HYDRODYNAMICAL MODELS FOR TIDAL AND WIND-DRIVEN CIRCULATION IN THE ARABIAN GULF

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ABSTRACT. This paper describes two hydrodynamic models, HYDRO I and HYDRO II. HYDRO I is a hydrodynamic model to simulate tidal and wind-driven flows in the Arabian Gulf. It solves the depth-averaged Navier-Stokes equations over the whole Gulf, and, at the user's option, solves the three-dimensional Navier-Stokes equations over a user-selected sub-region. This model is useful if the user requires the pattern of a particular flow over the whole Gulf or if the water velocities at different levels at a few particular locations are required. HYDRO II is a hydrodynamic model to simulate on a fine scale the tidal and wind-driven flows in an arbitrary sub-region of the Arabian Gulf. It solves the depth-averaged Navier-Stokes equations over the whole Gulf, using a 10 km grid, and then solves either the two- or three-dimensional Navier-Stokes equations over the chosen sub-region using a finer grid. This model is useful for computing the currents and surface elevations in small sub-regions of the Gulf. Both models include user friendly interfaces and meaningful graphics.

1. INTRODUCTION

This paper describes two hydrodynamic models developed by the Hydrodynamic and Environmental Modeling Group (HEMG) at KFUPM Research Institute. The software has been adapted to run interactively on 486-based PCs. Two models have been developed, called HYDRO I and HYDRO II.

HYDRO I is a hydrodynamic model to simulate tidal and wind-driven flows in the Arabian Gulf. It solves the depth-averaged Navier-Stokes equations over the whole Gulf, and, at the user's option, solves the three-dimensional Navier-Stokes equations over a user-selected sub-region. This model is useful if the user requires the pattern of a particular flow over the whole Gulf or if the water velocities at different levels at a few particular locations are required or if the times and levels of high and low waters at a few locations are required.

HYDRO II is a hydrodynamic model to simulate on a fine scale the tidal and wind-driven flows in an arbitrary sub-region of the Arabian Gulf. It solves the depth-averaged Navier-Stokes equations over the whole Gulf, using a 10 km grid, and then solves either the two- or three-dimensional Navier-Stokes equations over the chosen sub-region using a finer grid. This model is useful for computing the currents and surface elevations in small sub-regions of the Gulf in much more detail than is obtained from HYDRO I. It is more accurate than HYDRO I within the chosen sub-region, though it is usually slower to run (depending on the size of the fine grid). HYDRO II is one of the main tools for engineering studies.

Both models include user friendly interfaces and meaningful graphics. HYDRO II also includes an automatic grid generation system that simplifies its use.

The Vertical Horizontal Splitting (VHS) algorithm employed by HYDRO I and HYDRO II is of the type sometimes called direction-splitting or mode-splitting methods [1-9]. An explicit method is used to step forward the depth-integrated equations that govern the barotropic mode and an implicit method is used to step forward the horizontal momentum equations that govern the baroclinic mode. One advantage of this type of algorithm is that the stability restriction on the time step applies only to the barotropic equations and the full momentum equations can be stepped forward with a much larger time step, thus providing significant economies in computing requirements. A second advantage is that it is relatively inexpensive to include models in which the eddy viscosity varies with, for example, water speed or wind speed.

Much recent work on three-dimensional modeling of oceanographic flows is contained in the collections edited by Heaps [10], Nihoul and Jamart [11], and Spaulding [12-13].

Flows in coastal seas can be classified into three types: the almost periodic tidal flows, the time scale for whose variations is a few hours; the transient flows driven by storms, whose time scale is typically one or two days; and the currents that remain after these two are subtracted. These latter are called *residual currents*, and they typically vary over time scales of one to several weeks.

In the Arabian Gulf, any or all of these three types of flow may be significant, depending on the problem under consideration. Generally, tides make the greatest contribution to the current, and so are important in, for example, problems involving the forces on marine structures or in the erosion and deposition of sediment. The most important effect of storms is the *surge*, or increase in water level, which may cause flooding of coastal installations or low-lying areas, or the negative surge that may uncover intakes for desalination and power plants. (Storms also generate wind waves that contribute significantly to the forces on structures and to sediment transport, but discussion of wind waves is outside the scope of the present report.) The residual currents, although in general much smaller than the other two, by virtue of their persistence play the dominant role in long-term transport problems, such as the movement of oil slicks and other forms of pollution. HYDRO I and HYDRO II are capable of simulating all three types of flow, although in their basic forms the residual flow generated by density gradient is not included. The basis for the models and simulation algorithms is described in detail in Lardner et. el.[8].

2. APPLICATION TO THE ARABIAN GULF

The program HYDRO I uses the above algorithm to compute the flows in the Arabian Gulf. The grid used by this program has spacing of approximately 10 km, the direction of the grid being chosen roughly parallel to the Saudi coast (see Figure 1). The intersections of grid lines on this figure are the points at which ζ is computed. The position of the numerical coastline is shown in the figure, passing through points at which either p or q is computed, which are midway between ζ points.

