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Oceanographic modelling of the Kuwait Action Plan (KAP) Region

Report of a symposium-workshop
University of Petroleum
and Minerals,
Dhahran, Kingdom of Saudi Arabia,
15-18 October, 1983

Sponsored by:
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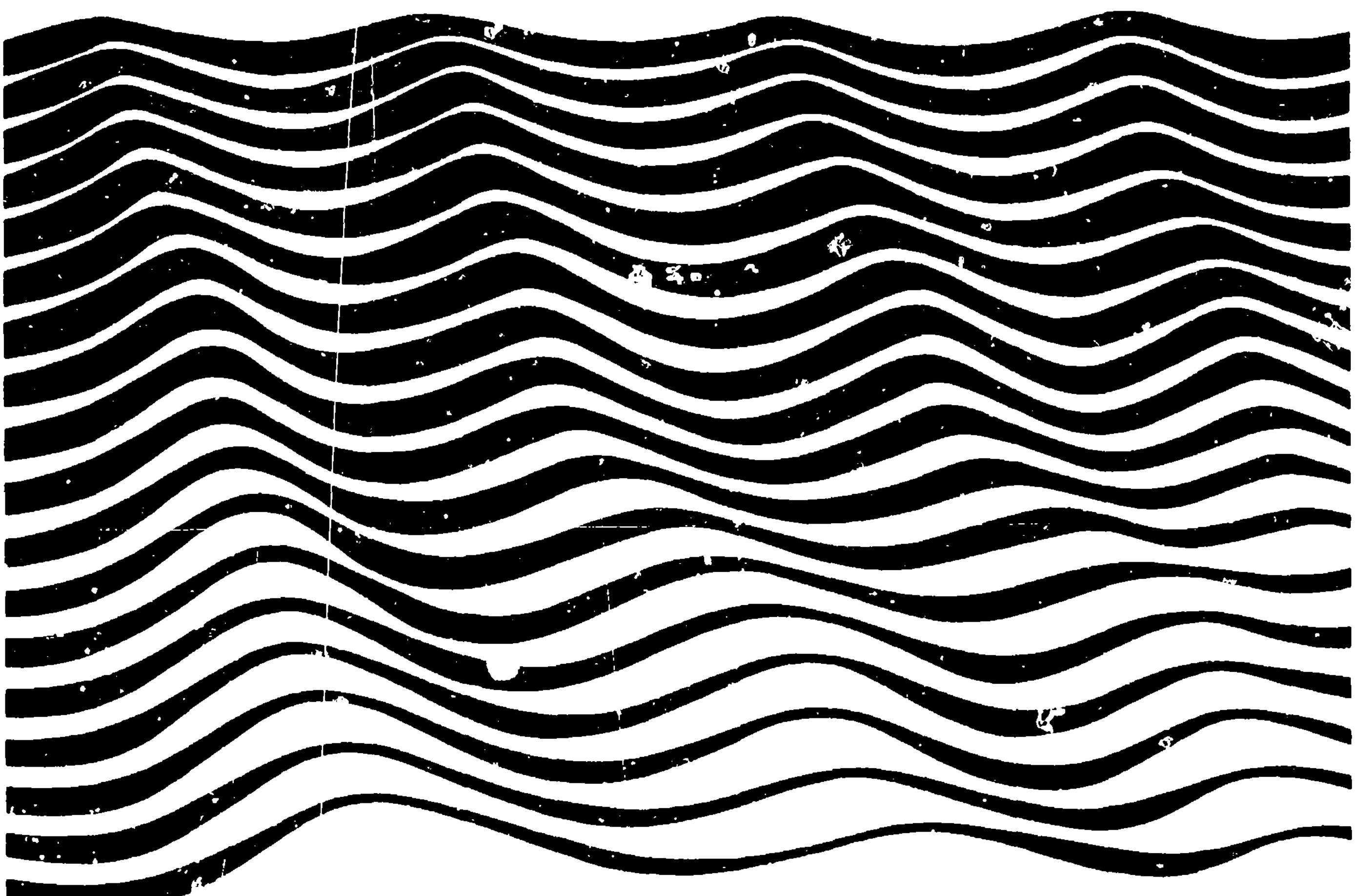

Unesco, 1984

UNESCO REPORTS IN MARINE SCIENCE

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21 Comparing coral reef survey methods A regional Unesco/UNEP workshop, Phuket Marine Biological Centre, Thailand, December 1982 English only	1983
22 Guidelines for marine biological reference collections Prepared in response to a recommendation by a meeting of experts from the Mediterranean Arab countries Available in English, French and Arabic	1983
23 Coral reefs, seagrass beds and mangroves: their interaction in the coastal zones of the Caribbean Report of a workshop held at West Indies Laboratory, St. Croix, U.S. Virgin Islands, May, 1982 English only	1983
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25 Ocean engineering teaching at the university level Recommended guidelines from the Unesco/IOC/ECOR workshop on advanced university curricula in ocean engineering and related fields, Paris, October 1982 Available in English, French, Spanish, Russian, Arabic and Chinese	1983
26 Global survey and analysis of post-graduate curricula in ocean engineering English only	1984
27 Productivity and processes in island marine ecosystems. Recommendations and scientific papers from the Unesco/IOC sessions on marine science co-operation in the Pacific, at the XVth Pacific Science Congress, Dunedin, New Zealand, February 1983 English only	1984

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PREFACE

Unesco Reports in Marine Science are issued by the Unesco Division of Marine Sciences. The series includes papers designed to serve specific program needs and to report on project developments. Collaborative activities of the Division and the Intergovernmental Oceanographic Commission, particularly in the field of training and education, are also represented in the series.

