EXTREME NORTHERLY WIND STORMS IN THE EASTERN MEDITERRANEAN BASIN AND THEIR WAVE IMPACT IN DEEP WATER IN HAIFA BAY

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1. INTRODUCTION

As part of the planning of an expansion of Haifa Harbor, concern has been raised regardingthe possibility of rare, but not uncommon, northerly windstorm (hereafter NWS) events. Because the bay does not offer protection from winds and waves arriving from the northerly sector (see Figure 1), human intervention in the form of appropriately engineered breakwaters needs to be taken. Such protection is obviously costly and needs to be carefully considered using reliable design wave statistics. In recent years fully spectral, instrumental wave observations were implemented in Haifa Bay. These can be augmented with reliable numerical wave models that allow the extrapolation of the measurements from the buoy site to the harbor. However the length of the observed wave record is relatively short (6 years) and its statistics need to be supported by other sources to assure correct planning of the harbor. The present study is meant to address this particular concern by building on a much longer record (41-years) of synoptic meteorological data. As explained below, these data are analyzed in two stages to first assess the synoptic conditions that could develop in an extreme NWS and then using the corresponding surface wind evolution to drive a numerical wave model and assess the corresponding wave statistics in the Bay.

2. DATA AND METHODOLOGY

2.1 Wind data

Almost all NWS observed in Haifa Bay occur during winter, which is the stormiest season of the year in the Eastern Mediterranean (EM) region. To determine the distribution of NWS events we use data from the first version of the NCEP/NCAR Climate Data Assimilation System (CDAS-1, Kalnay et al., 1996). The CDAS-1 dataset is based on synoptic meteorological observations (both surface and upper air), which were assimilated into a state-of-the art numerical atmospheric model to produce a spatially uniform representation of both observed and derived variable (those calculated by the model as constrained by the observations) at 6-hour time interval.

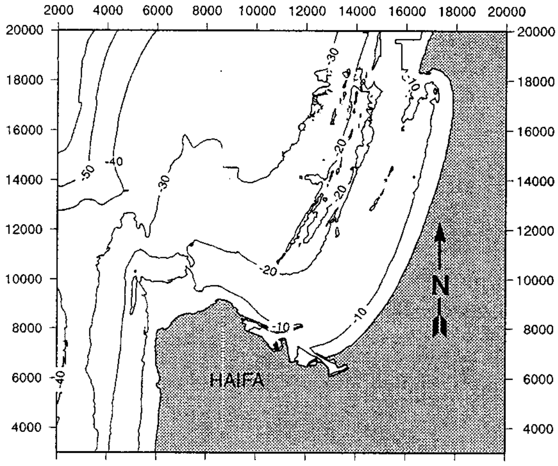

Figure 1: A map of Haifa Bay with bathymetry drawn every 10 m. Vertical and horizontal axes are scaled in meters.

One of the derived variables is a vector representing the wind 10-m above the surface. It is presented on a Gaussian grid with a resolution of 1.875° longitude and approximately 2° latitude. In order to identify all the historical NWS events data at the following 4 grid points are examined:

1. 33.750°E, 33.333°N
2. 35.625°E, 33.333°N
3. 33.750°N, 35.238°N
4. 35.625°E, 35.238°N

These points define a box lying parallel to the coast of Lebanon and Syria, northwest of Haifa Bay (see Figure 3), in the NWS occurrence region. We extracted daily averages of u10 and v10 (west-east and south-north wind components of the 10-m wind vector,