The open boundary lies inside the Strait of Hormuz, on the grid line $n = 46$ and with $68 \leq m \leq 80$. It has been chosen there to run from the tide station at Bandar Lingeh on the Iranian side to the station at Umm al Qaywaym on the Emirates side. In the center it runs between tide stations on the islands Jezirat-Tunbh and Jezirat-Sirri so that reasonable values of the main tidal constituents can be obtained by interpolating from these four stations.

The base bathymetry for the model has been read from navigation charts for the Gulf, values being averaged over each grid square. In a number of cases, these depths have been modified to incorporate data supplied by Saudi Aramco. To take account of the fact that charted depths do not coincide with mean water depths, a correction H_{mean} is added to each value, this value being treated as one of the parameters to be tuned by fitting model output to observed data.

The bottom friction coefficient κ_2 in Eq. (15) is expressed in terms of a Chezy coefficient c as $\kappa_2 = g/c^2$. Using a turbulent boundary layer model of the near-bottom flow, we are led to an expression for c of the form

$$c = C \ln H \tag{1}$$

where C is a constant. This expression is used with C treated as another parameter to be tuned.

The wind friction coefficient γ in Eq. (20) has been given values ranging between 0.0015 and 0.0028 by various authors. We have tuned the value of this parameter using observations of floating buoys in the Gulf.

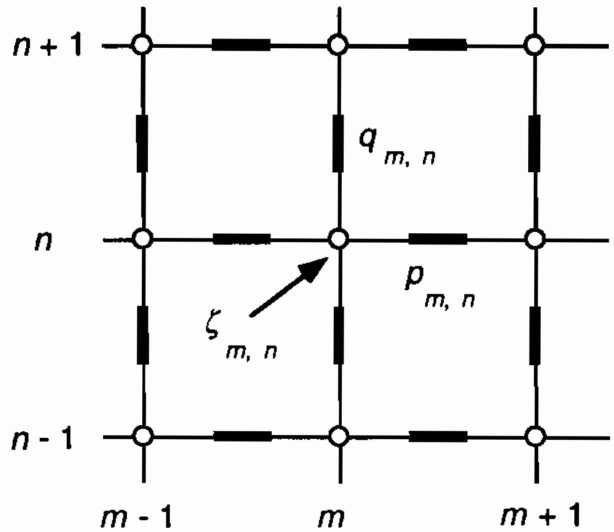

Figure 1: Arakawa C-grid showing points at which ζ, p and q are computed.

The kinematical eddy viscosity N is assumed to vary with depth in the form shown in Figure 2. At the free surface, the value of N is denoted by N_s and it assumed that N changes linearly over a depth d_1 to a value N_m. Over the central portion of the water column N is assumed constant, then over a distance d_2 near the bottom it again changes linearly from N_m to a bottom value N_b.

The thicknesses d_1 and d_2 of the top and bottom penetration layers have been taken as 10 meters. The three values N_s, N_m and N_b are treated as parameters to be tuned to appropriate measured data. However, it is found that, except near the bottom, the currents are relatively insensitive to N_b, and data on near-bottom currents has not been available, so we have set $N_b = N_m$, leaving two parameters to be tuned. The following argument provides theoretical estimates of these two, which can be taken as a rough guide to the choice of values.

Over the bulk of the water column, eddy viscosity can be estimated by the formula of Neumann and Pierson [23],

$$N_m = 1.8 \times 10^{-4} V^{2.5} \qquad \text{(MKS units)} \tag{2}$$

where V is the wind speed. The annual mean wind speed is $\bar{V} \approx 5$ m/s. Substituting this value into the Neumann-Pierson formula gives a bulk eddy viscosity $N_m = 0.01$ m²/s. This argument neglects the fact that the mean value of $V^{2.5}$ will be greater than $\bar{V}^{2.5}$, and also neglects the suppressive effect on turbulence of density stratification, which is relatively stable in the Gulf. Assuming that these opposite effects will tend to cancel one another, we are left with the estimate $N_m = 0.01$ m²/s

The value of N_s can be estimated from turbulent boundary layer theory, following the approach of Davies [21]. Davies proposes that $N_s = k_0 u_* z_0$ where $k_0 = 0.4$ is von Karman's constant, z_0 is a roughness length and u_* is related to the mean surface shear stress, $\tau^{(s)}$ by the turbulent boundary layer equation $\tau^{(s)} = \rho u_*^2$. The roughness length is associated with the mean amplitude of surface waves and is taken as 0.3m. The mean surface shear stress, $\tau^{(s)}$ is computed from the wind data using the formula $\tau^{(s)} = \gamma \rho_a V^2$ where ρ_a is air density, V the mean wind speed and γ a friction coefficient whose value is generally accepted as 0.0026. We thus obtain $u_* = V\sqrt{\gamma \rho_a / \rho} = 0.0086$ and hence $N_s = 0.0010$ m^2/s.

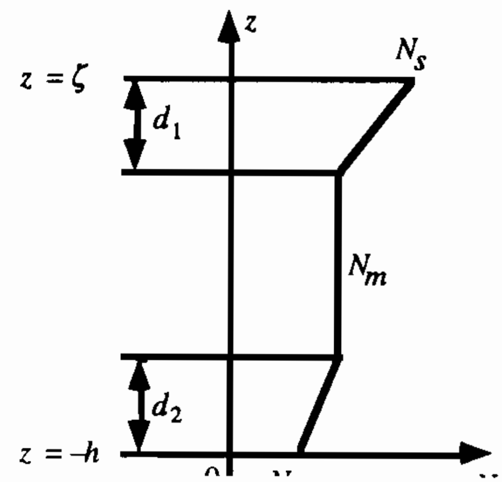

Figure 2: The assumed form of the eddy viscosity function.

