CHAPTER 29

Effects of the Gulf Stream on nearby coastal waves

L.H. Holthuijsen[1] and H.L. Tolman[2]

Abstract

In the present study a third-generation numerical wave model is used to study effects of a straight Gulf Stream and a Gulf Stream ring, on ocean waves along the coast in swell and storm conditions. The model accounts for all relevant processes of propagation, generation and dissipation of the waves (including current effects) without imposing a priori restraints on the spectral development of the waves. The dominating mechanism affecting the waves appears to be current induced refraction even though the short-crestedness of the incoming waves tends to mask its effects. Depending on wind and wave conditions, refraction may trap locally generated waves in the straight Gulf Stream or it may reflect wave energy back to the open ocean. In the Gulf Stream ring, refraction induces a considerable variation in significant wave height and short-crestedness but it hardly affects the mean wave direction. In storm conditions the processes of generation and dissipation are considerably enhanced in counter-current situations and reduced in following-current situations.

1. Introduction

Observations from ships, aircraft and spacecraft show that ocean waves approaching the east coast of the United States are affected by the presence of the Gulf Stream (e.g. Meadows et al., 1983; McLeish and Ross, 1985; Mapp et al., 1985). The currents tend to create a confused sea state, often with waves that are higher than the incoming waves. In this study a distinction is made between a straight Gulf Stream and a Gulf Stream ring. In the straight Gulf Stream, the wave-current interactions will obviously modify the waves uniformly along the coast whereas down-wave from the ring, the along-shore variations may be appreciable. Several studies have

[1] Delft University of Technology, Department of Civil Engineering, P.O. Box 5048, 2600 GA Delft, the Netherlands

[2] Delft University of Technology, presently at NASA, Goddard Space Flight Center, Laboratory for Atmospheres, Code 911, Greenbelt, MD 20771, U.S.A.

been carried out to model such modifications of waves across a shear-current or a ring (e.g. Kenyon, 1971; Gutshabash and Lavrenov, 1986; Mathiesen, 1987) but no attempt seems to have been made to include the effects of wind. We therefore use in the present study a numerical wave propagation model extended with source terms representing wave generation and dissipation to propagate waves across a straight Gulf Stream and across a Gulf Stream ring in swell and storm conditions.

2. The wave model

The wave model which we use is a numerical wave prediction model for random, short-crested waves in arbitrary conditions of wind, currents and bathymetry (Tolman, 1989, 1990a, 1990b). It is a discrete spectral wave model accounting for such wave-current interactions as Doppler shifts, radiation stresses and current-induced refraction. It also explicitly models all relevant processes of wave generation by wind and dissipation by white-capping, including an explicit treatment of the nonlinear resonant wave-wave interactions (the WAMDI group, 1988). The model is based on the discrete spectral action balance (e.g. Hasselmann et al., 1973):

$$\frac{\partial N(\omega,\theta)}{\partial t} + \frac{\partial C_x N(\omega,\theta)}{\partial x} + \frac{\partial C_y N(\omega,\theta)}{\partial y} + \frac{\partial C_\omega N(\omega,\theta)}{\partial \omega} + \frac{\partial C_\theta N(\omega,\theta)}{\partial \theta} = \frac{S(\omega,\theta)}{\sigma} \tag{1}$$

where $N(\omega,\theta)$ is the action density of the waves as a function of absolute frequency ω and direction of wave propagation θ (normal to the wave crest) and σ is the relative frequency (as observed in a frame of reference moving with the current).

The left hand side of Eq. 1 represents the local rate of change of the action density (first term), rectilinear propagation in geographic space (second and third term with C_x and C_y), shifting of the absolute frequency due to time variations in depth and currents (fourth term with C_ω) and refraction (fifth term with C_θ). The propagation speeds in geographic space (C_x and C_y) are the group velocity components in x- and y-direction respectively (current speed included). The propagation speeds C_ω and C_θ are given by (Christoffersen, 1982; Mei, 1983):

$$C_\omega = \frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial t} + \underline{k}\cdot\frac{\partial \underline{U}}{\partial t} \tag{2}$$

$$C_\theta = -\frac{1}{k}\left[\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial m} + \underline{k}\cdot\frac{\partial \underline{U}}{\partial m}\right] \tag{3}$$

in which d is depth, $\underline{k}$ is the wave number vector, $\underline{U}$ is the current velocity vector and m is a coordinate orthogonal to the wave direction. These propagation speeds fully account for the depth and current effects on propagation within the linear theory of slowly-varying surface gravity waves. The depth induced variations of C_x and C_y are normally referred to as "shoaling". To include the current induced variations we use the term "straining" instead. We consider stationary situations in deep water so that all terms involving finite depth and time derivatives of the current are zero (i.e. no shoaling, no depth refraction and no shift of absolute frequencies).

