Analysis of an Event of "Parametric Rolling" Onboard RV "Polarstern" Based on Shipborne Wave Radar and Satellite Data

Thomas Bruns, Susanne Lehner, Xiao-Ming Li, Katrin Hessner, and Wolfgang Rosenthal

***Abstract*—During the Antarctic summer season 2008/2009 the wave radar system WaMoS II was installed onboard of the German research vessel "Polarstern." The purpose was to collect quasi-*in situ* data for the comparison with satellite-borne SAR and altimeter instruments (Envisat, TerraSAR-X, Jason). The experiment was part of the German research project *DeMarine-Security*. On 7 March 2009 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, i.e., an oscillation about its length axis, 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 natural rolling period. We conclude that an onboard wave radar can be helpful in diagnosing and forecasting critical conditions.**

***Index Terms*— Ocean surface waves, parametric rolling, shipborne wave radar, synthetic aperture radar.**

I. INTRODUCTION

MOST of the goods produced worldwide 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 underwater 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 276-m long vessel "APL China" was hit by typhoon "Babs" in the North Pacific Ocean. Approximately 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 worldwide 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 of DWD and ECMWF (European Centre for Medium Range Weather Forecast) 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 II wave radar system is introduced in Section II. The experiment will hopefully result in improved algorithms to retrieve wave spectra and significant wave heights 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 Cape Town to Punta Arenas, is the main subject of this paper and will be analysed in detail in Sections IV and V. The theory of parametric rolling will briefly be reviewed in Section III.

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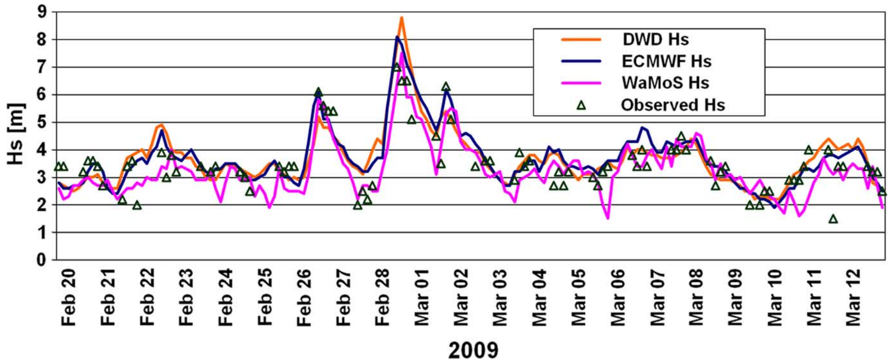

Fig. 1. Cut-out of time series (February/March 2009) of significant wave height measured by WaMoS II (violet), observed visually (green triangles) and analysed and forecast by DWD (orange) and ECMWF (blue).

II. 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 wavelength (λ_p) and peak wave direction (θ_p). 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. No images were recorded when the nearness of coasts, ship routes and icebergs required radar operation in long pulse mode. During the first two legs of ANT-XXV ([1] 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. As an example, Fig. 1 shows a time series of significant wave height measured by WaMoS II (1-hourly-average) during leg 3 in comparison with onboard visual observations, wave analyses and short-term forecasts (up to T+9h) by DWD and ECMWF. The correlation between wave models and WaMoS II exceeds the correlation between models and visual observations.

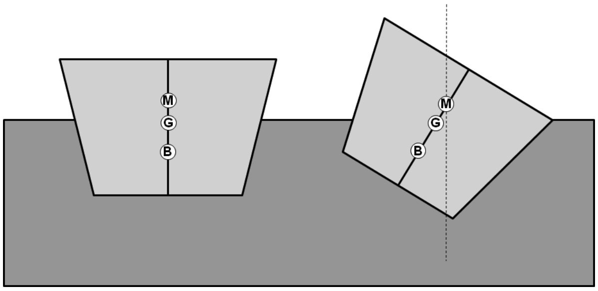

Fig. 2. Location of the center of gravity (G), the center of buoyancy (B) and the metacenter (M) of a ship.

III. 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. 2). 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 moment whose strength depends on the angle of inclination. The pivoting point of the corresponding moment 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 $\mathrm{GM_0}$. For small angles $\mathrm{GM_0}$ is assumed to be constant and determines the natural rolling period $\mathrm{T_R}$ at which the ship is swinging back to rest

$$\mathrm{T_R} = \mathrm{fB}(\mathrm{GM_0})^{-1/2} \tag{1}$$

where B is the breadth of the ship, and f is an empirical constant somewhere in the range from 0.75 to 0.8. B and $\mathrm{GM_0}$ are given in meters, $\mathrm{T_R}$ in seconds. In practice, it is difficult to evaluate $\mathrm{GM_0}$ without detailed knowledge of the ship’s shape and mass distribution. Moreover, $\mathrm{GM_0}$ and thus $\mathrm{T_R}$ may change at higher inclinations (for more details see [2] Barrass and Derrett, 2006 or [3] Comstock, 1967).

