Delft Hydraulics Laboratory
Ministry of Transport and Public Works
Royal Netherlands Meteorological Institute

Wave prediction modelling for the North Sea

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Raad van Overleg
voor het Fysisch Oceanografisch Onderzoek van de Noordzee

Final Report Project G 2
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To the Reader

This Summary contains the complete text of the Final Report "Wave prediction modelling for the North Sea". However, it does not contain the Appendices.
The complete Report (in two Volumes) is available for reading at the libraries of the following Institutes:

- Delft Hydraulics Laboratory
  (Waterloopkundig Laboratorium, Delft en Marknesse)
- Ministry of Transport and Public Works
  (Rijkswaterstaat, Dienst Getijdewateren, Den Haag)
- Royal Netherlands Meteorological Institute
  (Koninklijk Nederlands Meteorologisch Instituut, De Bilt)

WAVE PREDICTION MODELLING FOR THE NORTH SEA

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General Introduction

In the beginning of the seventies, J.W. Sanders started to develop at the Royal Netherlands Meteorological Institute (KNMI) the wave prediction model GONO (GOlven NOordzee) together with its operational system (Sanders, 1976, 1979). In the following years the model was extended with shallow water effects, necessitated by its application in the southern part of the North Sea. A first operational verification of GONO at that stage of development has been reported by Saraber (Saraber, 1980). At the end of the seventies further developments and evaluations of GONO took place in a joint effort by Delft Hydraulics Laboratory (DHL), the Ministry of Transport and Public Works (RWS), and KNMI (Sanders et al., 1980). This latter within the framework of "Thematiek 2" of the first medium-term plan (MLTP) of the "Raad van Overleg voor het Fysisch Oceanografisch Onderzoek van de Noordzee", a council for physical-oceanographic research in the North Sea. Near the end of the first medium-term plan, a Working Group with representatives of DHL, KNMI, RWS, and Delft University of Technology (THD) was set up with the task to develop plans for future development and improvement of wave prediction techniques. At the same time, Holthuijsen (THD) was performing a desk study of wave forecasting methods (Holthuijsen, 1980). The Working Group in her final report (Note RWS WWKZ-79G.009) proposed the realisation of a sophisticated (2nd generation) operational numerical wave prediction model for the North Sea, needed for:

- day to day wave forecasts with applications to storm warning systems, ship-traffic control, ship routeing, and offshore activities,
- wave climate studies with applications to the design and management of maritime structures, coasts, harbours, and harbour entrance channels.

To achieve the goal set in her proposal, the Working Group recommended a phasic approach. The research activities in Phase I (1980-1982) should be directed towards gaining better insight into the internal intricasies of GONO. Its status in relation to other wave models should be established, and it should be improved where necessary and possible. Furthermore, the Working Group stressed the importance of international cooperation in model development. The results and conclusions from Phase I should be initial conditions for the activities to be undertaken in Phase II (1983-1985). The Working Group's proposal and recommendations initiated the Joint Wave Modelling Program of DHL, KNMI and RWS, which started March 1980. The Program has been adopted as Project G 2 by the "Raad van Overleg voor het Fysisch Oceanografisch Onderzoek van de Noordzee", as part of her second medium-term plan. Following closely the outline of research activities by the Working Group, the Program focussed in Phase I on the following subjects:

- a description and improvements of GONO,
- operational evaluations of GONO and intercomparisons of its performance with that of other models,
- participation in an international intercomparison study of wave prediction models under conditions of deep water and idealized windfields (now known as SWAMP),
- a study of physical processes governing the build-up and decay of a wave field,
- international cooperation.

Several of the Phase I activities have been continued in Phase II, with more emphasis on shallow water aspects, however. In addition, Phase II aimed at further improvements of GONO:

- detailed investigations of the energy balance equation,
- improvements of GONO with respect to dissipation and propagation in shallow water,
- participation in an international intercomparison study of wave prediction models under conditions of shallow water and both idealized and real windfields (now known as SWIM).
- retuning of the growth characteristics.

This Final Report reviews, summarizes and concludes the above mentioned activities of Phases I and II of the Joint Wave Modelling Program.
Part 1 presents a survey of the activities undertaken during the Program (Phases I and II). This survey is in the form of brief discussions of the main written material produced during the Program. These writings (memo's, reports, publications) in their original form are included in this Report as Appendices. The relation of the Joint Wave Modelling Program with other wave prediction activities in The Netherlands is discussed.

Part 2 is devoted to hindcast results for the MLTP-storm set obtained by the present operational version of GONO. A comparison is made with similar results obtained by an earlier version of the model as reported in Ref. 4. The conclusions and recommendations derived from the Program (including the intercomparison of MLTP-storm results) are presented in this second part as well.

General conclusions

1) The efforts have lead to a flexible software system, applicable in any sea and on every grid size.
2) The empiricism in GONO developed in MLTP-1 has been reduced and replaced by formulations derived from basic physics, resulting in more transparency, and improvements in especially E_{10} predictions.
3) The status of GONO as an adequate second generation model has been established through comparisons with data and other wave models.
4) The wave modelling activities of the Dutch group have been recognized by the international wave modelling community, resulting in key positions in the development activities of a third generation model.
5) The operational practice and the intercomparison studies have learned that further substantial improvements of wave forecasts with GONO should be obtained through improvements in the input wind fields and through the application of real-time data assimilation techniques.
6) Apart from the ways of improvements mentioned above, the next step is to develop a third generation model as the only approach to remedy the problem of swell-wind sea interaction: → WAM!

Acknowledgements

We would like to thank the many people who contributed to GONO:
Evert Bouws, Hugo Brunsveld van Hulten, Jan Bruinsma, Henk de Froe, Rik de Gier, Henk Kalle, Pieter Kruseman, Roel van Moerkerken, Huib Oude Groen, Harger Peeck, Wolfgang Rosenthal, Jan Sanders, Michael Saraber, Gerard Snijders.

Part 1. A survey of activities performed under the Joint Wave Modelling Program during the period 1980 - 1985.

Introduction

As already mentioned in the General Introduction, this survey is in the form of brief discussions of the main written material produced during the Program. For the more interested reader the original writings are included as Appendices. In order to structure the discussions (and the Appendices), we have grouped the memo's, reports and publications into six categories, according to their principal character:

A. Descriptions of the physics and numerics of GONO,

B. Experimental and operational evaluations of GONO,

C. Theoretical studies on wave modelling,

D. Improvements of GONO and its algorithm,

E. Intercomparison studies,

F. Miscellanea.

It is certainly not so that a paper fits into only one category, some papers (e.g. SWAMP, App. E 5) could easily fall into two or more categories. Within each category the papers are ordered chronologically. It is hoped that this way of grouping and ordering facilitates the reader to get an overall impression of the performed work and its coherence.

A. Descriptions of the physics and numerics of GONO

At the start of the Program in 1980 a description of GONO's algorithm was lacking. Hence, in order to facilitate interpretation and further research, the activities started with a rather comprehensive description of GONO's computer code at that time (A 1). Subsequently, more detailed insight into the numerical representation of the physics of wave propagation and growth was obtained by further analysis of the advection scheme (A 2, A 5) and the growth characteristics (A 4). Some special aspects have been enlightened in papers on spherical earth effects (A 3), and on the swell scanning procedure (A 6). A concise description of GONO's principles was first communicated to the international community of wave researchers in a contribution to the Symposium on Wave Dynamics and Radio Probing of the Ocean Surface, in 1981 (A 7). A description of the model's highly empirical shallow water aspects marked the start of Phase II of the Program (A 8). Finally, these descriptions (and evaluations, see Category B) resulted in a comprehensive presentation in the scientific literature (A 9).

B. Experimental and operational evaluations of GONO

A systematic comparison of model results on wave height, low frequency energy, wind speed and wind direction with observations at five locations in the North Sea started in December 1979. An account of these comparisons, also including the results of the wave model of the U.K. Met. Office, was presented at the earlier mentioned Symposium on Wave Dynamics etc. (B 1). In fact, this study was the first in a series of model intercomparisons. The occasionally large differences between calculated and measured low-frequency energy as apparent from the comparisons motivated a study on the influence of inaccuracies in the calculated winds on the low-frequency energy predictions (B 2). The influence of input wind errors on wave predictions has been studied further from two different windfield analyses for the same November 1981 storm (B 8). Comparisons on a routine basis of measurements with operational model results started in October 1980. Since then, reviews of the complete time series and the statistics of the comparisons have been published in Technical Reports (B 4, B 5, B 6 en B 7). Monthly evaluations of these comparisons are reported since January 1981. An experimental evaluation of GONO, i.e. an evaluation under ideal but hypothetic wind and fetch conditions, was performed through participation in the Sea Wave Modelling Project (SWAMP), see also Category E. This evaluation for ideal conditions produced a sizeable set of test results for study purposes (B 3).

C. Theoretical studies on wave modelling

The theoretical studies performed in relation to the Joint Wave Modelling Program have been focussed on the source terms in the energy balance equation, i.e. the advection, the wind input, the nonlinear wave-wave interactions, and the dissipation.

Advection

Janssen and Komen studied the general relation between duration- and fetch-limited wave growth in aid of the descriptions of GONO (C 1).

Atmospheric input

Janssen studied the wind profile changes in time due to the transfer of energy to the waves, thereby extending the validity of Miles' theory of wave growth (C 3). Results of that study were also presented at the First International Conference on Meteorology and Air/Sea Interaction of the Coastal Zone (C 6). For long durations, asymptotic expressions could be obtained for the wind velocity profile and the wave spectrum. A time history of the spectral evolution could only be obtained by numerical integration of the governing quasilinear equations. This has been done and reported by Janssen and Peeck (C 10). The consequences of the resulting asymptotic "f^{-4}" wave spectrum for the prediction of waves in a parametric model were also discussed by Janssen (C 2). An important aspect of wind wave growth is the influence of atmospheric stability. These effects have been studied by Janssen and Komen (C 12). The results of the study were also reported briefly at the Symposium on Wave Breaking, Turbulent Mixing and Radio Probing of the Ocean Surface in Japan (C 9). Another important aspect of wind wave growth is the question whether the friction velocity or the wind speed at a certain height is the appropriate parameter for the scaling of the sea-state parameters. Janssen, Komen and De Voogt have reported on some experimental evidence for a preference of scaling with the friction velocity (C 13).

Nonlinear interactions

Bouws and Komen did research on the delicate balance of the source terms in the energy balance equation for the extreme storm event in shallow water on

January 3, 1976, near Texel (C 5). In this study the nonlinear interactions have been calculated using an algorithm by S. Hasselmann et al. (Max-Planck-Institut für Meteorologie, Hamburg) which was put at the disposal of the dutch wave modelling group. Bouws did some preparatory work for this numerical experiment in providing realistic initial values for the sea-state parameters (C 4). Komen, in cooperation with S. and K. Hasselmann, tested the balance of wind input, nonlinear interactions and surface dissipation for the existence of a fully developed wave spectrum in deep water (C 11). Results of that work have been communicated at the earlier mentioned Symposium on Wave Breaking, etc., in Japan (C 14). At the same Symposium, Janssen reported on the stability of narrow spectral distributions under the influence of nonlinear interactions in a random inhomogeneous wave field (C 7).

Bottom friction

Janssen and De Voogt contributed also to that Symposium with a presentation of their work on the influence of bottom friction on wind-sea development (C 8).

D. Improvements of GONO and its algorithm

From the insight obtained into GONO by its description, by the operational evaluations, and by the participation in SWAMP (see Category E) it was concluded at the end of Phase I that the status of GONO was that of a 2nd-generation wave model which in general could compete in performance with any other model, hybrid/parametric or spectral. It was, however, also concluded that GONO's shallow water part was highly empirical and should be improved. Hence, apart from some (rather minor) general corrections, the attention focussed on further development of the shallow water modelling. The advection in shallow water has been improved through a suitable parameterization of the depth-dependent group velocity (D 1). Much empiricism could be removed from the modelling of depth-limited wave growth in GONO through a more direct solution of the energy balance with a linearized form of the "JONSWAP"-dissipation as energy sink (D 2). An important feature has been the refinement of GONO's bathymetry (D 3). It is now possible to do calculations with the model on a grid with mesh width 50 km, thus having the possibility of dealing more accurately with bottom influences. A very important improvement of the manageability of GONO's algorithm has been achieved through a complete re-programming (D 4). The main advantages of the new code are its better computing efficiency and its modular structure. Also its improved and extended output facilities have already proven their usefulness in both operational and research modes of application. During its re-programming GONO has been subjected to slight improvements and modifications. Many of the ideas gained in the evaluations and the theoretical studies have been tested in modified versions of GONO. Some results of these tests have been reported (D 5).

E. Intercomparison studies

A first step in the establishment of the status of GONO in relation to other models has been made through comparing operational results of GONO and the British Met. Office model BMO with observations at five locations in the North Sea for the period December 1979 - April 1980 (E 1, E 2).
A substantial part of the Joint Wave Modelling Program has been devoted to participation in an international intercomparison study of wave prediction models under conditions of deep water and idealized wind fields. This study, proposed in 1979 by a group of wave researchers, was meant to test our present understanding of the physics of wind-generated surface waves from the viewpoint of wave modelling. As such, taking part in this study fitted extremely well into the Phase I -activities. A total number of ten wave modelling groups from the USA, Japan and Europe finally participated in what is now known as the Sea Wave Modelling Project (SWAMP). A major advantage of the participation with GONO in this study was the insight gained into the physics and the computing techniques used in the various models. Gathering this information (a task of the Joint Wave Modelling Program) in a different way would have been very time consuming and difficult, if not impossible. Besides, the intercomparison study revealed sharply the weak and strong points of the various types of models (linear, parametric, spectral) in general, and of the individual models (including GONO) in particular. Through the participation and the GONO results, the Dutch wave model-

ling group became accepted as a serious partner in international wave modelling activities. Preliminary results of GONO related to the Intercomparison Studies have been presented at international meetings (E 3, E 4). The principal results and conclusions of SWAMP have been presented at a Symposium on Wave Dynamics and Radio Probing of the Ocean Surface, in 1981. The publishing of the results and conclusions as a book authored by the SWAMP-Group marked the success of international cooperation. (E 5). The complete set of results in the form of graphs has appeared as a KNMI-publication (E 6). Further actions on intercomparisons of models have been taken for HYPA (the German wave model) and GONO (E 7). A follow-up of SWAMP, but now for shallow water and on a more modest scale, has been organized by the British-, German-, and Dutch wave modelling groups in a study called SWIM. Results of that study have been communicated at the Symposium on Wave Breaking, etc., in Japan (E 9), and a complete account has been published in the scientific literature (E 8).

F. Miscellanea

Collected under this heading are some published writings which are an extra illustration of the scala of activities undertaken in the Program. To be mentioned are the first attempts to join the international wave modelling community, i.e. a presentation of GONO at a workshop in France, 1980 (F 1), and an account of one of the very first meetings of the SWAMP-Group in 1981 (F 2). GONO's algorithm had to be modified to some extent in order to run the SWAMP test cases, these adaptations have been reported (F 3). The key-researchers of the Joint Wave Modelling Program reported on progress at the end of Phase I (F 4). A request for contributing to the MIAS Catalogue of wave prediction models has been honoured (F 5). The future role of satellites in wave forecasting has been anticipated (F 6).

Relation of the Joint Wave Modelling Program with other wave prediction activities in the Netherlands

Parallel to the Joint Wave Modelling Program (JWMP) described above in Sections A-F, several other activities related to wave prediction took place in the Netherlands. These activities will be briefly described in this Section. In essence two kinds of activities can be distinguished:

- activities related to the production of daily operational wave forecasts,
- other research and model development activities.

Operational wave forecasting in the Netherlands

Daily wave forecasts 0-24 hours ahead are made for three main applications (NOZEDA-Report, 1984):

a. Guidance of large ships to dutch harbours (e.g. Rotterdam-Europoort).
b. Guidance of the construction of the Storm Surge Barrier (SVKO) in the mouth of the Oosterschelde in the south-western part of the Netherlands.
c. General offshore activities, e.g. fishery, sea mining, oil and gas exploration and exploitation, water recreation, etc.