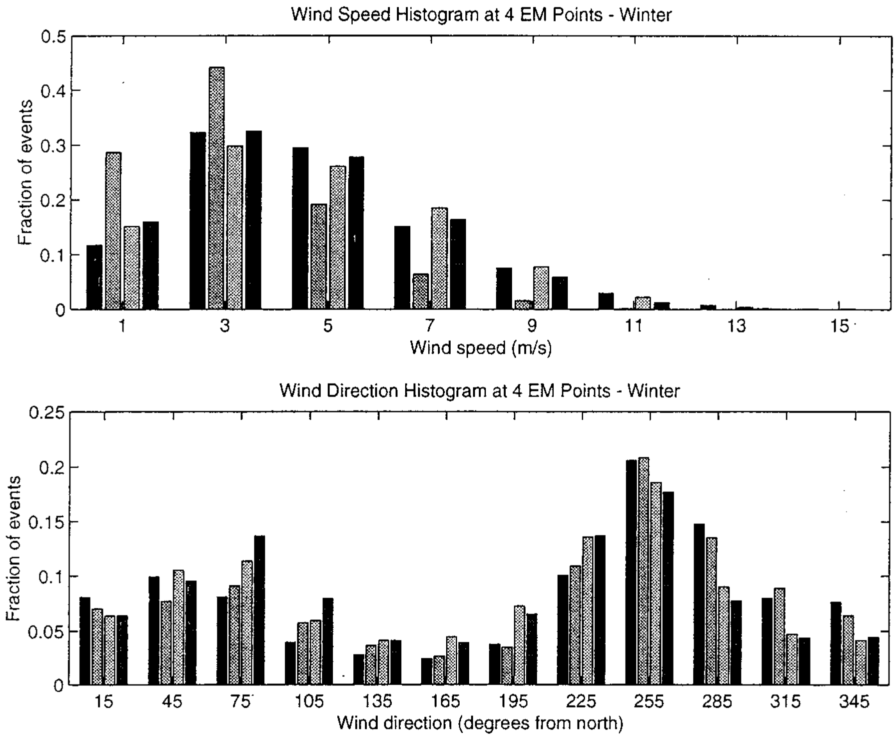

Figure 2: Histogram of CDAS-1 wintertime 10-m surface winds (all directions, 1958-1998) found at the four EM grid points listed in the text above. Top panel is for windspeedin m/s (bin width is 2 m/s centereda 1, 3, 5 etc.) and bottom panel is for wind direction (bin width is 30° centered at 15, 45, 75 etc.). The 4 bars in each bin correspond to points 1-4 in that order, from left to right. Point 2 is second from left.

respectively) at these grid points from the CDAS-1 dataset, for the winter season (defined here as interval between the 1st of November of one year and the 30th of April of the following year). A histogram of daily averaged wind speed and direction at the four grid points is shown in Figure 2. The histograms depict a homogeneous statistics of speeds and direction at grid point 1, 3, and 4. Grid point 2 displays noticeably weaker winds than the other points and we therefore exclude it from the subsequent extreme-value analysis (see below). We attempted to validate the CDAS-1 10-m wind data against actual wind observations in the Haifa Port station. The agreement was reasonable considering the fact that the Port station is not ideally exposed to open sea condition and is affected by the steep topography around the Bay. However, the actual wind data validation (and calibration) was done using the numerical wave model as described below.

2.2. Wave hindcast procedure

An accurate determination of the sea-state at a given point depends on the history of the surface wind field in a relatively large geographical region because both locally formed waves and swell are important. To achieve a depiction of the growth and decay of a NWS in Haifa Bay we forced a third-generation wave model (WAM) of the entire EM basin with the 10-m wind data from CDAS-1. The integration was started from rest (cold start) 3 days prior to the day of maximum windspeed and was forced with the 10-m winds at 6-hour intervals for 7 consecutive days. For the purpose of integrating the model the 10-m wind vectors were linearly interpolated to a high resolution 1/4° grid for the region bounded by the longitudes of 15°E and 36°E, and the latitudes of 30°N and 38.5°N (Figure 3). The hindcast technique is similar to that described in Stiassnie and Kunitsa, (1998 a, b). A complete description of the model and its integration methodology can be found in Kunitsa (1997).

To test the hindcast methodology we integrated the model with observed winds for two NWS events that occurred in the Februarys of 1959 and 1997. The first event (centered on 24 February 1959) is the second largest NWS event in the 41-year wind record. The second event (centered on 4 February 1997) is the 12th largest overall and the second largest in the recent period when instrumental wave data from Haifa and Ashdod are available (Ashdod is a second port city on the coast of Israel, south of Haifa, see Figure 3). A comparison between the hindcast and the observations