In the case discussed here it was easy to determine $\mathrm{T_R}$ empirically. From Fig. 13(a) (see Section V) we found a rolling period of 17.3 s, which was nearly constant over the hours preceding the event. Therefore, we consider this value as the natural rolling period of the vessel for the current loading.

In heading or following seas wave crests pass along the ship’s hull. If the wavelength is of the order of one to two ship lengths (“Polarstern”: 118 m) lateral stability depends strongly on the position of the crest. When the crest is located at the midship section the ends of the hull will emerge from the water and bend towards the wave troughs (“hogging”). In this situation

Fig. 3. Schematic view of a ship temporarily losing stability in a heading sea when “hogging” on a wave crest.

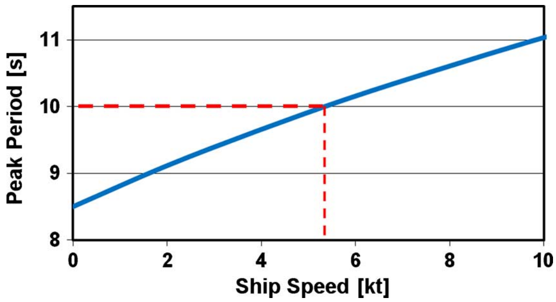

Fig. 4. Resonance condition for a rolling period of 17 s and waves coming directly from ahead. For example, the condition is fulfilled for a peak period of 10 s and a ship speed of 5.2 kn.

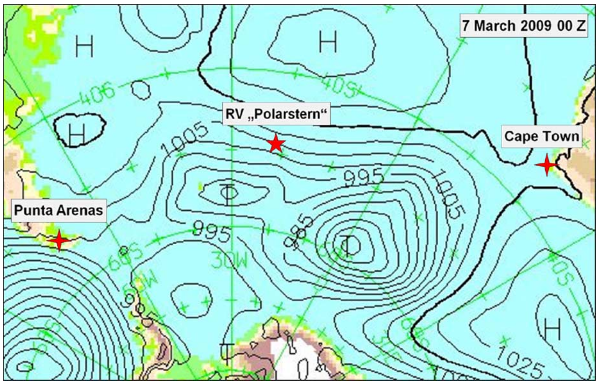

Fig. 5. Surface pressure analysis (ECMWF model) on 7 March 2009, 00Z and approximate position of RV “Polarstern.” Isolines are labeled in hektopascal.

the righting moments are reduced resulting in a significant loss of stability (see Fig. 3). Otherwise, stability will increase when the midship section 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 the “hogging” situation, i.e. with reduced stability, the ship is quite sensitive to relatively small excitations from the broadside. In the following phase of “sagging” stability increases rapidly such that 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” ([4] Ammersdorfer, 1998). From experiments in towing tanks it is known that parametric rolling may occur even under uniform wave conditions where lateral excitations are very small.

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

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

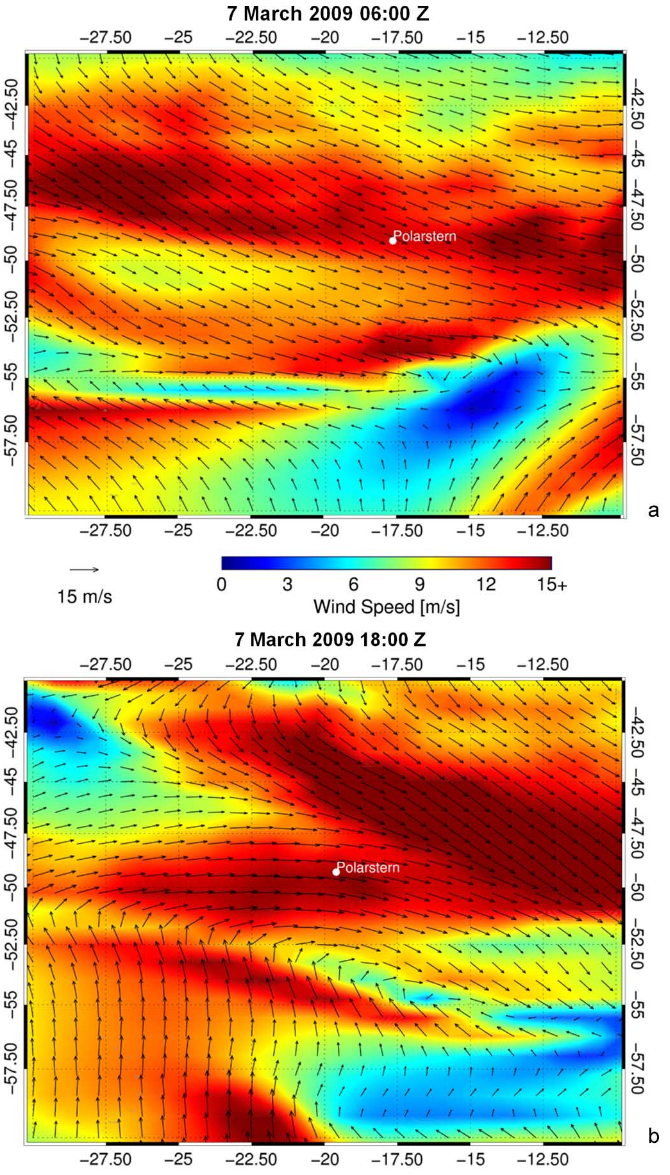

Fig. 6. Wind field derived from the DWD wave model for 7 March 2009: (a) 06:00Z and (b) 18:00Z (both 6-h forecasts).

