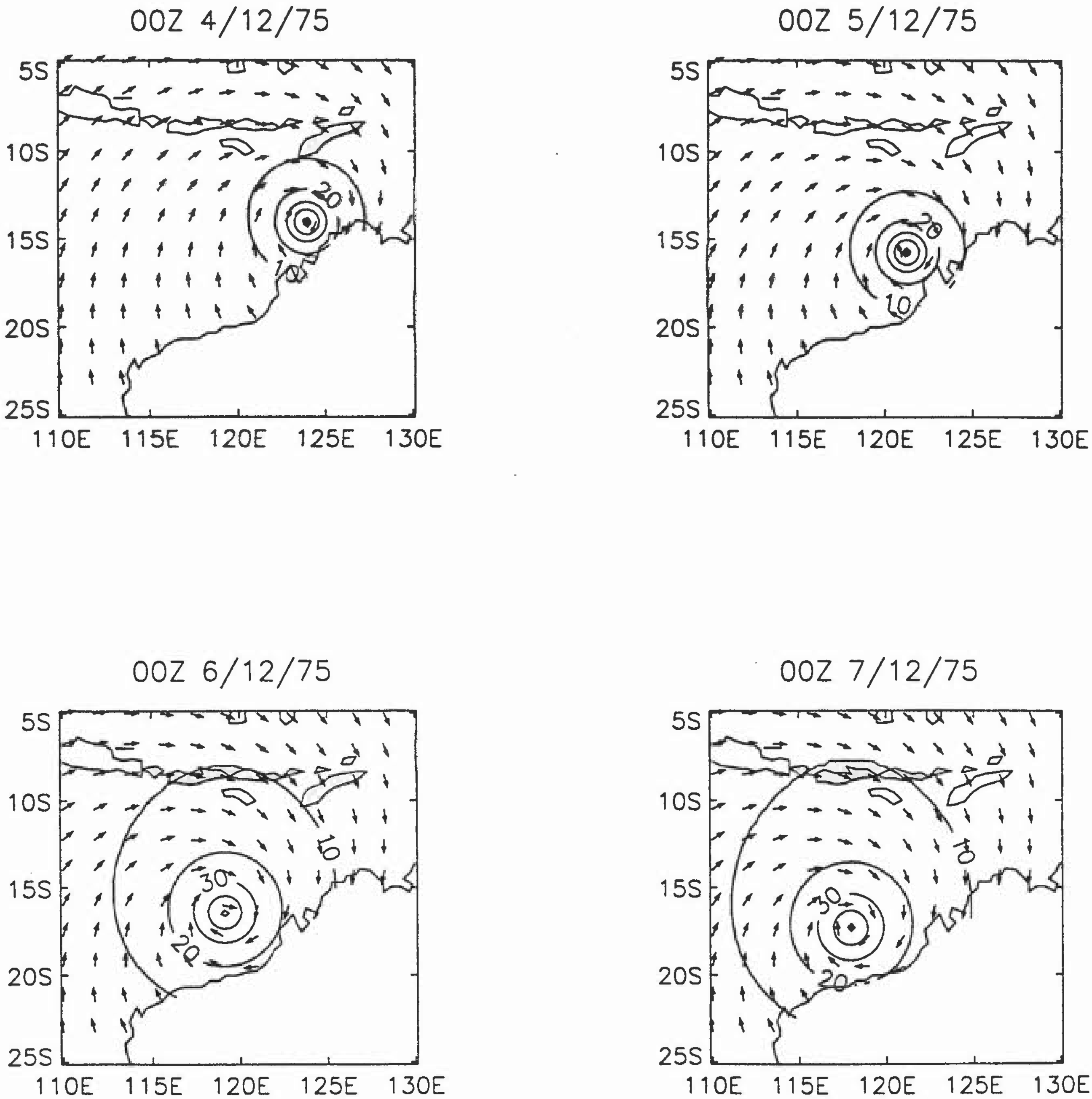

Figure 1b. Wind field *timeseries* for Hurricane Joan, calculated at a spatial resolution of 0.25° latitude by 0.25° longitude. The contours indicate the wind speed, and the arrows the wind direction. The lowest contour value is 10 ms^{-1}, and the contour interval is 10 ms^{-1}.

3.1.1 Wind speed and direction

Figure 2 shows contour plots of the surface wind speed calculated by the wind model when run at each resolution for two different times. The arrows on each plot represent the direction of the surface wind. Note that for clarity, every seventh arrow has been plotted for the high resolution case, and every other arrow has been plotted for the global grid resolution case. The resolution of the wind model appears to have little impact on the calculated wind speed and direction, particularly at a fair distance away from the centre of the storm. Close to the centre of the storm, the effect of lower resolution becomes more noticeable. The wind speed contours close to the centre of the storm lose their smooth circular shape at global resolution. The central calm region, called the eye, which is picked up at high resolution, is lost at global resolution. Nevertheless, the region of maximum winds is well represented at global grid resolution.

Another notable feature of these plots is the north-south asymmetry in the wind speed. This arises because the wind speed calculation is dependant upon the Coriolis parameter, f. Apart from this, the wind speed field produced by the wind model is axisymmetric. In reality, the surface wind field within a tropical cyclone is asymmetric, due to the movement of the storm itself. Further work is required to determine whether the wind model should be modified to take into account the movement of the tropical cyclone.

3.1.2 Wind generated waves (windsea)

Figure 3 shows contour plots of the windsea height at each of the times illustrated in Figure 2. The results from both wave model resolution runs are shown. Superimposed on each contour plot are arrows which indicate the principal direction of propagation of the windsea. As in Figure 2, every seventh arrow has been drawn for the high resolution case and every other arrow has been drawn for the global resolution case. In general, the resolution of both the wind and the wave model appear to have little effect on the height and direction of the windsea. However, the fine detail in the height contours close to the centre of the storm picked up at high resolution is lost at the lower global resolution. The effect of spatial resolution and the resulting difference in coastal representation is also apparent over Indonesia. In this region, the height of the wind generated waves is about 1 metre larger when the wave model is run at the higher resolution than when it is run at the global resolution.

