Analysis of an Event of „Parametric Rolling" onboard RV "Polarstern" based on Data from a Shipborne Wave Radar

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Abstract

During the Antarctic summer season 2008/2009 the wave radar system WaMoS® II was installed onboard of the German research vessel „Polarstern". The experiment was part of the German project *DeMarine-Security,* which is financed by the Minister of Economy and supervised by DLR-Agency. It contributes to the ESA/EU-Initiative *Global Monitoring for Environment and Security* (GMES). Purpose was to collect quasi-in-situ data for the comparison with satellite-borne SAR and altimeter instruments (Envisat, TerraSAR-X, Jason).

On March 7th in the central South Atlantic Ocean "Polarstern" was heading towards Punta Arenas against a rough cross sea. In the night, a sudden event of heavy rolling hit the vessel and lasted for a few minutes. Using WaMoS® II data, as well as ENVISAT and wave model data, we investigate the conditions under which the event occurred.

It is shown that the rolling was caused by a "parametric" resonance when the period of encounter came close to one half of the vessels's Eigen-period. We conclude that an onboard wave radar can be helpful in diagnosing and forecasting critical conditions.

1. Introduction

Most of the goods produced world-wide are transported over the sea. The growth of global trade was associated with a doubling of the fleet capacity of container vessels within 10 years. In order to increase the efficiency of container transport, ships have been developed with a slender under water hull but large overhanging deck. The specific danger of these modern constructions consists in the variability of lateral stability in heading and following seas. Excited by heavy pitching and heaving the ship may suddenly be caught in resonant rolling. This problem has long been known by mariners. Typically, small vessels of low stability experienced resonance in following seas. With the introduction of larger container vessels, the problem of rolling in heading seas came to the fore. In October 1998, the 276m long vessel "APL China" was hit by typhoon "Babs" in the North Pacific Ocean. Approximatly 400 containers were lost and another 1000 containers were damaged due to "parametric rolling". This was the first and most spectacular case of similar incidents in the subsequent years with losses of up to 100 Million $.

In 2007 the German research project *DeMarine-Security/**PaRol*** (see www.demarine-sicherheit.de) was established with the aim to improve the security of navigation by forecasting dangerous events. *DeMarine* is the German gateway to the European programme *Global Monitoring for Environment and Security* (GMES) (see ec.europa.eu/gmes/ www.gmes.info/ www.esa.int/esaLP/LPgmes.html). Within ***PaRol*** it was planned to contribute to the development of a future warning system based on in-situ and remotely measured sea states.

Partners in the project are the German Aerospace Center (Deutsches Zentrum für Luft und Raumfahrt, DLR), OHB Technology AG (Bremen), GAUSS mbH (Bremen) and the German Weather Service (Deutscher Wetterdienst, DWD). The DWD branch office in Hamburg provides special maritime weather services and consultancy such as world wide ship routing. In particular, DWD meteorologists are regularly employed onboard of German research vessels "Polarstern" and "Meteor" as consultants for mariners, scientists and helicopter pilots. The scientific activities of these ships often critically depend on the sea state. Therefore, products of operational wave forecast models (DWD and ECMWF) have become an important component of the onboard weather advisories.

The Antarctic Expedition ANT-XXV 2008/2009 of "Polarstern" offered the opportunity to measure ocean waves in areas with exceptional sea states, using jointly remote sensing techniques from satellite-borne altimeter and imaging radar (ENVISAT ASAR and TerraSAR-X) as well as onboard visual observations and marine wave radar. The WaMoS® wave radar system is introduced in Section 2. The experiment will hopefully result in improved algorithms to retrieve wave spectra and significant wave height from SAR-data.

The expedition started in October 2008 in Bremerhaven and ended there in May 2009. In between "Polarstern" visited the Antarctic research sites Neumayer Station and King George Island. The event of parametric rolling that occurred during leg 3, from Capetown to Punta Arenas, is the main subject of this paper and will be analysed in detail in sections 4 to 6. The theory of parametric rolling will briefly be reviewed in Section 3.

2. The Wave Radar

In October 2008, the wave radar system WaMoS® II was installed in the Meteorological Office on A-Deck of "Polarstern" for the duration of ANT-XXV. The system had been developed at the GKSS-Research Centre, Geesthacht and rented for the project from OCEANWAVES GmbH. It consisted of a standard PC with an integrated PCI-card and evaluation software, being connected to the ship's marine X-Band radar. The system software is designed to extract wave information from the radar images (up to 3 miles from the antenna) by analyzing the spatial and temporal changes of the radar backscatter from the sea surface (sea clutter), and to determine directional wave and surface current information. Products are the complete two-dimensional wave spectrum, from which the statistical sea state parameters are derived in real time, including significant wave height (H_s), peak wave period (T_p), peak wave length (λ_p) and peak wave direction (θ_p). Fig.1 shows a WaMoS® screen shot. More information on the system and further literature can be found at www.oceanwaves.de .

In agreement with the ship's command the radar range had to be set to 1.5 nm (short pulse mode) in order to record useable images. This was possible only in a distance to coasts, ship routes and icebergs. During the first two legs of ANT-XXV (Bruns et.al. 2009) work on the wave radar concentrated on finding the optimal radar settings and calibrating the system using onboard visual observations and available buoy data.

With the exception of a few days when the presence of fast ice or icebergs demanded radar operation in the far range, wave spectra have continuously been recorded between November 2008 and May 2009. Fig.2 shows a time series of significant wave height measured by WaMoS® (1-hourly-average) during legs 3 and 4 in comparison with onboard visual observations, wave analyses and short-term forecasts (up to T+9h) by DWD and the European Centre for Medium Range Weather Forecast (ECMWF). The correlation between wave models and WaMoS® exceeds the correlation between models and visual observations.

3. Parametric Rolling

The lateral stability of a ship is characterized by the location of the center of buoyancy (center of the water volume displaced by the hull) relative to the center of gravity G (Fig.3). In calm water buoyancy force and gravity force balance each other along a vertical line. When the ship is heeled, however, the center of buoyancy center is moving laterally resulting in a righting force whose strength depends on the angle of inclination. The rocking point of the corresponding torque is called the metacenter M. To ensure stability, the metacenter must always be located above the center of gravity. The initial vertical distance between the two is the metacentric height GM_0. For small angles GM_0 is assumed to be constant and determines the Eigenperiod T_R at which the ship is swinging back to rest

$$T_R = f\ B\ (GM_0)^{-1/2} \tag{1}$$

where B is the breadth of the ship, and f=0.75..0.8. is an empirical constant. B and GM_0 are given in meters, T_R in seconds. In practice it is difficult to evaluate GM_0 without detailed knowledge of the ship's shape and mass distribution. Moreover, GM_0 and thus T_R may change at higher inclinations (for more details see Barrass and Derrett, 2006 or Comstock, 1967).

In the case discussed here it was easy to determine T_R empirically. From the upper panel of fig.8 we found a rolling period of 17.3s, which was nearly constant over the preceeding hours. Therefore, we consider this value as the Eigenperiod of the vessel for the current loading.

In heading or following seas wave crests pass along the ship's hulk. If the wave length is of the order of one to two ship lengths ("Polarstern" : 118m) lateral stability depends strongly on the position of the crest. When the crest is located at the midship section the ends of the hulk will emerge from the water and bend towards the wave troughs ("hogging"). In this situation the erecting moments are reduced resulting in a significant loss of stability (see fig. 4). Otherwise stability will increase when the main frame is located in the wave trough ("sagging"). Further variations of stability are induced by pitching motions.

Resonant rolling in heading or following seas is therefore not directly forced by the waves but is coupled to periodic variations in stability. In a phase of low stability small wave components from aside can sufficiently trigger an initial inclination. In the following phase of high stability the ship is accelerated back into the zero position and beyond - just when stability tends to decrease again. This kind of resonance is called "Parametric Rolling" (Ammersdorfer, 1998).

The criterion for resonance is thus determined by the period at which the waves are encountered by the ship. This period of encounter T_E is given by

$$T_E = (1 / T - V_s \cos(\mu) / L_p)^{-1} \tag{2}$$

with the peak wave period T_p and peak wave length $L_p = g\ T_p^{\ 2}/2\pi$, ship speed V_s and angle of encounter μ.

Following the concept of periodic stability variations parametric rolling is possible if $T_E = n/2\ T_R$. For common ships only two cases are of practical relevance:

n=1: $T_E = ½\, T_R$. This case typically occures in heading seas.
n=2: $T_E = T_R$. This case typically occures in following seas.