The right hand side of Eq. 1 (the net production of wave action) represents all effects of generation and dissipation of the waves. The processes which are included in the model are:

wave generation by wind (Snyder et al., 1981), nonlinear resonant wave-wave interactions (Hasselmann, 1960; Phillips, 1960), white-capping (Komen et al., 1984) and bottom induced dissipation (Madsen et al., 1988). The actual formulations which are used are those of the WAM model (the WAMDI group, 1988) except for the formulation of the bottom dissipation (but as it has no relevance for the present study, it will be ignored in the following). The model is therefore, like the WAM model, a third-generation wave model in which the wave spectrum develops free of any a priori restraints. All of these processes of generation and dissipation are formulated in a frame of reference moving with the current (implying the use of the relative wind speed). The effects of currents are accounted for by a Jacobian transformation of the computed source term $S(\omega,\theta)/\sigma$ to a stationary reference frame in each time step in the model. The numerical schemes that are used to propagate the waves are predominantly second-order accurate (also refraction). Occasionally the schemes reduce to first-order accuracy when the gradients in the wave field are too sharp. The geographic resolution of the model is $\Delta x = \Delta y = 13.9$ km for the straight Gulf Stream and 15 km for the ring respectively. The spectral resolution is $\Delta f = 0.1 f$ in frequency and $\Delta\theta = 15^0$ (storm cases) and $\Delta\theta = 7.5^0$ (swell cases) in direction. The time step is $\Delta t = 7.5$ min.

3. The Gulf Stream

The current field for this study has been provided by Scott Glenn of Harvard University who used the Harvard Gulf Stream Forecasting Program (Glenn et al., 1987; Robinson et al., 1988) with the Gulf Stream at its climatological location and a warm core ring in a typical location. The currents thus obtained vary sufficiently slowly in time to treat the current field as stationary. For reasons of computational capacity the wave hindcast experiments have been carried out for an infinitely long and straight Gulf Stream and for a ring separately. To obtain the infinitely long, straight Gulf Stream we synthesize a 150 km-wide transverse surface-current profile by averaging the surface-current profile of the forecasted Gulf Stream over a 250 km-long section (Fig. 1). For convenience of discussion, we take the current in this synthesized Gulf Stream to run from south to north (the actual direction is immaterial as only the relative directions of waves and currents are relevant). The surface-current field of the ring (radius to maximum current about 45 km) has been obtained by isolating a 250 x 250 km^2 area from the forecasted field (Fig. 2).

4. The waves

We take uniform wave boundary conditions at the open-ocean side of the current fields (some distance up-wave from the current-boundary). The wave condition there are characterized in the storm (wind speed at 10 m elevation $U_{10} = 20$ ms^{-1}) with a two-dimensional JONSWAP spectrum (Hasselmann et al., 1973) of nearly fully developed waves with a $\cos^{2s}((\theta-\theta_0)/2)$-directional energy distribution. The value of the directional width parameter s is taken from Hasselmann et al. (1980). The swell is characterized with a Gaussian-shaped frequency energy spectrum (standard deviation σ_f) and a $\cos^{20}(\theta-\theta_0)$-directional energy distribution. Details of the spectral characteristics are given in Table 1. We consider two incoming wave directions relative to the Gulf Stream (swell and storm): 45° from a counter-direction (i.e. waves from north-east) and 45° from a following direction (i.e. waves from south-east). In the case of the ring the direction of approach is not relevant as the current field is practically rotationally symmetrical. We therefore consider for the ring only one mean wave direction (from east to west for convenience of the discussion).

spectral characteristics		**storm**	**swell**
peak frequency	f_{peak}	0.073 Hz	0.071 Hz
peak width	σ_a σ_b σ_f	0.07 0.09 --	-- -- 0.007 Hz
peak enhancement	γ	1.49	--
sign. wave height	H_s	8.10 m	1.99 m
directional width	σ_θ	34.5^0	12.4^0

Table 1. The spectral characteristics of the wave boundary conditions in the storm and swell cases. For the definition of σ_a, σ_b and γ see Hasselmann et al. (1973).