3. CALIBRATION AND TESTING OF THE MODELS

The various parameters of the model have been adjusted to optimize agreement with certain observed data. The data used has fallen into three categories:

1. Tide heights at several Saudi Aramco tide stations
2. Observed tracks of the floating buoys released by MEPA during December 1983 to February 1984.
3. Current data collected by KFUPM Research Institute near Safaniya in 1990, and Ras Tanura in 1992.
4. Current data collected during the Mount Mitchell cruise in 1992.

The parameters that have been adjusted are H_{mean}, C, N_s, N_m and γ.

3.1. Predictions of Tidal Elevations

The first type of data used to tune the model was tidal data for the year 1990 from several of the Saudi Aramco tide stations. This data was used to determine the optimal values of the parameters H_{mean} and C. Four Saudi Aramco tide stations (ABUS, ARBY, MJ46 and SFPL) have been chosen because they provide a good spread of tide types, the tide being semi-diurnal at ABUS, diurnal at MJ46 and mixed at ARBY and SFPL. The "observed" elevations have been computed using the tidal constants at the four stations, which have been calculated from past tidal observations. Again, the agreement with observations is quite good. Bearing in mind that tidal elevations computed with a maximum of 37 constituents can be expected to contain errors of at least 5% on average, we can see that the differences between the computed and observed curves are of the same order as these expected errors in the "observed" data.

Figures 3 shows the computed and observed surface elevations for the month of January 1993 at tide station ABUS. Computed elevations are shown in the figure as the solid curves and observed values as the dashed curves. It should be noted that the SA and SSA constituents have been omitted from both the observed and computed values in this figure. The reason for this is that these two constituents are caused by seasonal meteorological factors that are not included in the HYDRO I model. They are very slowly varying constituents and generate very little contribution to the currents, so neglecting them produces little error in the computed currents (which form the output of the model that is of main interest).

3.2. Movements of Floating Buoys

In 1983 and 1984, MEPA launched a number of floating buoys off the Saudi coast and followed their movements by satellite [16]. We have used the observed motions of the group of buoys that were tracked during the period December 1983 to March 1984 in order to determine the parameters N_s, N_m and γ. The buoys that we used together with their launch and recovery dates are listed in Table 1.

The basic assumption in our use of the buoy data is that the floating buoys move with the surface current, and we have tuned the parameters so that this current fits as closely as possible, on average, the motion of all the buoys in the chosen group.

Table 1. The MEPA buoys used to determine eddy viscosity and wind drag coefficient.

Buoy number	Launch date	Recovery date
23506	13 Dec 1983	7 Jan 1984
23507	13 Dec 1983	13 Jan 1984
23508	20 Dec 1983	9 Jan 1984
23509	20 Dec 1983	12 Jan 1984
23508A	9 Jan 1984	8 Feb 1984
23509A	13 Jan 1984	22 Feb 1984
23513	7 Feb 1984	1 Mar 1984

We have examined the feasibility of using the formulas for eddy viscosity proposed by earlier investigators [17-19] in which the surface eddy viscosity, N_s, is taken as a function of wind speed and the eddy viscosity in the bulk of the water column, N_m, a function of water speed. However, the conclusion we have reached is that a better fit can be obtained to the observed buoy motions by using constant values for N_s and N_m as indicated in Section 2. However, for the wind drag coefficient, we have found that a value of 0.0027 gives the best fit at low wind speeds while a value of 0.0015 fits best at wind speeds above 10 m/s, as indicated by the values quoted in Section 3.1. (This result can be rationalized in that wind speeds above about 7 m/s generate increasingly many whitecaps and much of the momentum imparted by the wind to the water is dissipated by the breaking waves.)

The computed and observed tracks of the buoy 23507 are shown in Figure 4 as an example. Each track has been divided into segments and the segments computed separately. (If this is not done, then the errors in computing the early portion of any buoy track make it impossible to assess the accuracy of the computation of later portions of the track.) The partitioning of each track has been based on the wind regime: any period in which the wind direction remained essentially constant and the observed motion of the buoy remained predominantly in one direction has been taken as defining a track segment. Such segments are interspersed with other periods of variable winds in which the buoy followed a haphazard track.

3.3. Current Predictions

Current data were collected during Spring 1990 at a location close to Safaniya platform, 28°10.7′N, 48°52.0′E. Two current meters were placed depths of 3 meters below the surface and 3 meters above the bottom. In total, data for about 50 days were collected. We have used the measurements from the 10-day period from 15 to 24 April 1990 as a second source of data from which to estimate the values of the parameters N_s, N_m and γ. The reasons for choosing this particular period were twofold: first the data contain no obvious defects and second, this period was one in which the winds blew more or less continuously from the northwest. Conditions of strong and steady winds may be expected to be optimal for estimating the three parameters N_s, N_m and γ. (Under variable wind conditions, the currents are dominated by tidal effects, which are insensitive to eddy viscosity and wind drag coefficient.)