Fig.5 shows the coherence between ship speed and peak period as a condition for resonance in the case T_R=17s. Here, parametric rolling can be expected when the ship is heading against waves with T_p =10s at a speed of V_s = 5.2kn.

4. The Rolling Event

Leg 3 of the Polarstern-Expedition ANT-XXV started on January 8th 2009 in Capetown. Destination was the sea area northeast of South Georgia, where a team of Indian and German Scientists performed the iron-fertilization experiment „LOHAFEX“ (see www.lohafex.com). On March 6th the scientific work had been accomplished and the vessel was heading towards Punta Arenas. In the evening of March 7th, the cruise participants celebrated their successful work.

In the report of the onboard weather office we find the following note:
„The cruise to Punta Arenas began with stormy winds from West to Northwest and a rough sea, as well. When the wind decreased in the night, „Polarstern“ was hit by a cross sea which led to resonance and heavy rolling between 23:25 and 23:30 UTC. Five persons were injured (lacerations, contusions) and some hardware and material was damaged in the laboratories. The day after, winds ceased and the sea decreased to a residual swell… “

At the time of the rolling event the position of "Polarstern" was 49°22'S 20°45'W. Fig.6 gives an overview over the large scale weather situation in terms of surface pressure as analysed for 00 UTC by the ECMWF atmospheric forecast model. Throughout the day "Polarstern" was cruising between a large subtropic high and a weakening and eastward moving low pressure systems. Southwesterly wind shifted west and increased in the aftenoon when the frontal trough associated with the low in the southwest passed the ship. Details of the weather development are discussed in the following section.

Fig. 7a shows that the rolling angle reached almost 20° during this event. Although the vessel was far from tipping over (which becomes possible at angles exceeding 45°), the inclination was large enough to let furniture slip across the flour and force people to cling to the next reachable holds. A further growth of rolling amplitudes could finally be avoided when the mate on duty changed the heading (orange line) from about 255° to about 290°.

Minor rolling events with angles up to 5° had previously occurred in the two hours before the extreme event. The figure also shows a time series of ship ground speed. As can be seen in fig. 7b there is a certain coincidence of the major and minor rolling events with minima of speed. These events, however, ended without the need to change the heading.

A zoom into eight minutes around the extreme event. Rolling angle and speed are shown in fig. 8 together with other characteristics of ship motion. When the rolling started, the ship slowed down and simultaneously began to pitch and heave heavily. It seems obvious that a group of exceptional high waves may have caused the pitching which in turn resulted in a reduction of speed. It will be shown in the following that a lower speed was a necessary condition for resonance.

Therefore an explanation for this case of parametric rolling would be that a group of high waves slowed down the vessel which in turn made the frequency of wave encounter change exactly into the regime where parametric rolling occurred. This is detailed in the following.

5. Analysis of the Weather Situation

The following description of the weather situation on March 7/8th is based on the operational ECMWF and DWD wave model analyses and short-term forecasts ("quasi analyses") up to T+09 hrs. On the 7th at 06 UTC "Polarstern" was located in a region of relatively high winds (~14m/s) from northwest according to the DWD wave model (fig.9a). Twelve hours later wind had shifted west and slightly increased (fig.9b). An eastward moving frontal trough had passed the ship around midday. Figures 10 to 14 compare model analyses with the actually observed winds and waves over 48 hours.

In the first half of the 7th anememeter winds (reduced to 10m) increased from 12 up to17 m/s around midday. In the second half of the day winds slowly shifted more and more to a westerly direction (fig.11) and, shortly before the rolling event, decreased continuously to about 8 m/s on the 8th. The ECMWF model agrees very well with this development. The temporal underestimation by the DWD model is presumably due to a northerly shift of the wind speed maximum in the model data (Fig.9).

The comparison between model wave heights, visual observations and WaMoS®-measurements (fig.12) is also quite satisfying. Total significant wave heights (SWH) first varied around 4 m and then slightly increased to 4.5 m. The wind sea fraction reached about 3.5m (not shown) at a peak period of 9 s, while swell waves of 2 m (not shown) height and a peak period of 10 s arrived from southwest (fig.13). This corresponds well with the above mentioned "cross sea" statement. The direction of wind waves (fig. 13) shifted west in correspondence with the wind direction. Otherwise, swell changed direction from southwest to westnorthwest. The WaMoS-measurements indicate that actually two swell peaks existed (fig.17), but only the dominant swell is resolved in the model output.

Fig.15 shows the large scale sea state situation (DWD model) on March 8th at 00 UTC, 30 minutes after the rolling event. Superimposed on the plot are ENVISAT ASAR radar observations of significant wave height acquired during an ascending orbit at around 0:04 UTC on March 8th. Squares represent SWH derived from ASAR by using the CWAVE_ENV algorithm (Schulz-Stellenfleth 2007 et al., Li et al. 2009). In a distance of about 300 km and parallel to the ASAR track runs the RA-2 nadir sub-satellite track, as both instruments are onboard the same platform. Another track from radar altimeter JASON is also shown in the plot. This track is far from the research vessel, while it can still be used for validating the DWD wave model.

Fig. 16 shows a cutout of fig.15 and three ASAR wave mode image spectra taken nearby (195-233 km) the position of "Polarstern". The 180° ambiguity has been removed using the cross-spectral technique. Although these spectra were calculated directly from the raw radar image without consideration of non-linear imaging effects, the directions and length scales are consistent with the wave model data. The spatial variability of the spectra and in particular the pronounced double peak of the spectrum in the center suggests that "Polarstern" could have had better conditions a few miles more north or south of the actual track.

Another confirmation of the cross sea situation is achieved from the 2-dimensional WaMoS® wave spectra shown in fig.17. The correspondence with the ASAR image spectra is striking. In the hours before the event the measured spectra were characterized by a large directional spread. Besides the dominant wind sea peak (290° / 10s) two secondary swell peaks existed, one from Southwest and the other from Northwest (the direction of wind hours ago). Shortly before the event the latter peak began to change direction, i.e. it slowly merged with the wind sea peak. This might have resulted in a more uniform wave field and an increased risk for resonance.

6. Analysis of Wave Encounter

For a more detailed analysis time series of integrated wave periods and directions have been investigated. Standard output frequency of WaMoS® is every 2 minutes. Available were either instant data (averaged over 32 radar images) or 20-minute averages (640 radar images). The long averaging interval provides relatively stable statistical parameters, however, it imposes a filter on the data such that single events will be smoothed out and and phase shifted, as well. Since the focus of this study is a particular event we will therefore use the instant data despite their higher variablity.

The main peak period is derived from the 1-dimensional wave spectrum. During the 3.5 hours before the rolling event the period slowly increased from 9.7s to 10.1s (not shown). This was e.g. predicted by the DWD-wave model (fig. 14). Simultaneously, the peak direction (fig. 18) varied between 280° and 290° most of the time and finally approached 270°. Obviously, the 1-dimensional peak mainly represents the wind sea part of the spectrum. On the other hand, periods and directions of secondary spectral maxima taken from the 2-dimensional wave spectrum exhibit a quite erratic behaviour (not shown). The angle of encounter in this figure remained nearly constant in the last 30 minutes before the rolling event since the ship's course was simultaneously adjusted to the changing peak direction. This may be an indication that navigation became difficult at that time.

Ship speed was measured onboard by independent systems which partly distinguish between speed over ground and speed through water. Since some deviations between the different speed data sets were found, we estimated speed simply by dividing the space and time distances (~2 minutes) between the GPS-postions stored by WaMoS®, assuming further that ocean currents were neglectable. These speed values agree well with 2-minute averages of the MINS-Scientifc Navigation System.

A time series of the period of encounter calculated from the peak wave period and direction is shown in fig. 19. The period is found to stay below the critical value of 8.65s (half of the roll period) most of the time. On the average there was a slight increase and the period was getting close to the critical value for a couple of times as a result of the variable ship speed. During the event itself the encounter period was reduced, but immediately thereafter it reached 8.7s. This delay can be explained by the 2-minute averaging interval and therefore confirmes the assumption that the condition for resonance was satisfied. Under this consideration we also find a coincidence of the two maxima at 23:08 and 23:21 UTC with the two minor events shown in fig. 7. For the other minor events, however, such a good correspondence was not found.