5. Results for the straight Gulf Stream

5.1 Waves from NE

In the NE swell case the significant wave height shows rather small variations (Fig. 1). An analytical inspection for a monochromatic wave with the same frequency as the peak frequency of the incoming waves shows that this mild variation is mostly due to the opposing effects of refraction on the one hand (which would decrease the significant wave height in the centre of the Gulf Stream) and straining and radiation stresses on the other (which would increase the significant wave height there). The mean wave direction turns only 6^0 at the centre of the Gulf Stream (more orthogonal to the current) where they are slightly more long-crested than at the open ocean side (quantified with the rms directional width σ_θ of the energy distribution of 12.2^0 versus 9.5^0). The wave field has returned to its undisturbed state after crossing the Gulf Stream.

In the NE storm case the significant wave height increases across the Gulf Stream with an overshoot at the center of the Gulf Stream (Fig. 1) and the relative variations are much larger than in the above swell case. The variations in the other wave parameters such as the mean

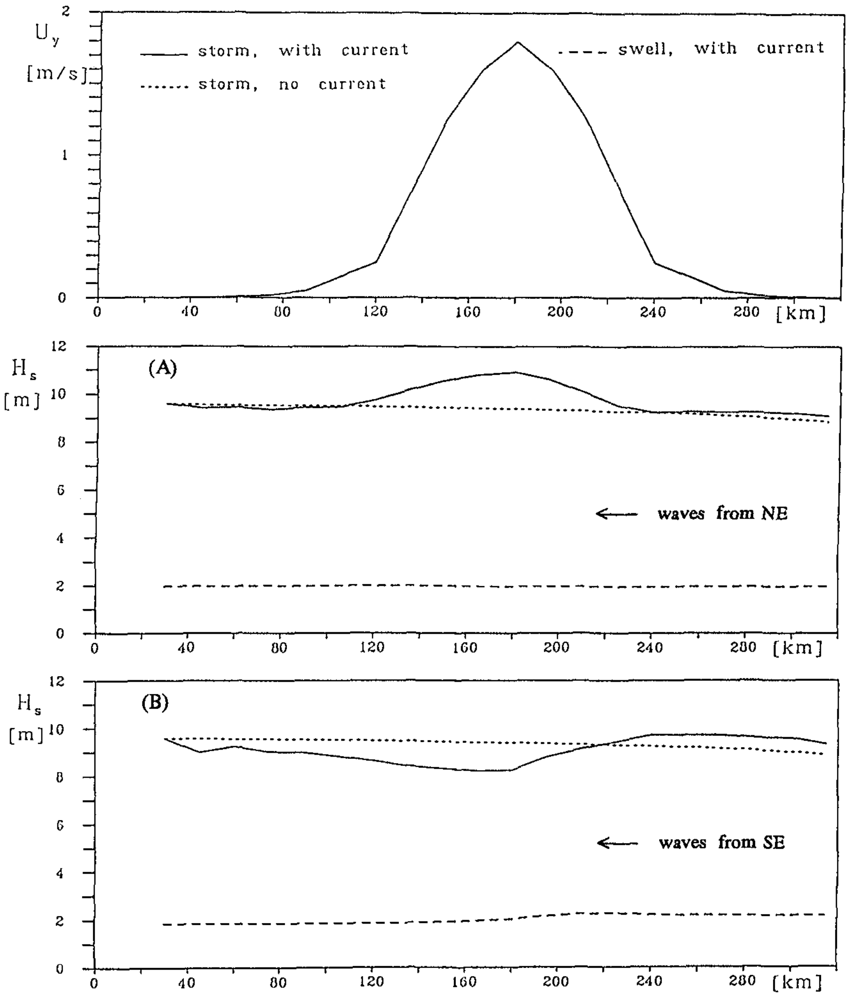

Fig. 1 Profiles in the straight Gulf Stream: current speed (U_y) and significant wave height (H_s). Panel A: waves from counter-current direction (NE). Panel B: waves from following direction (SE).

wave direction are also rather different from those in the swell case. In fact the tendencies are opposite to those in the swell case (e.g. waves turn counter-clockwise towards the centre of the Gulf Stream instead of clock-wise). An inspection of the two-dimensional spectra in this case shows that this is due to wave energy from northerly directions which is added to the incoming spectrum. An analytical inspection shows that this energy propagates along undulating wave rays near the center of the Gulf Stream. It is locally generated hy the wind and cannot escape (it is trapped). Our computations therefore confirm the possihility of trapping locally generated waves as suggested earlier by Johnson (1947) and Kenyon (1971). In this storm case the generation and dissipation are much more active in the Gulf Stream than outside the Gulf Stream (in the centre the wind input is enhanced by 48%, dissipation hy 80% and nonlinear interactions hy 96%, compared with the undisturbed situation). These considerahle effects are probahly due to a large extent to the trapping of the locally generated waves. They increase the wave steepness, thereby increasing the nonlinear wave-wave interactions and the white-capping. The increase in apparent wind speed (due to the counter-current) may also have some effect.