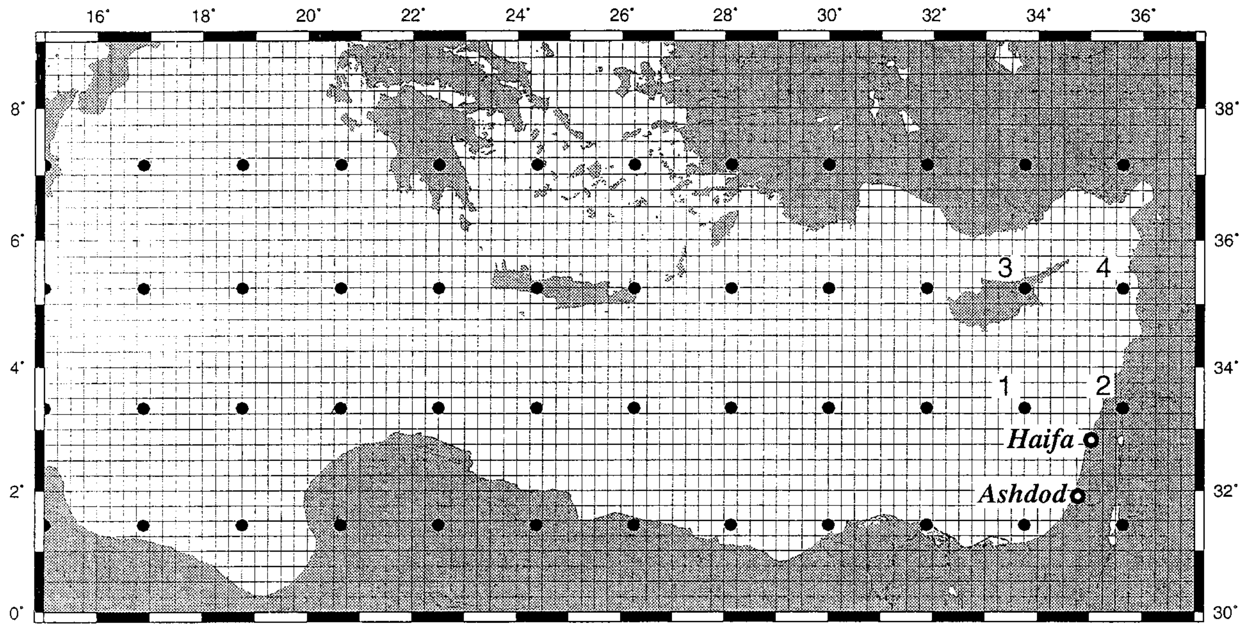

Figure 3: A map of the wave model domain. The model grid is presented by the vertical and horizontal mesh. The black dots are CDAS-1 10-m wind grid points. The four, numbered grid points north of Haifa are the ones used to determine the storm statistics relevant for Haifa. Open circles mark the ports of Haifa and Ashdod.