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ABSTRACT

A Symposium/Workshop on Oceanographic Modelling of the Kuwait Action Plan (KAP) Sea Region was held at the University of Petroleum and Minerals (UPM) in Dhahran, Saudi Arabia, 15-18 October, 1983. A total of nineteen scientific papers were contributed by the participants and were made available for advance circulation, to outline the state-of-the-art in the area of oceanographic modelling of the KAP region, and to focus attention on relevant key problems. This report presents all scientific papers given by the invited speakers to the Symposium and abstracts of the contributed papers which were presented at the Symposium, as well as the adopted recommendations. The Symposium was sponsored by the UPM, the Meteorological and Environmental Protection Administration of Saudi Arabia (MEPA), the Regional Organization for the Protection of the Marine Environment of the Gulf (ROPME), the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the United Nations Environment Programme (UNEP).

RESUME

Un Colloque sur la modélisation océanographique de la région du Plan d'action de Koweït (PAK) s'est tenu à l'Université du pétrole et des minerais (UPM) de Dharan (Arabie saoudite), du 15 au 18 octobre 1983. Au total, 19 communications scientifiques, destinées à faire le point de la modélisation océanographique de la région du PAK et à appeler l'attention sur certains problèmes essentiels, ont été préalablement mises à la disposition des participants. On trouvera dans ce document toutes les communications scientifiques présentées par les orateurs invités au Colloque et des résumés des communications d'autres participants, ainsi que les recommandations adoptées à cette occasion. Ce Colloque s'est tenu sous les auspices de l'UPM, de l'Office de météorologie et de protection de l'environnement de l'Arabie saoudite, de l'Organisation régionale pour la protection du milieu marin du Golfe (ROPME), de l'Organisation des Nations Unies pour l'éducation, la science et la culture (Unesco) et du Programme des Nations Unies pour l'environnement (PNUE).

RESUMEN ANALITICO

Del 15 al 18 de octubre de 1983 tuvo lugar en la Universidad de Estudios del Petróleo y Minerales (UEPM) de Dhahran (Arabia Saudita) un Simposio/Reunión de Trabajo sobre Modelización Oceanográfica de la Región Marina del Plan de Acción de Kuwait (KAP). Se presentaron 19 estudios científicos que habían sido distribuidos con anterioridad, dedicados a actualizar los conocimientos relativos a la modelización oceanográfica en la región del KAP y a definir los principales problemas pertinentes. En el presente documento figuran todos los estudios científicos presentados por los oradores invitados y resúmenes analíticos de los estudios que se expusieron en el Simposio, así como las recomendaciones aprobadas. El Simposio fue auspiciado por la UEPM, el Servicio de Meteorología y Protección Ambiental de Arabia Saudita, la Organización Regional para la Protección del Medio Ambiente Marino del Golfo, la Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura (Unesco) y el Programa de las Naciones Unidas para el Medio Ambiente (PNUMA).

РЕЗЮМЕ

Симпозиум/учебно-практический семинар по океанографическому моделированию морского района Кувейтского плана действий (КАП) состоялся 15-18 октября 1983 г. в Университете нефти и минералов (УПМ), Дахран. Участники представили для заблаговременного распространения в общей сложности 19 научных работ, посвященных вопросам океанографического моделирования района КАП и сосредоточивающих внимание на соответствующих ключевых проблемах. Доклад представляет все работы, переданные приглашенными на симпозиум учеными, и резюме других представленных работ, а также принятые рекомендации. Симпозиум был организован УПМ, Управлением по метеорологии и охране окружающей среды Саудовской Аравии (МЕПА), Региональной организацией по охране морской среды Залива (РОПМЕ), Организацией Объединенных Наций по вопросам образования, науки и культуры (ЮНЕСКО) и Программой ООН по окружающей среде (ЮНЕП).

ملخص

عقدت فى الفترة من ١٥ الى ١٨ أكتوبر/تشرين الأول ١٩٨٣ ندوة للتدارس بشأن وضع النماذج الاقيانوغرافية الخاصة بالمنطقة البحرية لخطة لعمل الكويتية ، فى جامعة البترول والمعادن بالظهران ، المملكة العربية السعودية . وأسهم المشتركون فى الندوة بما مجموعه تسع عشرة دراسة علمية أتيحت للتداول مقدما ، وكان الغرض منها عرض الوضع المعرفى الراهن فى مجال النماذج الاقيانوغرافية لمنطقة خطة العمل الكويتية ، وتوجيه الاهتمام الى المشكلات الرئيسية . ويعرض هذا التقرير جميع الدراسات العلمية التى قدمها المدعوون للحديث فى الندوة وملخصات للدراسات التى عرضت فيها ، كما يتضمن التوصيات التى اعتمدت ، وقد عقدت الندوة تحت رعاية جامعة البترول والمعادن وادارة الأرصاد الجوية وحماية البيئة بالمملكة العربية السعودية والمنظمة الاقليمية لحماية البيئة البحرية فى منطقة الخليج ، ومنظمة الأمم المتحدة للتربية والعلم والثقافة (اليونسكو) ، وبرنامج الأمم المتحدة للبيئة (بامبيئة) .