5.2 Waves from SE

If swell enters the Gulf Stream from the SE direction, the variations in the wave field are somewhat larger than in the NE case (Fig. 1). The behaviour of the significant wave height to increase up-wave from the Gulf Stream and to decrease down-wave from its centre is related to the reflection of some wave energy hack to the open ocean. This is clearly visihle in the two-dimensional spectra at various locations (not shown here). It is also noticeahle in the short-crestedness: the reflected waves travel across the incoming waves at the open ocean side and consequently increase the short-crestedness there (σ_θ increases from the undisturhed value of 12.4° to 24.9°). Beyond the center of the Gulf Stream the ahsence of the reflected energy turns the mean wave direction slightly counter-clockwise. The spectrum there has a correspondingly narrower directional distrihution. Such reflection in a straight (or meandering) shear current is a well-known phenomenon (e.g. Kenyon, 1971; Jonsson and Skovgaard, 1979; Hayes, 1980; Irvine and Tilley, 1988).

In the case of the SE storm, the variations in the wave field are fairly similar to those in the above swell case and reflection is even more important than in the swell case (Fig. 1). This is evident in a sharp decrease of the computed significant wave height near the center of the Gulf Stream and some increase at the up-wave side of the Gulf Stream. However, at some distance beyond the Gulf Stream the wind has generated sufficient wave energy to compensate the reflected energy. In contrast to the NE storm, the intensity of all processes of generation and dissipation are somewhat reduced in the center of the Gulf Stream compared with the undisturbed situation and somewhat enhanced at the boundaries. This is probahly due to the current-induced decrease in wave steepness in the following current (lower and longer waves) and a reduction of the apparent wind speed.

The above effects of the Gulf Stream are uniform along the coast so that no variations occur in the wave field along the coast (only across the Gulf Stream). In a more realistic, meandering Gulf Stream, along-shore variations will occur. The wave field in the most extreme meander, a ring, is considered next.

6. Results for the Gulf Stream ring

In the swell case for the ring, the significant wave height increases from 2.0 m up-wave from the ring to 2.7 m just down-wave from the counter-current region and it decreases to 1.4 m just beyond the following-current region (Fig. 2). A ship may therefore encounter nearly a doubling of the significant wave height when travelling from south to north along the lee side of the ring in this situation. In the storm case the pattern of the significant wave height is fairly similar to that in the swell case but with some obvious differences (Fig. 3). The location and extent of the perturbation of the wave field is more confined to the ring and the relative variations are smaller (but still considerable). The variations are largest within the ring (storm case) or just down-wave from the ring (swell case). From there they dampen in the down-wave direction to a situation almost equal to the undisturbed situation (in all respects except that some bimodality in the directional energy distribution is maintained; not shown here). The extent of the disturbance is about one ring diameter in the storm case down-wave from the ring (90 km, affecting coastal waves only if the coast is within this range) whereas in the swell case the effects are still noticeable after two ring diameters (180 km, affecting coastal waves only if the coast is within this range). These wave height variations are well understood from refraction and straining effects. Refraction induces convergence of wave propagation in and beyond the counter-current region and divergence in and beyond the following-current region. Fig. 4 shows the ray pattern for a monochromatic wave with the same frequency as the peak frequency of the swell propagating across the ring. The regions of ray convergence and divergence just beyond the regions of counter-current and following current respectively correspond well with the areas of maximum and minimum significant wave height in the swell case. Such convergence and divergence of wave rays has also been shown by others (e.g. Mathiessen, 1987). The differences in extent and location of the wave field disturbance between the swell case and the storm case seems to be mostly due to the difference in short-crestedness of the incoming waves (see below).