Fig.20 illustrates the increasing danger in the course of the day in a sequence of resonance diagrams. The diagrams shown here visualize eq.2 in section 3. They combine the vessel's ground speed and heading with regions of (near) resonance ($T_E \sim ½ T_R$). The resonance condition is satisfied when the end of the ship speed vector lies exactly on the pink line. During daytime the situation was not critical. In the evening wave heights (fig. 12) and wave periods slowly increased resulting in a speed reduction. The situation first became critical at 22:33 UTC but no heavy rolling was observed at that time.

7. Conclusions

An event of parametric rolling that occurred during the “Polarstern” voyage ANT-XXV on May 7th was analysed using onboard marine radar, satellite SAR and operational wave models. The existence of a cross sea with significant wave heights up to 4.5 m was consistently confirmed.

Our analysis suggests that changes in the wave spectrum, namely the increase of the 1-dimensional peak period and the merging of wind sea and swell peaks, have slowly increased the probability for parametric rolling. The rolling event finally took place at 23:30 UTC, but it could have occurred already earlier (after 20:00UTC).

For the ship’s mate on duty it would have been helpful to recognize the danger of resonance early in time just by monitoring the period and angle of encounter. Commercial software tools (e.g. Benedict, 2004) already exist to support navigational decisions in critical situations based on resonance diagrams as the ones shown in fig. 20. Input data are either wave parameters estimated by eye or numerical wave forecasts in case of advanced systems. In combination with an onboard wave radar a further improvement could be achieved.

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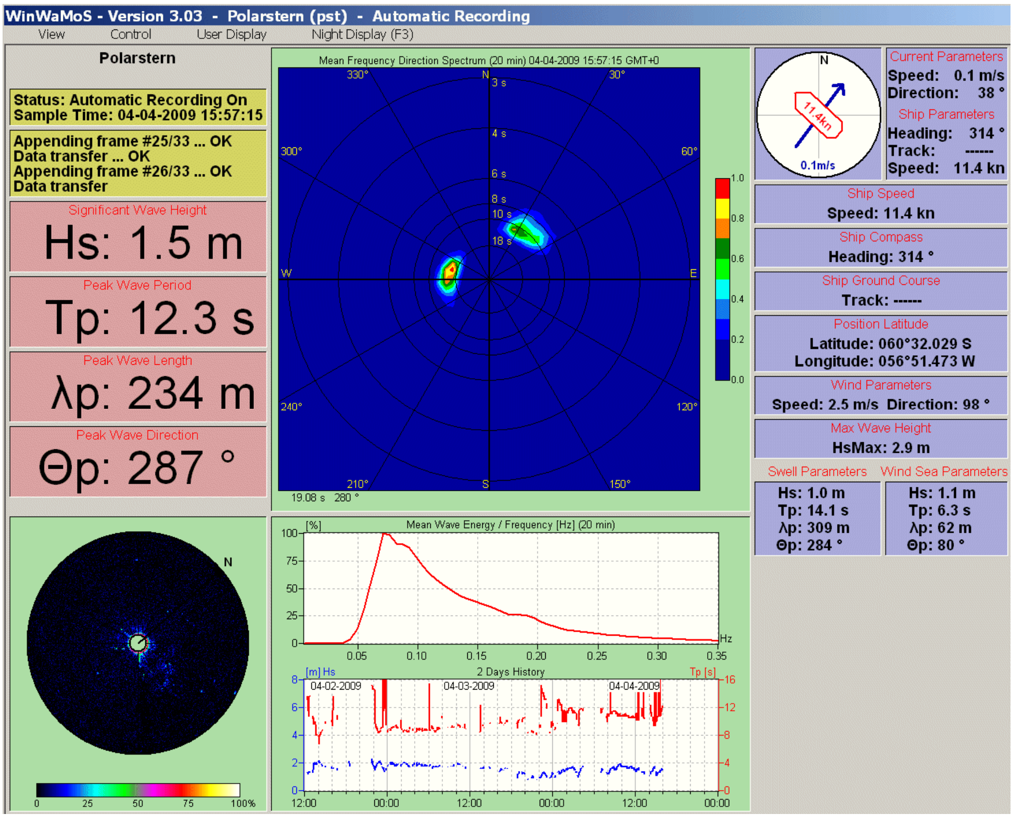

Fig.1 Screen shot of the WaMoS® wave radar: Two- and one-dimensional wave spectra, display of integral parameters and ship specific data, taken on April 4th, 2009.

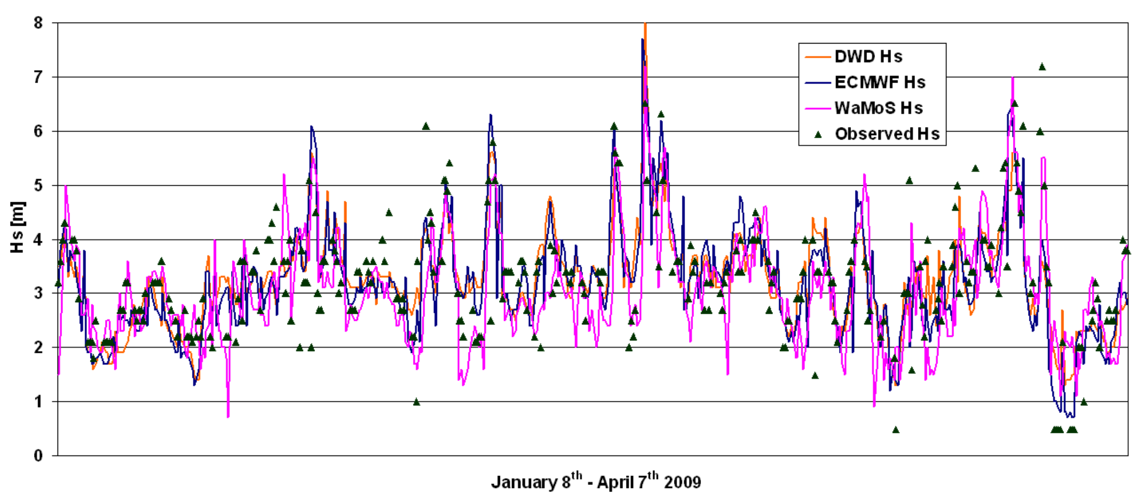

Fig. 2 Time series of significant wave height measured by WaMoS® (violet), observed visually (green triangles) and analysed and forecast by DWD (orange) and ECMWF (blue).

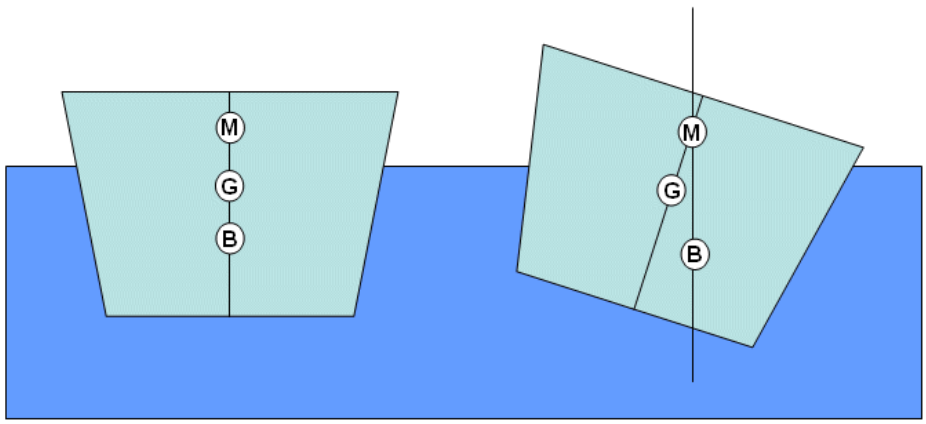

Fig.3 Location of the center of gravity (G), the center of buoyancy (B) and the metacenter (M) of a ship.

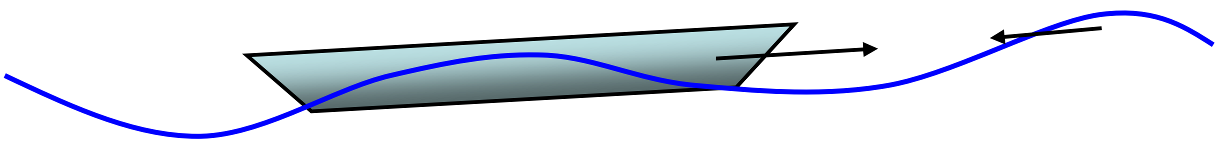

Fig.4 Schematic view of a ship temporarily losing stability in a heading sea.