A start of routine wave forecasting for application -a- was made in the seventies. The need for quantitative forecasts of swell grew because of the optimized usage of the navigation channels for Very Large Crude Carriers (Schilperoort et al., 1985). Of this swell the time of arrival and its energy content for wave periods of ten seconds and higher (E10) are important prognostic parameters.
For application -b-, routine wave forecasting started in the early eighties and will continue until 1987 (end of construction of the SVKO). During the construction special ships are operative which are sensitive to wave motion. For that reasons quantitative predictions of the most critical motions are required. To meet these requirements accurate forecasts of the full wave spectrum are to be made on which (theoretical) response transfer functions can be applied. To this end, forecasts of wind speed, wind direction, the significant wave height and the low frequency energy (E10) are made from which the wave spectrum is reconstructed in a diagnostic way. For more detailed information the interested reader is referred to RWS-Note "BEGOLF", 1985. The wave forecasts for applications -a- and -b- are made and issued by the Hydro Meteo

Centre in Zierikzee (KNMI/Rijkswaterstaat). The wave forecasts for application -c- are issued by KNMI in De Bilt. Because of the above mentioned growing need, activities are now under way to optimize the wave forecasting process both technically and logistically. This is done in the framework of the so-called GOWA-project, a joint KNMI-RWS activity which comprises the following.

1. Development of a Man-Machine Mix forecasting system.
2. Application of an extensive statistical software package for the analysis and verification of wave forecasts.
3. The operation of four (five in the future) WAVEC directional buoys in the North Sea.
4. The improvement of E10-predictions by ARMAX-modelling techniques (Kuik, 1985).
5. The testing of GONO by running it on wind fields from the Meteorological Office, U.K.

For details of the above items the reader is referred to the Projectgroep-GOWA Report, 1985.

Other research activities

To complete the picture of activities concerning wave forecasting in the Netherlands, the following additional research carried out outside JWMP or GOWA should finally be mentioned.

Because of the poor predictability of E10 and its importance, relatively much attention was paid to the analysis of the E10-prediction. A desk study has been performed to determine the sensitivity of E10-predictions to several sources of inaccuracy, such as inaccuracies in the input wind fields, the spectrum of the swell-generating sea, the swell dissipation, etc. This study is presently being extended with Monte-Carlo computer experiments which aim at providing insight into the relative contribution of the various sources of errors in the E10-prediction. Results of these activities will be reported in 1986.

A simple "wave data assimilation" method has been developed to improve the swell predictions of GONO for swell originating from the Norwegian Sea or the northern North Sea. This method was demonstrated for one swell case (in October 1981) and reported at a conference on The Use of Satellite Data in Climate Models (Komen, 1985).

Based on measurements with the WAVEC directional buoy, a study has been initiated to establish the prediction accuracy of GONO for the directional para-

meters. The first results of this study were presented at a WAM-meeting in Bergen, Norway, May 1985.
The analysis and interpretation of directional wave data has been the subject of several studies, see for instance Kuik et al., 1981, Kuik et al., 1984, and Holthuijsen et al., 1985.

List of Appendices

A. Descriptions of the wave prediction model GONO

A 1. Bruinsma, J., P.A.E.M. Janssen, G.J. Komen, H.H. Peeck, M.J.M. Saraber, and W.J.P. de Voogt.
Description of the KNMI operational wave forecast model GONO.
KNMI - WR 80 - 8, 1980.

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A 3. De Voogt, W.J.P.
Spherical-earth effects in GONO.
WL R 1570-3, 1981.

A 4. De Voogt, W.J.P.
The fetch-limited growth curve in GONO.
WL R 1570-4, 1981.

A 5. Janssen, P.A.E.M.
Numerical diffusion in the GONO advection scheme.
KNMI Memo 81-1, 1981.

A 6. Komen, G.J.
The calculation and propagation of swell in GONO.
KNMI Memo 81-13, 1981.

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In: The SWAMP Group, Ocean wave modeling, 193-200, Plenum, 1985.
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Shallow water aspects of the KNMI operational wave prediction model GONO.
KNMI Memo 00 82-14; WL R 1570-7, 1982.

A 9. Janssen, P.A.E.M., G.J. Komen, and W.J.P. de Voogt.
An operational coupled hybrid wave prediction model.
J.Geophys.Res., 89, 3635-3654, 1984.

B. Operational and experimental evaluations of GONO

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An evaluation of operational wave forecasts on shallow water.
To appear in: Proc. IUCRM Symposium on Wave Dynamics and Radio Probing of the Ocean Surface, Miami, 1981.

B 2. Komen, G.J., and M.J.M. Saraber.
Het effekt van onnauwkeurigheden in de wind op de E10-berekening door GONO.
KNMI Memo 00-CWD 82-3, 1982.

B 3. De Voogt, W.J.P., and G.J. Komen.
SWAMP: The collection of test results obtained with the KNMI operational wave model GONO.
WL R 1570-10, 1982.

B 4. Bouws, E., G.J. Komen, R.A. van Moerkerken, H.H. Peeck, and M.J.M. Saraber.
An evaluation of the KNMI operational wave model GONO for the period October 1980 - April 1981.
KNMI TR-11, 1982.

B 5. Bouws, E., G.J. Komen, R.A. van Moerkerken, H.H. Peeck, and M.J.M. Saraber.
Evaluatie van de golfberekeningen met GONO over de periode oktober 1981 - april 1982.
KNMI TR-22, 1982.

B 6. Bouws, E., G.J. Komen, R.A. van Moerkerken, H.H. Peeck, and M.J.M. Saraber.
Evaluatie van de golfberekeningen met GONO over de periode oktober 1982 - april 1983.
KNMI TR - 37, 1983.

B 7. Bouws, E., G.J. Komen, R.A. van Moerkerken, H.H. Peeck, and M.J.M. Saraber.
Evaluatie van de golfberekeningen met GONO over de periode oktober 1983 - april 1984
KNMI TR-56, 1984.

B 8. Bouws, E., and G.J. Komen.
Een vergelijking van GONO-resultaten voor twee stormen in november 1981, met twee verschillende windvelden.
KNMI Memo 84-05, 1984.

C. Theoretical studies on wave modelling

C 1. Janssen, P.A.E.M., and G.J. Komen.
On the relation between duration-limited and fetch-limited growth.
KNMI Memo 80-12, 1980.

C 2. Janssen, P.A.E.M.
Some consequences of an f^{-4} power law for wave prediction.
KNMI Memo 81-7, 1981.

C 3. Janssen, P.A.E.M.
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J. Fluid Mech., 117, 493-506, 1982.

C 4. Bouws, E.

A simple model of time-dependent wave growth in shallow water, compared with storm wave data near lightship Texel (3 Jan. 1976). KNMI Memo 82-11, 1982.

C 5. Bouws, E., and G.J. Komen.

On the balance between growth and dissipation in an extreme depth-limited wind-sea in the southern North Sea. J. Phys.Oceanogr., 13, 1653-1658, 1983.

C 6. Janssen, P.A.E.M.

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C 7. Janssen, P.A.E.M.

Stability of a random inhomogeneous field of weakly nonlinear surface gravity waves with application to the JONSWAP-study. The Ocean Surface: Wave breaking, turbulent mixing and radio probing, Y. Toba and H. Mitsuyasu (Eds.), 39-49, D. Reidel Publ. Comp., 1985.

First presented at a Symposium on Wave Breaking, Turbulent Mixing and Radio Probing of the Ocean Surface, Sendai, 1984.

C 8. Janssen, P.A.E.M., and W.J.P. de Voogt.

On the effect of bottom friction on wind sea. The Ocean Surface: Wave Breaking, Turbulent Mixing and Radio Probing, Y. Toba and H. Mitsuyasu (Eds.), 185-192, D. Reidel Publ.Comp., 1985.

First presented at a Symposium on Wave breaking, Turbulent Mixing and Radio Probing of the Ocean Surface, Sendai, 1984.

C 9. Janssen, P.A.E.M., and G.J. Komen.
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Part 2. An evaluation of the present operational wave model GONO on the basis of the MLTP storm set.

I. Introduction

In this part we report on our progress in improving the operational wave prediction model GONO by incorporating new and/or better physics. Possible changes in GONO's operational performance due to the input of wind fields from the Meteorological Office instead of BK-4 wind fields are not reported here.
The wave model GONO is based on a hybrid approach. On the one hand the waves under the action of wind are assumed to have a spectrum with an invariant shape. This assumption is supported by experimental evidence (cf. Hasselmann et al., 1973). The result is that pure wind sea may be described by a few spectral parameters, such as total energy and peak frequency, only.
By means of a simple spectral shape, the Kruseman spectrum (Kruseman, 1976) the advection of sea energy is calculated via a time-forward, upwind, finite-difference scheme, whereas the growth of the wind-sea energy is calculated on the basis of an empirical growth curve and dissipation by bottom friction is calculated on an ad hoc basis.
On the other hand, swell spectra have no invariant shape, so that swell is treated by means of a spectral technique. If one is only interested in swell information at particular points (e.g. Europoort, Pennzoil etc), it is tempting to use a ray technique. The advantage of this technique over a finite-difference scheme is that it is very accurate with no numerical diffusion. This is important since swell may propagate over large distances.

We have mainly concentrated on improving the wind-sea part of the model. The starting point is the energy balance equation, describing the rate of change of the wave variance spectrum $F(f, \Theta; x, y, t)$ caused by advection, wind input, nonlinear interactions, wave breaking and bottom dissipation. If no refraction is taken into account the energy balance equation reads

$$\frac{\partial}{\partial t} F + \nabla . \vec{c}_g F = S_{in} + S_{nl} + S_{br} + S_{diss} , \quad (1)$$

where $\vec{c}_g = \partial\omega/\partial\vec{k}$, $\omega=2\pi f = \{gk \tanh kD\}^{\frac{1}{2}}$, k is the wave number and D the depth. The symbols S_{in}, S_{nl}, S_{br} and S_{diss} represent the rate of change of wave variance due to wind input, nonlinear interactions, wave breaking and bottom dissipation.

We illustrate the improvements on the wind-sea part of GONO in the simple case of a constant windfield and constant depth only. Then, the rate of change of the total wind-sea energy, $\varepsilon = \int F \, df d\theta$ follows from an integration of the energy balance equation (1) over frequency and direction. The result is

$$\frac{\partial}{\partial t} \varepsilon + \nabla . \langle \vec{c}_g \rangle \varepsilon = S = \langle S_{in} \rangle + \langle S_{br} \rangle + \langle S_{diss} \rangle, \quad (2)$$

where $\langle \vec{c}_g \rangle$ is the averaged group velocity, known in terms of the spectral parameters such as peak frequency (cf. Janssen et al., (1984). We have investigated in detail the following aspects of the source terms:

(i) Wind input

The appropriate scaling of windsea parameters such as waveheight, peak frequency, duration, fetch, is a problem. Although it is customary to scale these parameters in terms of the wind speed at ten meters height, U_{10}, we have investigated the possibility of scaling with the friction velocity U_*.

(ii) Dissipation

Dissipation by bottom friction in the old version of GONO is modelled by ad hoc formulea. Instead, we have derived an expression for the spectral averaged dissipation for windsea from the "well-established" empirical formula for the decay of swell trains (JONSWAP, 1973).

In the following we shall discuss the above mentioned aspects in more detail. This discussion is followed by a comparison of observations with results from two versions of GONO, namely one based on friction velocity scaling and one based on U_{10}-scaling. We conclude with a number of recommendations.

II. The scaling of wind-wave growth

In the past it was common practice to analyse the growth of wind waves and the wave variance spectra on the basis of the wind speed at a fixed height, say at 10 metres, see for instance the JONSWAP-study (1973). Also many wave prediction models of the hybrid-parametrical type (e.g. Günther et al., 1979, Janssen et al., 1984) make use of scaling laws based on U_{10}-scaling.

However, many authors have stressed the importance of scaling wave growth with the friction velocity U_*. The difference in scaling procedures would be immaterial if the ratio U_*/U_{10} were a constant. However, there is evidence that this ratio increases with increasing wind speed. Recently, Wu (1982) found that for a wide range of wind speeds the formula

$$C_{10} = (U_*/U_{10})^2 = (0.8 + 0.065\ U_{10}) \times 10^{-3} \qquad (3)$$

is applicable. It is clear that this result must have important consequences for wave modelling. Consider for instance the effect of U_*-scaling on the growth curve. To be consistent one should then expect a universal relation between the non-dimensional wave height gH_s/U_*^2 and the non-dimensional time gT/U_*, hence, following the curve fitting of Sanders et al., (1980),

$$\frac{gH_s}{U_*^2} = \beta_* \tanh \left\{a_* \left(\frac{gT}{U_*}\right)^{b_*}\right\}. \qquad (4)$$

If one now plots the growth curve in terms of the usual quantities gH_s/U_{10}^2 and gT/U_{10}, then the effect on the wind-dependent drag coefficent C_{10} can be seen most clearly. This we have shown in Fig. 1 for $\beta_* = 100$, $a_* = 6 \times 10^{-5}$, and $b_* = 0.75$. The maximum non-dimensional wave height $gH_s(\infty)/U_{10}^2$ is just proportional to the drag coefficient, giving an increase of dimensionless wave height by a factor of two if the wind speed increases from 10 to 30 m/s.

An indication of the validity of U_*-scaling is that one obtains a universal relation between $\nu_* = U_* f_p/g$ and ε_* (Janssen et al., 1985). This is shown in Fig. 2 where we have plotted ν_* versus ε_* for the KNMI and JONSWAP data sets (Sanders et al., 1980, Müller, 1976). The friction velocity is obtained from Eq. (1). From both data sets we obtain

$$\nu_* = 0.061\ \varepsilon_*^{-0.333} \quad . \tag{5}$$

From this result we conclude that it is very tempting to adopt U_*-scaling although in practice there is one important drawback. The results for wave height, peak frequency and low frequency energy (ε_{10}) will be more sensitive to errors in the wind speed. In addition, to be consistent, the wind speeds from the atmospheric model should be calculated with the drag law, Eq. (3).

III. Dissipation of wave energy by bottom friction

Depth limitations are of great significance in practical applications concerning offshore constructions and coastal protection. Typically, extreme storms generate in the southern part of the North Sea (depth~25 m) significant wave heights which are only half as large as in the deeper central part. This sizeable energy reduction occurs because dissipation by bottom effects can be important.
In the old operational version of the GONO model the dissipation by bottom friction was based on an ad-hoc formula (Sanders et al., 1980). In addition, there were several empirical limiters for wave height and stage of development parameter (Komen et al., 1982). These tuning facilities are not very desirable as they have no solid foundation in physics.
The JONSWAP experiment (Hasselman et al., 1973) gave results on the decay of swell trains due to bottom friction. It was found that the rate of change of swell energy of frequency ω was well described by

$$\frac{1}{E(\omega)} \frac{\partial E(\omega)}{\partial t} \bigg|_{diss} = - \frac{\Gamma}{gD}\, \phi\, (\omega_D), \tag{6}$$

where D is the depth, $\phi(\omega_D) = \omega_D^2/\sinh^2 kD$. $\omega_D = \omega(D/g)^{\frac{1}{2}} = (kD\tanh\, kD)^{\frac{1}{2}}$, k is the wave number and Γ is the decay parameter with an average value of $0.038\ m^2 s^{-3}$. Assuming that Eq. (6) is also a good approximation for wind sea the dissipation source term is then given by

$$\langle S_{diss} \rangle = - \frac{\Gamma}{gD} \int_0^\infty \phi\, (\omega_D)\, E(f)\, df, \tag{7}$$

where E(f) is the one-dimensional variance density spectrum.
Using the Kruseman spectrum for E(f) and a linear approximation for $\phi(\omega_D)$ one obtains (De Voogt, 1984):

$$\langle S_{diss} \rangle = -\frac{2}{3}\frac{\Gamma\varepsilon}{gD}\frac{a}{\delta(3-2\mu)} \times \begin{cases} 0 & , \quad \delta \leq \mu, \\ \dfrac{(\delta-\mu)^3}{(1-\mu)} & , \quad \mu < \delta < 1, \\ (\frac{9}{2}\delta + \mu - 3\delta\mu + \mu^2 + \dfrac{1}{2\delta^3} - 4), & \quad \delta \geq 1, \end{cases} \tag{8}$$

where $\delta = f_o/f_p$, $\mu = f_{min}/f_p$, $f_o = \frac{a}{2\pi b}(g/D)$, and f_{min}, f_p are the minimum- and peak frequency of the Kruseman spectrum, respectively.
In order to verify the assumption of Eq. (7) we have solved the energy balance equation for infinite fetch, i.e.:

$$\frac{\partial\varepsilon}{\partial t} = \langle S_{in} \rangle + \langle S_{diss} \rangle, \tag{9}$$

with $\langle S_{in} \rangle$ taken from Janssen et al. (1984). As a result we found a relation between non-dimensional wave height gH_s/U_{10}^2 and non-dimensional depth gD/U_{10}^2 which is in good agreement with observations (cf. Fig. 3).