We have found that the values of these parameters that give the best fit to the observed currents are the same as those found from the buoy data. It is also worth mentioning that we have found that the formulas for eddy viscosity proposed by Davies [17] do not give a very good fit to the current data.

Figure 5(a) and (b) show the computed and observed currents at the meter located at a depth of 3 meters below the surface during the selected 10 day period. As before, part (a) of the figure shows the magnitude of the current and part (b) its direction. Again the phases of the current are computed very accurately. The directions and the magnitudes of the current are computed reasonably accurately, though not as accurately as the depth-averaged current.

During the period February through June of 1992, the research vessel *Mt. Mitchell* made a cruise of the Arabian Gulf [20]. During a large part of this period current measurements were taken at several locations. Figures 6(a) and (b) show the magnitudes and directions of the computed and observed currents at the M7 mooring (which, located at 27°11.09′N, 51°19.46′E, is the nearest location to Abu Safa). The amount of data collected on this cruise is immense, so we have simply selected the first 10 days during which the current meters placed by the vessel were all in operation. This period started at 0000 hours on 6 March, 1992.

Unfortunately, none of the meters placed by the vessel were close to Saudi waters, so one should not expect perfect agreement with the predictions of a model such as HYDRO I that has been tuned using data solely from the Saudi coastal area. Furthermore, in running the model, we had available wind data only from Saudi Aramco weather stations, all of which are quite distant from the meter positions. In actual fact, we used the wind data from Abu Safa, that being the weather station nearest to the meter positions. In view of these expected deficiencies, the predictions of the model are surprisingly good.

The agreement is quite good except during the period between about 100 and 150 hours from the start. The wind data at Abu Safa indicates that this was a period of sustained high winds, with hourly average wind speeds between 9 and 12 m/s, and there can be little doubt that the errors in the computed currents are due to there being very different winds blowing at the meter location. This is supported by the improvement in the agreement as we move down the water column, the computed and measured currents being quite close at 50 m depth, where the influence of the incorrect wind stress is much less than at the surface.

4. CONCLUSION

The models HYDRO I and HYDRO II provide accurate methods for computing the water velocities and surface elevations in the Arabian Gulf for flows driven by tides and wind. HYDRO I computes the flow over the whole Gulf using a single 10 km grid and is quite easy for the user to execute. HYDRO II is designed to compute with greater accuracy the flow in a user-selected sub-region of the Gulf and requires more work from the user to set up the grid for the chosen sub-region. However, this model does generate more detailed information on the currents in that sub-region than does HYDRO I.

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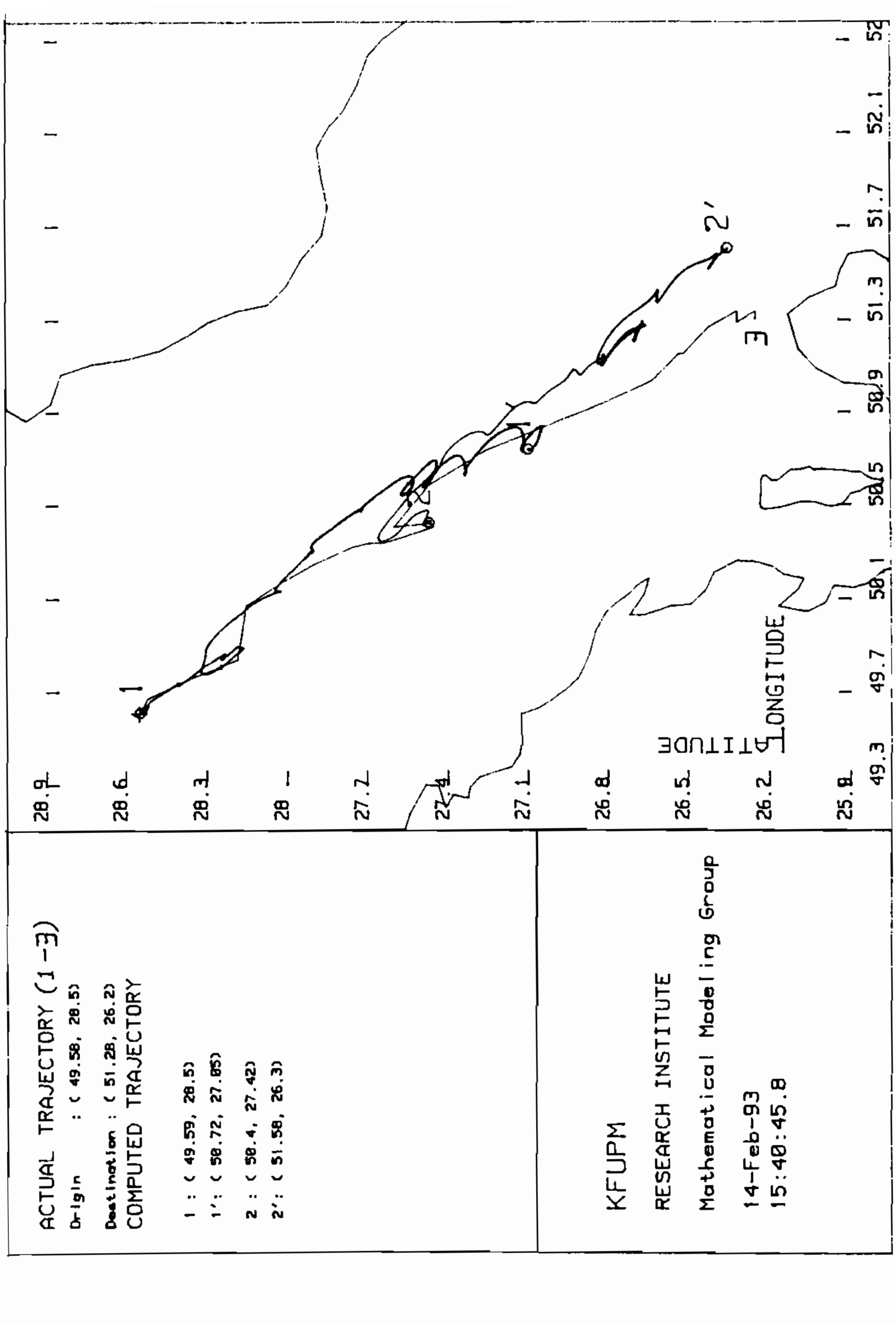