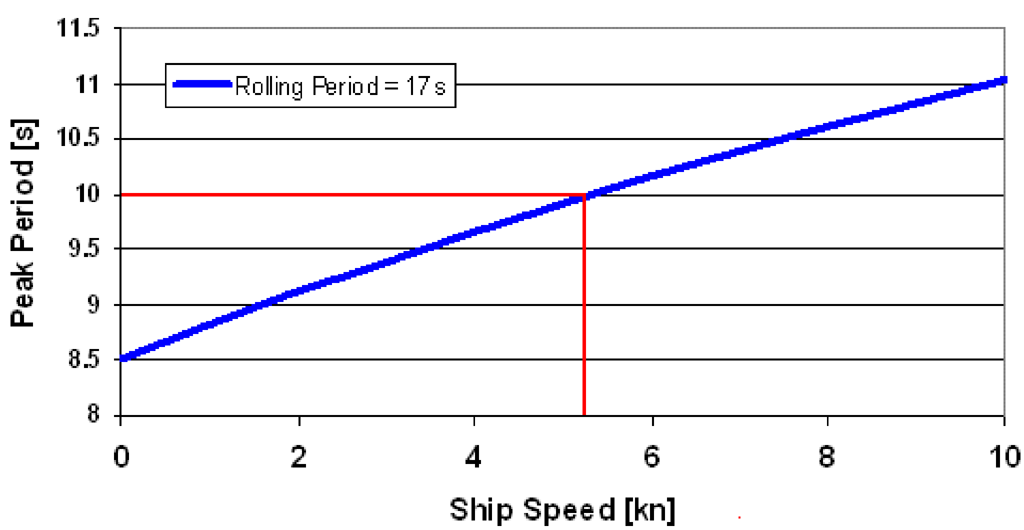

Fig.5 Resonance condition for a rolling period of 17s and waves coming directly from ahead. For example, the condition is fulfilled for a peak period of 10s and a ship speed of 5.2kn.

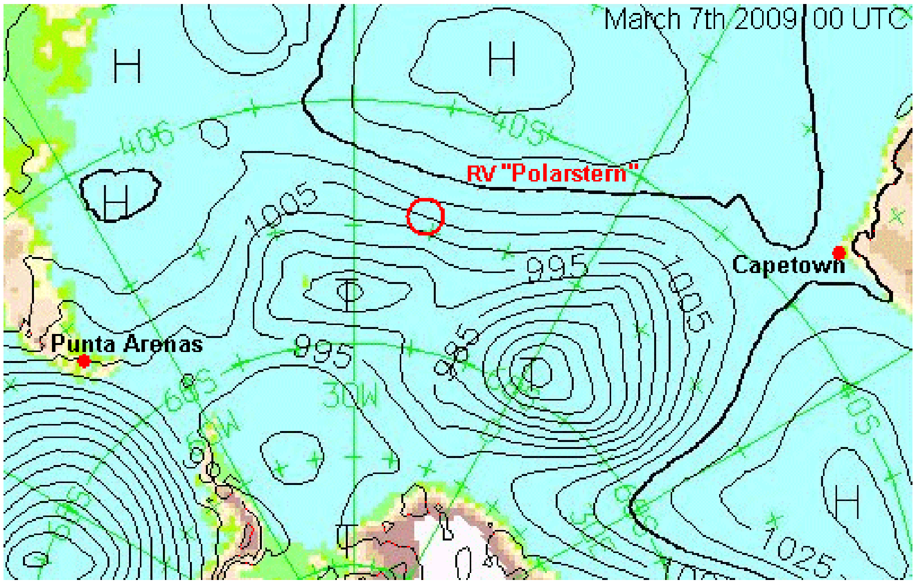

Fig. 6 ECMWF – Surface pressure analysis March 7th 2009, 00 UTC and approximate position of RV „Polarstern" UTC

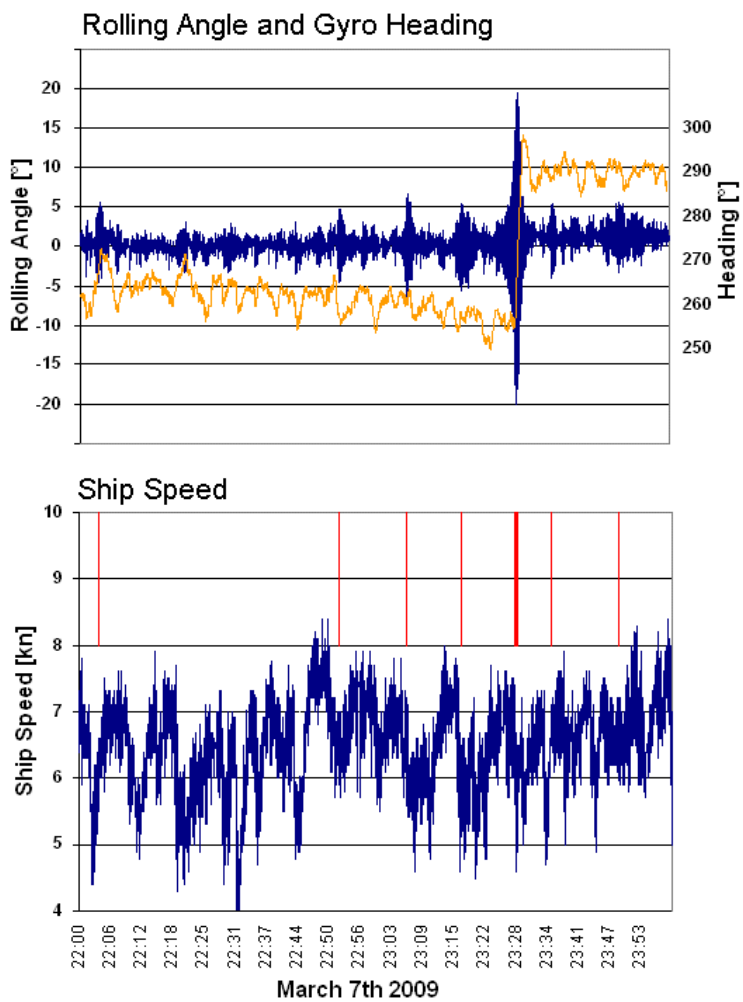

Fig.7 High resolution (1sec) time series of rolling angle, gyro heading (a) and ship (ground) speed (b) of "Polarstern" on March 7th between 22:00 and 24:00 UTC. Red lines mark the begin of extreme rolling and other near resonant events as well.