IV Results of some new tests versions of GONO

We have tested the various new parameterizations discussed above in versions of the GONO algorithm, applying the following procedure.
Firstly, we tuned the model versions to two gales in November 1981, in the North Sea. Accurate wind fields of these storm events were made available by the Met. Office, U.K. (cf. Bouws et al., 1985). The associated sea states showed both deep and shallow water aspects, and included significant contributions of swell.
Secondly, we used the various model versions to hindcast events in December 1979, January 1980, April 1980, and storm events of the so-called MLTP-set. We have tested the following versions.

A. GONO/U_{10}

This version originated by stripping all the heuristic tuning facilities of the model GONO/OPER (cf. Komen and De Voogt, 1982). This latter model was introduced into the operational services after Phase I of the Joint Wave Modelling Activities and differed only in computer technical aspects from the model described by Sanders et al., 1980, and by Bruinsma et al., 1980 (App. A1). An f^{-5} spectrum was assumed, the average dissipation was taken as in (8), and the wind input was taken from (4) with, however, a constant drag coefficient $C_{10} = 2.2 \times 10^{-3}$. The remaining four adjustable parameters were given the following values:

$$\beta_* = 100,\ a_* = 6 \times 10^{-5},\ b_* = 0.75,\ \Gamma/g^2 = 3.5 \times 10^{-4}\ s. \qquad (10)$$

In Table 1 the results for the November 1981 gales are presented. For comparison we have included the results of GONO/OPER (and of GONO/U_*, see next section).

Location	Model	Depth (m)	Number of obs.	Av.obs. (m)	Av. error (m)	standard deviation (m)
Auk A	GONO/OPER	80	31	6.08	+ 0.39	0.85
	GONO/U_{10}	80	39	4.13	+ 0.23	0.78
	GONO/U_*	80	31	6.08	+ 0.60	0.77
K13	GONO/OPER	25	50	3.30	+ 0.39	0.46
	GONO/U_{10}	25	40	3.09	+ 0.25	0.46
	GONO/U_*	25	50	3.30	+ 0.25	0.49
EURO	GONO/OPER	25	51	2.41	0.00	0.31
	GONO/U_{10}	25	39	2.32	- 0.22	0.27
	GONO/U_*	25	51	2.41	- 0.26	0.29

Table 1. Tuning results of versions of GONO for November 1981

The results of GONO/OPER and GONO/U_{10} for the MLTP set of storms are presented in Tables 2a and 2b.

It is to be noted that the windspeeds at the various locations now (Table 2b) deviate somewhat from the ones in GONO/OPER (Table 2a). This is due to a slight herorientation of the GONO grid in the course of the reprogramming. However, the overall statistics have not changed (Compare Tables 2a and 2b). We conclude from the Tables that the statistics for Hm_o are similar for GONO/OPER and GONO/U_{10}, but that the $\sqrt{E_{10}}$ - statistics have improved in general for the shallow water stations. The lack of improvement of the statistics for Hm_o confirms the fact that wind errors are the main source of uncertainties in wave model performance. The improvement of the E_{10}-predictions is apparently obtained through the better shallow water features in the GONO model.

GONO/OPER			U_{10}					H_{m_0}					$\sqrt{E_{10}}$				
Period/location	model depth (m)	number of obs	Av. obs (m/s)	Av. error (m/s)	RMS (m/s)	S.I. (%)	+ -	Av. obs (m)	Av. error (m)	RMS (m)	S.I. (%)	+ -	Av. obs (m)	Av. error (m)	RMS (m)	S.I. (%)	+ -
1 1 Jan - 14 Jan 1974 Stevenson (7,17)	200	49	16.7	- 2.64	3.23	19	7- 38	6.10	- 1.12	1.17	19	6- 42	1.15	- 0.42	0.33	28	6- 43
2 1 Jan - 14 Jan 1974 Penrod/Texel (13,6)	30	52	8.6	+ 1.15	2.93	34	32- 19	1.53	- 0.01	0.47	31	24- 26	0.05	- 0.02	0.05	109	12- 39
3 2 Jan - 4 Jan 1976 Stevenson (7,17)	200	10	9.9	+ 0.75	2.89	29	6- 3	4.75	- 0.67	1.06	22	3- 7	0.90	- 0.28	0.19	21	0- 10
4 3 Jan - 4 Jan 1976 Texel (13,6)	30	4	29.4	- 4.25	2.51	9	0- 4	5.88	+ 0.13	0.29	5	2- 1	1.05	- 0.17	0.11	11	1- 3
5 1 Jan - 5 Jan 1976 L.E. Goeree (13,4)	25	16	13.1	+ 1.35	2.59	20	11- 3	2.78	+ 0.32	0.43	16	11- 5	0.28	- 0.02	0.10	34	5- 11
6 23 Jan - 30 Jan 1976 Mike (7,24)	200	8	11.4	- 2.82	2.14	19	0- 7	3.90	- 0.55	0.76	19	2- 6	0.73	- 0.28	0.17	23	0- 8
7 23 Jan - 30 Jan 1976 Brent-B (8,17)	200	23	15.8	- 1.22	2.44	15	5- 13	4.87	- 0.09	0.92	19	10- 13	0.89	- 0.12	0.30	34	6- 17
8 23 Jan - 29 Jan 1976 Fitzroy (4,15)	200	15	15.8	- 3.10	1.92	12	0- 10	5.05	- 1.52	1.06	21	0- 15	0.94	- 0.44	0.24	25	0- 15
9 23 Jan - 30 Jan 1976 Petten (13,6)	30	30	10.0	- 0.24	3.05	31	14- 16	1.39	+ 0.86	0.54	39	29- 1	0.12	+ 0.07	0.13	107	15- 11
10 29 Jan - 30 Jan 1976 IJmuiden (13,5)	25	5	9.8	+ 4.00	2.61	27	4- 0	1.40	+ 0.06	0.37	27	2- 2	0.02	+ 0.01	0.04	161	2- 3
11 23 Jan - 30 Jan 1976 Euro (13,4)	25	26	9.1	+ 0.71	2.30	25	16- 10	1.71	+ 0.37	0.40	24	20- 4	0.11	+ 0.03	0.07	64	14- 12
12 9 Sep - 12 Sep 1976 Brent-B (8,17)	200	15	11.6	+ 0.70	2.05	18	9- 5	4.03	- 0.24	0.55	14	3- 10	0.60	- 0.21	0.11	18	1- 14
13 9 Sep - 12 Sep 1976 IJmuiden (13,5)	25	15	9.9	+ 1.38	3.97	40	9- 6	2.17	+ 0.36	0.69	32	8- 4	0.17	- 0.01	0.07	38	5- 10
14 9 Sep - 12 Sep 1976 Euro (13,4)	25	15	12.0	+ 0.60	3.19	16	7- 4	2.26	+ 0.16	0.43	19	9- 6	0.11	+ 0.02	0.03	30	11- 4
Shallow (2,4,5,9,10,11,13,14)		163	10.4	+ 0.77	3.15	31	93- 62	1.88	+ 0.30	0.57	30	105- 49	0.14	+ 0.01	0.09	68	65- 93
Deep (1,3,6,7,8,12)		120	14.9	- 1.74	3.06	21	27- 76	5.22	- 0.79	1.13	22	24- 93	0.96	- 0.32	0.30	32	13-107
Total		283	12.3	- 0.29	3.35	27	120-138	3.30	- 0.16	1.01	31	129-142	0.48	- 0.13	0.26	54	78-200

Table 2a Results of GONO/OPER for the MLTP set of storms (s.d. = standard deviation; S.I. = (s.d./av.obs.) x 100%

GONO/U_{10}			U_{10}					H_{m_0}					$\sqrt{E_{10}}$				
Period/location	model depth (m)	number of obs	Av. obs (m/s)	Av. error (m/s)	s.d. (m/s)	S.I. (%)	+ -	Av. obs (m)	Av. error (m)	s.d. (m)	S.I. (%)	+ -	Av. obs (m)	Av. error (m)	s.d. (m)	S.I. (%)	+ -
1 1 Jan - 14 Jan 1974 Stevenson (7,17)	200	49	16.7	- 2.52	3.39	20	8- 37	6.10	- 1.33	1.08	18	4- 45	1.15	- 0.44	0.31	27	2- 47
2 1 Jan - 14 Jan 1974 Penrod/Texel (13,6)	30	52	8.6	+ 1.13	2.94	34	32- 19	1.53	+ 0.00	0.45	29	24- 27	0.05	- 0.01	0.06	128	16- 32
3 2 Jan - 4 Jan 1976 Stevenson (7,17)	200	10	9.9	+ 0.75	2.88	29	7- 3	4.75	- 0.88	1.41	30	3- 7	0.90	- 0.35	0.34	38	1- 9
4 3 Jan - 4 Jan 1976 Texel (13,6)	30	4	29.4	- 4.50	2.03	7	0- 4	5.88	+ 0.94	0.23	4	4- 0	1.05	+ 0.02	0.12	11	2- 2
5 1 Jan - 5 Jan 1976 L.E. Goeree (13,4)	25	16	13.1	+ 1.38	2.40	18	12- 3	2.78	+ 0.39	0.39	14	14- 2	0.28	- 0.03	0.08	29	6- 9
6 23 Jan - 30 Jan 1976 Mike (7,24)	200	8	11.4	- 2.69	2.20	19	1- 7	3.90	- 0.62	0.79	20	2- 6	0.73	- 0.24	0.18	25	1- 6
7 23 Jan - 30 Jan 1976 Brent-B (8,17)	200	23	15.8	- 1.03	2.52	16	6- 17	4.87	- 0.36	0.83	17	10- 13	0.89	- 0.15	0.26	29	7- 16
8 23 Jan - 29 Jan 1976 Fitzroy (4,15)	200	15	15.8	- 3.30	1.93	12	0- 10	5.05	- 1.80	0.83	17	0- 15	0.94	- 0.48	0.19	20	0- 15
9 23 Jan - 30 Jan 1976 Petten (13,6)	30	30	10.0	- 0.08	3.05	31	15- 15	1.39	+ 0.66	0.50	36	25- 5	0.12	+ 0.04	0.08	69	16- 14
10 29 Jan - 30 Jan 1976 IJmuiden (13,5)	25	5	9.8	+ 4.10	2.69	27	4- 0	1.40	- 0.04	0.76	55	3- 2	0.02	- 0.01	0.02	73	2- 3
11 23 Jan - 30 Jan 1976 Euro (13,4)	25	26	9.1	+ 0.68	2.50	27	14- 10	1.71	+ 0.16	0.38	22	17- 9	0.11	- 0.02	0.04	39	9- 15
12 9 Sep - 12 Sep 1976 Brent-B (8,17)	200	15	11.6	+ 0.54	2.26	19	7- 5	4.03	- 0.36	0.44	11	2- 13	0.60	- 0.17	0.11	18	1- 14
13 9 Sep - 12 Sep 1976 IJmuiden (13,5)	25	15	9.9	+ 1.81	4.00	40	11- 4	2.17	+ 0.20	0.60	27	7- 8	0.17	- 0.05	0.07	41	4- 11
14 9 Sep - 12 Sep 1976 Euro (13,4)	25	15	12.0	+ 0.67	1.88	16	8- 4	2.26	+ 0.06	0.48	21	10- 4	0.11	- 0.01	0.04	32	4- 10
Shallow (2,4,5,9,10,11,13,14)		163	10.4	+ 0.83	3.08	30	93- 59	1.88	+ 0.23	0.54	29	104- 57	0.14	- 0.01	0.07	52	59- 96
Deep (1,3,6,7,8,12)		120	14.9	- 1.69	3.15	21	29- 79	5.22	- 1.00	1.09	21	21- 99	0.96	- 0.33	0.30	31	12-107
Total		283	12.3	- 0.24	3.35	27	122-138	3.30	- 0.29	1.02	31	125-156	0.48	- 0.15	0.26	53	71-203

Table 2b Results of GONO U_{10} for the MLTP set of storms (s.d. = standard deviations; S.I. = (s.d./av.obs.) x 100%

For completeness we have presented time series obtained with GONO/U_{10} for Hm_o and $\sqrt{E_{10}}$ with measurements for a number of locations in the North Sea in Fig. 4. Overall scatter diagrams are presented in Figures 5 and 6.
We have also run the model GONO/U_{10} on the selected months, December 1979, January 1980 and April 1980.
In Figs. 7 and 8 we have presented some interesting time series of swell (generated by a severe gale in the Norwegian Sea) calculated and measured at Europoort, on January 16, 1980, and of a severe gale at Europoort in April 1980. Also, the results of the version GONO/OPER are presented. In both cases GONO/U_{10} performs better.

B. GONO/U_*

GONO/U_* is essentially the same model as GONO/U_{10}, the only difference being that now the drag coefficient C_{10} has been taken to be wind dependent according to (3). The values of the adjustable parameters are as in (10). Results of GONO/U_* for the November 1981 storms are given in Table 1. Looking at these results it is concluded that GONO/U_* performs equally well as GONO/OPER and GONO/U_{10}. The scatter indices for the new versions are slightly better than those for the operational version (GONO/OPER), whereas for the latter model slightly better average errors are obtained. It has to be noted that the performance of GONO/U_* is more sensitive to errors in the input wind fields due to the wind speed dependence of C_{10}. Test runs done with operational (and hence less accurate) wind fields therefore gave larger (negative) average errors (not reported). This situation is even worse when realizing that, to be consistent, the wind fields itself should be calculated using the drag law (3), and not with a constant drag coefficient.

V. Conclusions and recommendations of Part 2

1) GONO/U_{10} is a well-tested model that produces better results than the original GONO/OPER, in particular for the shallow water locations. Especially the swell events of January 1980 and April 1980 were better simulated in GONO/U_{10} then in GONO/OPER.

2) One might argue that GONO/U_* is in theory a better model, based on the evidence presented in Appendix C 13 of this report.

3) Nevertheless it was decided to introduce GONO/U_{10} in the operational series because in the operational practice (with BK 4 wind fields) this model produces smaller r.m.s errors in the wave height than GONO/U_*.

4) One should finally discuss an important limitation of hybrid - parameter models, such as GONO, namely the interaction of wind-sea and swell. In these type of models this is treated on a rather ad-hoc basis. As shown in the SWAMP exercise improvement can only be expected from models that solve the full energy balance equation (1). This is one of the main reasons that we are now involved in the WAM (WAve Modelling) project.

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Figure captions

Fig. 1 The effect of U_*-scaling on the duration-limited wave growth scaled in terms of U_{10}.

Fig. 2 Energy versus peak frequency scaled by U_* for KNMI (X) and JONSWAP (0) data. The full and and broken line, respectively, represent the least-squares power law fits to KNMI- and JONSWAP-data.

Fig. 3 Non-dimensional wave height and peak period versus non-dimensional depth for infinite fetch and duration. Full lines are calculated from (9), using (8).

Fig. 4a Measured (——) and calculated (---, GONO/U_{10}) wave heights H_{mo} and low frequency energies $\sqrt{E_{10}}$ at location STEVENSON for January 1-13, 1974.

Fig. 4b Idem at location STEVENSON for January 2-4, 1976.

Fig. 4c Idem at location TEXEL for January 3, 1976.

Fig. 4d Idem at location BRENT-B for January 23-30, 1976.

Fig. 4e Idem at location PETTEN for January 23-30, 1976.

Fig. 4f Idem at location BRENT-B for September 9-12, 1976.

Fig. 4g Idem at location IJMUIDEN for September 9-12, 1976.

Fig. 5 Scatterdiagram ("model" versus "measured") for the shallow water stations obtained with GONO/U_{10}. Solid line represents the best linear fit. Dashed line represents model = measured.

Fig. 6 Scatterdiagram ("model" versus "measured") for the deep water stations obtained with GONO/U_{10}. Solid line represents the best linear fit. Dashed line represents model = measured.

Fig. 7 Calculated (GONO/U_{10}) and measured low frequency energy at location EURO in January 1980.

Fig. 8 Calculated (GONO/U_{10}) and measured wave heights at location EURO in April 1980.