Figure 3: Computed and observed trajectories of the Buoy No.23507

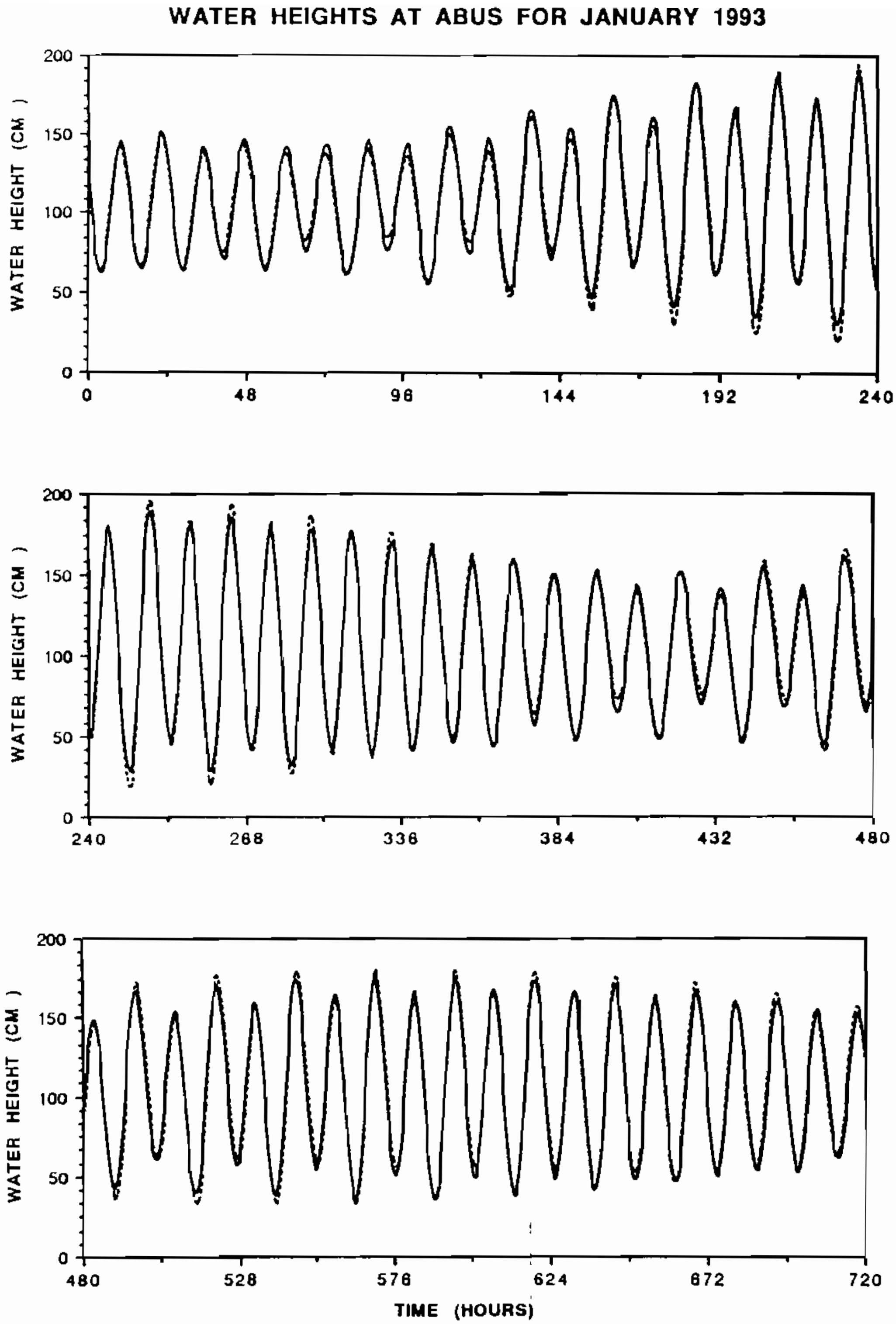

Figure 4: Computed and observed surface elevations at ABUS Saudi Aramco tide station.