Over most of the region of study the direction of windsea propagation follows the wind direction fairly closely. However, within the storm itself, there is a difference of as much as 80° between the wind direction and the direction of propagation of the wind generated waves. This occurs when the wave model is run both at global and high resolution. Figure 4 shows a contour plot of the wave energy spectrum at a gridpoint where this happens. The wave energy spectrum is plotted as a function of frequency and direction in polar representation. The frequency increases from zero at the centre of the plot to 0.4 Hz at the edge of the plot. The direction, which is taken from the centre of the plot outwards, gives the direction of propagation of the wave energy. The contours are of log(energy), with contour interval 1, and lowest contour value -1. The arrow indicates the direction of the wind, and the dashed line indicates the separation between windsea and swell. The largest amount of wave energy lies close to the boundary between the windsea and swell. Since the wind direction is not changing rapidly at this point, the difference between the wind direction and the windsea

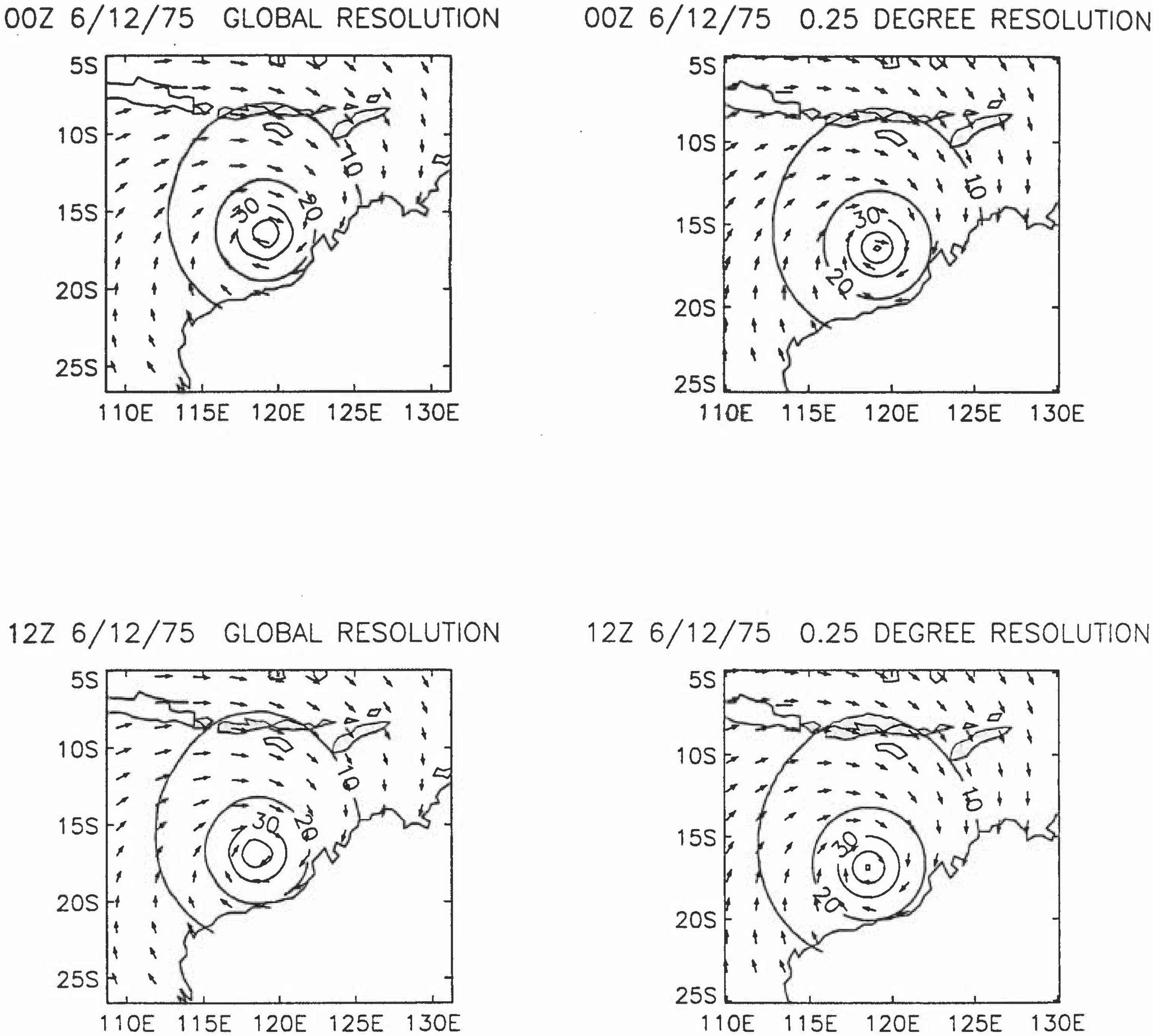

Figure 2. Wind speed and direction (Hurricane Joan). The contours indicate the wind speed, and the arrows the wind direction. The lowest contour value is 10 ms^{-1}, and the contour interval is 10 ms^{-1}.