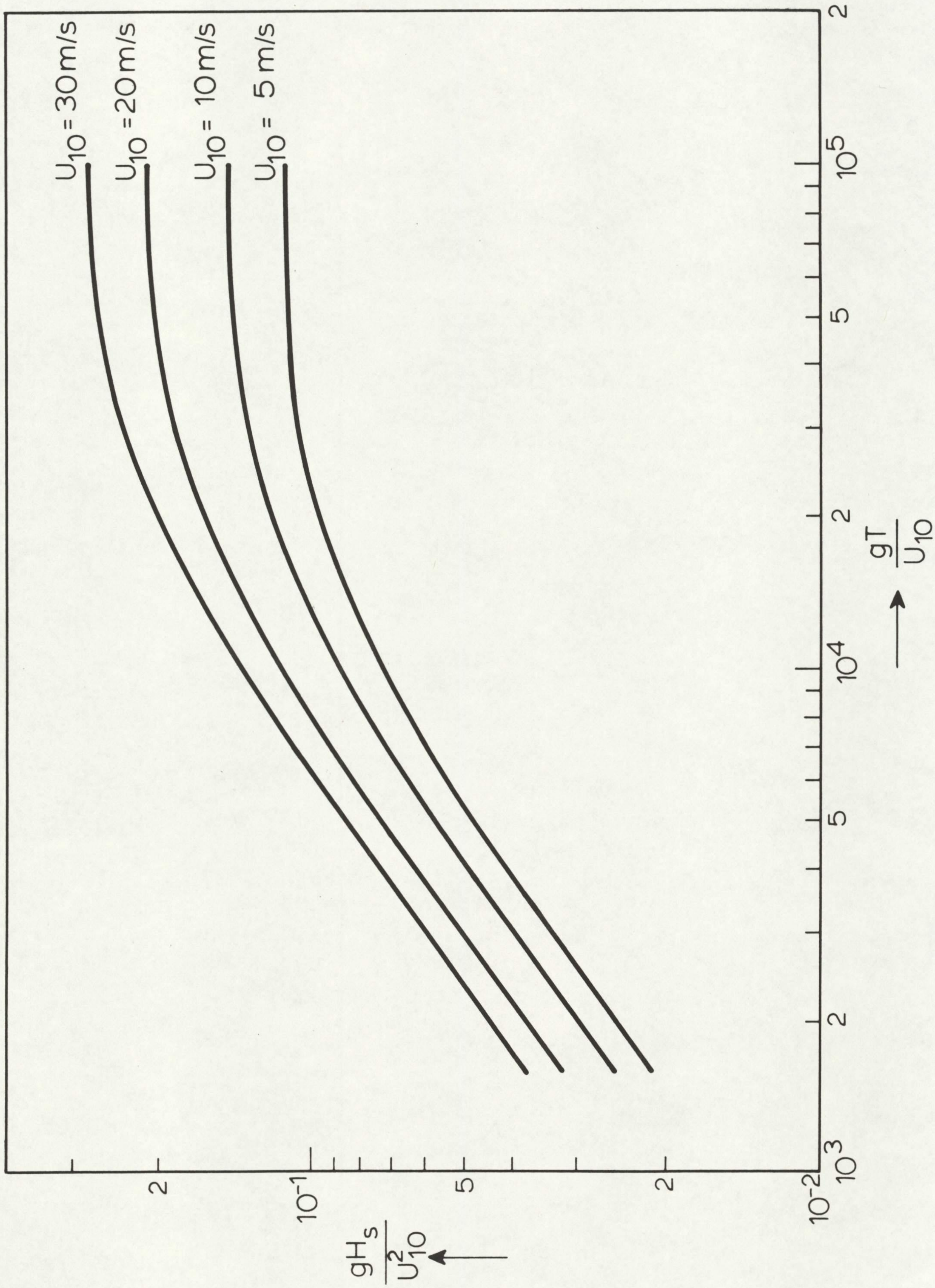


FIG. 1 THE EFFECT OF U_*-SCALING ON THE DURATION - LIMITED WAVE GROWTH SCALED IN TERMS OF U_{10}

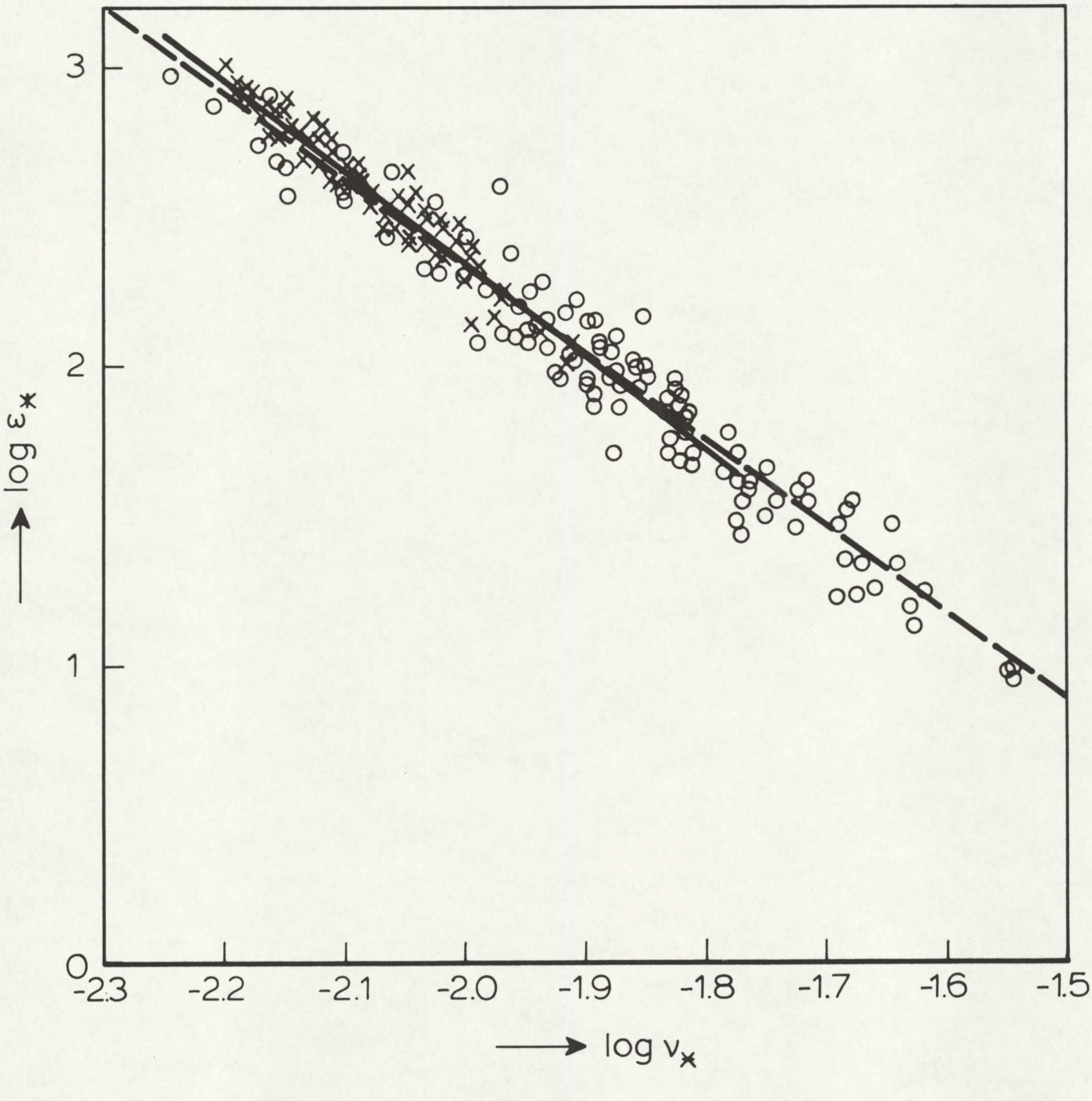


FIG. 2 ENERGY VERSUS PEAK FREQUENCY SCALED BY U_* FOR KNMI (x) AND JONSWAP (o) DATA. THE FULL AND BROKEN LINE, RESPECTIVELY, REPRESENT THE LEASTSQUARES POWER LAW FITS TO KNMI- AND JONSWAP-DATA.

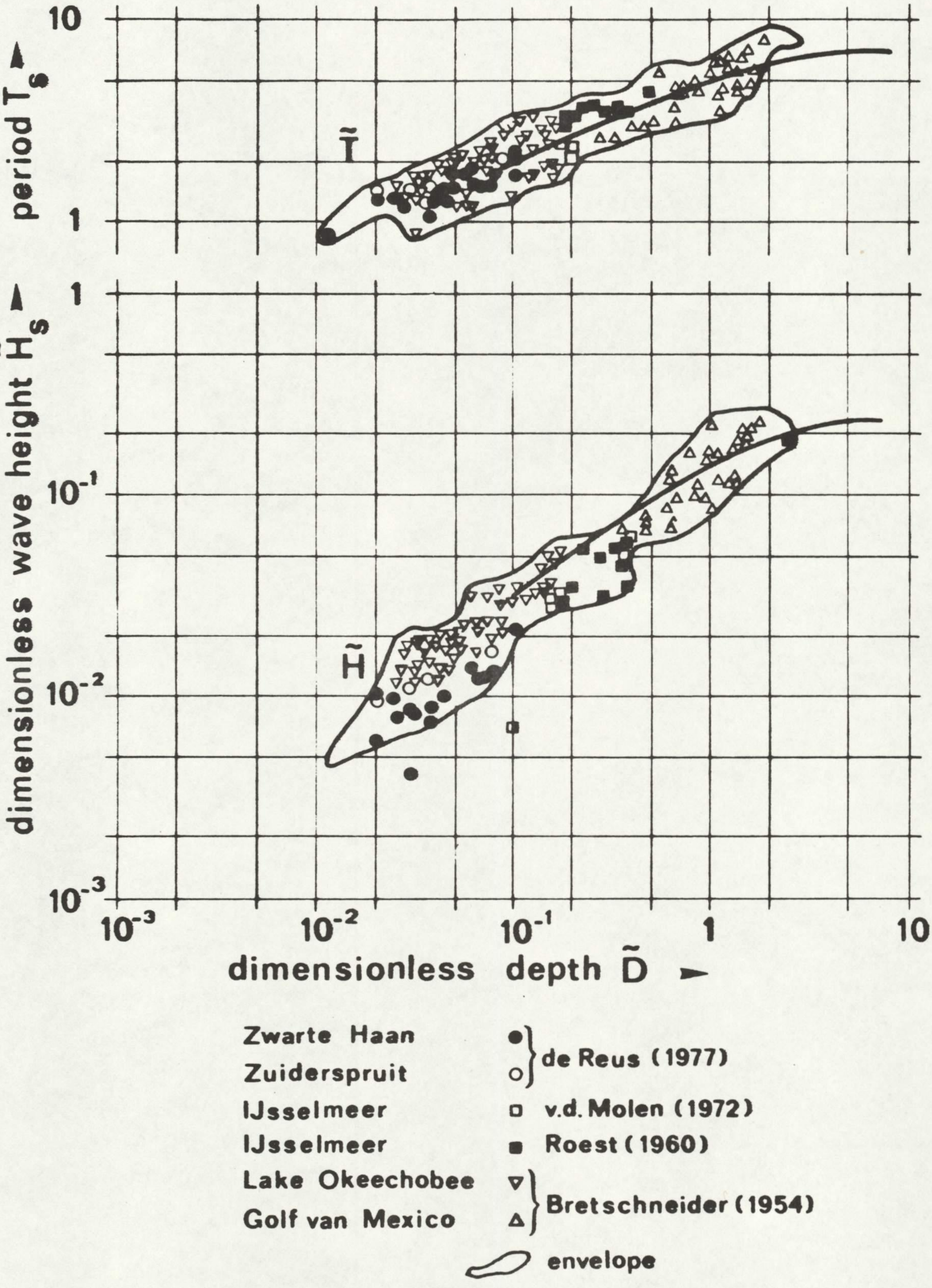


FIG. 3 NON - DIMENSIONAL WAVE HEIGHT AND PEAK PERIOD VERSUS NON - DIMENSIONAL DEPTH FOR INFINITE FETCH AND DURATION.

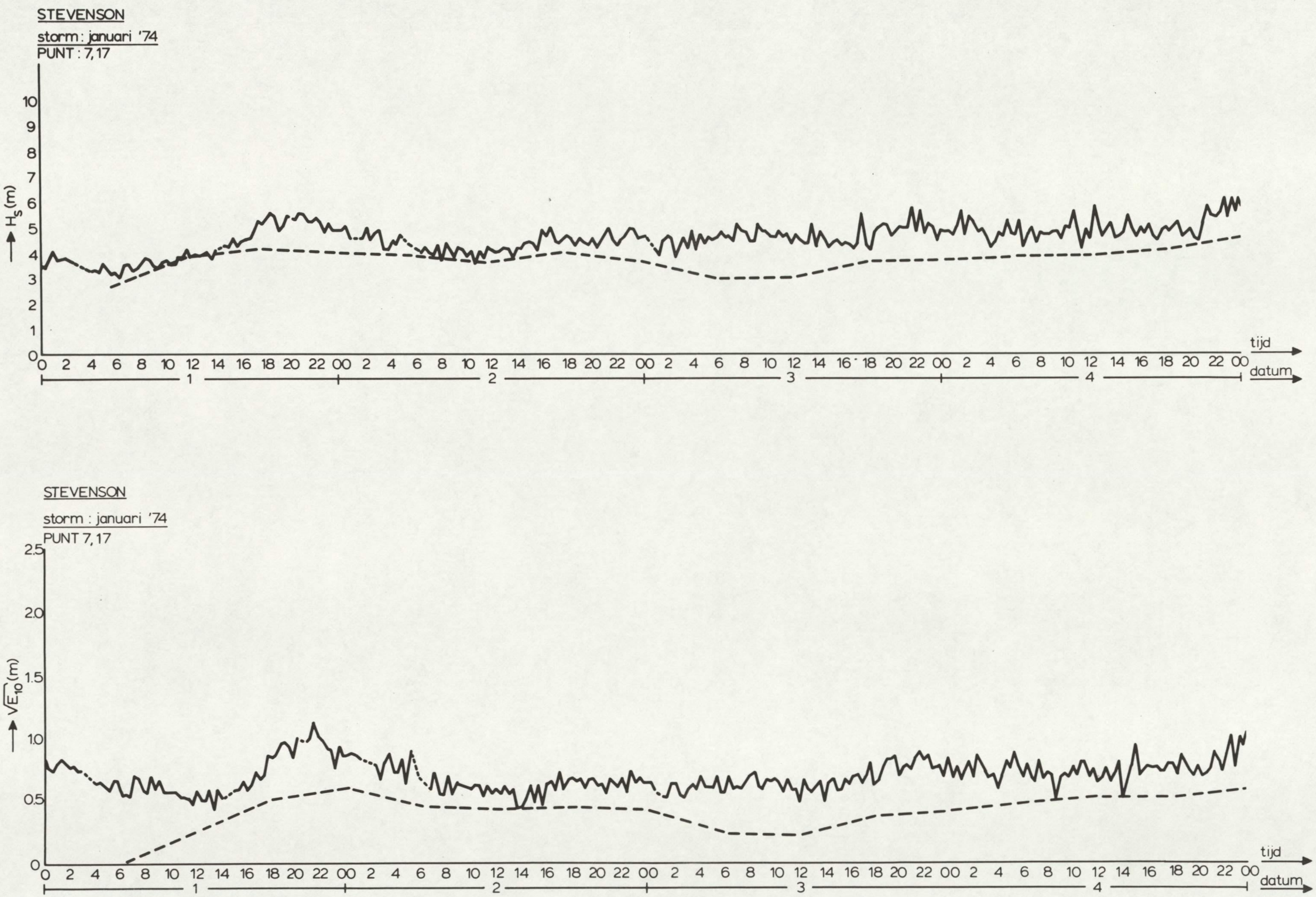

STEVENSON
storm : januari '74
PUNT : 7,17
H_s (m)
tijd
datum
STEVENSON
storm : januari '74
PUNT 7,17
$\sqrt{E_{10}}$ (m)
tijd
datum