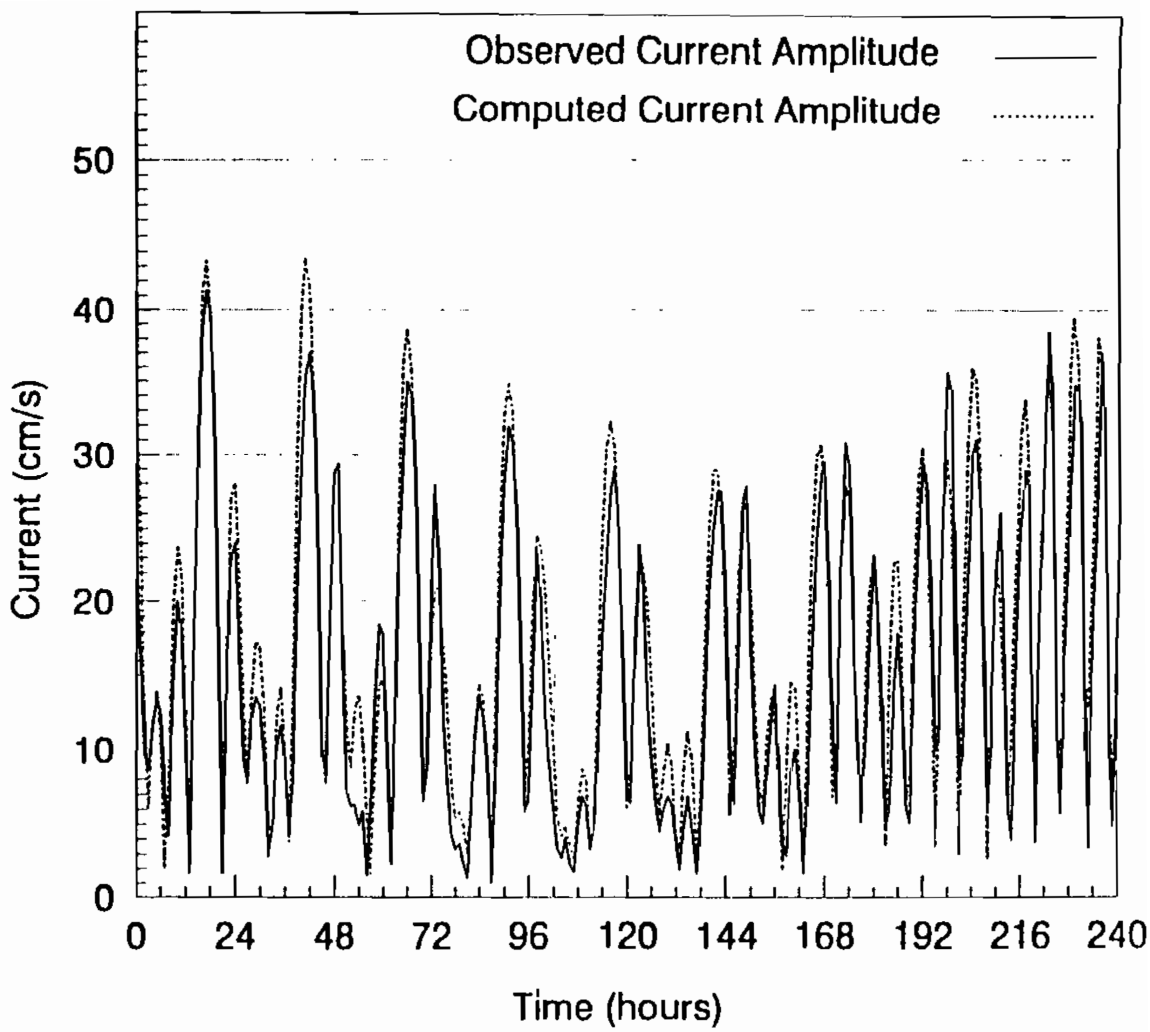

Figure 5(a): Computed and observed current amplitudes.