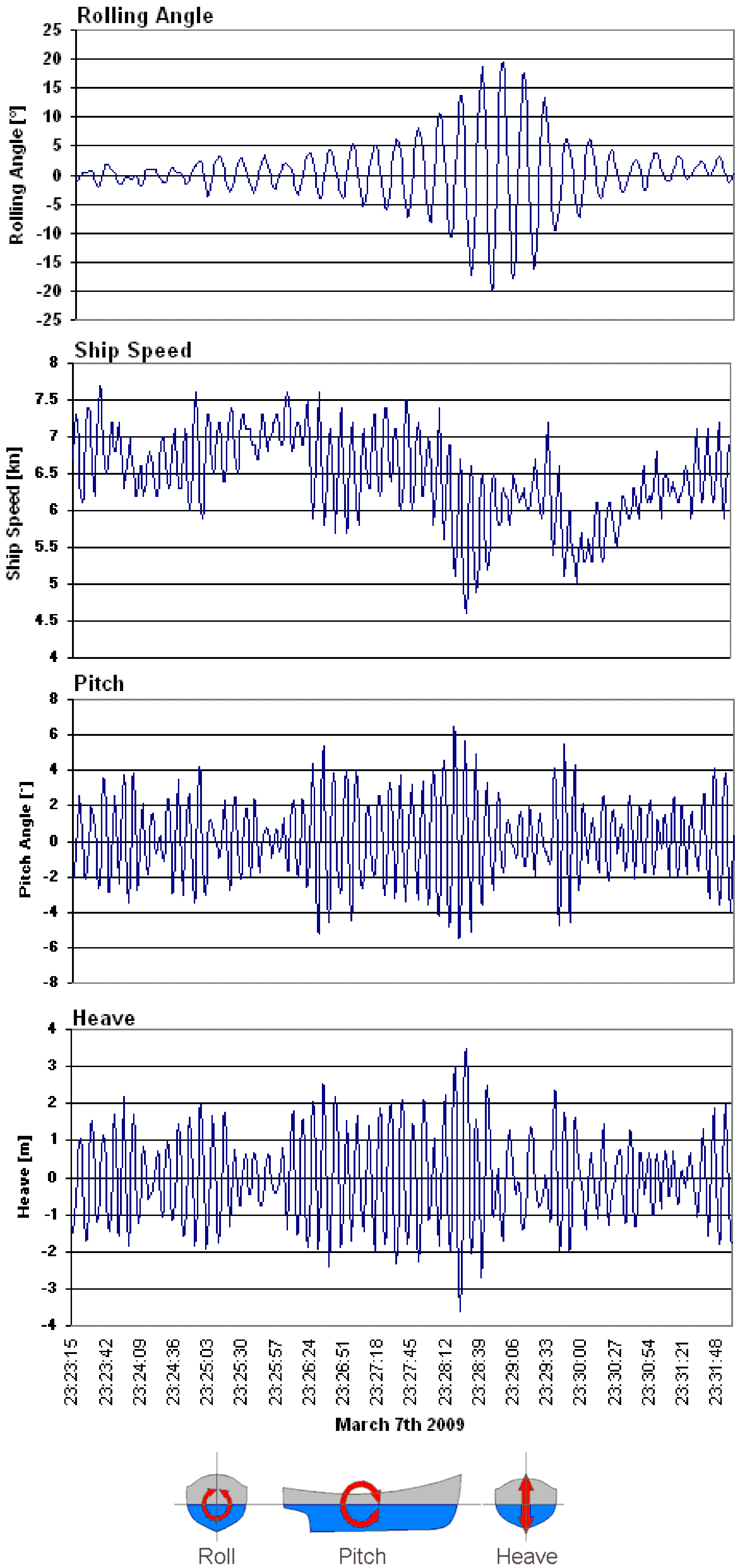

Fig. 8 High resolution (1sec) time series of ship motions between 23:23 und 23:32 UTC. The average rolling period estimated from this diagram is 17.3sec.

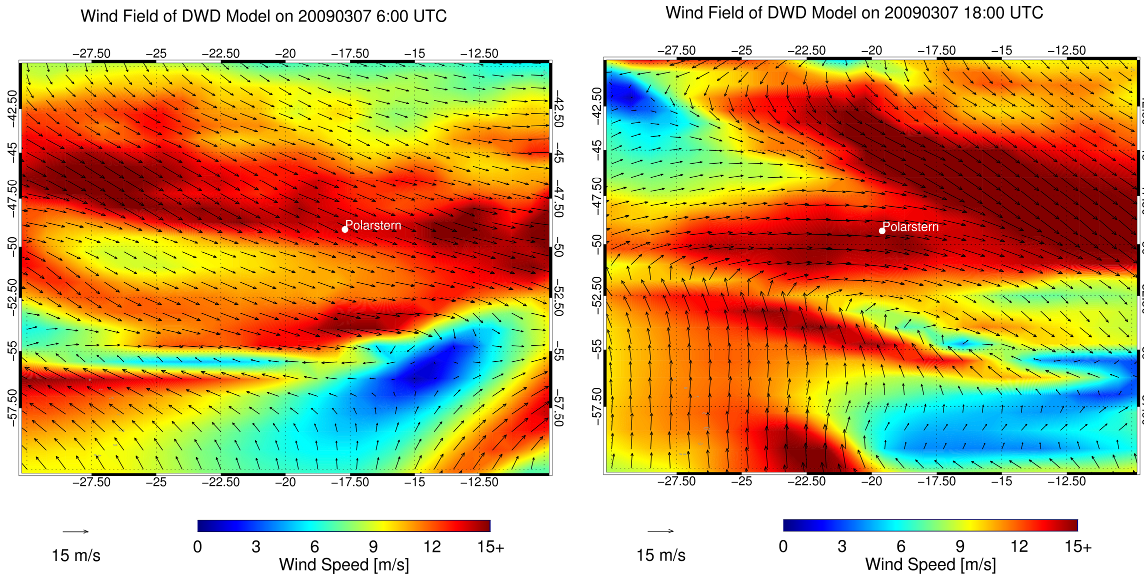

Fig. 9 Wind field derived from the DWD wave model for March 7th (a) 06:00 UTC and (b) 18:00 UTC (both 6hourly-forecasts).

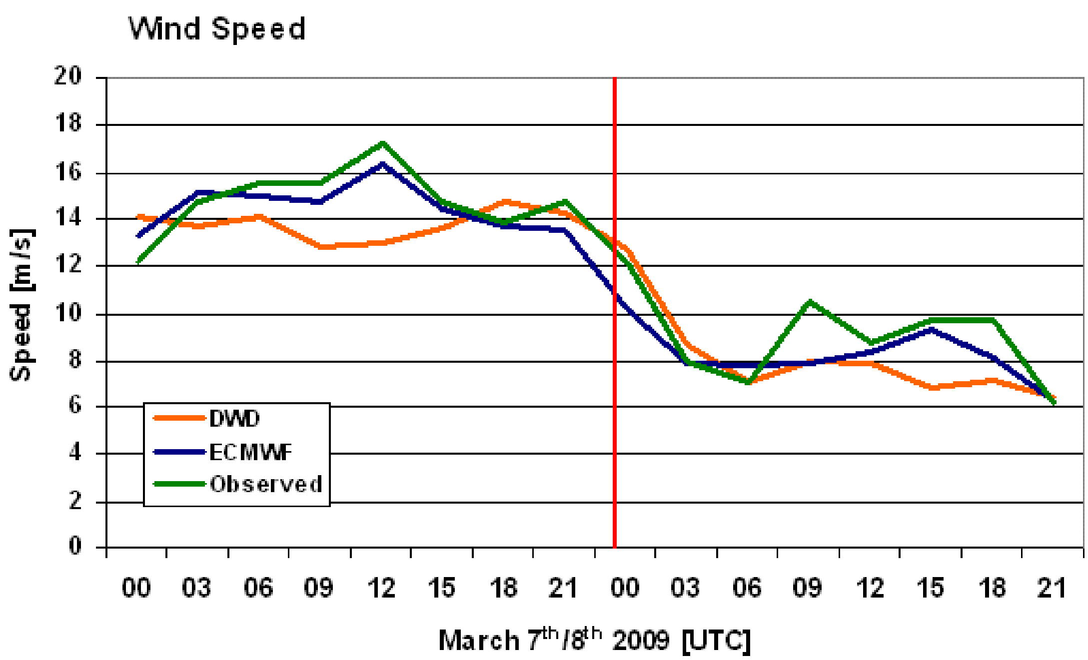

Fig.10 Short-term (T+00 to T+09) forecasts and anemometer measurements of 3-hourly wind speed (reduced to 10m).

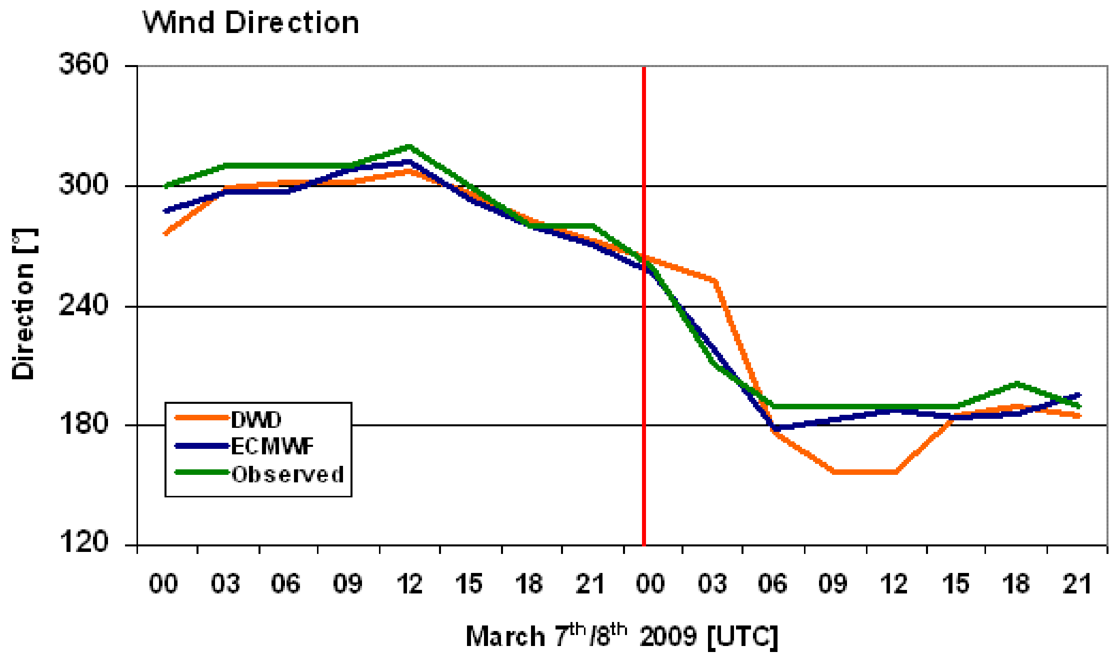

Fig.11 Short-term (T+00 to T+09) forecasts and anemometer measurements of 3-hourly wind direction.