FIG. 4a

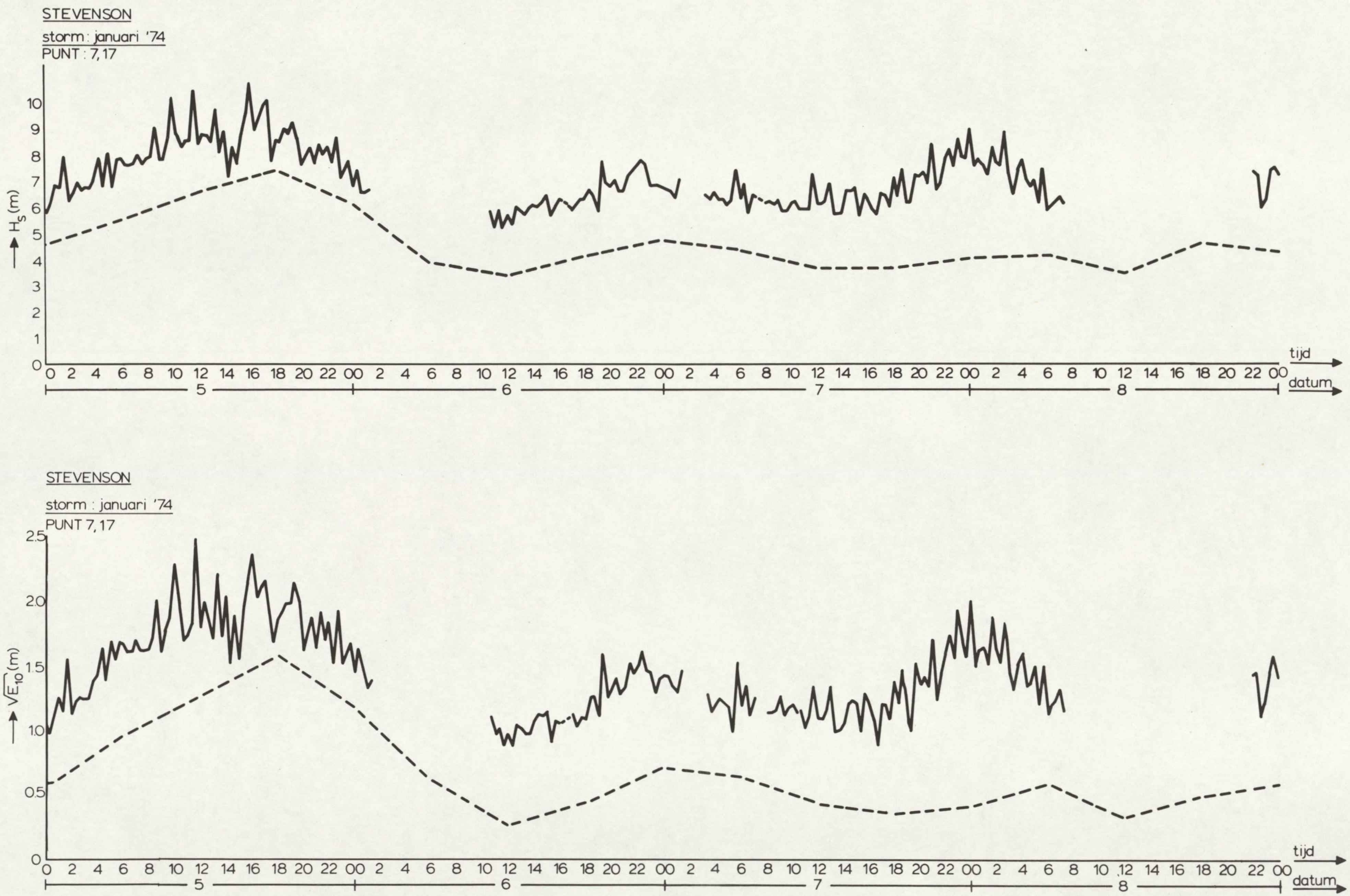

STEVENSON
storm : januari '74
PUNT : 7,17
H_s (m)
tijd
datum
STEVENSON
storm : januari '74
PUNT 7,17
$\sqrt{E_{10}}$ (m)
tijd
datum

FIG. 4a

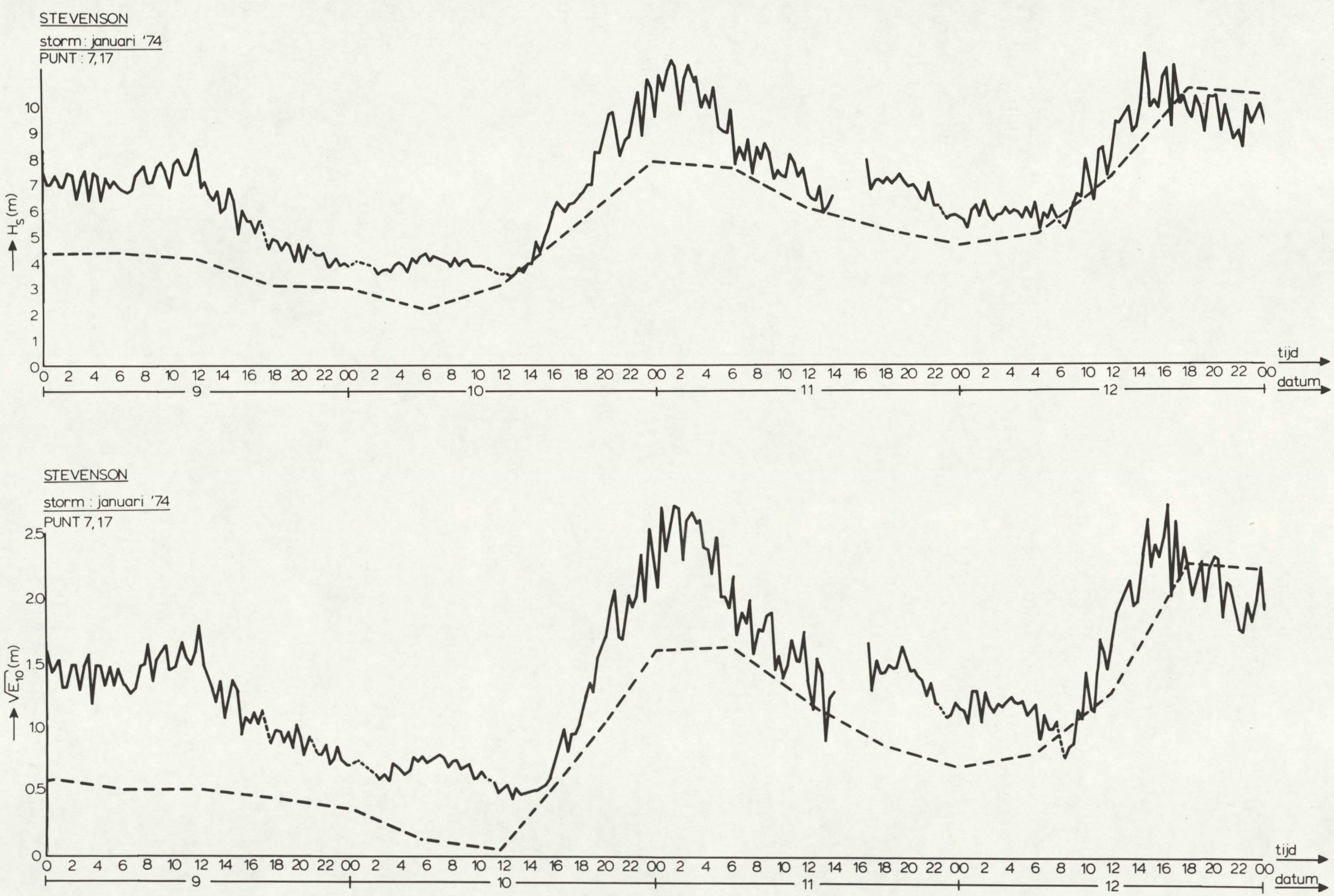

STEVENSON
storm : januari '74
PUNT : 7,17
H_s (m)
0 1 2 3 4 5 6 7 8 9 10
0 2 4 6 8 10 12 14 16 18 20 22 00 2 4 6 8 10 12 14 16 18 20 22 00 2 4 6 8 10 12 14 16 18 20 22 00 2 4 4 6 10 12 14 16 18 20 22 00
tijd
9 10 11 12
datum
STEVENSON
storm : januari '74
PUNT 7,17
$\sqrt{E_{10}}$ (m)
0 0.5 1.0 1.5 2.0 2.5
0 2 4 6 8 10 12 14 16 18 20 22 00 2 4 6 8 10 12 14 16 18 20 22 00 2 4 6 8 10 12 14 16 18 20 22 00 2 4 6 8 10 12 14 16 18 20 22 00
tijd
9 10 11 12
datum

FIG. 4a

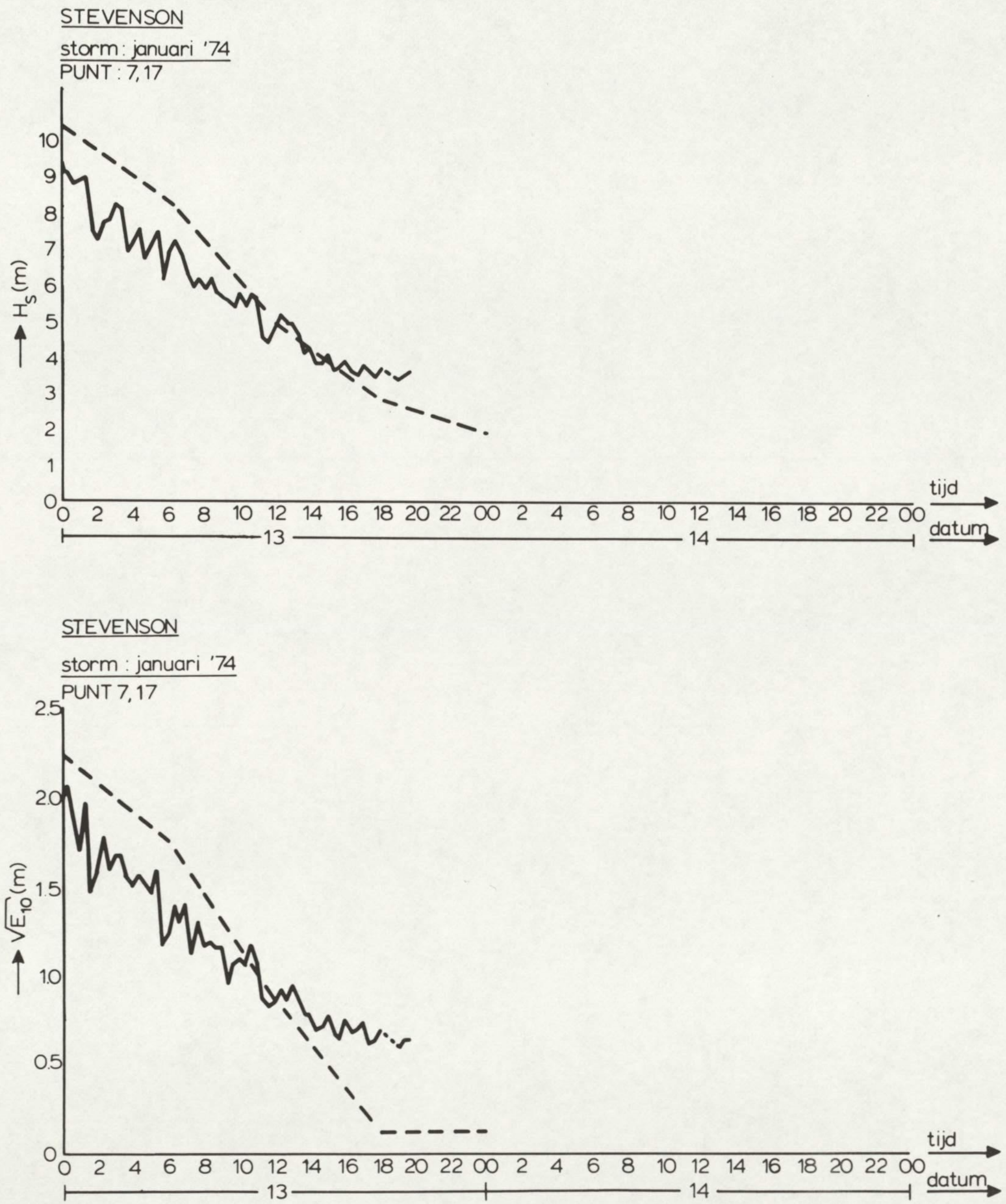
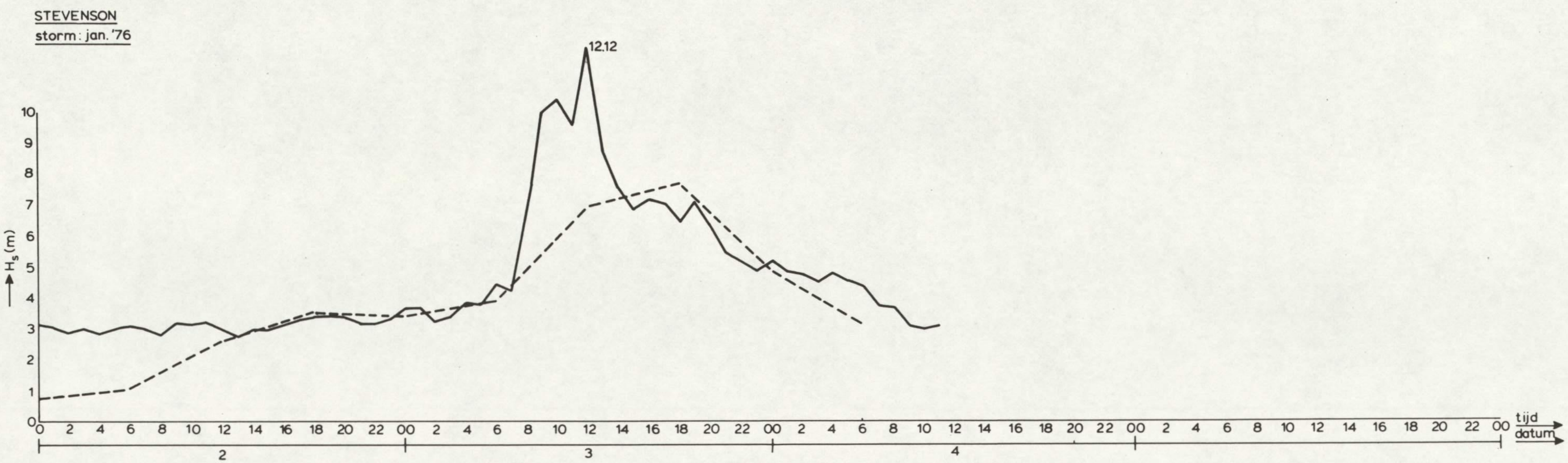

STEVENSON
storm : januari '74
PUNT : 7, 17
H_s (m)
tijd
datum
13
14
STEVENSON
storm : januari '74
PUNT 7, 17
√E_10 (m)
tijd
datum
13
14