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

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

$\mathrm{n} = 1 : \mathrm{T_E} = 1/2\ \mathrm{T_R}$:	This case typically occurs in heading seas.
$\mathrm{n} = 2 : \mathrm{T_E} = \mathrm{T_R}$:	This case typically occurs in following seas.

These criteria are not compelling but necessary conditions for parametric rolling.

Fig. 4 shows the relation between ship speed and peak period as a condition for resonance in the case $\mathrm{T_R} = 17\ \mathrm{s}$. Here, parametric rolling can be expected when the ship is heading against waves with $\mathrm{T_p} = 10\ \mathrm{s}$ at a speed of $\mathrm{V_s} = 5.2\ \mathrm{kn}$.

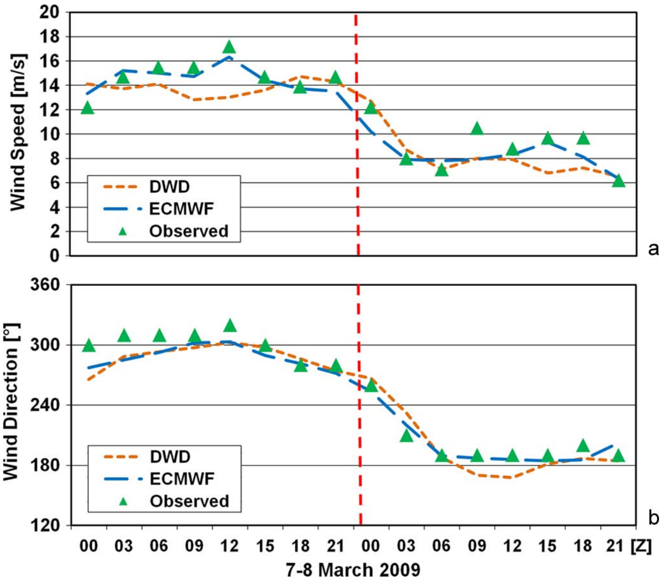

Fig. 7. Short-term (T+00 h to T+09 h) forecasts of the DWD and ECMWF models, anemometer measurements of three hourly (a) wind speed (observations reduced to 10 m) and (b) wind direction. The rolling event is marked by a vertical dashed line.

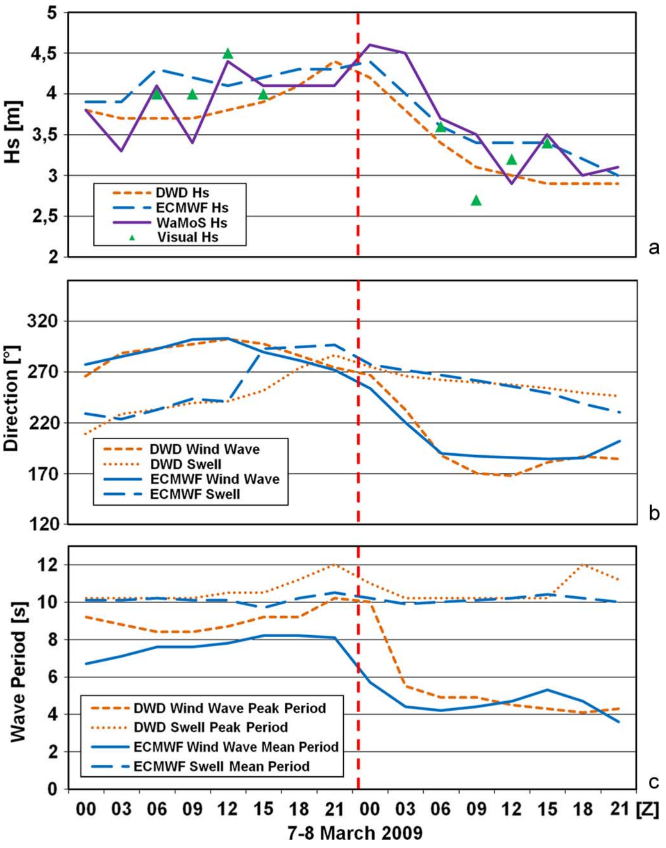

Fig. 8. Short-term (T+00 h to T+09 h) wave model forecasts of (a) Significant wave height compared to WaMoS II -measurements (three-hourly averages); and visual wave height observations (daytime only). (b) Wind sea and swell direction. (c) Periods of wind sea and swell. The rolling event is marked by vertical dashed lines.