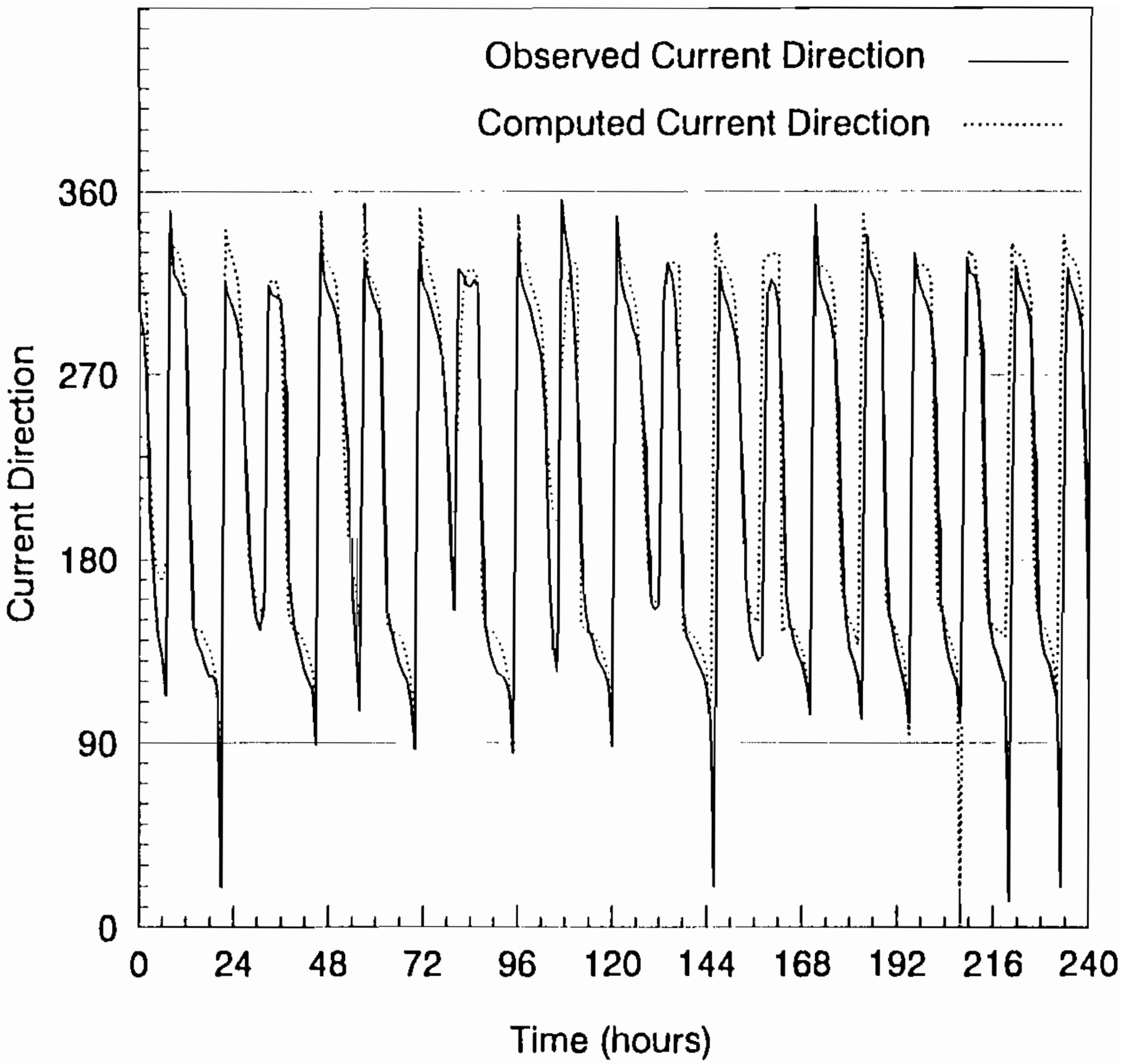

Figure 5(b): Computed and observed current directions.