FIG. 4a


STEVENSON
storm: jan. '76
12.12
H_s (m)
tijd
datum

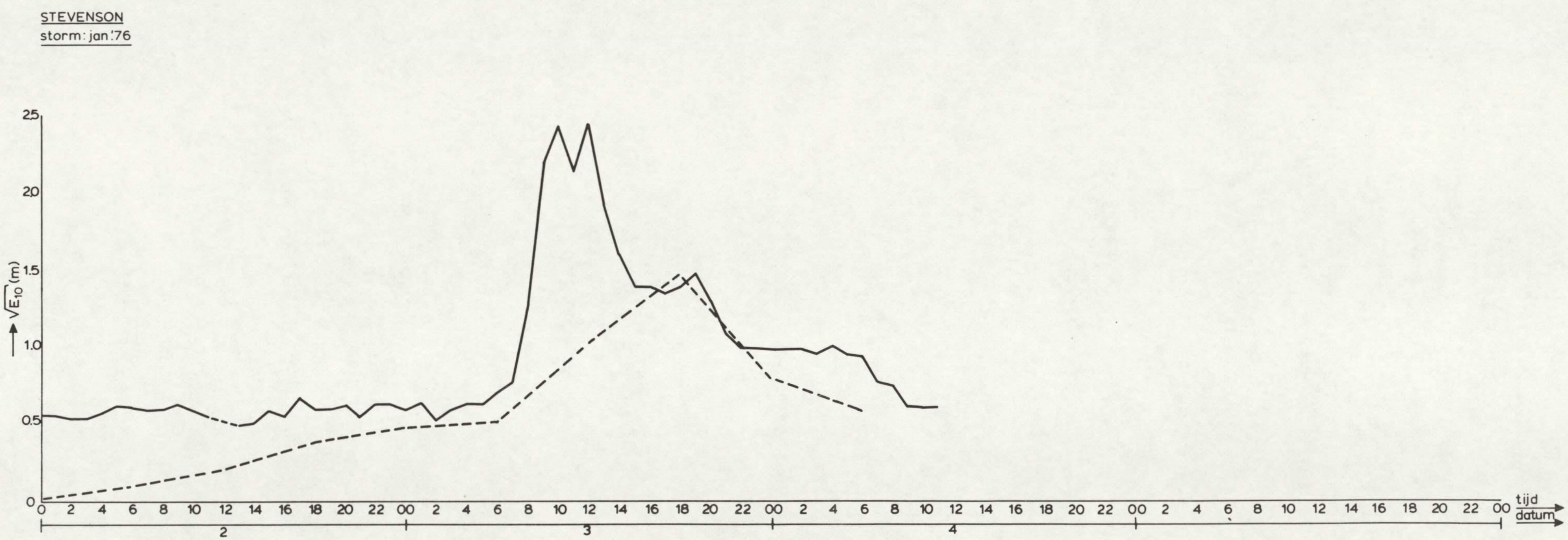
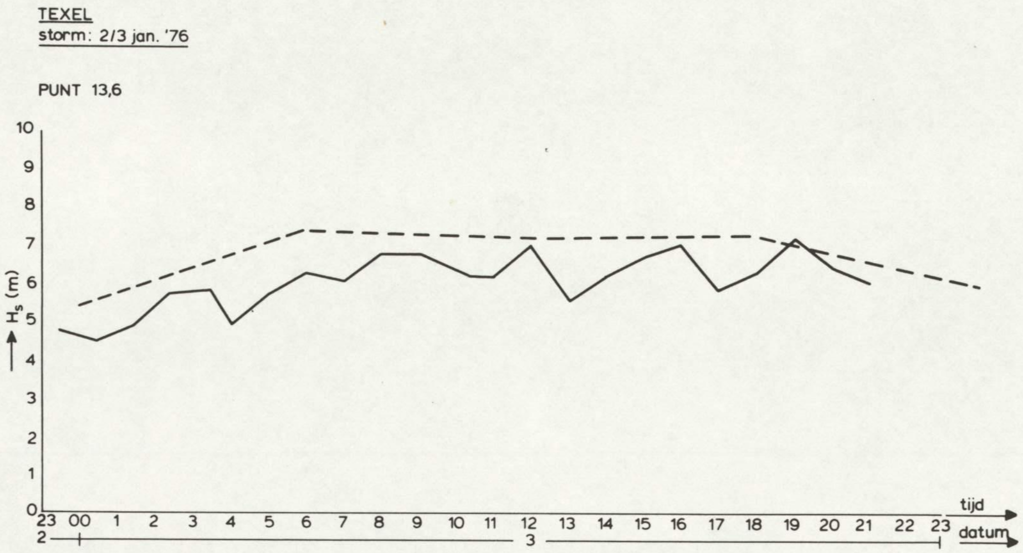

STEVENSON
storm: jan.'76
$\sqrt{E_{10}}$ (m)
tijd
datum

FIG. 4b


TEXEL
storm: 2/3 jan. '76
PUNT 13,6
H_s (m)
10
9
8
7
6
5
4
3
2
1
0
23 00 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
tijd
2
3
datum

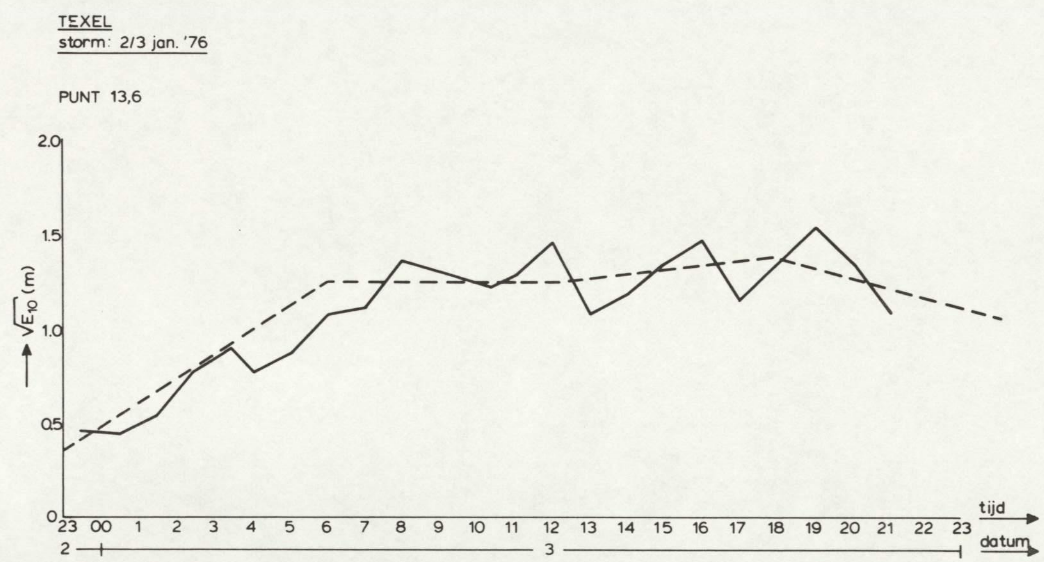

TEXEL
storm: 2/3 jan. '76
PUNT 13,6
$\sqrt{E_{10}}$ (m)
2.0
1.5
1.0
0.5
0
23 00 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
tijd
2
3
datum

FIG. 4c

BRENT-B
storm: 23 t/m30 jan '76

PUNT 8.17

BRENT-B
storm: 23 t/m 30 jan.'76

PUNT 8,17

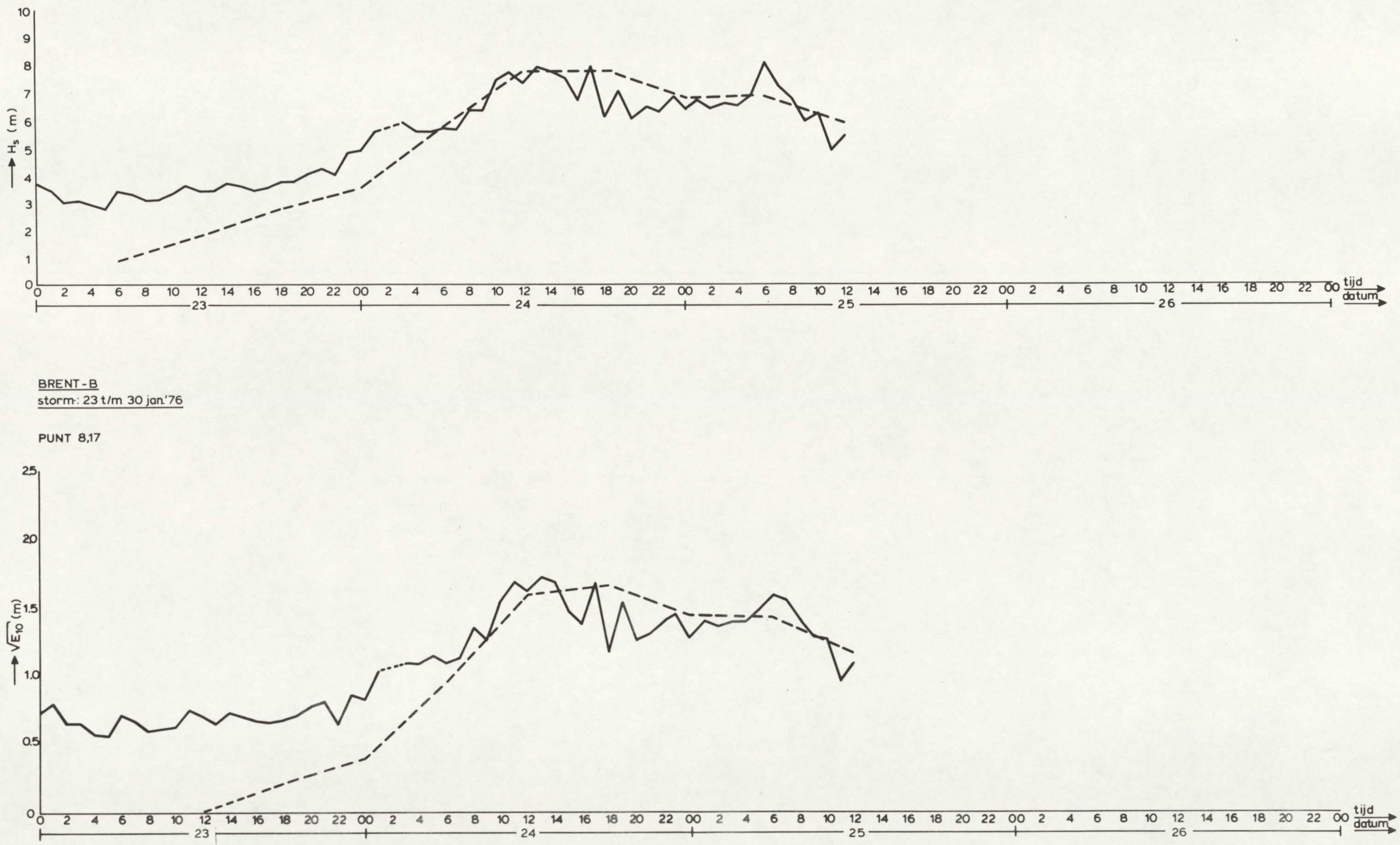
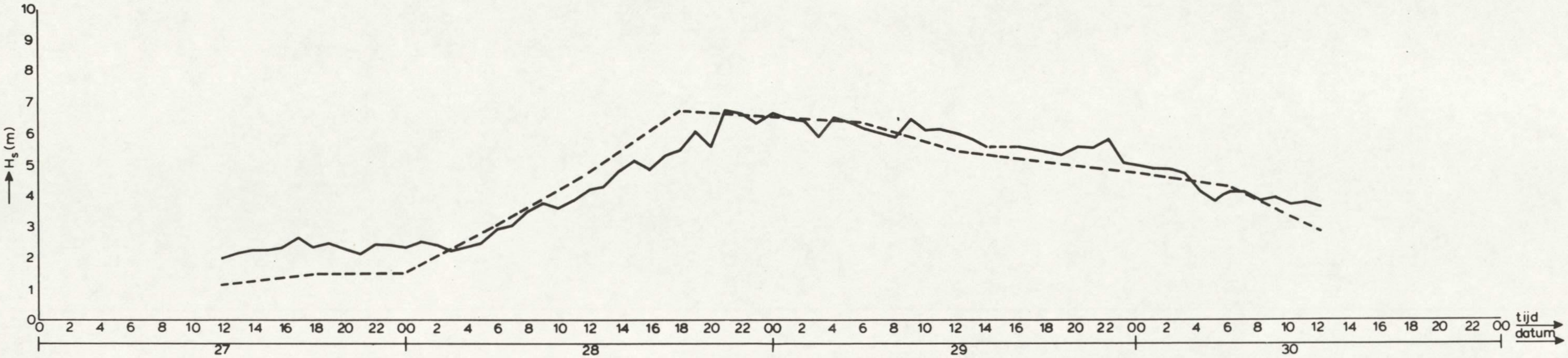


FIG. 4 d

BRENT-B
storm: 23 t/m 30 jan.'76

PUNT 8.17



BRENT-B
storm: 23 t/m 30 jan.'76

PUNT 8,17

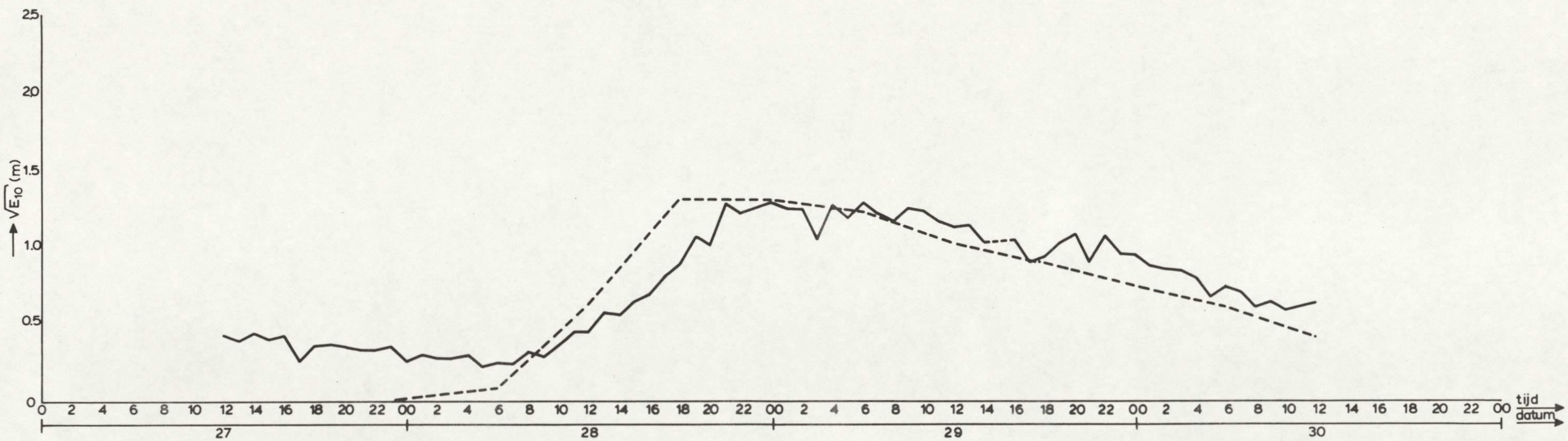
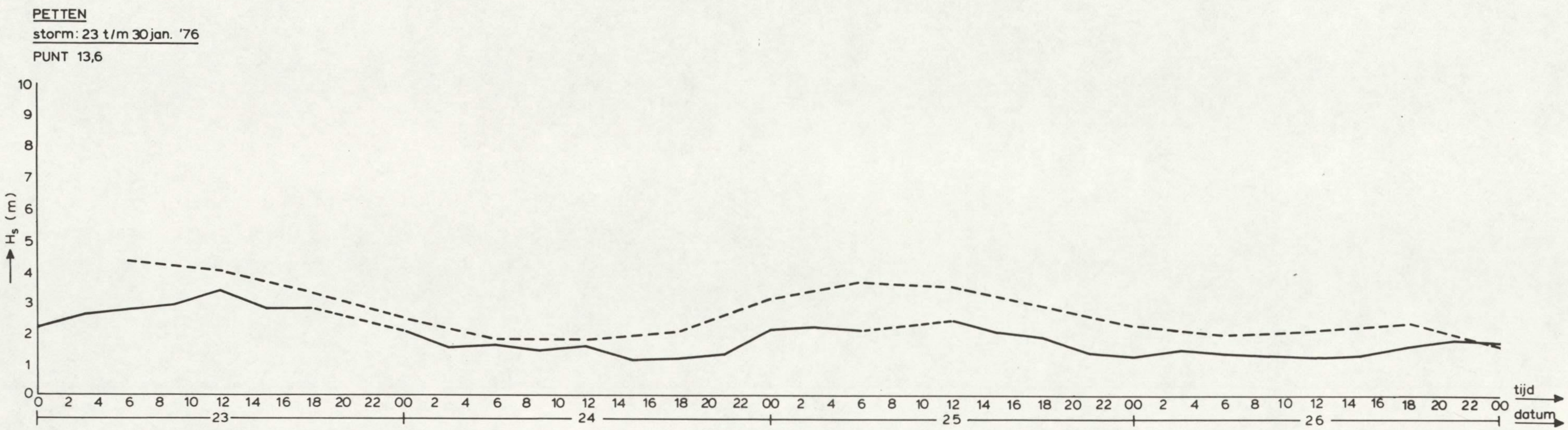