Cross seas can play an important role in exciting parametric rolling. Interfering waves of similar periods may produce wave trains with extraordinary high amlitudes. The effect of these waves is twofold: On the one hand, heavy pitching reduces ship speed and also causes stronger lateral excitations. On the other hand, higher wave crests result in an amplified loss and gain of stability. Essential for the onset of resonant rolling is, however, the periodic recurrence of “hogging” and “sagging”. Thus, (2) is adequate for evaluating the observed rolling event.

IV. THE WEATHER SITUATION DURING THE ROLLING EVENT

Leg 3 of the Polarstern-Expedition ANT-XXV started on 8 January 2009 in Capetown. The destination was the sea area northeast of South Georgia, where a team of Indian and German scientists performed the iron-fertilization experiment “LOHAFEX” [5]. On 6 March 2009, the scientific work had been accomplished and the vessel was heading towards Punta Arenas. In the evening of 7 March 2009, 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 23:30Z. 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. . .”

The following description of the weather situation on 7–8 March 2009 is based on the operational ECMWF and DWD wave model analyses and short-term forecasts (“quasi-analyses”) up to T+09 h. Fig. 5 gives an overview over the large scale weather situation in terms of surface pressure as analyzed for 00Z by the ECMWF atmospheric forecast model. Throughout the day “Polarstern” was cruising between a large subtropic high and weakening and eastward moving low pressure systems.

At 06Z “Polarstern” was located in a region of relatively high winds (∼14 m/s) from northwest according to the DWD wave model [see Fig. 6(a)]. Twelve hours later wind had shifted west and slightly increased [see Fig. 6(b)]. An eastward moving frontal trough had passed the ship around midday. At the time of the rolling event the ships position was $49^\circ 22' \mathrm{S} 20^\circ 45' \mathrm{W}$.

In Figs. 7 and 8, model analyses are compared with the actually observed winds and waves over 48 h. In the first half of 7 March 2009, anemometer winds (reduced to 10 m) increased from 12 up to17 m/s around midday [see Fig. 7(a)]. In the second half of the day, winds slowly shifted more and more to a westerly direction [see Fig. 7(b)] and, shortly before the rolling event, decreased continuously to about 8 m/s on 8 March 2009. 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 [see Fig. 6].

The comparison between model wave heights, visual observations and WaMoS II -measurements [see Fig. 8(a)] is also quite satisfying. Total significant wave heights first varied

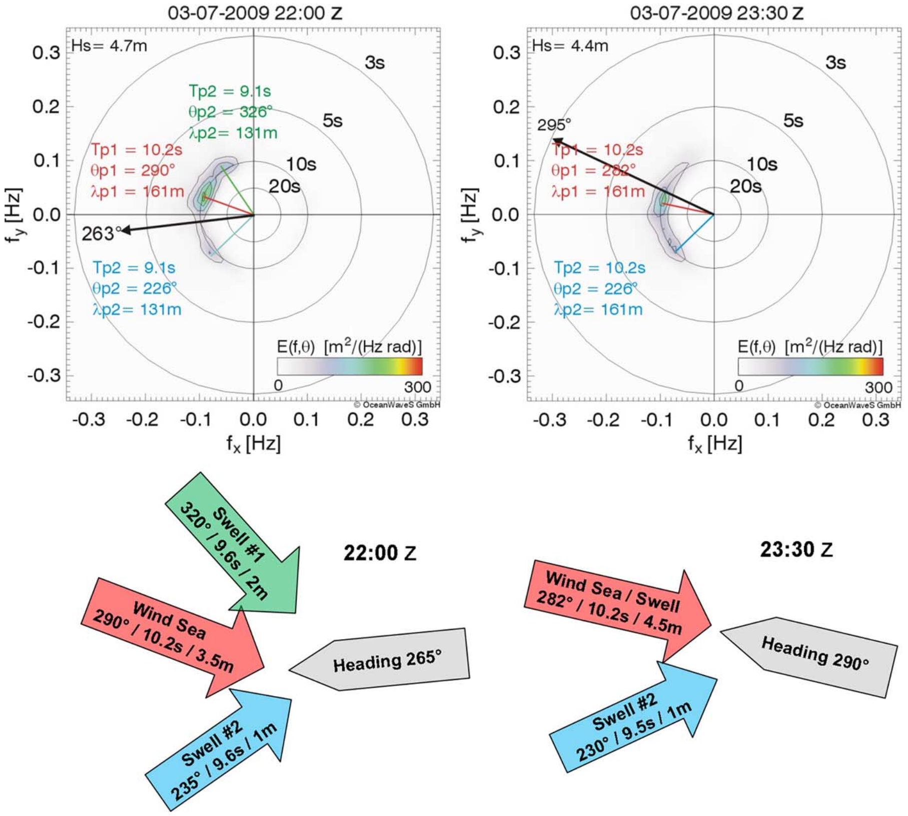

Fig. 9. Two-dimensional WaMoS II wave spectra representing the cross sea situation about 90 min before (22:00Z) and shortly after (23:30Z) the rolling event.