摘　要

1983年10月15-18日，在沙特阿拉伯达兰的石油矿业大学（UPM）举办了一期关于科威特行动计划（KAP）海区海洋学模型制造的讨论会／讲习班。参加者共提交了十九份科学论文，供预先分发；这些论文概述了科威特行动计划区域海洋学模型制造的现状，并重点阐述了有关的关键问题。本报告载有应邀在讨论会上发言者提供的所有科学论文、提交讨论会的其他论文的摘要以及所通过的建议。讨论会系由下述组织联合主办：石油矿业大学、沙特阿拉伯气象和环境保护局（MEPA）、保护海湾海洋环境地区组织（ROPME）、联合国教育、科学及文化组织（UNESCO）和联合国环境规划署（UNEP）。

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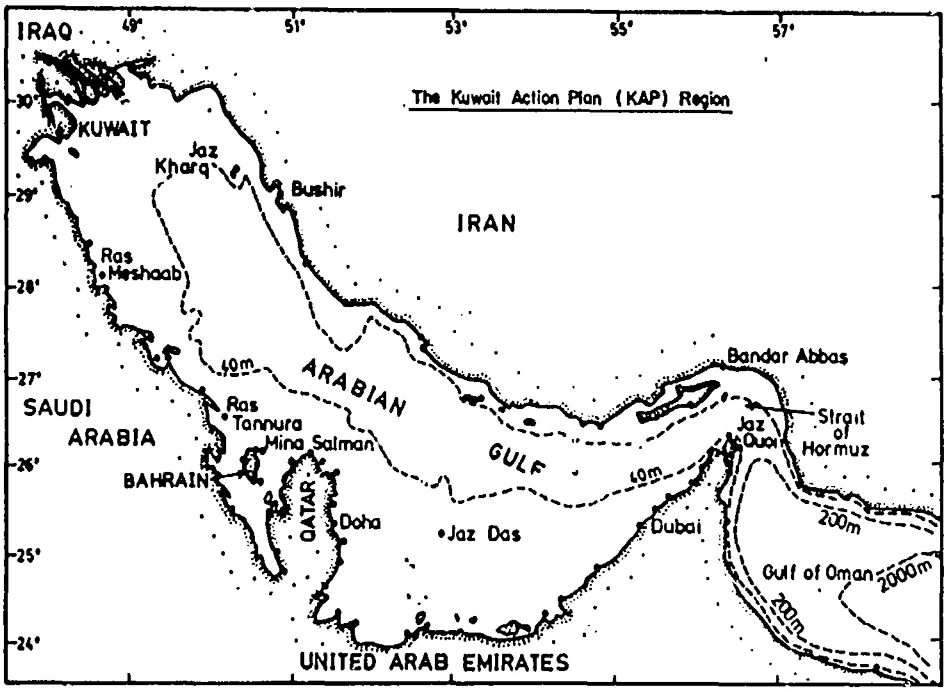
PART III

FOREWORD



This report presents all invited papers and abstracts of the contributed papers which were presented October 15-18, 1983 at an international symposium by the same title, held at the University of Petroleum and Minerals in Dhahran, Saudi Arabia. The symposium was sponsored by the University of Petroleum and Minerals (UPM), the Meteorological and Environmental Protection Administration (MEPA), the Regional Organization for the Protection of the Marine Environment (ROPME), the United Nations Educational, Scientific and Cultural Organization (Unesco) and the United Nations Environment Program (UNEP).

Under the patronage of His Highness Prince Abdul Mohsein Bin Jalawi, Prince of the Eastern Province, the Symposium was opened in the morning of 15 October 1983, with welcoming addresses by His Excellency Dr. B. Bakr, Rector of UPM, Dr. A. Al-Dabhagh, Director of the Research Institute, UPM, Dr. Layth Al-Kassab, representing ROPME, and Dr. Makram Gerges, representing Unesco. About one hundred and fifteen research scientists from ten countries (Saudi Arabia, Kuwait, Iraq, Canada, France, USA, Qatar, UK, W. Germany and Switzerland) participated in the technical sessions.

A total of nineteen scientific papers were contributed by the participants for advance circulation, to outline the state-of-the-art in the area of oceanographic modelling of the Kuwait Action Plan Region, and to focus attention on key problems. The availability of this background material precluded the need for lengthy introductory presentations and permitted rapid initiation of fruitful discussions. All participants gave generously and enthusiastically of their expertise and efforts during the four days of the meeting.