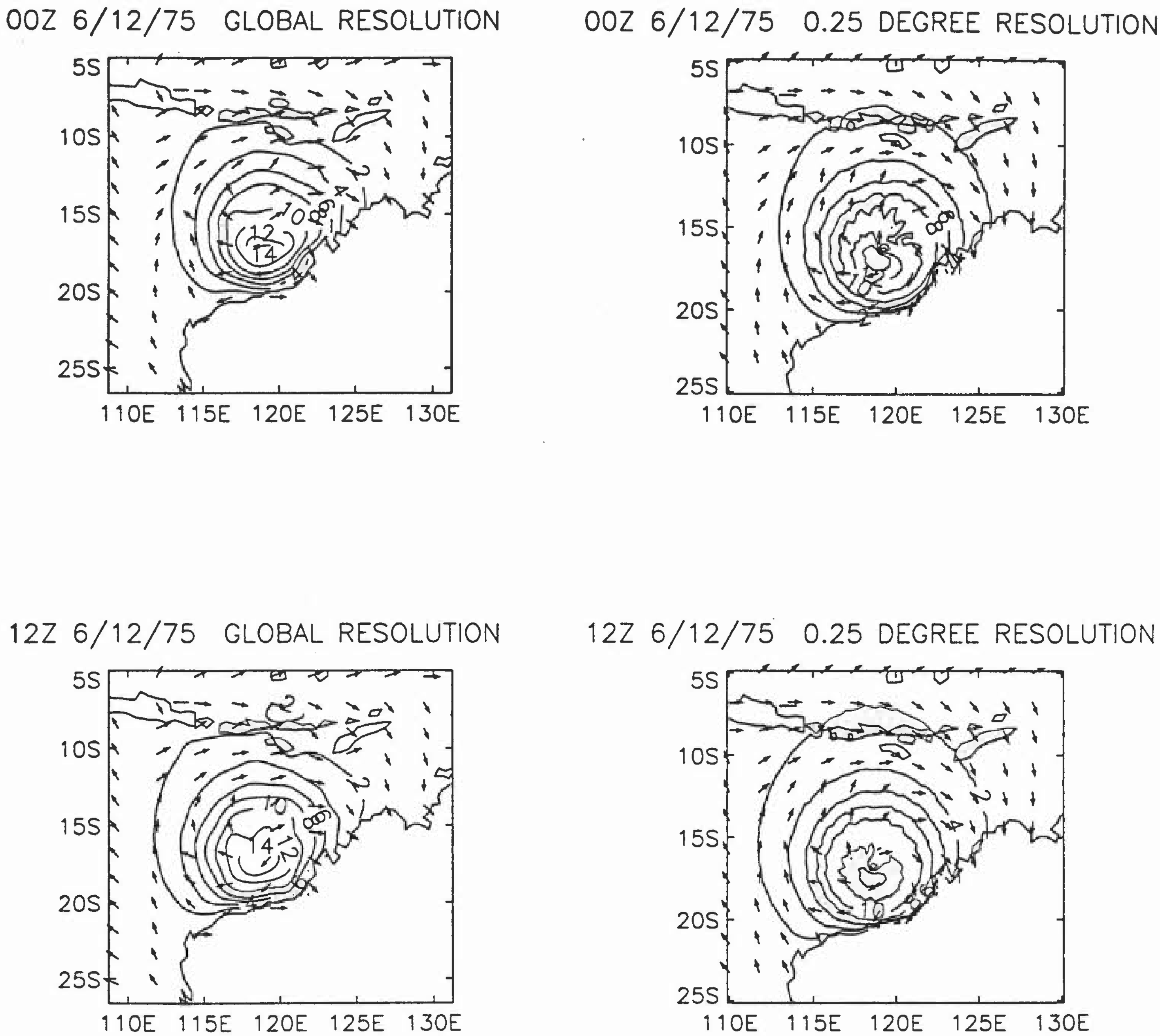

Figure 3. Height and direction of propagation of wind generated waves (Hurricane Joan). The contours indicate the wave height, and the arrows the direction of propagation. The lowest contour value is 2 m, and the contour interval is 2 m. The arrow length is proportional to the wave height.

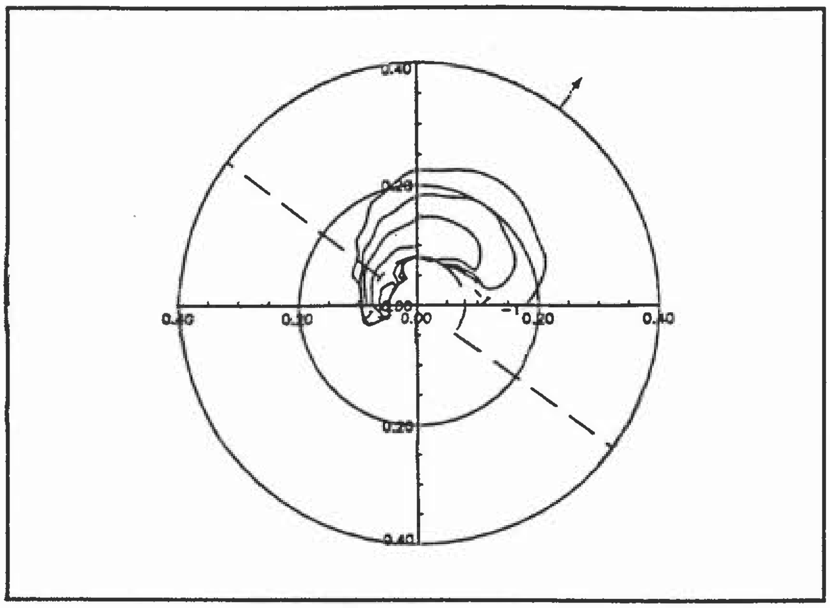

Figure 4. Wave energy spectrum at 15.37°S, 114.38°E at 00Z 6/12/75. The arrow indicates the wind direction and the dashed line the model separation between windsea and swell.

direction results from the separation of windsea and swell in the wave model. In the wave model, windsea is defined as all wave energy lying within 90° of the wind direction with a frequency greater than 0.8 times the peak frequency of the Pierson-Moskowitz spectrum for the wind speed (Pierson and Moskowitz 1964). All the rest of the wave energy is counted as swell. Therefore, if there is any swell energy lying within 90° of the wind direction (which may have been generated elsewhere in the tropical cyclone and advected to this point) and the wind speed then increases, some of this swell may be counted as windsea instead. Since the principal windsea direction is calculated as the mean direction of the waves at the frequency with the most energy, there may then be a marked difference between the wind direction and windsea direction.

The asymmetry in the windsea height at the centre of the tropical cyclone also results from the wave model definition of windsea. This asymmetry arises because the wind direction at a particular point changes as the tropical cyclone passes. Therefore some of the original windsea at the point may become classified as swell after the centre of the storm has passed, which will result in a decrease in diagnosed windsea height.

Figure 5 illustrates the zero-upcrossing period of the windsea for each of the times illustrated in Figure 3, calculated by each wave model run. As with the windsea height, there is very little difference in the windsea period when the wave model is run at the two different resolutions. Some small differences do occur to the north of Indonesia and in locations far from the storm where the winds are very light.