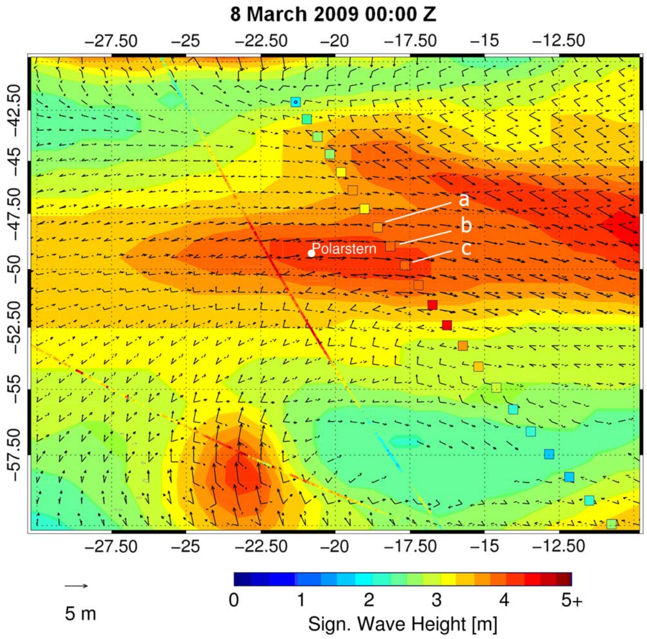

Fig. 10. Analysed wave field of the DWD wave model on 8 March 2009 at 00 Z. Background is the colour-coded significant wave height. Solid and dash-dot lines show the peak wave direction for wind sea and swell, while arrow lengths represent the corresponding wave heights. Superimposed are the tracks of ENVISAT SAR- and Radar-Altimeter measurements. Radar image spectra were derived for three track positions a, b and c (see Fig. 11).

around 4 m and then slightly increased to 4.5 m at the time of the event. The wind sea was first coming from northwest, shifted to west and reached up to 3.5 m (not shown), while the peak period (DWD) increased from 8.5 s to 10 s [see Fig. 8(c)]. Unfortunately, only mean wave periods were available from the ECMWF model. However, the tendency to longer waves is obvious here, too. A similar increase of the peak period was measured by WaMoS II. Because the wave model output resolves only one dominant swell component, we find a sudden shift of wave direction around 15 Z [see Fig. 8(b)]. This was probably because of a simultaneous vanishing of the southwesterly swell and increase of the northwesterly swell. Finally, we may conclude that the models were capable of describing the observed cross sea situation as well as the merging of the spectral peaks.

Additional confirmation of the reported cross sea situation is achieved from the two-dimensional WaMoS II wave spectra also indicating the existence of two swell peaks [see Fig. 9]. In the hours before the event, the measured spectra were characterized by a large directional spread. Besides the dominant wind sea peak (290°/10 s) two secondary swell peaks existed, one from southwest and the other from northwest (the direction of wind about 10 h ago). Shortly before the event, the latter peak began to change direction, i.e., it slowly merged with the wind sea peak.

Fig. 10 shows the large-scale sea state situation (DWD model) on 8 March 2009 at 00Z, 30 min after the rolling event. Superimposed on the plot are ENVISAT ASAR radar observations of significant wave height acquired during an ascending orbit around 0:04Z on 8 March 2009. Squares represent significant wave heights derived from ASAR by using the