The sponsoring organizations thank all the persons who made that Symposium possible. Special thanks are addressed to: Dr. Mustafa Ukayli, the Chairman of the local Organizing Committee, and to other members of this Committee for the excellent and noteworthy hospitality and their dedicated work in preparing and animating the Symposium, to all invited and contributed speakers and all other participants for their valuable and enthusiastic contributions, and to the chairmen and rapporteurs of the technical sessions for their indispensable dedication. The work of the Scientific Coordinator, Dr. Mohammed I. El-Sabh, in organizing the symposium-workshop and in preparing this report of the results, is especially appreciated. Finally, thanks are also due to Richard Fournier, from the Université du Québec à Rimouski, Canada, who helped with the final preparation of this report.

Numerical Modelling : Capabilities and Limitations

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ABSTRACT

Assumptions underlying modelling are discussed. Different kinds of models are explained. Conditions and limitations are mentioned. Special conditions in the Gulf are exemplified, and the establishment of a strong modelling centre in the ROPME region is suggested.

Models are used for various objectives, the most important of which are :

1) To isolate and test hypotheses.

2) To predict the behavior of systems at future times or under specified conditions.

3) To help control systems by investigating the effects of modifying certain conditions.

The basic assumptions underlying modelling are again three : That nature follows certain laws (even if in certain circumstances, or for certain instance, they are stochastic); that natural systems are heirarchially separable; and that natural systems can be approximated as linear by parts. The 1st condition allows modelling in principle, if the laws are known or approximated. They do not have to be understood. An example is the tidal prediction in ports. Although it is well known that the gravitational forces of the moon and the sun cause the tides, these can be predicted from a long record of water elevations without reference to the tidal producing forces. The 2nd condition allows a system to be modelled without modelling the underlying systems, e.g. when modelling the ocean circulation, one does not consider in the model that water is composed of molecules made of Hydrogen and Oxygen etc. The third condition allows a part of the universe say the ocean, or part of it again, say the surface layer to be isolated and modelled without modelling the whole universe. Without the 2nd and 3rd assumptions, the simplest model of anything would be the thing itself and the shortest time taken to model would be the physical time.

Modelling is a characteristic activity of the brain that is done, mostly, subcontiously in order to achieve generalisations, extensions and predictions and thus allows the maximum and most efficient use of the brain rather than cramming it with unrelated items of information. The brain, thus, organizes the information in patterns and connects these patterns by rules which is the essence of modelling. Numerical modelling is usually done outside of the human brain, but in the brain of a computer which is a brain-child and an external extension of the human brain. The computer still needs the rules and conditions which allows it to proceed.

A model needs the following elements : Data to start it (even if it is a set of zeroes), rules to define its development and the routes it would take at logical branches, and boundary conditions in space and time (or other appropriate variables). In order for the system to be soluble, mathematical conditions have to be satisfied to assure the existence and uniqueness of the solution. These cannot always be worked out from the mathematical formulation, and they can be difficult even when they can be worked out. Most modellers, however, proceed happily where mathematicians fear to tread. The mathematical equations representing the model have to be complete from the mathematical point of view (necessary and sufficient), and correct from the natural (or physical) point of view. Inaccuracies in the initial or boundary conditions can be tolerated by models to some extent. If the rules that control the development of the model are wrong, however, the deviation between the model and the prototype increases with the increase of the number of iterations or of time steps. Other restrictions and errors are imposed on the model by the numerical process itself. These will be mentioned later.

Models can be divided in many ways. Four of the most important will be briefly mentioned :

1) Discrete and Continuous Models :

A discrete model has the quantities defined at a set of points in the space-time matrix. Interpolation among the points might or might not be possible, or it might be possible with further assumption to the model. A continuous model would have the variable know at all points of space and all instants of time. This occurs in analytically solved models and in analog models. Mixed models can be found where some variable are continuous in certain directions and discrete in others, or continuous in time but discrete in space, etc. Generally, numerical models are discrete. The discreteness puts more mathematical restrictions that will be mentioned later.

2) Kinematic and Dynamic Models :

A kinematic model models the motion without relating it to its causes in a cause and effect manner. Example of this is the tidal prediction which has been made for over one hundred years from the observations of water levels and not by using the lunar and solar gravitational forces. This kind of model depends to a great extent on the regularity of the phenomenon. Dynamical models use the causes (usually forces) as the starting point. They thus require a deeper level of understanding of the different relationships and boundary conditions of the system, but not necessarily as long a record as the kinematic models. Examples of dynamical models, are the weather prediction models and the ocean circulation models.

3) Deterministic and Stochastic Models :

A deterministic model does not have random variables in its system and always reaches the same ending from the same beginning through the same pathways. This is exemplified by a complete system of equations with fixed coefficients. Stochastic models contain random variables that would change the results of the runs of the model starting with the same data, and using the same conditions with the exception of the random variable (s) e.g. circulation models using windstress with a random element. Random variables in the model sometimes reflect the existence of variables below the level of detection, or the resolution of the model.