The mean wave direction varies only mildly across the ring (12° maximum in the swell case) and it returns to nearly its undisturbed value at a few diameters distance beyond the ring (swell case) or earlier (storm case). This mild variation of the mean wave direction seems to contrast with the strong refraction effects in the wave ray pattern of Fig. 4. Not only is this variation milder than the variation of individual ray directions, it is also not as lasting as the ray pattern suggests. The reason is that beyond the areas of divergence and convergence, the refracted rays diverge so that the energy represented by these rays decreases and the undisturbed rays dominate. In other words, the divergence of the refracted rays dilutes any effect that they may have on the mean wave direction. In addition, beyond the ring the short-crestedness of the incoming waves mixes disturbed and undisturbed wave components rapidly. It also determines the extent and location of the ring-induced disturbance of the wave field. These effects are stronger in the storm case (with a relatively wide directional energy distribution of the incoming waves, $\sigma_\theta = 34.5^0$) than in the swell case (with a relatively narrow directional energy distribution of the incoming waves, $\sigma_\theta = 12.4^0$). Across the ring the short-crestedness varies

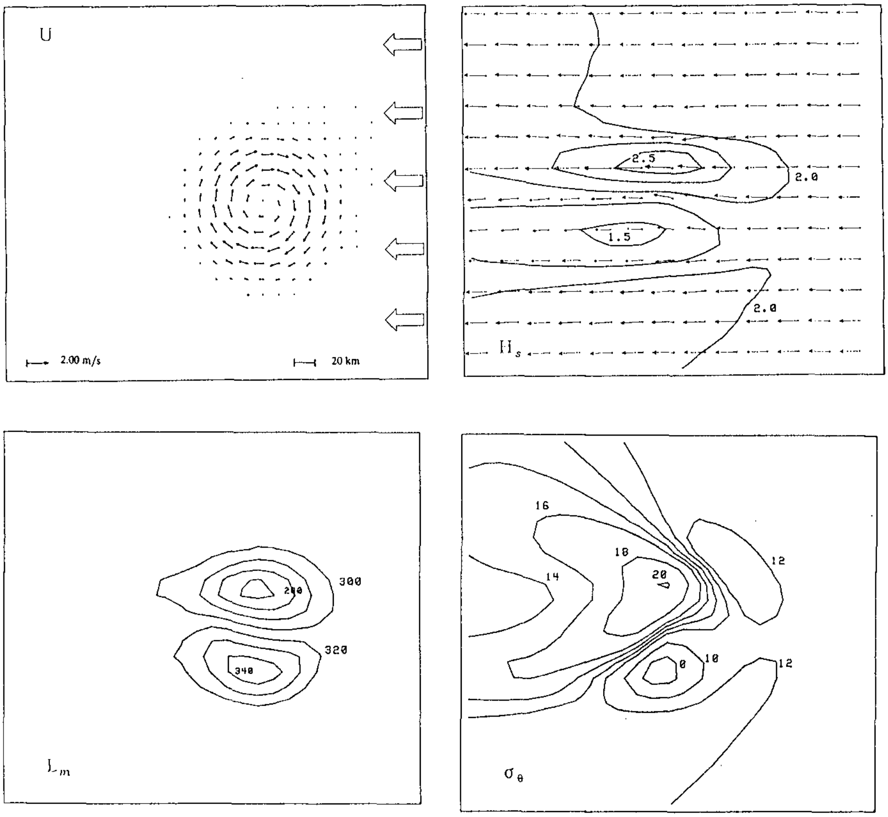

Fig. 2 Contour line plots in the ring area for swell: significant wave height (H_s in m), mean wave length (L_m in m) and directional spread (σ_θ in °). Vectors indicate current and mean wave direction.

considerably in the swell case. In the storm case it varies only slightly. Well defined cross-seas (i.e. bimodal spectral directional energy distributions) occur only beyond the counter-current region in the swell case.

Again, as in the Gulf Stream storm cases, the physical processes of wind generation, dissipation and nonlinear wave-wave interactions are considerably affected by the currents. Compared with the undisturbed situation, the wind input is enhanced by 46% (maximum, near the maximum counter-current) and reduced with 26% (minimum, near the maximum following-current). The dissipation is similarly enhanced or reduced with 89% and 46% and the nonlinear wave-wave interactions by 80% and 45% respectively. The computations show that the work done by the radiation stresses when the waves enter the ring is returned when the waves leave the ring.