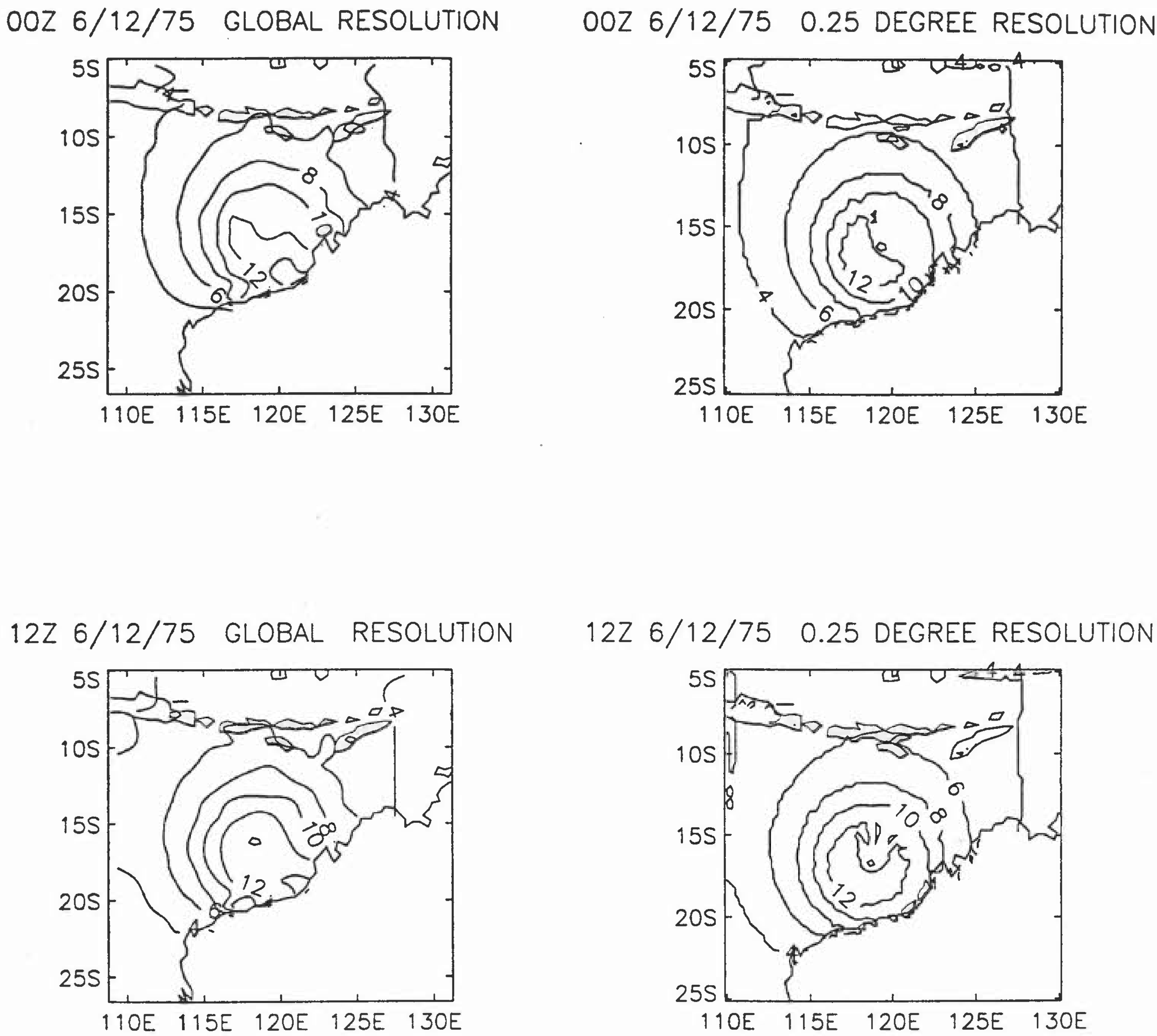

Figure 5. Zero upcrossing period of wind generated waves (Hurricane Joan). The lowest contour value is 4 s, and the contour interval is 2 s.

3.1.3 Swell

Figure 6 shows contour plots of the height of the swell at each of the times illustrated in Figure 2. The results from both wave model resolution runs are shown. The arrows superimposed on each contour plot indicate the direction of propagation of swell. Every seventh arrow has been drawn for the high resolution case and every other arrow has been drawn for the global resolution case. As with the windsea and wind speed, the detail of the swell height contours at the centre of the storm which is picked up at high resolution is lost at global resolution. More importantly, the swell height is 1 metre larger in most areas in the global resolution run than in the high resolution run. The zero-upcrossing period of the swell at each time at each resolution is illustrated in Figure 7. At both times, the period of the swell calculated by the global resolution run is longer in most areas than that calculated by the high resolution run. This is particularly noticeable at 00Z on 6th December, where the difference at some points is as great as 3 seconds. Since swell of longer period travels faster, the swell calculated by the global run will propagate out from the storm faster than in the high resolution case. This could explain the difference in swell height produced by the global resolution run and the high resolution run. The difference may also arise because of the variation in the balance between the source terms for wave growth and advection in the wave model with the grid spacing. It may also be due to the improvement in the representation of the wind speed gradient at higher resolution. Further investigation is needed to identify the exact cause.

There are significant differences in the swell height and direction north of Indonesia. This is a result of the difference in the representation of Indonesia in the global and high resolution grids.

It is apparent from Figure 6 that the height of the swell is also asymmetric about the storm centre, with the highest swell occurring to the northwest and the lowest swell to the southeast. This can be explained by considering the track of Hurricane Joan illustrated in Figure 1a and the timeseries of the surface wind field illustrated in Figure 1b. In the region northwest of the storm centre, the wind direction has changed very little and so the original swell has not been "absorbed" by the windsea. In contrast, to the southeast of the centre of the storm the wind direction has swung round to within 90° of the swell direction. Since the wind speed in this region is so high, all of the original swell has become classified as windsea.