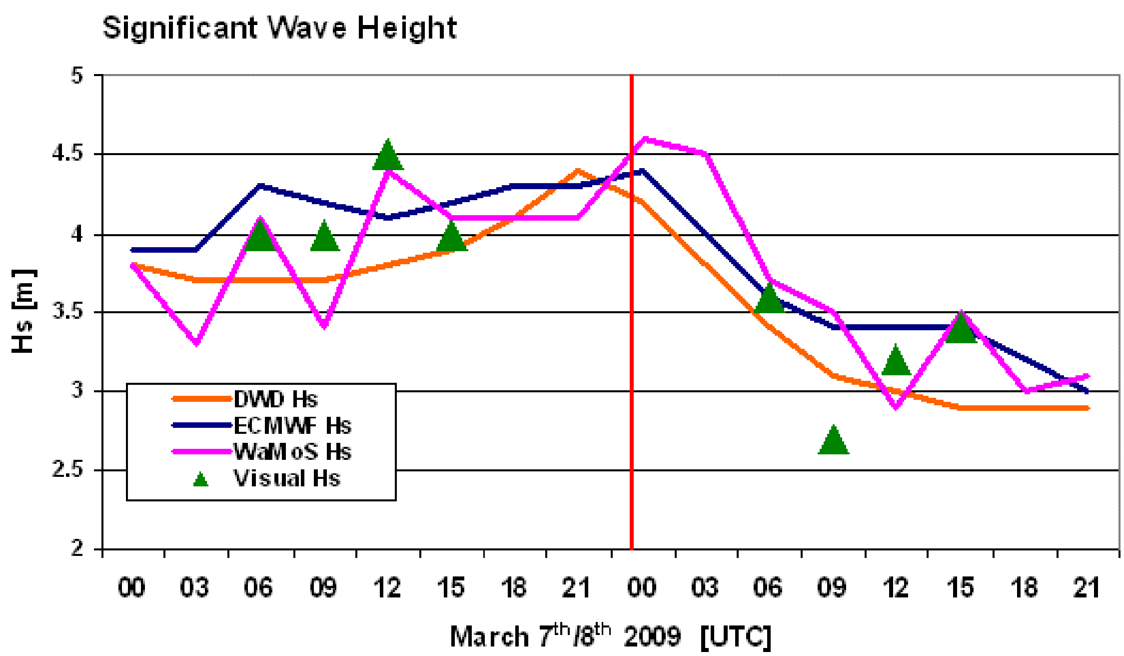

Fig.12 Short-term (T+00 to T+09) wave model forecasts of significant wave height compared to WaMoS-measurements (3-hourly averages) and visual wave height observations (daytime only).

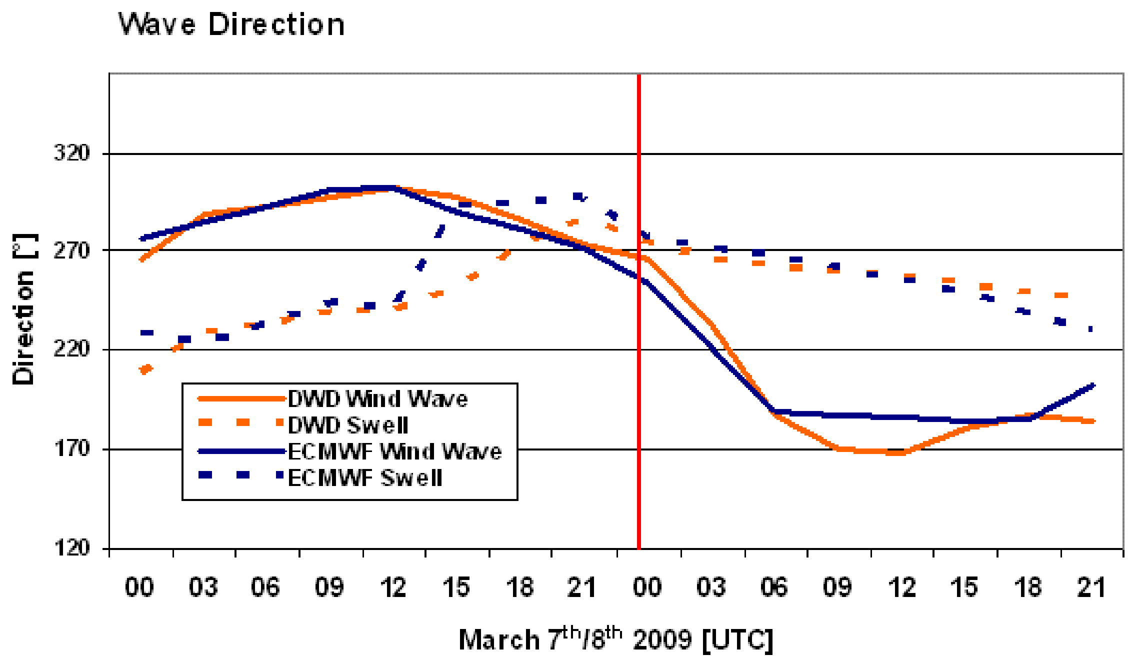

Fig.13 Short-term (T+00 to T+09) wave model forecasts of wind sea (solid lines) and swell direction (dotted lines).

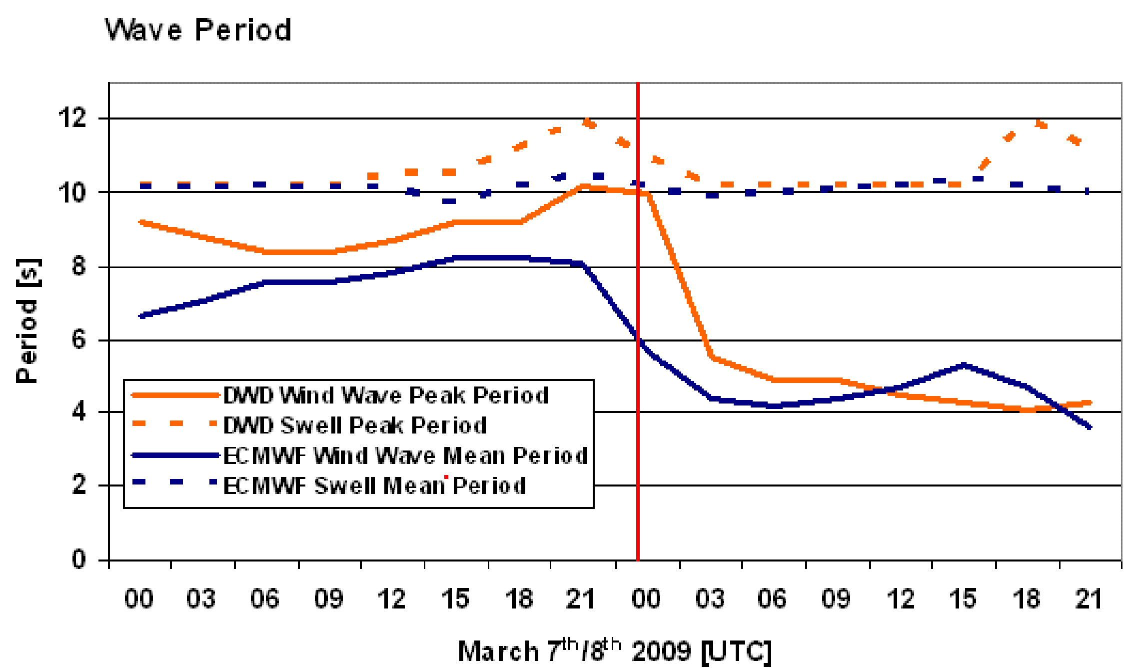

Fig. 14 Short-term (T+00 to T+09) wave model forecasts of periods of wind sea and swell (ECMWF mean wave periods, DWD peak periods).