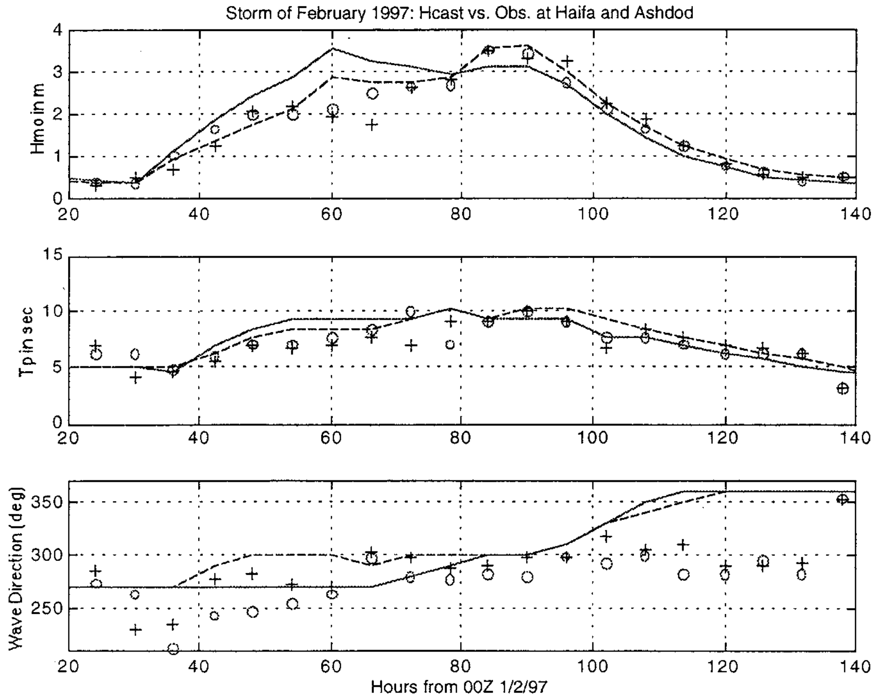

Figure 4: Evolution of the simulated wave field at a deep-water grid point near Haifa (solid line) and Ashdod (dashed lines) during the NWS of February 1997. The WAM was forced with a 6-hourly history of the 10-m wind from CDAS-1, uniformly augmented by a factor of 1.25. The 3 panels (top to bottom) are for significant wave height (Hmo), wave period (Tp), and wave direction, respectively. Instrumental observations are presented by 'o' (Haifa) and '+' (Ashdod). The time axis is in hours measured from 00Z, 1 February 1997 (the beginning of the hindcast run).

at Haifa and Ashdod indicated a need for calibration, as the hindcasted waves were consistently lower than the observed. From scaling arguments (wave height relationship to the square of the windspeed) we concluded that a simple calibration could be achieved by linearly enhancing the CDAS-1 10-m wind by a factor of 1.25. The results from the integration with the calibrated wind of the 1997 NWS event are shown in Figures. 4. They indicate that the simple calibration is excellent for period simulation. The wave heights are overestimate early is the storm evolution but reasonably simulated in the later stages. The simulated wave direction veer too far to the north during the storm decay phase. The event of 1959 (not shown) could only be verified at Ashdod where visual wave observations existed at that time. It also confirms that the simple calibration is equally satisfactory.

2.3 The case study approach

With the observed 10-m wind data, it is possible to force a numerical wave model for the entire CDAS-1 record, and hindcast the conditions during all the 41 winters. However, this would have been a considerable undertaking in time and resources. We therefore adopted a different approach that we shall refer to as the "case-study approach": A statistical extreme-value analysis was performed to project from the wind data the largest expected storm in a 100-year period. The ratio between the projected 100-year maximum and a real historical storm (such as the February 1997 one) was then calculated, and the entire 7-day wind record of that storm was enhanced by that ratio. The WAM was then integrated with the enhanced wind field to determine the waves corresponding to the 100-year storm. This case study approach forms the basis for our historical assessment of the harbor "design wave". Comparing the calculated wave condition with analysis based on the short instrumental wave record forms the final confirmation of the design wave information.

3. SYNOPTIC EVOLUTION OF EM NWS

The case study approach to calculating the design wave would work if all NWS events had a roughly similar synoptic evolution. If different NWS events follow different evolution cycles, their corresponding wave fields could look quite different, due to the non-local dynamics of ocean waves.

To study the evolution of NWS in the EM basin we first identified the largest annual storms, winter-by-winter from 1958 to 1998. The criterion for selecting these events was based on the magnitude and direction of the daily, vector-averaged wind at the points 1, 3, and 4 defined above in Section 2.1. Only winds blowing from the compass sector 310° - 10° were selected. Once these storms were identified we plotted the daily averaged maps of the sea level pressure filed provided in the CDAS-1 dataset, from 3 days before the day of maximum windspeed to 3 days after that. An examination of the 6 storms with average daily windspeed larger than 10 m/s confirmed that the NWS evolution is quite similar in all of these cases. We also examined several weaker NWS events (e.g., the one shown above in Figure 4, when the average speed at the 3 grid points was only 9.1 m/s) and were satisfied with the general similarity of all these events.

The evolution of a typical EM NWS event can be summarized by the 6-panel figure below (Figure 5), which shows the day-by-day composite evolution of the 6 largest storms in the record. The figure was calculated by averaging together day –3 to day +2 of each storm with respect to the day of maximum windspeed.