3.2 The impact of direction resolution

The aim of the second sensitivity test was to analyse the impact of direction resolution of the wave model when it was run with winds generated by the surface wind model. In this study, both the wind and the wave model were run over the area extending between 75°N to 55°N, 5°W to 15°E. This region was chosen because the operational wave model has a tendency to underestimate swell in the North Sea which has propagated around the headland of Norway from a storm in the Norwegian Sea. Since tropical cyclones do not occur over this region because the sea temperature is not high enough to support such systems, a hypothetical tropical cyclone was simulated in this study. The track of the hypothetical tropical cyclone is shown in Figure 8. The wind model was driven with the Hurricane Joan values for central

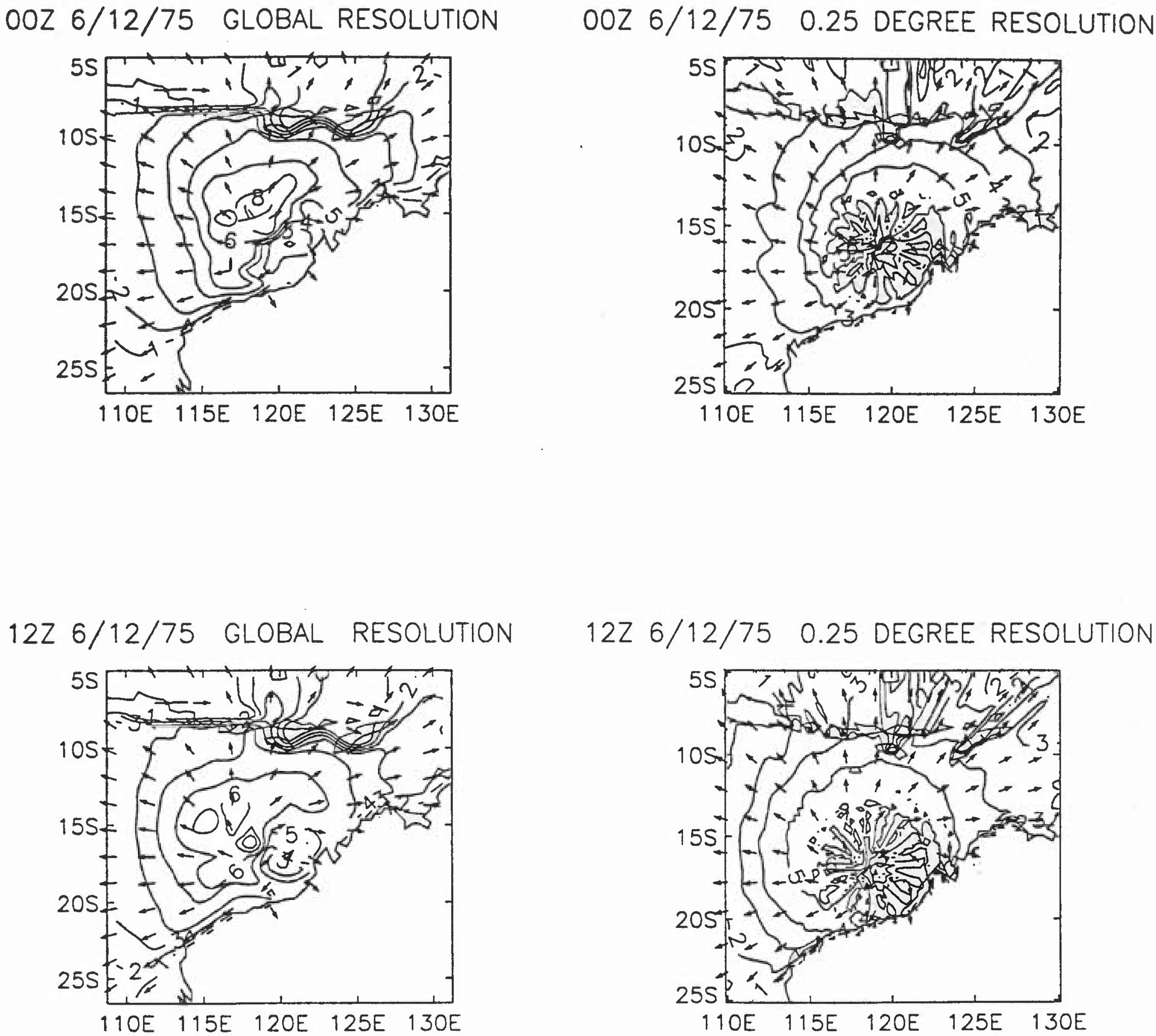

Figure 6. Height and direction of propagation of swell (Hurricane Joan). The contours indicate the swell height, and the arrows the direction of propagation. The lowest contour value is 1 m, and the contour interval is 1 m.