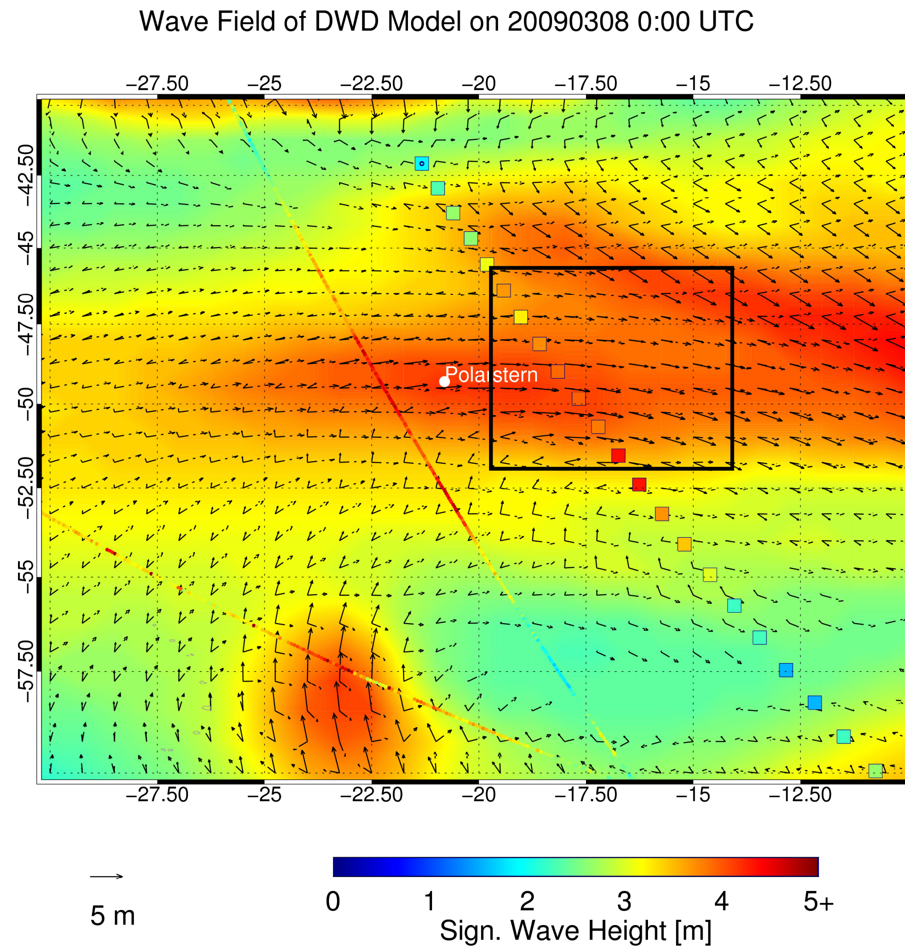

Fig.15 Analysed wave field of the DWD wave model on March 8th at 00 UTC. Background is the colour-coded significant wave height. Solid and dash-dot lines show the peak wave direction for wind sea and swell, while arrow lengths represent the corresponding wave heights. Superimposed are the tracks of ENVISAT SAR- and Radar-Altimeter measurements. For the details within the rectangle see fig. 16.

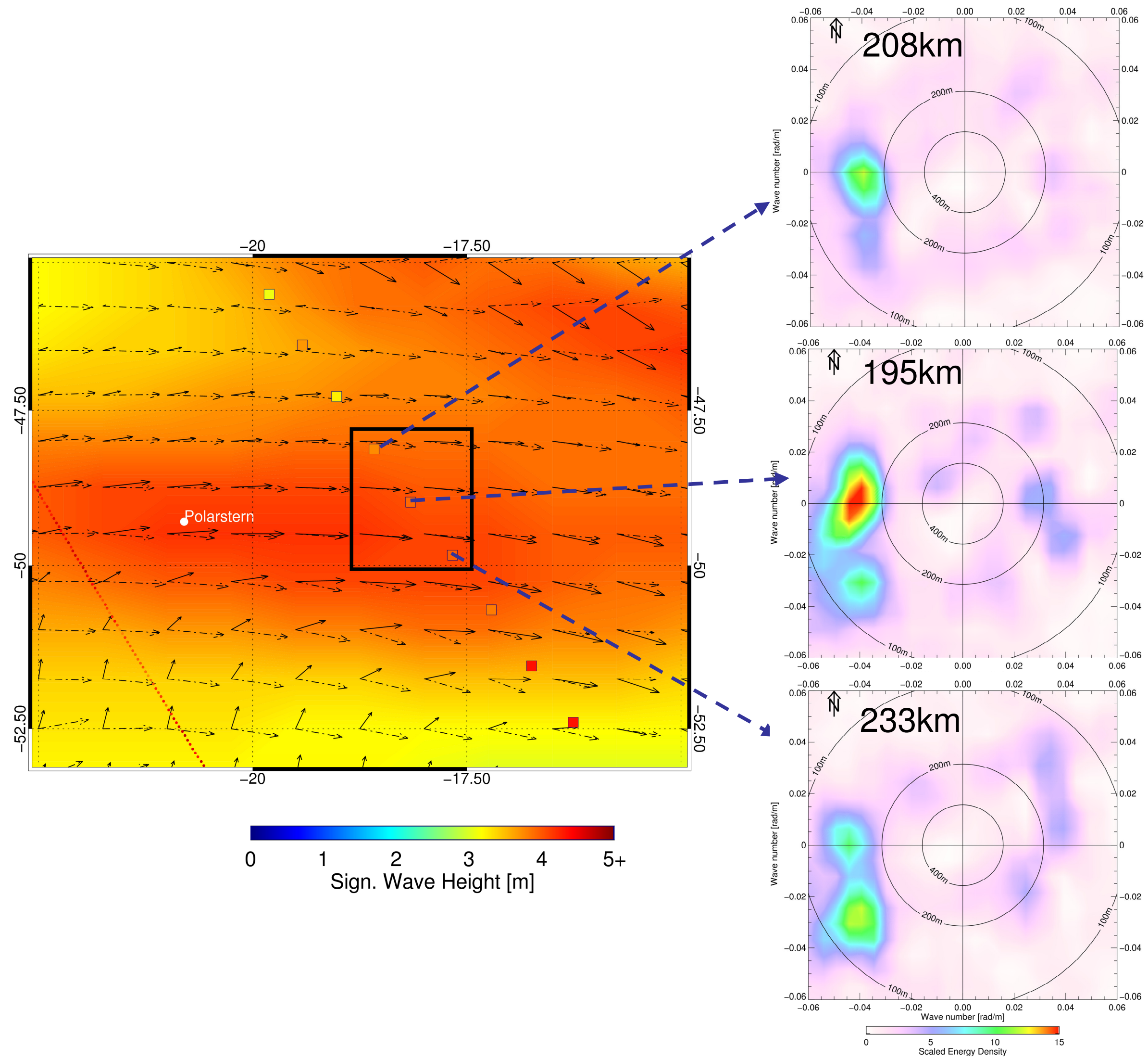

Fig. 16 Image spectra derived from ASAR wave mode data. The 180° ambiguity has been removed using the cross-spectral technique. The peaks indicate the wave direction of coming from