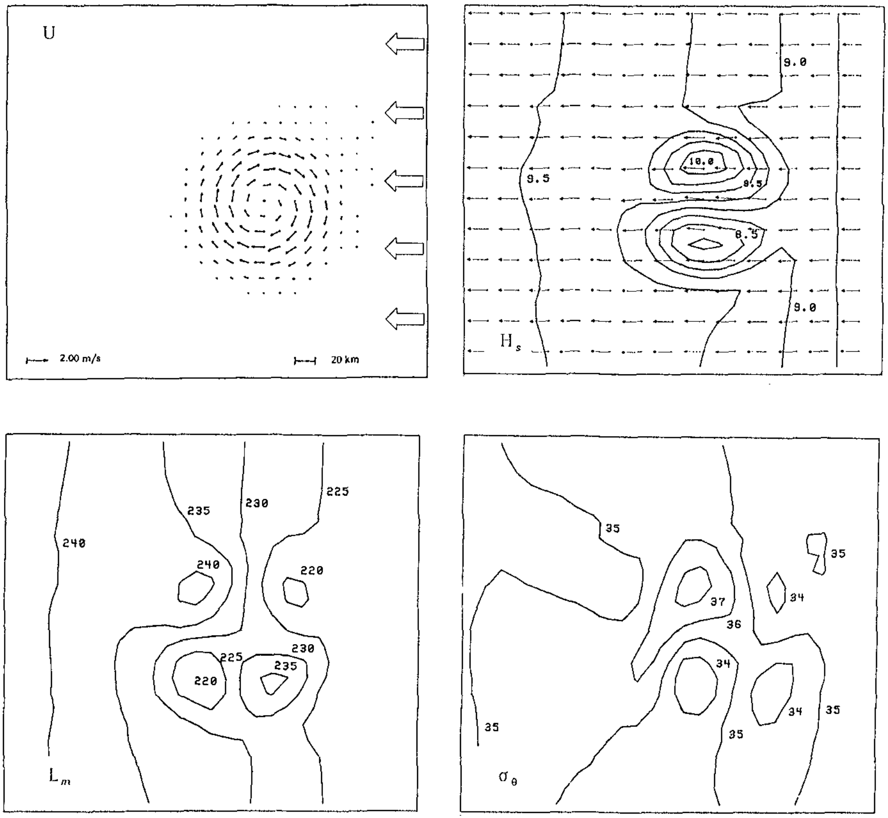

Fig. 3 Contour line plots in the ring area for storm condition: significant wave height (H_s in m), mean wave length (L_m in m) and directional spread (σ_θ in °). Vectors indicate current and mean wave direction.

7. Conclusions

If waves from the open ocean travel across the straight Gulf Stream, refraction is the dominating mechanism affecting the waves. Its most notable effect is the trapping of locally generated waves in an adverse-wind situation (wind against the current) and reflection of incoming waves if waves approach from a following direction (waves travelling with the current). In a Gulf Stream ring, refraction affects considerably the significant wave height and the short-crestedness but it affects the mean wave direction only slightly. Well-defined cross-seas occur beyond the ring in swell conditions but not in storm conditions. These effects are not as persistent as refraction computations for monochromatic, unidirectional waves suggest.

In fact, they disappear after a few ring diameters due to the diluting effect of frequency and direction dispersion of the waves. Along the United States east coast the presence of the Gulf Stream will therefore be noticeable in the wave field only from an occasional reduction of incoming swell and from along-shore swell variations at the lee-side of nearby rings (or meanders). In storms practically no effects on the wave field along the coast will be noticeable.

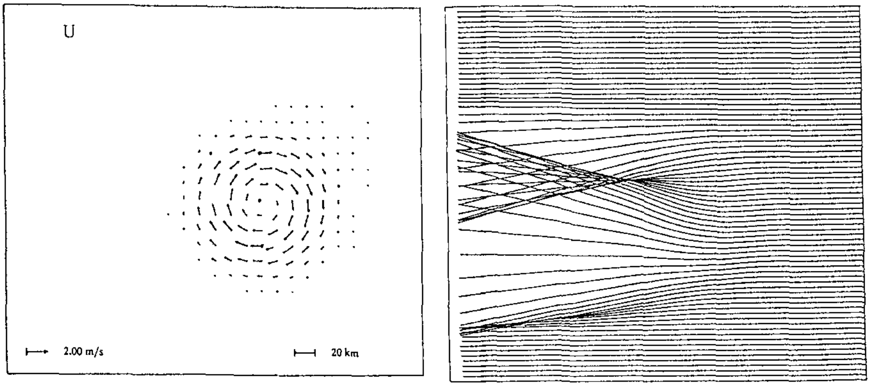

Fig. 4 Wave ray pattern for a 14 s period wave crossing the Gulf Stream ring of this study (courtesy Delft Hydraulics).

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