A NWS event appears to begin (day -3) with a movement of a low-pressure center into Russia with a trough into Turkey and the EM. At the same time the southern part of the EM is under the influence of a weak "Red Sea trough" and the entire western half of the plotted domain is under the influence of a strong high-pressure center. As the northern low-pressure center moves east (days -2 and -1) the trough over the northeastern Mediterranean deepens. This generally results in the intensification of winds from a westerly direction south of Cyprus. The early phase of the NWS thus tends to force waves from a westerly direction (see discussion of wave hindcast experiments below). The development of strong northerly winds north of Haifa occurs when the trough moves into Syria (day 0) and a secondary low-pressure center develops there. These conditions last for another day (day 1) as the trough continues to move east and begins to weaken. This is the time when waves reach their maximum heights and begin to veer northward (see below). On day 2 the storm has weakened considerably and moved out of the area. As we shall see below the concurrent waves continue to veer northward but their height drops quickly as the storm diminishes. The typical NWS event thus appears to be short lived. A rapid intensification of winds is followed by rapid weakening and actual storm conditions last for only 3 days or so.

4. EXTREME-VALUE ANALYSIS

To extrapolate the 41-year storm record and obtain the windspeed value corresponding to a hypothetical 100-year storm, we apply a well-tested extreme-value analysis attributed to Weibull (1939). The Weibull distribution is suitable for wind statistics, in particular when the analysis involves the use of a threshold value (see e.g., Leadbetter et al., 1983). The decision to use

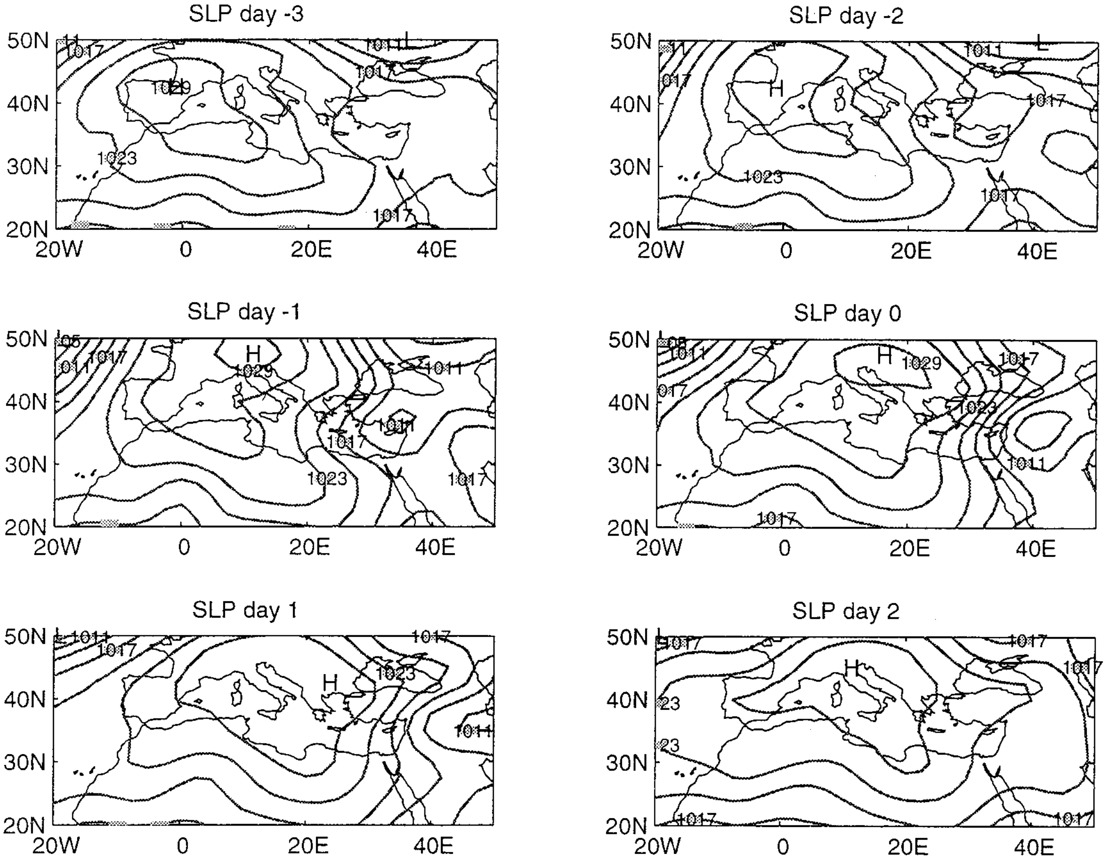

Figure 5: The composite NWS event based on 6 largest storms between 1958 and 1998. A sequence of daily sea level pressure maps is shown. The composite starts 3 days prior to the day of maximum winds in the gridbox north of Haifa Bay and ends 2 days after. Isobars are in mb. with an interval of 3.