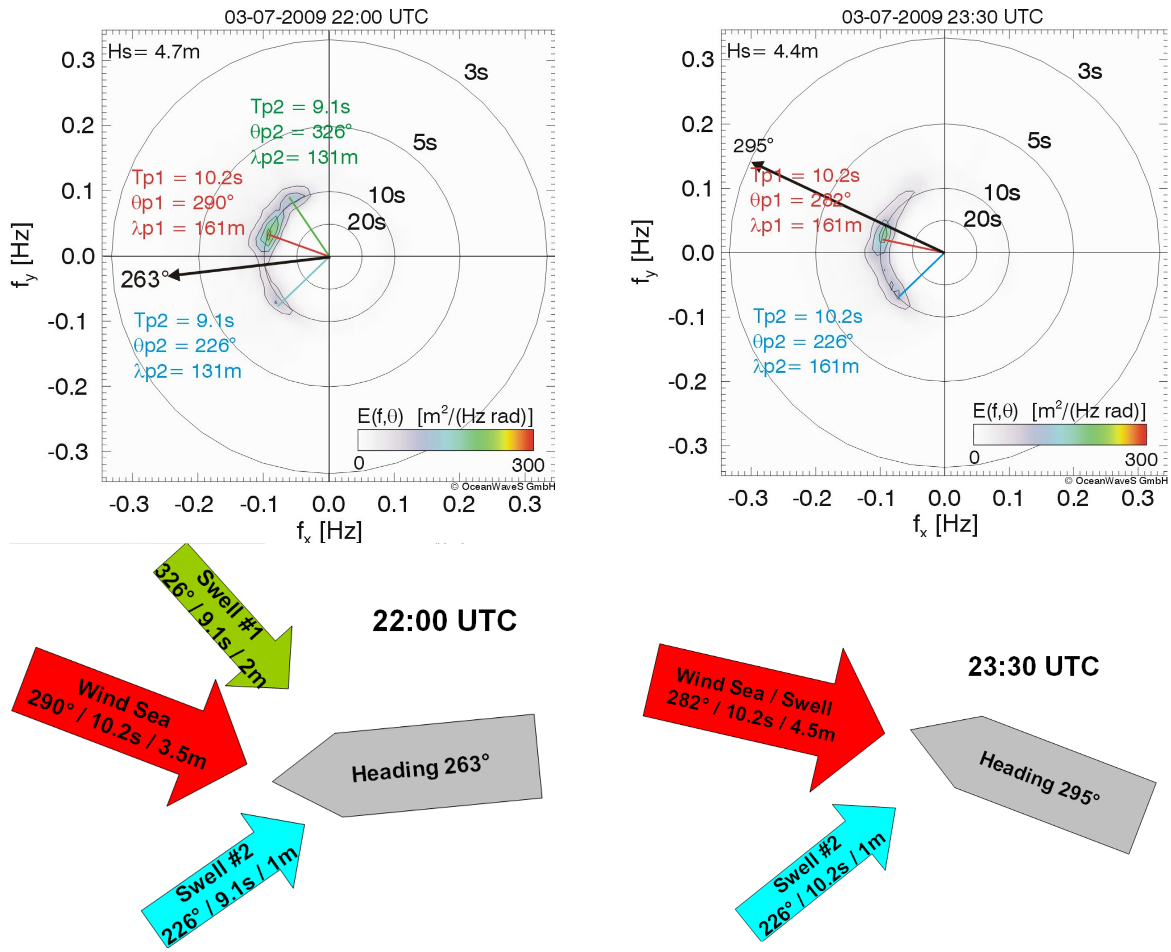

Fig.17 The cross-sea situation about 90 minutes before and shortly after the rolling event.

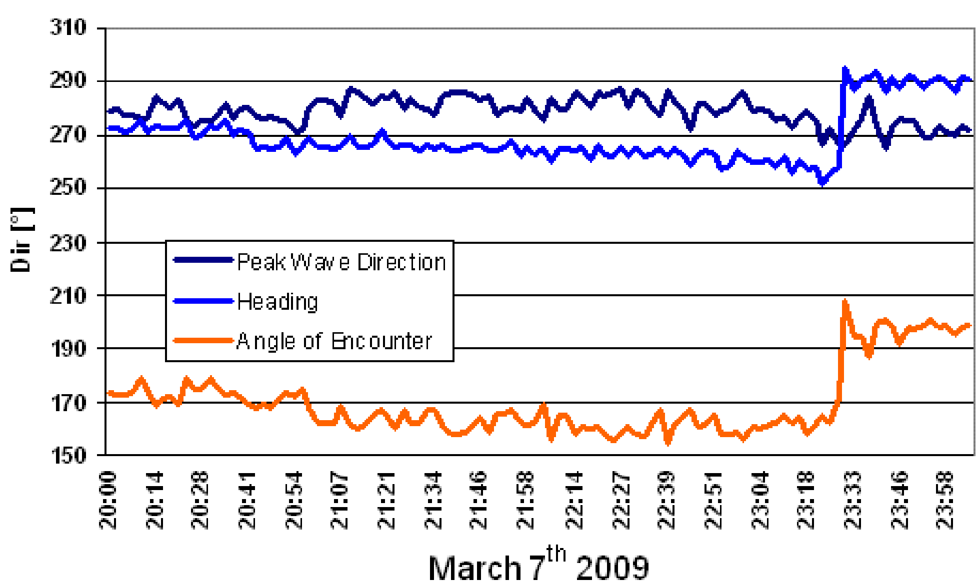

Fig.18 Peak wave direction, heading and angle of encounter (2-min-running mean). The heading was changed at the time of the rolling event.

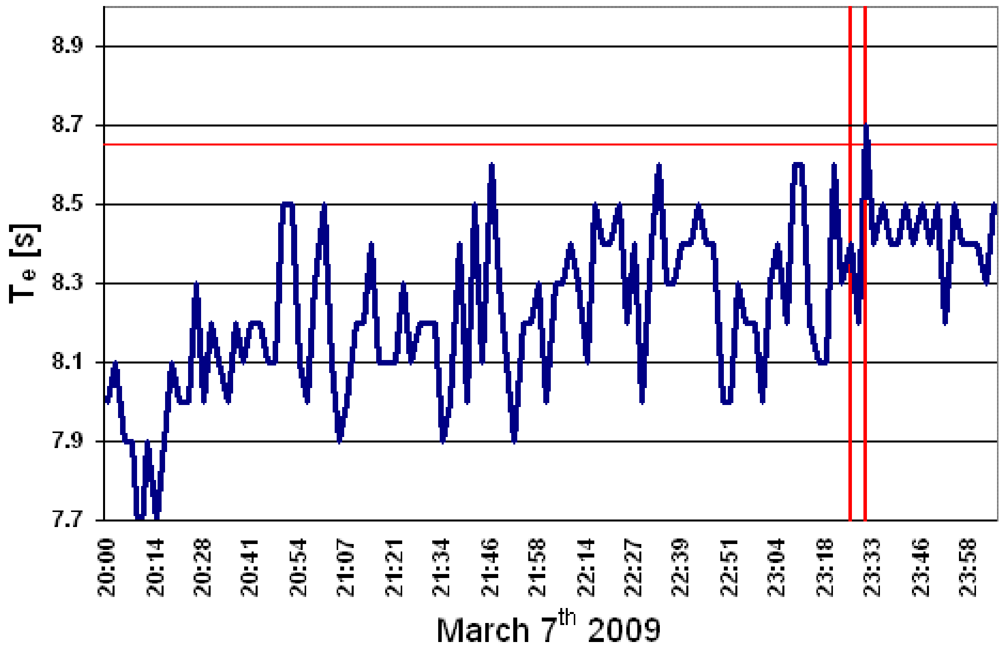

Fig. 19 Periods of encounter (2-min-running mean) relative to speed over ground (based on GPS-Positions). The rolling event is marked by vertical red lines. The horizontal red line corresponds to the critical value of 8.65s (half of the rolling period).

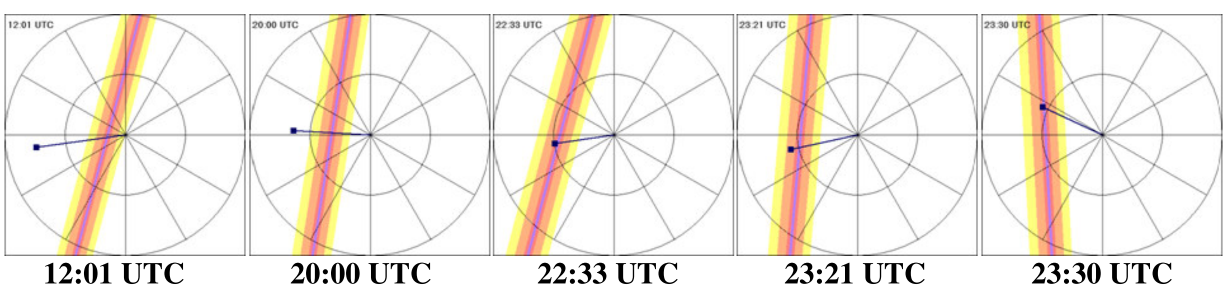

Fig. 20 Sequence of diagrams at different times on March 7th. The blue line represents the vessel's ground speed and heading. The coloured bar indicates regions of (near) resonance averaged over the preceding 2 minutes. At 23:30 UTC, shortly after the rolling event and the change of heading, the ship was still in danger. The resonance condition was also satisfied at 22:33 UTC without triggering heavy rolling.