4) Stationary (or Steady State) Models and Time Dependant Model :

A stationary model does not depend upon time and its results remain constant with respect to it. However, the steady state can appear as variable if presented in another framework. Example is the magnitude of a harmonic component which appears as a constant in the frequency space, but the velocity itself would appear as a variable in the time space. Essential time dependent models, however appear non-stationary in any framework. These result from non-stationary functions. The results would continue to grow, settle in an equilibrium range or die out according to the generative forces continuing to exceed, to equal or become less than the dissipative forces.

Because numerical models always contain discrete elements, they are subject to two further limitations. The first concerns the resolution of the model. It is obvious that the model cannot "see" to a resolution better than the spacing of its network. Thus, the level of details required in the result is an important factor in deciding the mesh size of the model. In particular, any periodic variable that has a period that exactly equals the mesh size will not be detected and will propagate through the system. The second is the problem of "aliasing". This results from variables that have periods slightly different from the mesh size. These would be "seen" by the model as variables with longer periods and cannot be separated from them.

Another kind of problems results from instabilities in the model when certain conditions about the sizes of different meshes are not observed, e.g. relationships between the time step and space step in the problem of diffusion, or when a certain kind of differences is used instead of another, e.g. using central differences in space under certain circumstances rather than one sided differences. These conditions can be worked out in simple cases, e.g. simple diffusion, but the difficulties increase rapidly as the system becomes more elaborate and are rarely found by theoretical considerations.

This gives a glimpse about the choices and the difficulties that the numerical modeller has in modelling aspects of the Gulf. To model the Gulf environment, however, many kinds of models have to be used. From the papers presented in this symposium, a start in developing these models has already been made. However, an enormous amount of systematic and coordinated observational and experimental programs will have to be made to feed the models and to test them, particularly in features that are unique to the Gulf. For example, the shallowness of the Gulf necessitates very careful considerations of the topography of the bottom and of bottom friction as a major dissipative force. Another feature is the amount of oil reaching the Gulf water daily in the normal operations. This would cover an area of about 2000 kms daily to a thickness of 10 micrometers, affecting energy and material exchange between the Gulf water and the atmosphere and affecting the characteristics of the water surface. What is the life time of this layer (before it dissolves or evaporates) and how much of the Gulf is covered by oil at any one time? Again, with a residence time of water in the Gulf between one and five years what is the residence time of oil that reaches this water? Does it sail with the wind, move with the water or creeps on the bottom? Again, what is the effect of the fresh water systematically removed from the Gulf by the numerous huge desalination-power plants and the heat systematically added to the Gulf, locally, and in the whole Gulf?

One complete area of modelling that is woefully deficient in the Gulf is the eco-system modelling. In certain ways this is the culmination and the purpose for other modelling, whose results would be inputs to the models of the eco-system. This area needs further attention and examination.

Modelling needs a powerful concentration of manpower of different disciplines, and powerful computing tools backed by good mathematical and statistical help and banks of observational material to construct and test models. Experience has shown that while the observational program is by necessity diffuse the modelling program should be concentrated in one location, e.g. NOAA fluid dynamic laboratory in Princeton and it is suggested that ROPME and its States consider the establishment of such a modelling centre of excellence.

To summarize and conclude: Numerical modelling is a very powerful tool for understanding, predicting and helping control natural phenomena, and for planning courses of action. It is limited by the limits of observations, the correctness of the laws used, the limits of detection and host of mathematical difficulties. Continuing interaction should be maintained between the modeller and the observational program. By its nature and by experience modelling is best carried out from a strong centre of excellence in order to achieve good results and it is suggested that such a centre be considered for the ROPME area.

A brief survey of oceanographic modelling and oil spill studies in the KAP region

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ABSTRACT:

A synopsis of the material to be covered in the workshop is presented.

The Kuwait Action Plan (KAP) Region is characterized by shallow waters of high temperature. The Gulf, making up the northern part of the region, has little fresh water inflow. This combined with liberal evaporation causes highly saline conditions particularly in parts of the Western Gulf. Water balance is maintained by flow through the straits of Hormuz resulting in a flushing time of a few years. Winds in the area generally blow from the Northwest with some variation in this pattern in winter and spring.

Tidal height patterns in the region are fairly well established and several 2 dimensional tidal models that agree reasonably well with actual results have been produced. Residual current models, however, are les perfected due in part to lack of adequate data and uncertainties over the driving mechanisms of the current.

Because of the abundant petroleum industry activities in the region, oil pullution is widespread. Oil spill modelling has shown some usefulness in the Gulf, particularly estimates of spill trajectories of the Hasbah and Nowruz oil spills. Standard models of the fate of spilled oil, however, may have to be modified to fit the unique Gulf conditions. Also, different types of models are needed for different modelling purposes in the region.

1. INTRODUCTION

The Nowruz oil spill highlights the importance in studying the hydrodynamics of the KAP region and thereby ascertaining the movement of spilled oil and other pollutants. We are fortunate to have assembled at the symposium/workshop experts in this field not only from the region but also from all over the globe. Hopefully the results of this effort will be to assist the development of a long-term oceanographic and pollution monitoring program in the region.