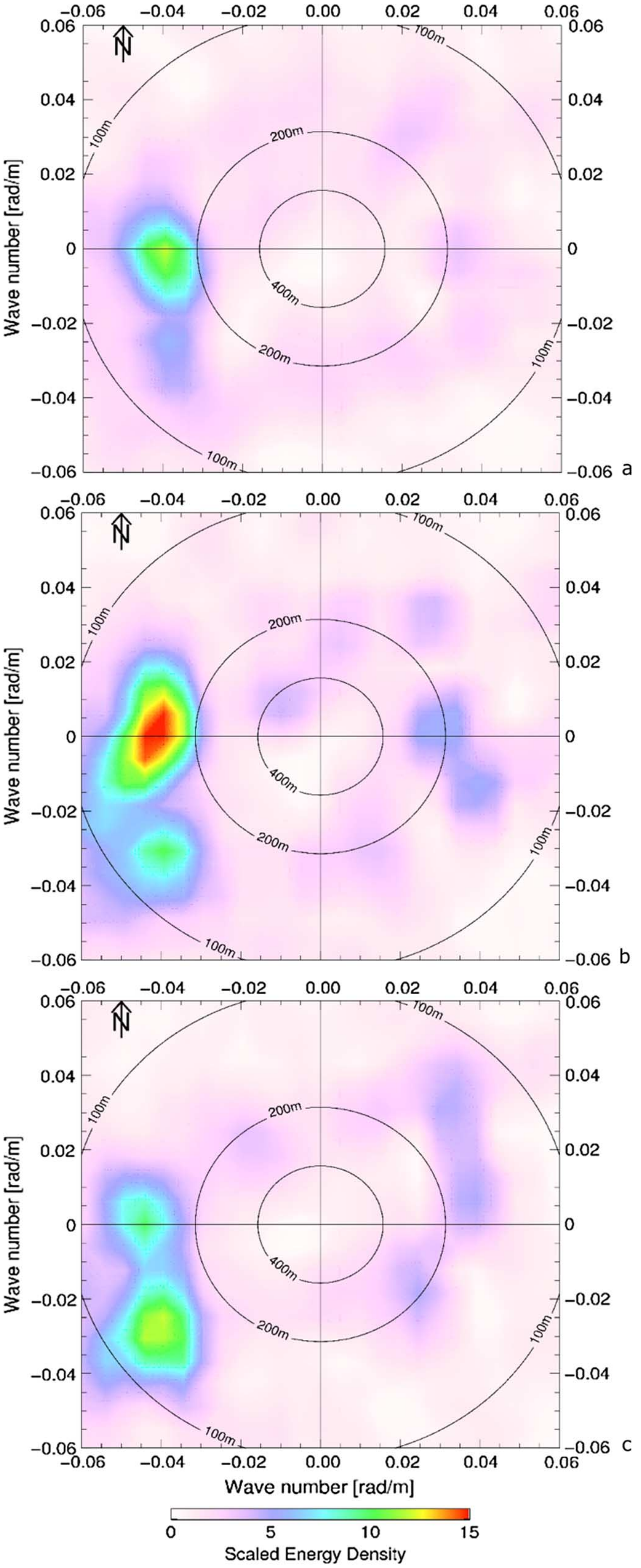

Fig. 11. Image spectra derived from ASAR wave mode data at three locations (see Fig. 10) east of the "Polarstern" position on 8 March 2009 at 00Z. The 180° ambiguity has been removed using the cross-spectral technique. Wave direction corresponds to the meteorological convention (waves are coming from).

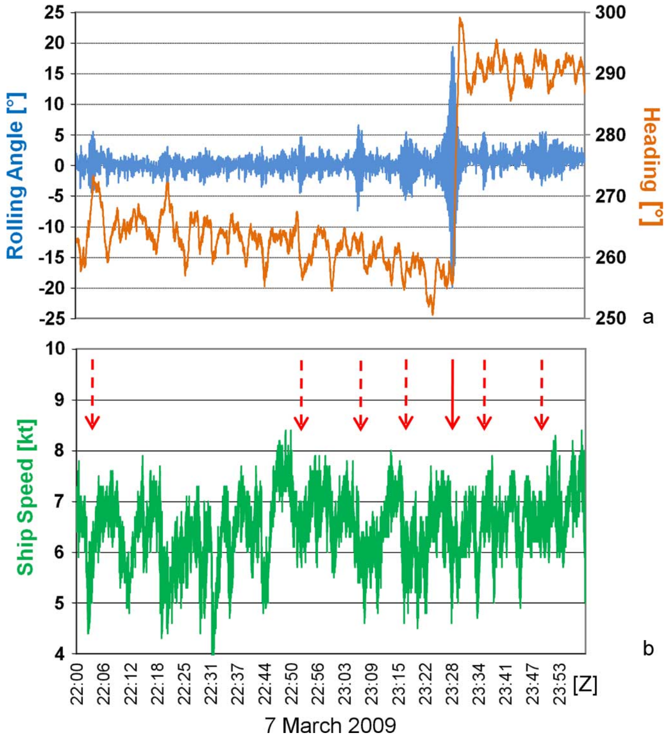

Fig. 12. High resolution (1 second) time series of rolling angle, gyro heading (a) and ship (ground) speed (b) of "Polarstern" on 7 March 2009 between 22:00 and 24:00Z. Arrows mark the beginning of extreme rolling and other near resonant events as well.

CWAVE_ENV algorithm ([6] Schulz-Stellenfleth 2007 *et al.*, [7] Li *et al.* 2009). The agreement between data and model is not convincing in this case, as model wave heights seem to be shifted northeastward by almost 2.5°. In the ECMWF-analysis (not shown) the area of high significant wave heights extends farther south in accordance with the satellite data. Near the position of the ship, however, both models reveal comparable results [see also Fig. 8]. The RA-2 (radar altimeter) nadir subsatellite track runs at a distance of about 300 km from (and parallel to) the ASAR track, as both instruments are onboard the same platform. Another track from radar altimeter JASON is also shown in the plot. Although this track is far from the research vessel, it can still be used for validating the DWD wave model.

Fig. 11 shows 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 nonlinear imaging effects, the directions and length scales are consistent with the wave model data. The correspondence with the WaMoS II -spectra [see Fig. 9] is also striking. 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.