the Weibull distribution was based on the superior fit between this distribution function and the data. Other extreme value functions such as the exponential and the Gumbel distribution functions (see Leadbetter et al., 1983) are visibly inferior (not shown). In Figure 6 we plot the annual maximum windspeed data on a diagram with an abscissa scaled according to the cumulative Weibull distribution. Clearly, the fit is extremely good in the strong windspeed end of the diagram. It points at the interesting fact that an event with a probability of occurrence of about 0.01 (a 100 year event) has actually been observed. A check of the list of the largest annual NWS events shows that the largest storm associated with a daily mean windspeed in the gridbox north of Haifa Bay of 12.9 m/s occurred on 11 January 1998. The strength of this storm is just 0.1 m/s short of the 100-year return value based on the parameters of the Weibull fit to our data. The Weibull fit in Fig. 6 shows no indication for the existence of two (or more) different sources of NWS distributions. If this was so, the data would deviate from a single theoretical line in a significant way. This is crucial for the validity of our attempt to use the case study approach.

5. THE 100-YEAR STORM

5.1 Case study with scaled up windspeeds

The Weibull function fit indication that the strongest wind expected in a 100-year record is 13 m/s allows us to calculate a wave hindcast for such event by scaling up accordingly the winds observed during any of the annual storms in the observed record. Application of this methodology to, for example, the storm of February 1997 implies that in addition to the calibration factor of 1.25, the 6-hourly wind data of this storm should be multiplied by a factor of 13/9 (the ratio between the 100-year windspeed and the daily averaged windspeed on 4 February 1997). The maximum wave height (Hmo) in Haifa Bay calculated by WAM is 7.39 m arriving from a compass direction of 280° with a peak period of 13.5 s. An examination of the wave field evolution (which follows with appropriate scaling the solid line in the top panel of Figure 4) indicates that the maximum wave height occurs about one day before maximum northerly windspeed are observed in