FIG. 4d


PETTEN
storm: 23 t/m 30 jan. '76
PUNT 13,6
H_s (m)
tijd
datum
23
24
25
26

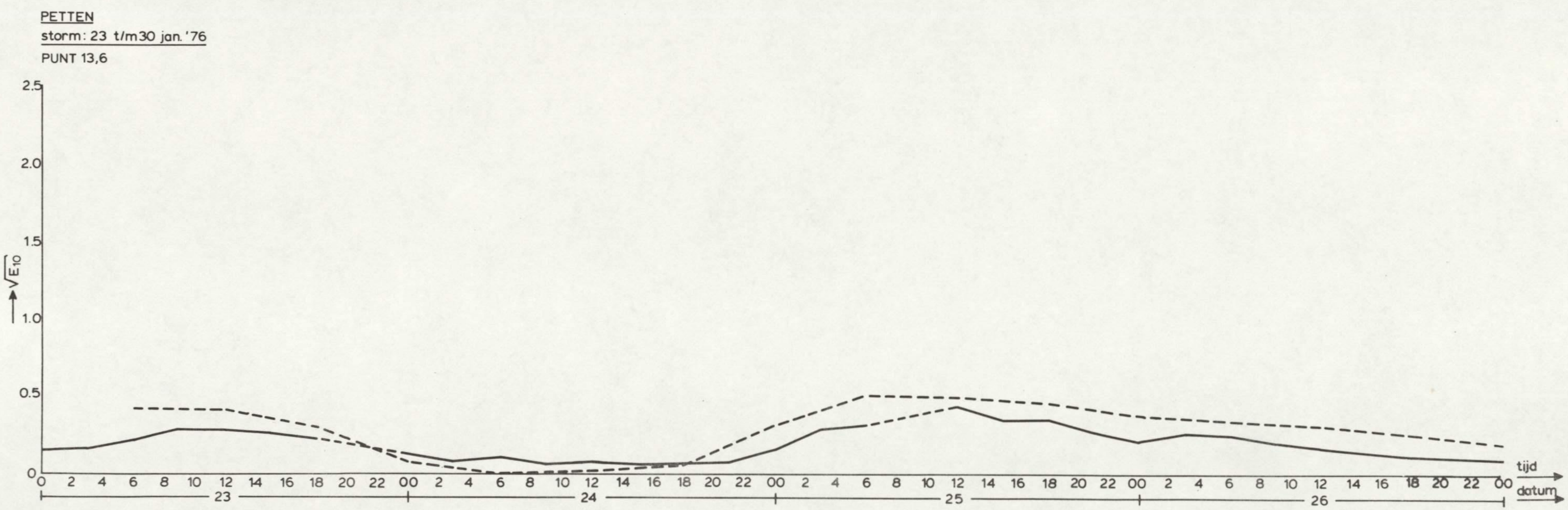

PETTEN
storm: 23 t/m30 jan. '76
PUNT 13,6
$\sqrt{E_{10}}$
tijd
datum
23
24
25
26

FIG. 4e

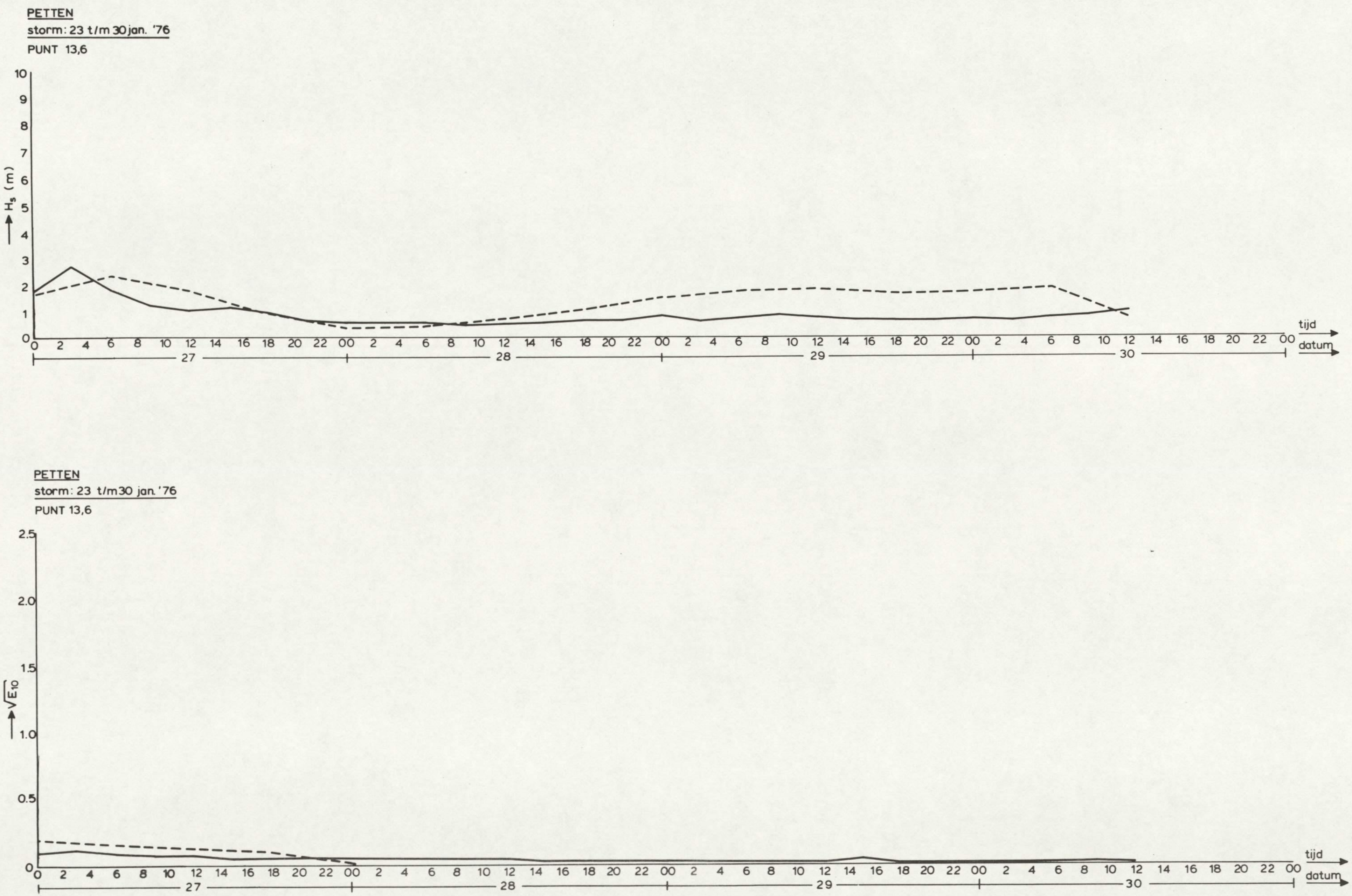
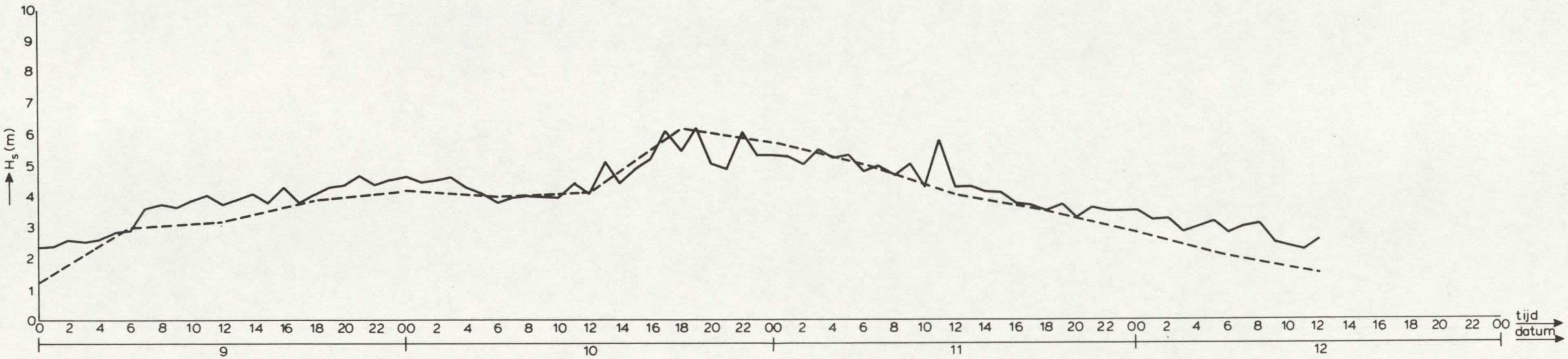

PETTEN
storm: 23 t/m 30 jan. '76
PUNT 13,6
H_s (m)
tijd
datum
27
28
29
30
PETTEN
storm: 23 t/m 30 jan. '76
PUNT 13,6
$\sqrt{E_{10}}$
tijd
datum
27
28
29
30

FIG.4e

BRENT-B
storm: 9 t/m 12 sept. '76

PUNT 8,17



BRENT-B
storm: 9 t/m 12 sept. '76

PUNT 8,17

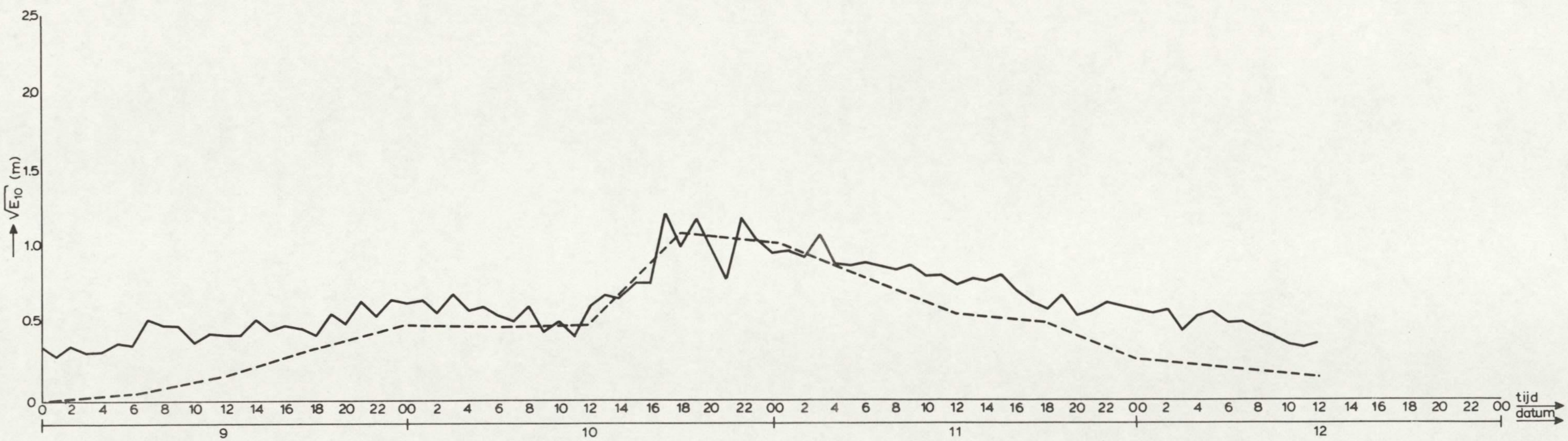
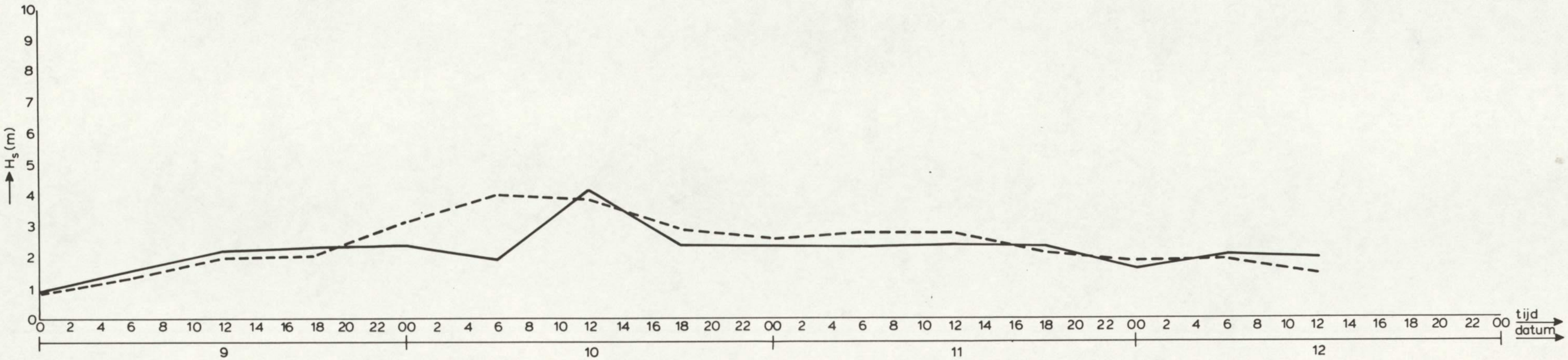


FIG. 4f

IJMUIDEN (MUN.)
storm: 9 t/m 12 sept. '76

PUNT 13,5



IJMUIDEN (MUN.)
storm: 9 t/m 12 sept. '76

PUNT 13,5

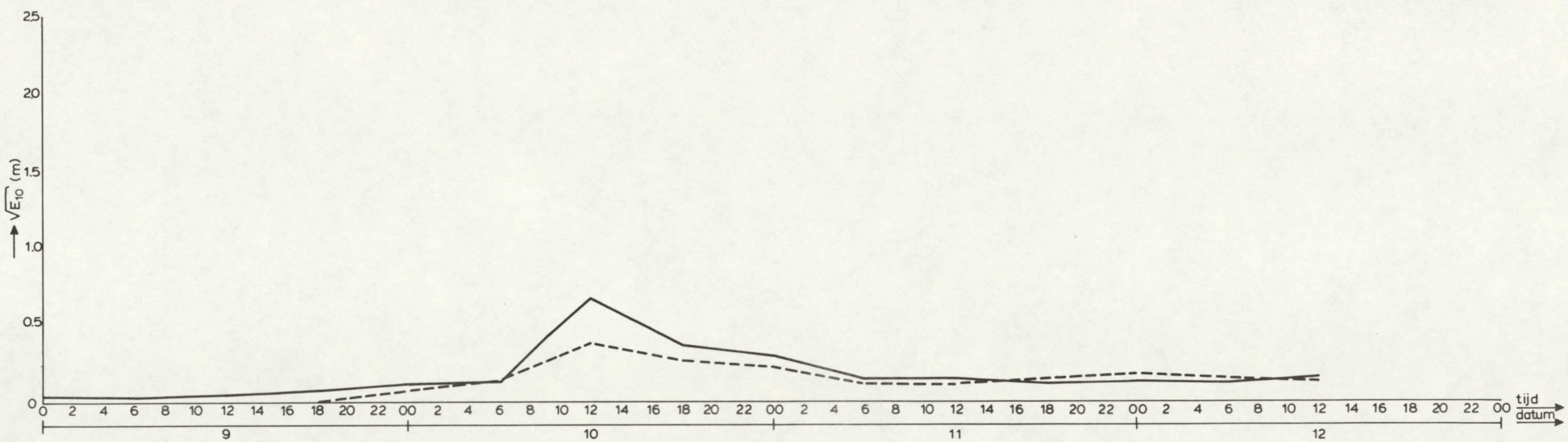
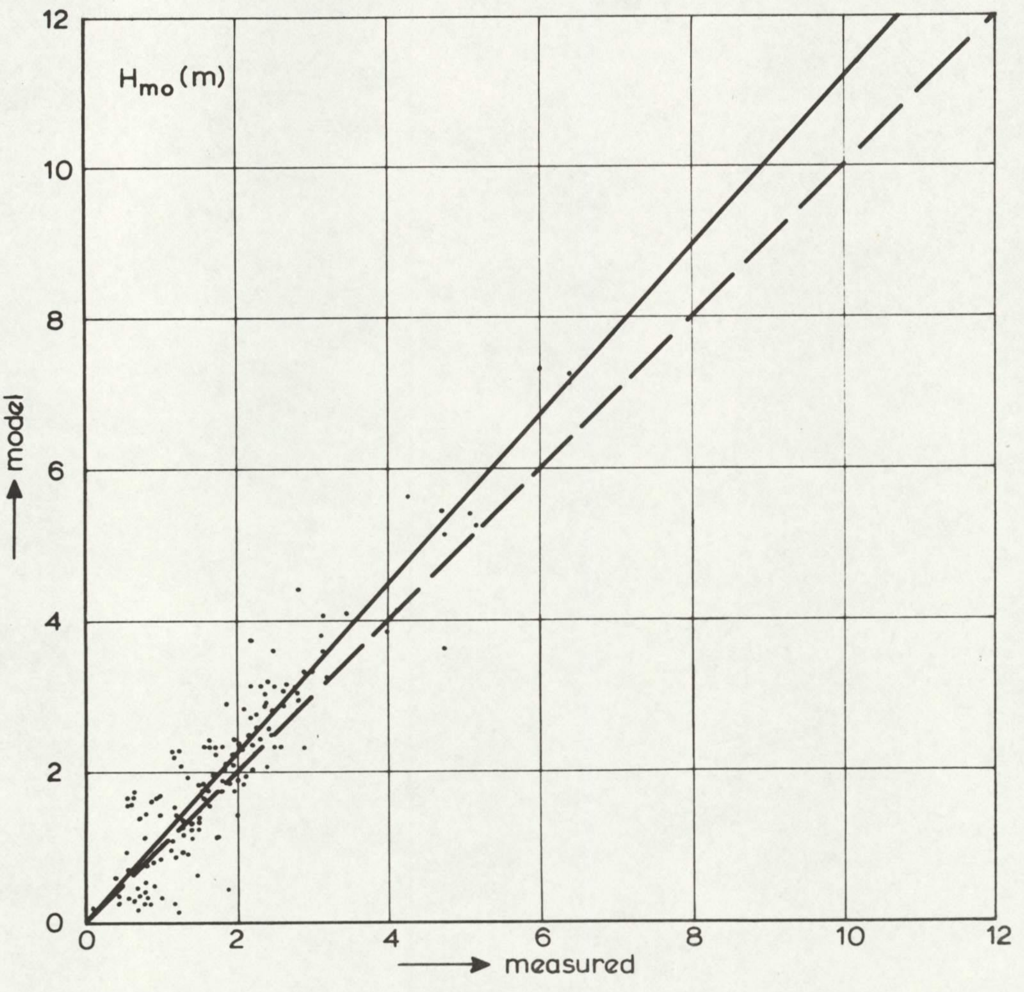