The purpose of this paper is to provide a brief 'state of the art' review of the known information about the topics covered in the symposium/workshop. The author will review the general environmental conditions of the KAP region, discuss the tides and tidal models for the area, look at residual current work, and finally examine relevant oil spill studies.

2. GENERAL ENVIRONMENT

With an average length of 1000 km, width of between 55 to 340 km and total area of about 240,000 square km., the Gulf is relatively small compared to other offshore oil producing areas such as the North Sea, twice its size, or the Gulf of Mexico, five times as large. It is also relatively young, geologically speaking, having been formed only 3 or 4 million years ago. During its brief history it has been reduced several times to an estuary of the Tigris-Euphrates river system when world-wide sea level lowering occured. The most recent such episode ended less than 20,000 years ago with the Gulf refilling during the sea level rise known as the "Flandrian Transgression" reaching its present level about 5000 years ago (Kassler, 1973).

The entire basin lies on the continental shelf whose slope into deeper waters occurs only in the Gulf of Oman. The result is that the Gulf is very shallow, rarely deeper than 100 meters with an average depth of between 31 to 37 meters. It is asymmetrical in profile with a gentle slope from the western to eastern side. A wide area of mud bottom is found in the northern and eastern parts of the Gulf with sand bottom predominant in the southern and western part. Rock is present at the bottom of the straits of Hormuz and in reef and island margin areas.

The eastern coastline is marked by mountains and cliffs whereas the western shore is often sandy. Industrial and commercial activities in populated areas have affected the shoreline and altered nearshore current patterns.

Studies by Emery (1956) found nearly uniform summer surface temperature in the Gulf of around 90°F with a general decrease of temperature to about 75°F in the Arabian Sea. Compilation of winter surface measurements by Schott (1908) and Blegvad (1944) show a variation of between 60°F in the northern Gulf to about 75°F at the straits of Hormuz. Due probably to extensive vertical mixing, Emery found only a small vertical temperature gradient with bottom and top water temperatures varying by about 20°F.

Privett (1959) has estimated the evaporation rate for the Gulf to vary between .2 and .6 gm./cm2-day. This means that the volume of water evaporated each year is equivalent to the volume of 4 million Nowruz spills. Privett claims that evaporation is at a maximum in December and a minimum in May although measurements conducted by some oil companies in the northern part of the region suggest the opposite situation, at least for the upper Gulf.

Fresh water inflow has been estimated (Grasshoff, 1976) at between 5 to 100 cu. kilometers per year. This represents only about 1.3% to 28% of the water loss to evaporation. Since precipitation is light in the region, consideration of the differential flow through the straits of Hormuz is crucial to the water balance in the Gulf. Koske (1972), assuming a shear flow through Hormuz, computed a flushing time for the basin of about 2.5 years. Hughes and Hunter (1979), using a less restrictive model derived a time for 90% flushing of 5.5 years. They also estimated the turnover time, the time it takes for all the water in the Gulf to come within the influence of the open sea boundary, of 230 days. However, if the interaction of vertical mixing is included with the residual current in the Gulf in their estimate, the turnover time increases to 2.4 years.

Highly saline conditions are found in the Gulf. Surface salinities in the summer range from 37°/oo in the Gulf of Oman to 42°/oo just off of Bahrain. In fact salinities as high a 70°/oo have been reported in the Gulf of Salwah at its extreme southern extremity (Basson et. al, 1977). The salinity in winter is somewhat higher than in summer, apparently related to the variation of fresh water influx through the Shatt Al-Arab, and meteorological effects, particularly evaporation (Schoot, 1918). Offshore winds in the Gulf area blow mainly from the Northwest and are particularly strong in early summer when, due to a counter-clockwise wind circulation around a low pressure area over the Asian continent, the so-called shamals (Arabic for north) blow down the Gulf with gusts of as much as 100 km/hr (Williams 1979). The most serious interference with this wind pattern occurs in winter or early spring, when passing depressions affect the Gulf in their movement from West to East. These can cause wind flow to change from northwest to southeast. Such exceptional wind pattern can last for a number of days before they revert to normal patterns (Wennink and Nelson-Smith, 1977).

3. TIDES AND TIDAL MODELS:

The tides in the Gulf are complex, consisting of a variety of tidal types (Figure 1). The tidal ranges