V. Analysis of Ship Motions and Wave Encounter

"Polarstern" is equipped with a system continuously monitoring ship motions and scientific data as well. Fig. 12(a) shows that the rolling angle reached almost 20° during the reported 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

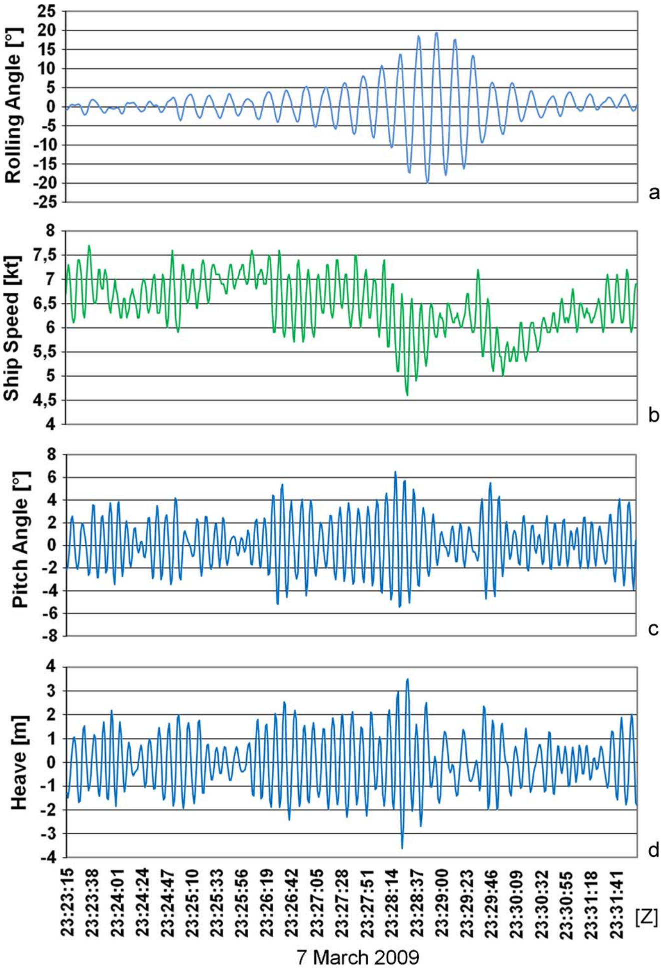

Fig. 13. High resolution (1 s) time series of ship motions between 23:23 and 23:32Z. The average rolling period estimated from this diagram is 17.3 s while the period of pitch and heave reached exactly half of it. This behaviour is characteristic for parametric rolling.

people to cling to anything that was available. A further growth of rolling amplitudes could finally be avoided when the mate on duty changed the heading 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. 12(b) 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.

Zooming into eight minutes around the extreme event, Fig. 13 shows rolling angle and ship speed 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 must have caused the pitching which in turn resulted in a reduction of speed and, according to (2), an increase of the period of wave encounter.

For a more detailed analysis, the time series of integrated wave periods and directions have been investigated. Standard output frequency of WaMoS II is every 2 min. Available were either instant data (averaged over 32 radar images) or 20-min 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 phase shifted, as well. Since the focus of this study is a particular event we will therefore use the instant data despite their higher variability.

The main peak period is derived from the one-dimensional wave spectrum. During the 3.5 hours before the rolling event the period slowly increased from 9.7 to 10.1 s [see Fig. 14(b)]. Simultaneously, the peak direction [see Fig. 14(a)] varied between 280° and 290° most of the time and finally approached 270°. As has been seen in Section IV, this change is in good correspondence with the change of wind direction. Therefore, the 1-dimensional peak obviously represents the wind sea part of the spectrum. On the other hand, periods and directions of secondary spectral maxima taken from the two-dimensional wave spectrum exhibit a quite erratic behaviour (not shown). The angle of encounter [see Fig. 14(a)] remained nearly constant in the last 30 min 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 ($\sim$2 min) between the GPS-positions stored by WaMoS II, assuming further that ocean currents were negligible. These speed values agree well with 2-min averages of the onboard Marine Integrated Navigation System (MINS).

A time series of the period of encounter, calculated from 2-min averages of the peak wave period, wave direction and ship speed is shown in Fig. 14(c). Due to the less variable wave period, fluctuations of this parameter mainly reflect variations of ship speed. A direct coincidence of a rolling event and a near resonant period of encounter will therefore be found only in those cases when speed variations are small within the 2-min averaging interval. Moreover, a time delay has to be considered as a consequence of the averaging.

The period of encounter stayed below the critical value of 8.65 s (half of the roll period) most of the time, but obviously there was an increasing disposition to rolling events and the period was getting close to the critical value for a couple of times. It was just a question of time that a wave train of exceptional high waves would decelerate the ship to a speed matching the resonance criterion.