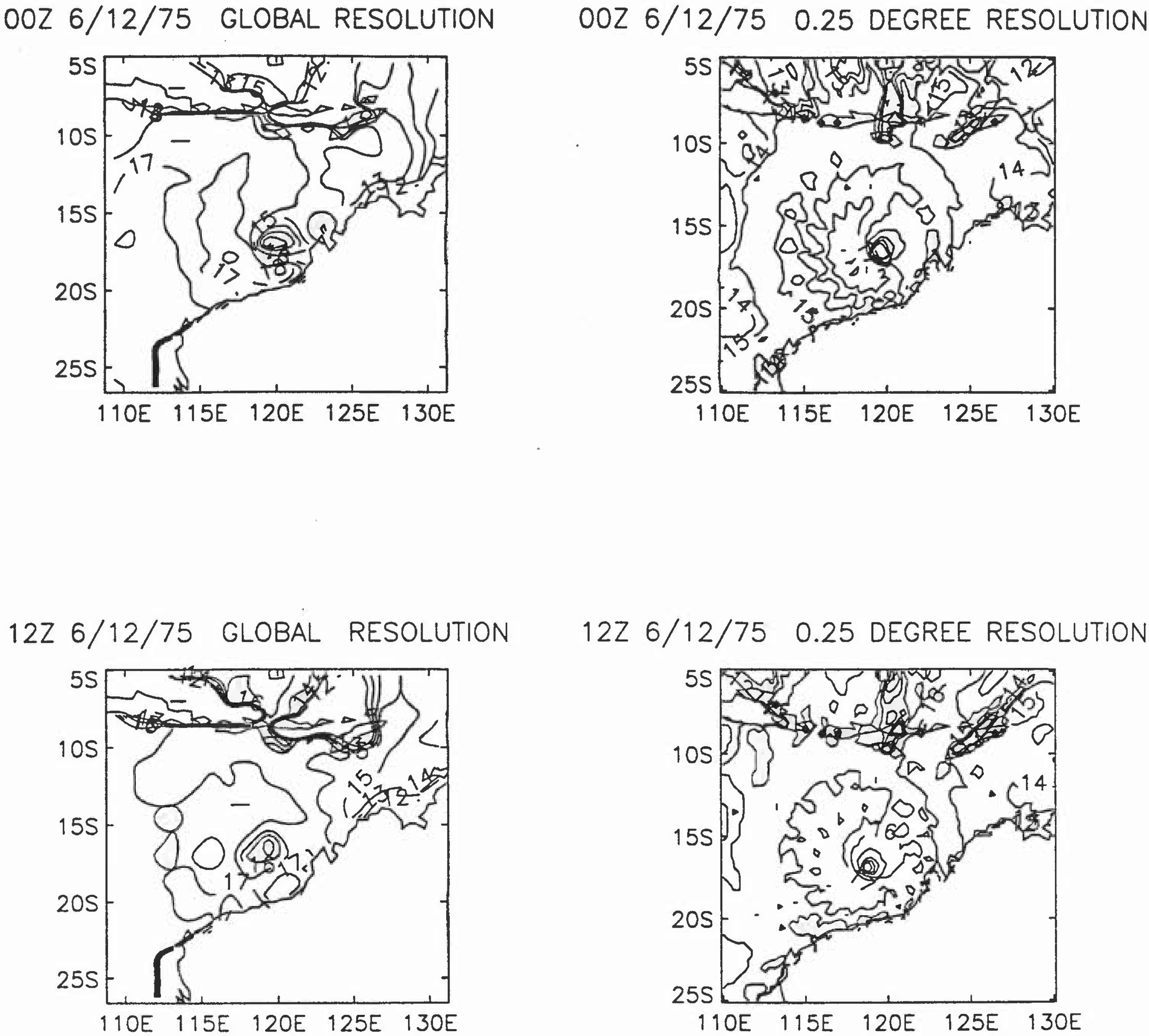

Figure 7. Zero upcrossing period of swell (Hurricane Joan). The lowest contour value is 12 s, and the contour interval is 1 s.

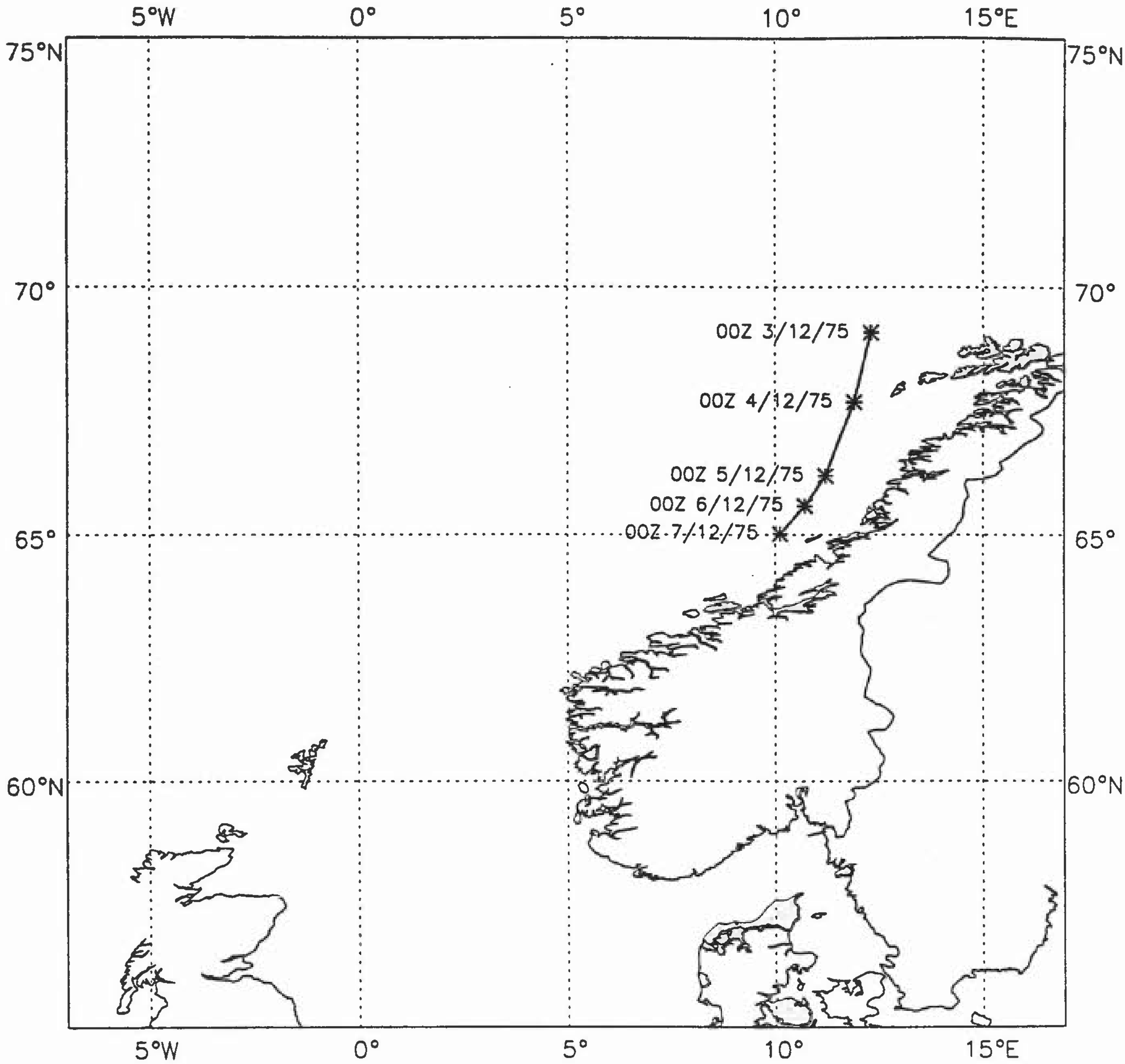

Figure 8. Track of hypothetical tropical cyclone in the Norwegian Sea.

Simulation	No. of direction components	Direction resolution
1	16	22.50°
2	24	15.00°
3	32	11.25°

Table 2. The direction resolution of the wave model for each simulation.

pressure, ambient pressure, radius of maximum wind speed and maximum wind speed. The wind model was run twice to produce 0.833° latitude by 1.25° longitude resolution and 0.25° latitude by 0.25° longitude resolution wind fields.