FIG. 4g

STATIONS: Penrod + Texel + Petten + IJmuiden + Euro-5 + L.E. Goeree



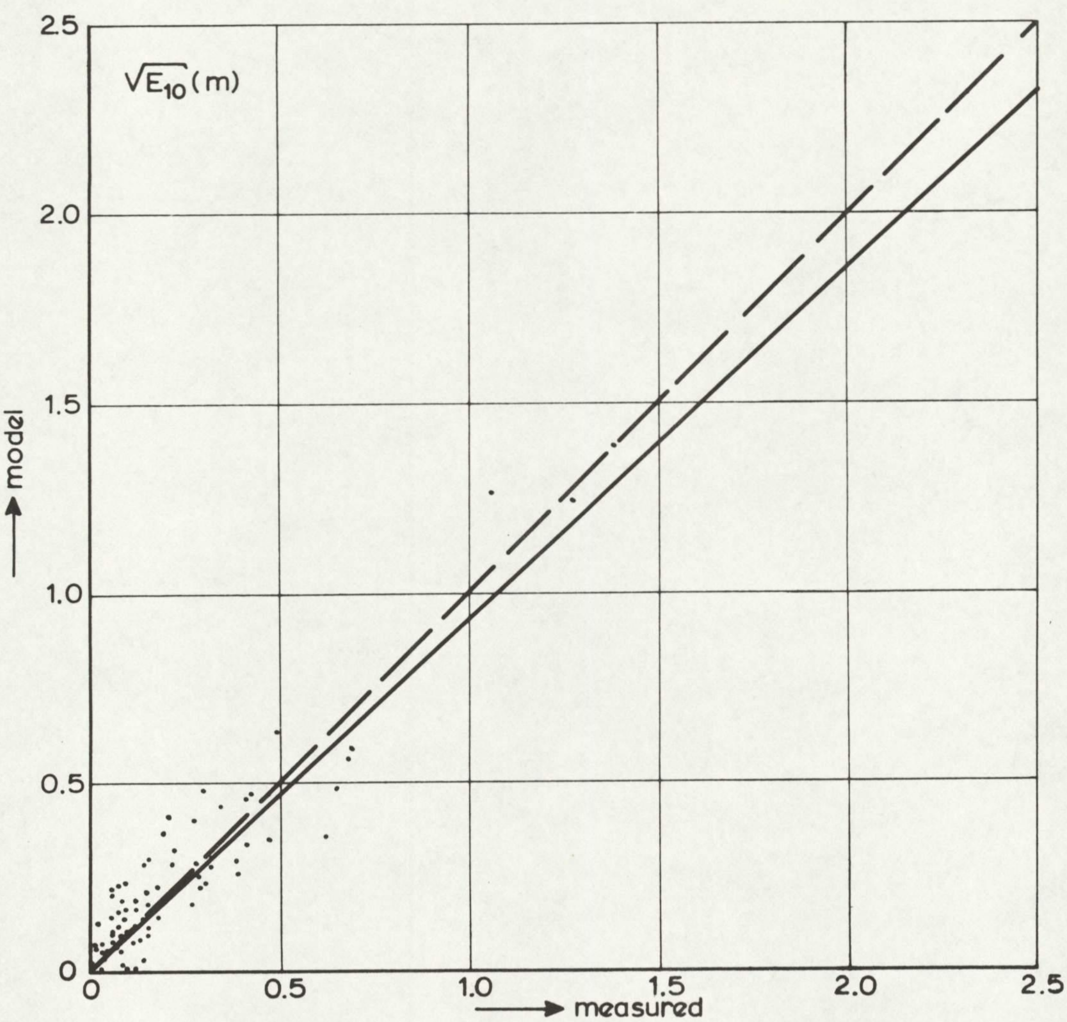
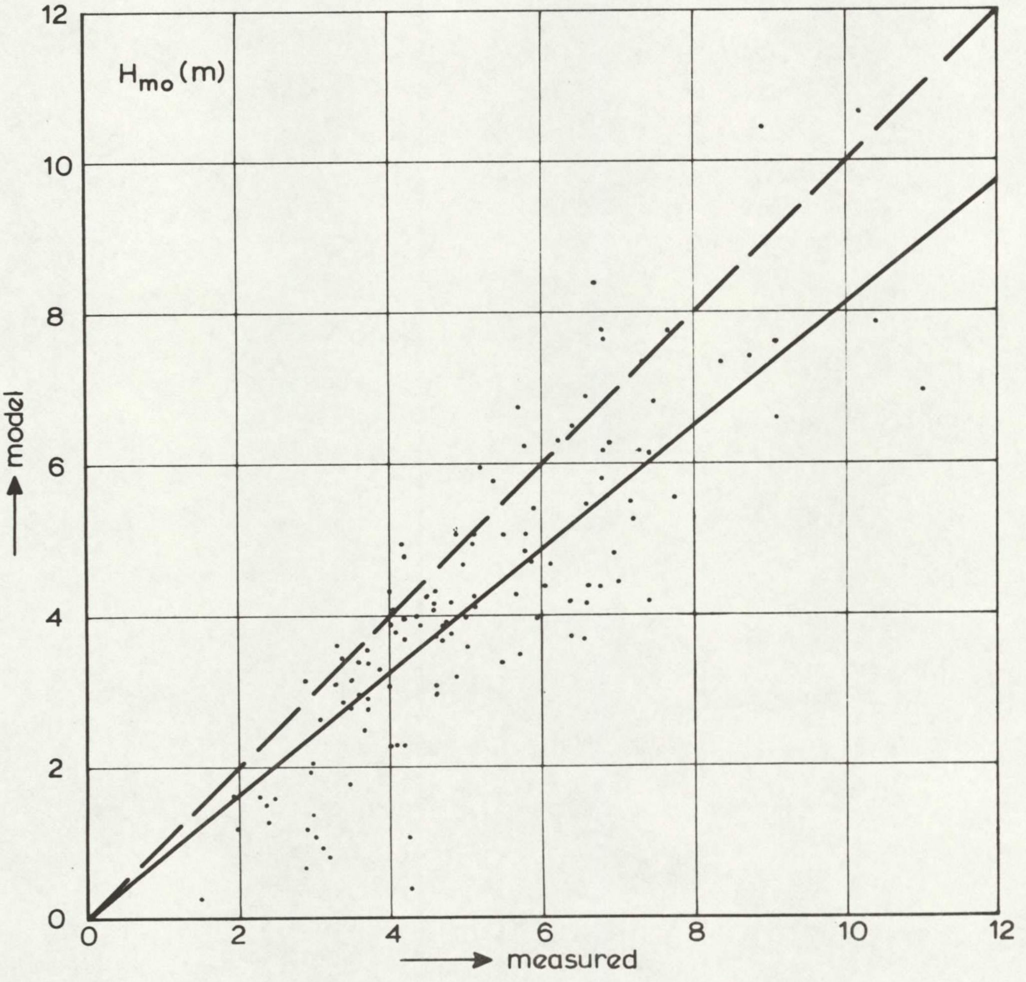


FIG. 5

STATIONS : Mike + Stevenson + Brent-B + Fitzroy



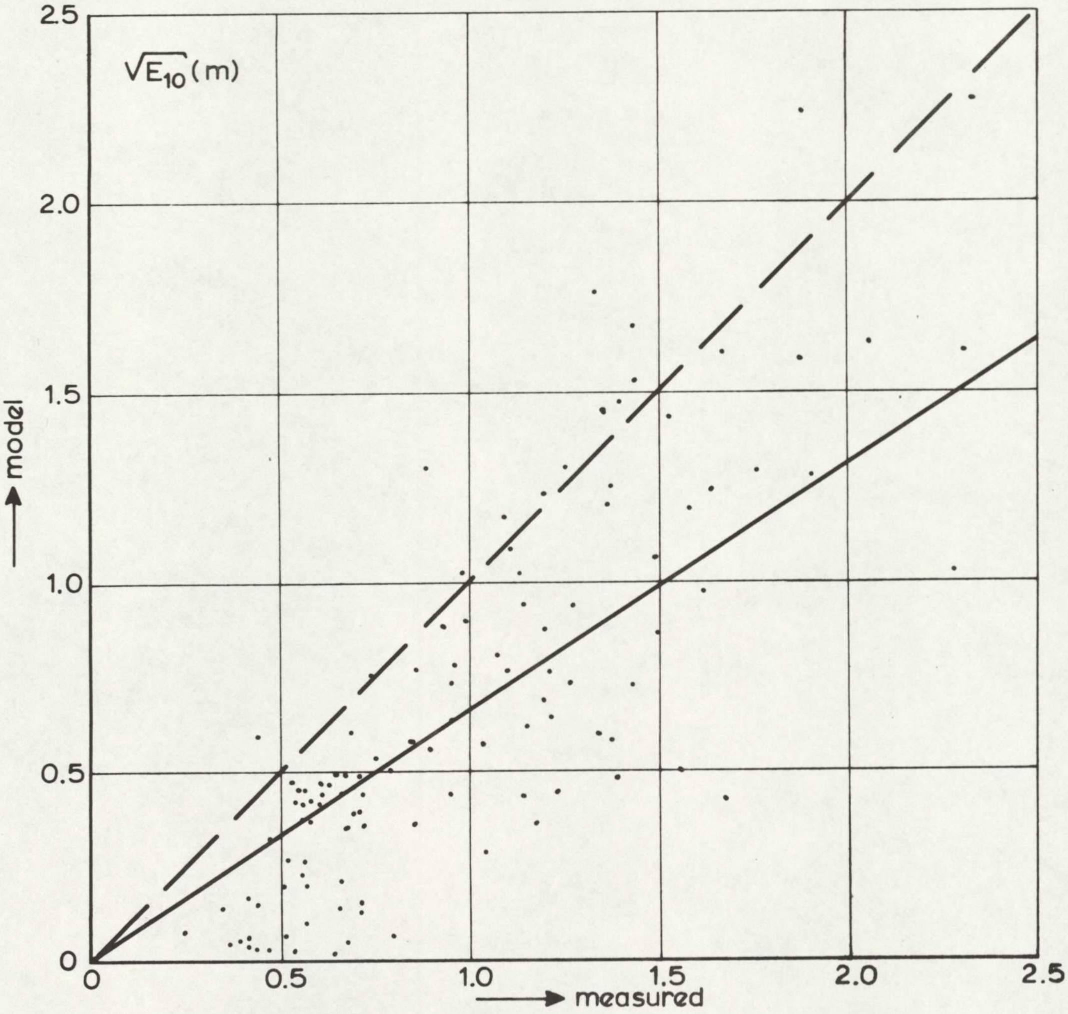


FIG 6

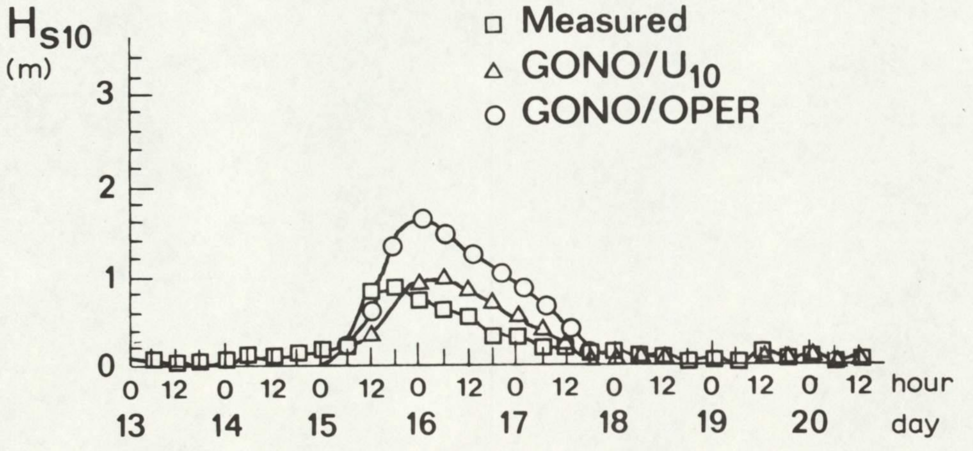


FIG. 7 CALCULATED AND MEASURED SWELL
AT LOCATION EURO IN JANUARI 1980

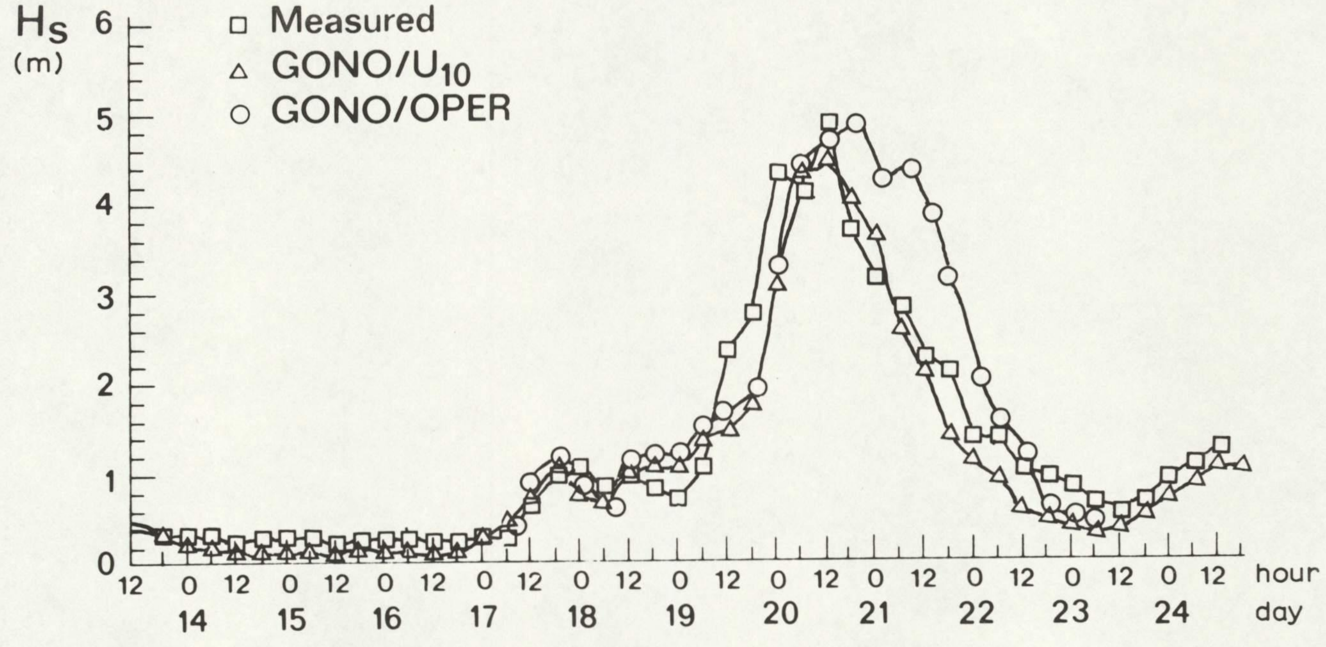


FIG. 8 CALCULATED AND MEASURED WAVE HEIGHTS
AT LOCATION EURO IN APRIL 1980