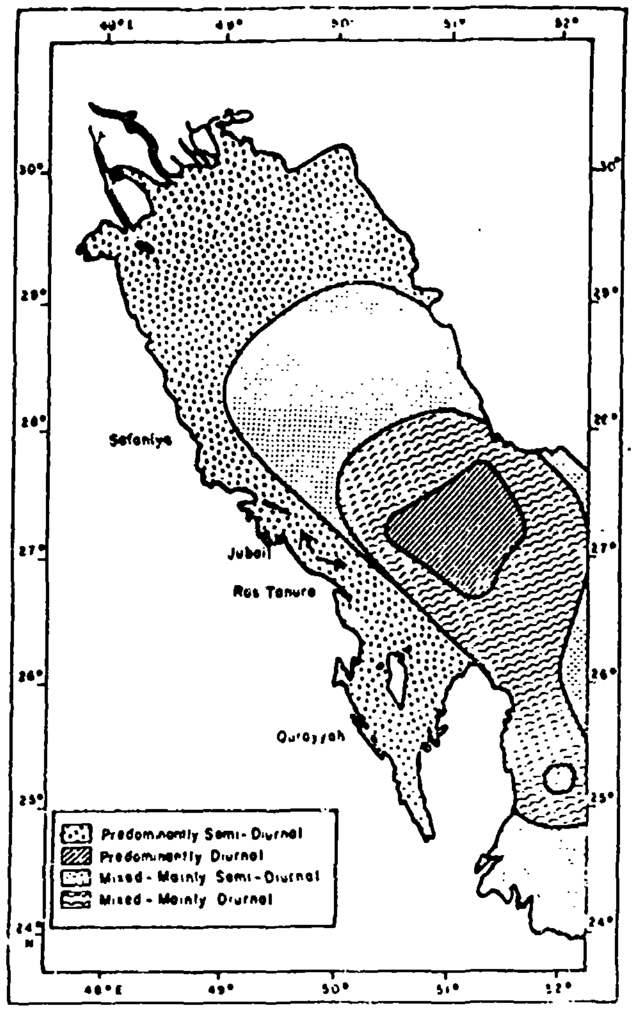

Figure 1. Tidal current regime for northern Gulf (from Williams, 1979).

are large throughout the Gulf, being over a meter everywhere and exceeding 3 meters at Shatt Al-Arab. These large amplitudes cause strong tidal currents which commonly exceed 0.5m/sec. at maximum ebb or flood. (Defense Mapping Agency, 1975). The tides generally flow westward and northwestward and ebb in the opposite directions. This gives the appearance of the tide progressing up the Iranian coast and down the Saudi side, with the range increasing from the middle of the Gulf in Kelvin wave style. The dimensions of the Gulf are such that the oscillations in the tide are not too far from resonance (Hughes and Hunter, 1979). The four main harmonic constituents of the tidal regime in the Gulf are M_2, S_2, O_1, and K_1. For a particular combination of the main constituents to repeat itself requires about 19 years although suitable approximations can construct an artificial tide cycle of about 24.8 hours which enables the main features of the Gulf tides to be studied (Evans-Roberts, 1979). The M_2 and S_2 constituents have two amphidromic points, one in the northwestern part of the Gulf and the other in the southwestern part (Figure 2). The K_1 and O_1 have a single amphidromic point.

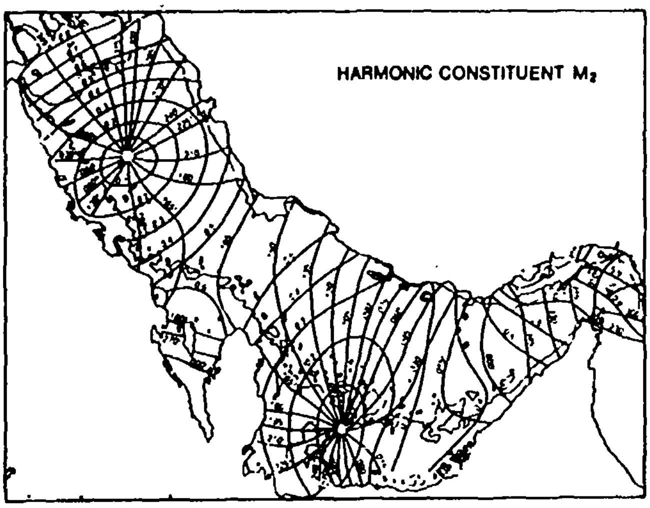

Figure 2. M_2-tide heights and phases from observations.

Several two-dimensional models of tides in the Gulf already exist (Trepka, 1968; Dames and Moore, 1975; Evans-Roberts, 1979; Danish Hydraulic Institute, 1980; Lardner et. al., 1982; Le-Provost, 1984; Murty and El-Sabh, 1983). An analysis of the one developed at the Research Institute of the University of Petroleum and Minerals (Lardner et. al., 1982) demonstrates the general nature of such models. The basic equations to be solved are the Navier-Stokes equation and the equation of continuity, which are subjected to the so-called shallow-water approximation i.e., the equations are depth averaged for the horizontal X and Y components and the hydrostatic equation approximates the vertical Navier-Stokes equation. The model neglects eddy viscosity and meteorological conditions and considers water density to be vertically uniform.

Then the governing equations can be reduced to

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(H\bar{u}) + \frac{\partial}{\partial y}(H\bar{v}) = 0$$