The wave model was then run three times at the operational global resolution, 0.833° latitude by 1.25° longitude, using the wind field of the same resolution produced by the wind model. The direction resolution of the wave model for each of these runs in displayed in Table 2. The simulations were then repeated with the resolution of the wave model increased to 0.25° latitude by 0.25° longitude. In this case, the 0.25° latitude by 0.25° longitude resolution wind field was used to drive the wave model.

Figure 9a and 9b show contour plots of swell height for two times produced by the global and high resolution wave model simulations. Superimposed on these plots are arrows indicating the direction of swell propagation. Again, the swell height is about 1 metre larger in most areas in the global resolution run than in the high resolution run.

One problem with the wave model is that swell tends to spread out from the storm along "fingers" aligned with each direction bin. This is known as the "Garden Sprinkler Effect" and is a problem particularly in the swell generated by slow moving, intense storms. This effect is more noticeable if the wave model is run at a high spatial resolution, because there are more gridpoints between each "finger" of swell. As the direction resolution increases, the Garden Sprinkler Effect decreases. The decrease in the Garden Sprinkler Effect is noticeable in the swell heights illustrated in Figures 9a and 9b, particularly in the north of the region.

Since the Garden Sprinkler Effect is greater when the wave model is run at higher resolution, the direction resolution at which the wave model needs to be run to eliminate the effect would be greater for a high resolution grid than for a low resolution grid. The results of this sensitivity test indicate that at global resolution, at least 24 direction components are needed, but it is not worth having more than 32 components. At a spatial resolution of 0.25° latitude by 0.25° longitude, at least 32 direction components are needed.

Figures 9a and 9b also show that for this case, the increase in direction resolution made little difference on the swell height in the North Sea. This may be because the majority of the swell is propagating out in a westerly direction from the storm and that the storm was not in the correct location to assess the swell heights reaching the North Sea.

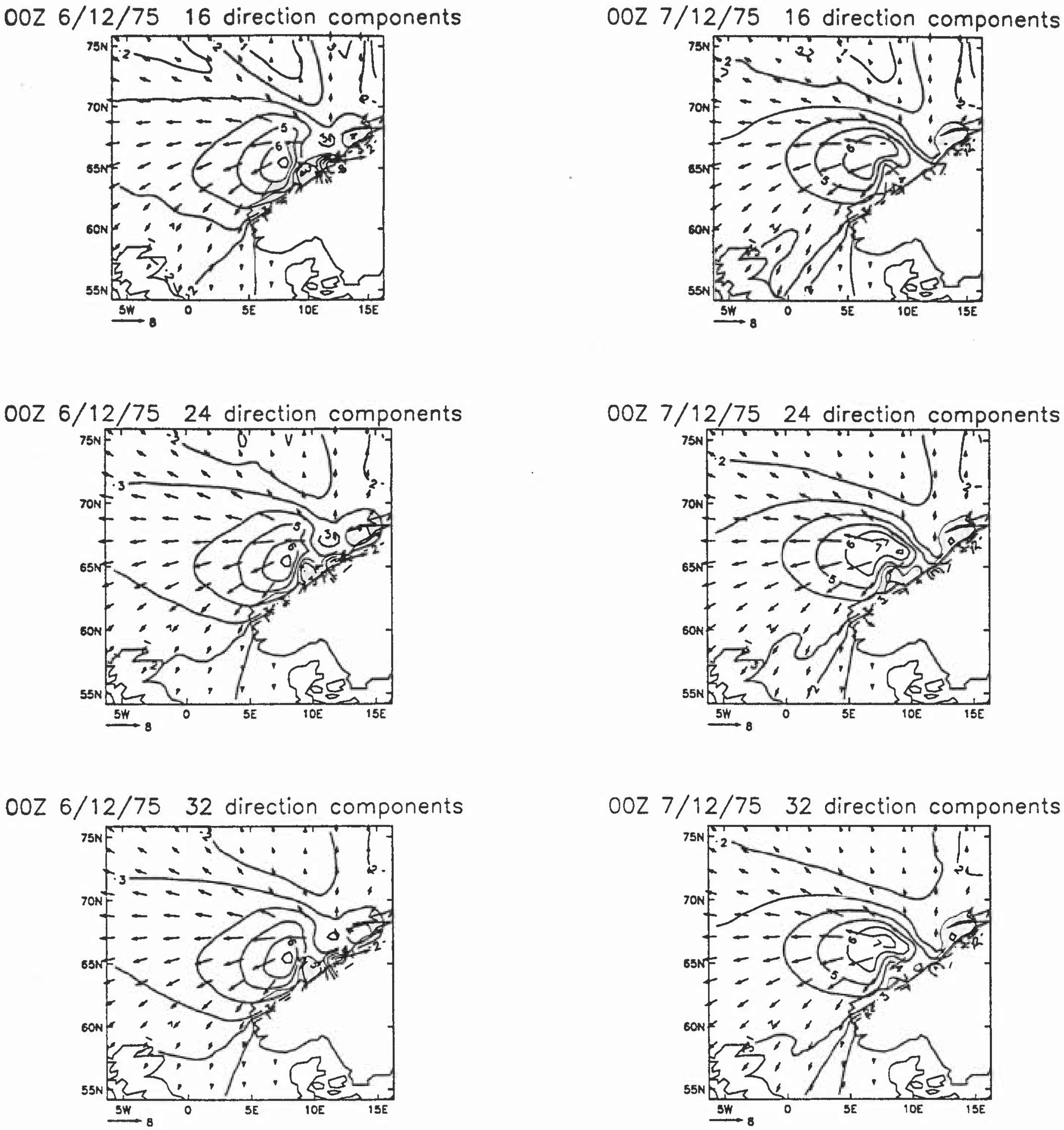

Figure 9a. Height and direction of propagation of swell when the wave model was run at a spatial resolution of 0.833° latitude by 1.25° longitude. The contours indicate the swell height, and the arrows the direction of propagation. The lowest contour value is 1 m, and the contour interval is 1 m. The arrow length is proportional to the swell height.