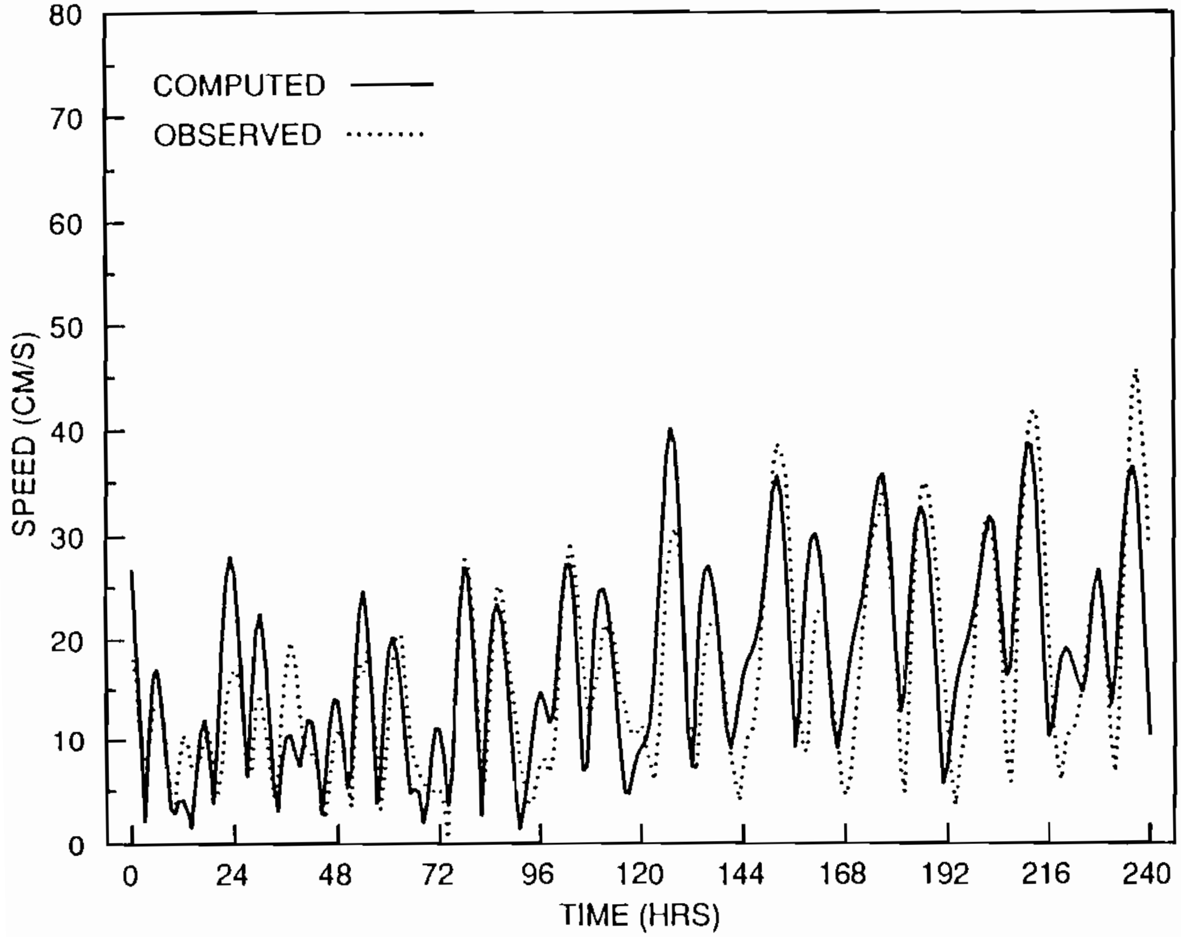

Figure 6(a): Computed and observed current amplitudes at the M7 current meter.

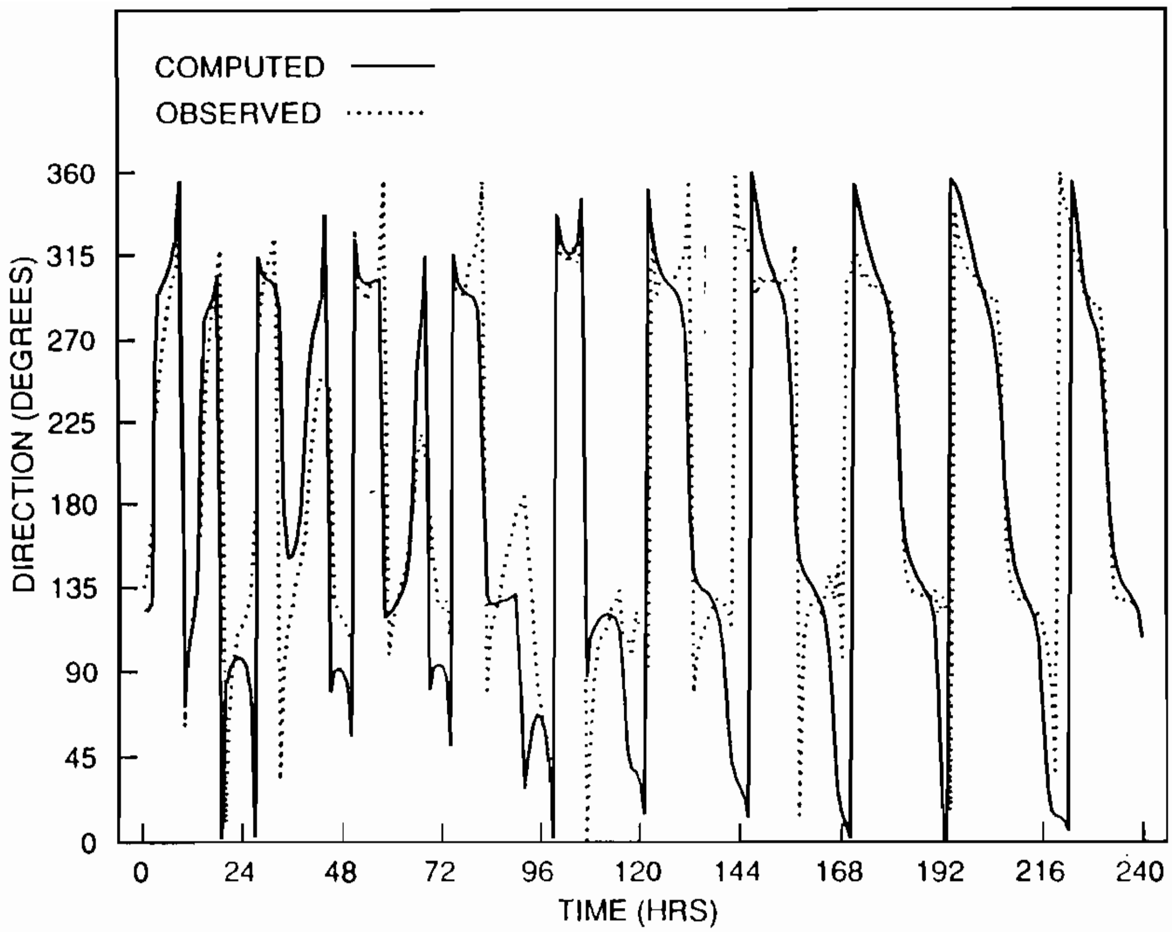

Figure 6(b): Computed and observed current directions at the M7 current meter.

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