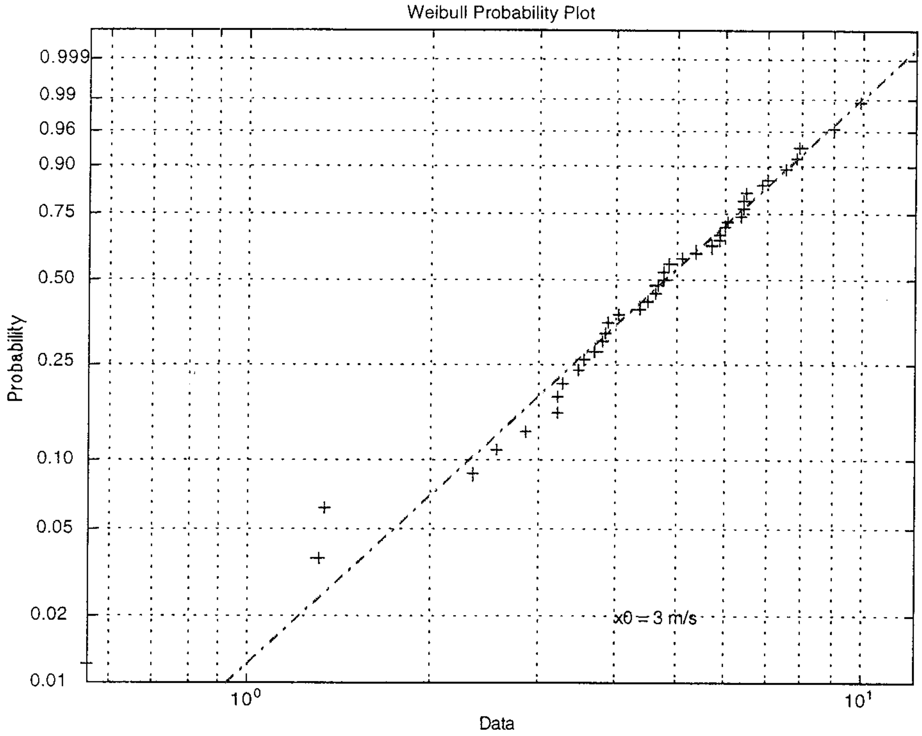

Figure 6: A scatter plot of the maximum, annual, northerly windspeed represented as the excess above a threshold value of 3 m/s, using scaling corresponding to the Weibull CDF. The ordinate is the cumulative probability and the abscissa is the wind speed value above the threshold in m/s. The dashed line is a regression line fitted to the upper and lower quartiles of the data. The slope of the regression line and its zero crossing along the ordinate determine the parameters of the Weibull CDF. The abscissa crossing at a probability value of 0.99 determines the 100-year return value above the threshold. The diagram was produced using the MATLAB Statistics Toolbox (Jones, 1996).

the gridbox north of Haifa Bay. At that stage the sea level pressure field resembles the pattern of day –1 in Figure 5, implying that these large waves result from the strong westerly winds blowing south of Cyprus and the large fetch they display. Notably however, the WAM simulation over estimatesthe wind speed in this phase in comparison to the observations (shown by '+' in Figure 4). When the northerly wind field reaches a maximum on day 0, the wave heights are lower at an Hmo of about 6 m from a direction of 300°. The wave heights decline steeply less than a day after that. Similar results are obtained by scaling up other large NWS events.

5.2 The storm of 1998

Because the 11 January 1998 NWS has been almost as strong as the estimated 100-year event, it is interesting to compare its observed and numerically calculated wave history with the enhanced 1997 storm described above. The evolution of wave properties between the 8th and the 14th of January 1998 is shown in Figure 7. Application of the linear calibration factor of 1.25 to the CDAS-1 10-m winds results in a hindcast which is somewhat stronger than the observed wave height record, particularlynear Haifa, while using the winds as is, results in an underestimate (not shown). Clearly the use of a simple linear adjustment has its disadvantages. However, both model and observationssuggest that the waves in this storm are far lower than in the upscaled hindcast of the February 1997 storm. The explanation of that difference is the lack of a westerly wind phase in advance of the 1998 storm. An examination of the synoptic conditions during this event displays a very strong high pressure area over Italy, and a deep Red Sea trough dominating the EM causing strong easterlies over the study area in advance of the NWS. The trough from Europe did not penetrate far enough into the EM region south of Turkey and instead deepened rapidly over Jordan and southern Syria replacing the easterlies with a strong northerly flow.

This evolution explains the rapid rise in wave heights from around 1 m on the 10th of January 1998 to about 3.7 m (observed) and 4.5 m (simulated) by the end of the 11th. Both the rapidity of the trough deepening and absence of westerly swell contributed to the low wave heights. Because most of the observed storms do

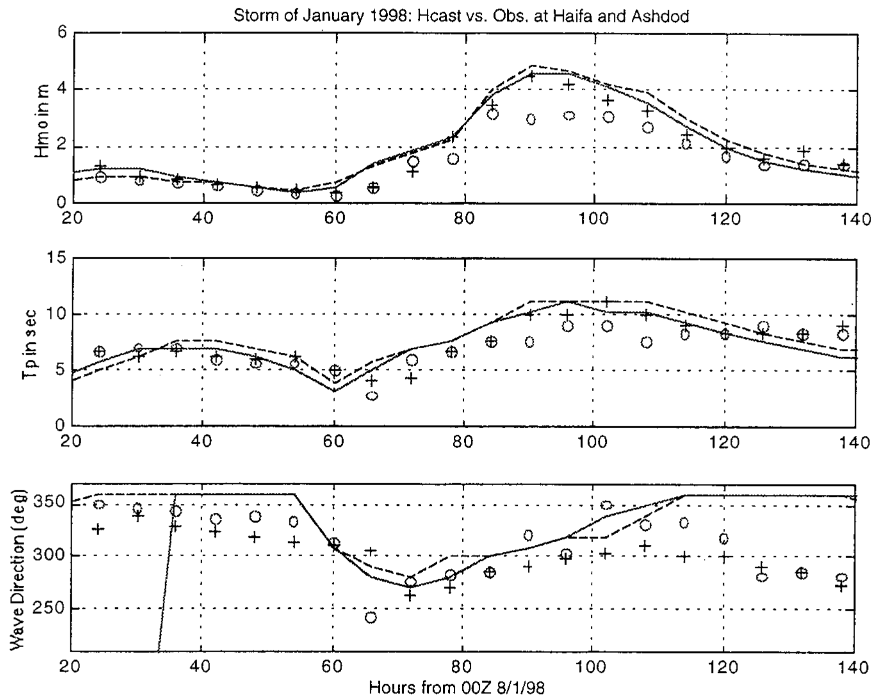

Figure 7: As in Figure 4 but for the NWS event centered on 11 January 1998.