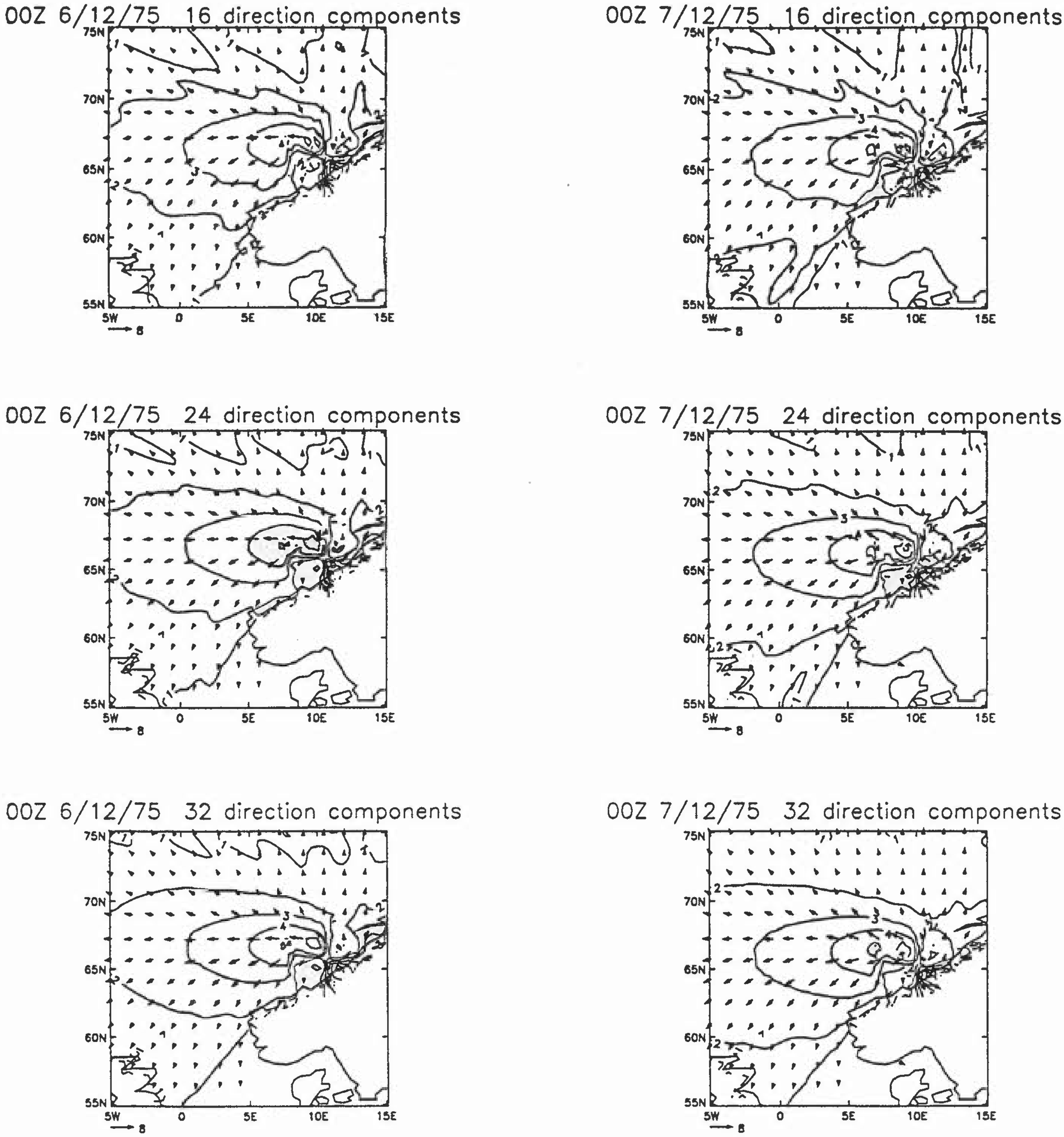

Figure 9b. Height and direction of propagation of swell when the wave model was run at a spatial resolution of 0.25° latitude by 0.25° longitude. The contours indicate the swell height, and the arrows the direction of propagation. The lowest contour value is 1 m, and the contour interval is 1 m. The arrow length is proportional to the swell height.

4. Conclusions

A model which will calculate the surface wind field within a tropical cyclone area to a required resolution has been developed. The wind field generated by this wind model could then be merged with the global NWP model background wind field for wave model runs. For input, the model requires the latitude and longitude of the centre of the storm, the atmospheric pressure at the centre of the storm, the maximum wind speed within the storm, the radius of maximum winds, and the ambient atmospheric pressure far from the storm. It also requires details of the grid resolution. The wind model could be improved further by taking into account the movement of the tropical cyclone and by introducing a friction coefficient.

In general, the results of the first sensitivity test indicate that the spatial resolution of the wind model has little effect on the calculated surface wind field, except in the centre of the tropical cyclone. The spatial resolution of the wind and wave model also appears to have little impact on windsea height, until the wind waves propagate through a chain of islands. However, the calculated swell height is 1 metre larger in most areas when the wave model is run at global resolution rather than at high resolution.

The results of the second sensitivity test indicate that as the direction resolution increases, the Garden Sprinkler Effect decreases, as expected. In addition, the extent of the Garden Sprinkler Effect is greater when the wave model is run at higher resolution.

5. Recommendations

A) The wind and wave models should be run at a high spatial resolution (such as 0.25° latitude by 0.25° longitude) with at least 32 direction components for consultancy hindcast studies. This would ensure that the surface wind field at the centre of the storm and any coastlines are adequately represented.

B) Ideally, the operational wave model should also be run at high spatial resolution in tropical cyclone areas, with 24 or 32 direction components. In practice, this would be difficult to do, since the high resolution grids have to be set up well in advance to allow the model sufficient time to spin up. The other option is to increase the global grid and direction resolution but this would be computationally expensive.

C) The tropical cyclone wind model should be developed to merge the tropical cyclone wind fields with the NWP background wind field for use in the operational global wave model.

D) Further work is required to investigate why the swell height is 1m larger and swell period is longer when calculated by the wave model when run at global resolution than when calculated by the wave model when run at high resolution.

E) Further work is also required to determine whether the wind model should be modified to take into account the movement of the tropical cyclone and surface friction.

F) A further sensitivity test should be performed to assess of the benefit of including the surface wind model into the operational wave model. In this test, the wind field produced by the tropical cyclone wind model should be merged with the background global NWP winds before running the wave model. The results from the wave model run should then compared with those produced by the operational wave model.

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