During the event itself the encounter period was reduced, but shortly delayed it reached 8.7 s and we may assume that the condition for resonance was satisfied. Similarly, we also find a coincidence of the two maxima at 23:08Z and 23:21Z with the two minor events shown in Fig. 13. For the other minor events, however, such a good correspondence was not found. In any case, the minor events damped out before amplitudes could grow high, either because the triggering waves were not high enough to slow down the ship or because the wave train was too short or became irregular.

Fig. 14(d) illustrates the increasing danger in the course of the day in a sequence of resonance diagrams. The diagrams shown

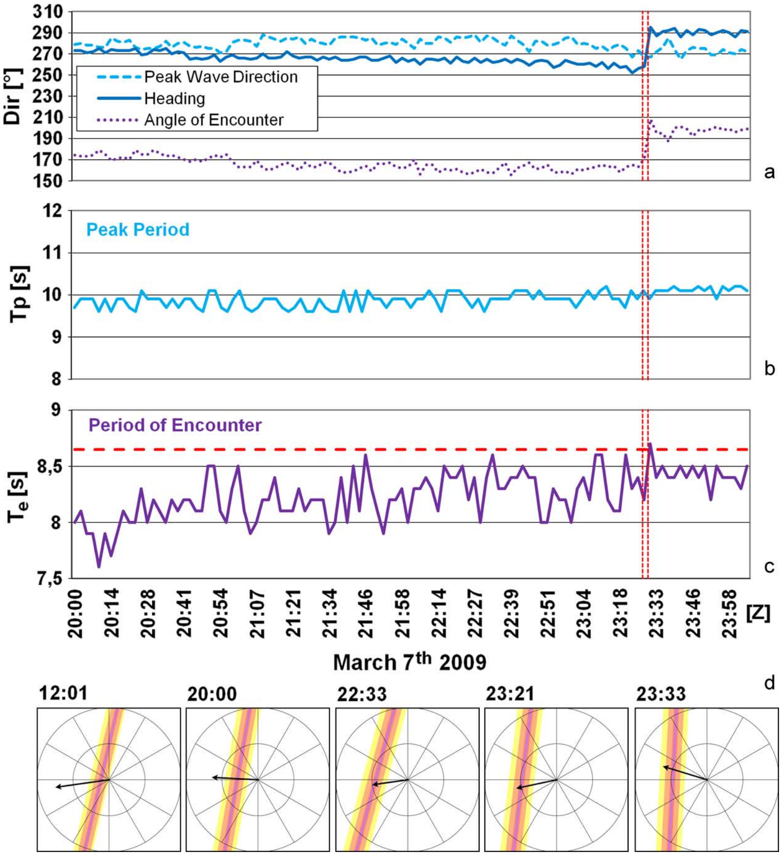

Fig. 14. Analysis of wave encounter. (a) Peak wave direction, heading and angle of encounter (2-min-running mean). The heading was changed at the time of the rolling event (marked by vertical dashed lines). (b) Peak wave period. (c) Periods of encounter (2-min-running mean) relative to speed over ground (based on GPS-Positions). The horizontal line corresponds to the critical value of 8.65 seconds (half of the rolling period). (d) Sequence of resonance diagrams at different times on 7 March 2009. The arrow indicates the vessel’s ground speed and heading. The shaded bar indicates regions of (near) resonance averaged over the preceding 2 min. At 23:33Z, shortly after the rolling event and the change of heading, the ship was still in danger. The resonance condition was also satisfied at 22:33Z without triggering heavy rolling.

here visualize (2) in Section III. They combine the vessel’s ground speed and heading with regions of (near) resonance $(\mathrm{T_E} \sim 1/2\ \mathrm{T_R})$. 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 and wave periods (see Fig. 8) slowly increased resulting in a speed reduction. The situation first became critical at 22:33Z but no heavy rolling was observed at that time.

With the change of the course the phase relation between the variations of ship stability and wave trains was distorted and the rolling was damped—probably coinciding with the end of a high wave train. However, the danger of parametric rolling remained even after the event.

VI. CONCLUSION

An event of parametric rolling that occurred during the “Polarstern” voyage ANT-XXV on May 7 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 one-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 23:30Z, but it could have occurred already earlier (after 21:45Z) under conditions close to resonance. As the rolling coincided with heavy pitch and heave motions the event was presumably triggered by a group of exceptional high waves that may have resulted from the interference of the two wave regimes of similar direction and period. It must be pointed out, however, that interference of much longer and even higher waves would not have caused parametric rolling.

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., [8, Benedict, 2004]) already exist to support navigational decisions in critical situations based on resonance diagrams such as those shown in Fig. 14. Input data are either wave parameters estimated by eye or numerical wave forecasts in case of advanced systems. Our analysis has shown that wave models indeed have the potential to forecast the probability of resonance. In combination with an onboard wave radar a further improvement could be achieved.

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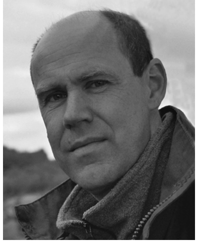

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