exhibit a westerly wind phase prior to the development of strong northerly winds off the shores of Lebanon and northern Israel, we recommended using the hindcast of the February 1997 storm, enhanced to the level of the 100-year event for the harbor expansion design.

6. SUMMARY

In order to arrive at an estimate of maximum wave heights expected from the north at Haifa Bay and enhance analysisbased on a short record of instrumental wave data, we applied a combination of extreme-value analysis and numerical wave hindcasting to a long record of synoptic meteorological observations. The method was designed to provide a picture of the wave field evolution during a hypothetical, extreme northerly wind storm event in the eastern Mediterranean close to the northern coast of Israel but such that is based on realistic situations that occurred in the past.

A 41-year record of 6-hourly analyses of the surface wind field at the 10-m level was used as a data source. The wind data were first analyzed to search for the maximum northerly storm of every winter in the record. Several integrations were then conducted, using the wind data to hindcast the wave history during these storms. The integrations indicated the need for calibration of the wind data against observations and a simple adjustment was adopted for further study that consisted of uniformly augmenting the windspeeds by a factor of 1.25.

The typical evolution of the wave field at Haifa Bay during northerly storms was studied using simulations with calibrated winds. It was found that northerly windstorms are generally short in duration lasting only two to three days. They are often preceded by a strong westerly wind phase that may cause high seas from the west, a direction from which Haifa Harbor is well protected. As the wave field veers northward it also loses energy and the wave height drop rapidly.

The annual maximum northerly-windspeed data were used to project the 100-year event using a Weibull distribution function. The results suggest that it is very rare that storms reach speeds higher than values found in the data record. Wind data corresponding to several historical storms were augmented to the level of the 100-year storm and wave heights were calculated using the numerical wave model. The analysis indicates that under such extreme conditions and during the westerly wind phase waves could reach a significant height of around 7.5 m. When the wave direction turns northerly the significant wave height drops to about 3.5 m. This projection was found consistent with the shorter record of instrumental observations.

The numerical hindcast experiments with winds taken from similar bus non-identical storm events shows that small differences in storm evolution can cause significant differences in wave statistics at some arbitrary target region. These differences can be attributed to both real differences in synoptic wind conditions and the quality of the wind data. Therefore some degree of subjectivity needs to be taken when applying this methodology for similar situations elswhere.

REFERENCES

Glozman, M. and N. Drimer, 1998: Haifa port development stage B.: Calculation of near port wave climate. CAMERI Report P.N. 504/98, 24pp.

Jones, B., 1996: *Statistics Tollbox for Use with MATLAB, Users Guide.* The MathWorks, Inc., Natick MA.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, et al., 1996: The Ncep/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, 77, 437-471.

Kunitsa, D., 1997: Application of an advanced forecasting Model to the study of the wave climate at the Israeli coast. MSc. Thesis, Technion, Israel Institute of Technology, Haifa, Israel, 97pp.

Leadbetter, M. R., G. Lindgren and H. Rootzén, 1983: *Extremes and Related Properties of Random Sequences and Processes.* Springer-Verlag, New York, 336 pp.

Stiassnie, M. and D. Kunitsa, 1998a: Wave hindcast study of three characteristic storms in Ashdod area. CAMERI Report P.N. 481/98, 21pp.

Stiassnie, M. and D. Kunitsa, 1998b: Wave hindcast study for the storm of 22-25.2.1959. CAMERI Report P.N. 486/98, 11pp.

Weibull, W., 1939: *A Statistical Theory of the Strength of Materials.* Ingeniors Vetenskaps Akademiens Handlingar, Royal Swedish Institute for Engineering Research. Stockholm, Sweeden, No. 153.