$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} = f\bar{v} - g\frac{\partial \zeta}{\partial x} + \tau_b^{x}$$

$$\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} = -f\bar{u} - g\frac{\partial \zeta}{\partial y} + \tau_b^{x}$$

where

$\bar{u}$, $\bar{v}$ are depth averaged horizontal fluid velocity components

f is the coriolis term

H is the total water depth

ζ is the height of free water surface above the reference plane $Z = 0$

$\tau_x^{\,b}$ and $\tau_y^{\,b}$ are the bottom stresses expressed in the form

$$\tau_x^{\,b} = -\frac{g\rho}{C^{2}}(\bar{u}^{2} + \bar{v}^{2})^{\frac{1}{2}}\,\bar{u}$$

$$\tau_y^{\,b} = \frac{g\rho}{C^{2}}(\bar{u}^{2} + \bar{v}^{2})^{\frac{1}{2}}\,\bar{v}$$

with C (the Chezy coefficient) empirically determined as a function of H. The boundary conditions chosen were zero normal velocity flow on any land boundary and specification of the water height at any open ocean boundary. A finite difference scheme using a coarse mesh (20 km mesh size) was chosen for whole Gulf with the option of interfacing with finer mesh for local regions of interest. The computations were started with initially flat conditions everywhere except the open boundary across Hormuz where each component was specified based on its co-tidal chart. The model was run for 75 hours of real time to allow for steady conditions to be reached. Figure 3 and 4 demonstrate the predicted tide amplitudes for the M_2 and K_1 components. As expected the M_2 shows the existence of two amphidromic points and K1 shows only one. One consistent discrepancy between the model and empirical results were in the M_2 and S_2 amplitudes, the model predictions of the former being somewhat smaller than observed and the model predictions of the latter being somewhat too large. One suggested explanation for this discrepancy was the neglecting of the linear damping mechanisms.

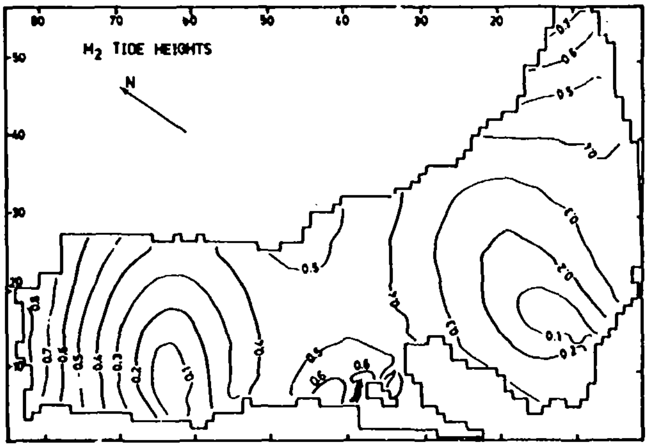

Figure 3. M_2-tide heights from UPM model.

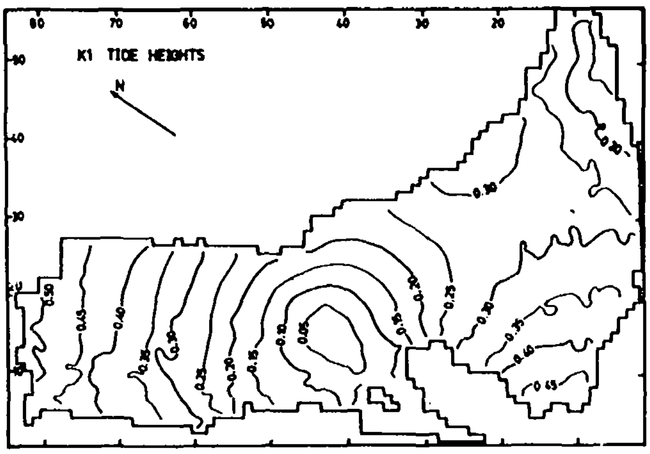

Figure 4. K_1-tide heights from UPM model.

The tidal current model by the Danish Hydraulic Institute (Danish Hydraulic Institute, 1980) is fairly similar to the UPM model although it is only a part of a more general package. It uses an 8 km coarse grid mesh for modelling the whole Gulf. It also has the capability to use the output of the coarse grid as input to a finer mesh grid for any localized area in the Gulf. The other models are discussed in another paper in this workshop (Le-Provost, 1983).

Tidal currents in the southern part of the KAP region have also been modelled (Elahi, 1983).

All of the models either have been used or are capable of predicting tidal currents as well as heights but there is almost a complete absence of systematic currents surveys to measure tidal current in detail in the Gulf (Hughes and Hunter, 1979) to provide empirical verification. IMCOS Marine (Hibbert, 1980) claims to have developed a verified model to predict currents from tide height predictions applicable to any part in the Gulf.

4. RESIDUAL CURRENTS:

Very little information exists describing the residual current field in the region. Schott (1918), Koske (1972) and Brewer et. al. (1978) describes an anticlockwise drift around the Gulf. Claims have been made that ship drift data support such circulation pattern. A recent effort by Hunter (1982) however, has criticized circulation patterns based on such ship drift data and claims that when considering only locations where there were sufficient and acceptable drift information, there was little evidence to suggest an anticlockwise pattern. Cognizant of Hunter's criticism of using drift information alone, the Research Institute has combined this data with some basic hydrodynamical considerations to develop a semi-empirical approach to residual currents. A multiple gyre pattern results (Lehr and Fraga, 1983).

Past studies have presented mixed answers for the major contributing factor to residual flow in the Gulf. Hughes and Hunter (1979) concluded that the major contributor to the residual flow was wind driven currents based on Ekman dynamics. More recently, Hunter (1982; 1984) has argued that a better hypothesis would be to assume a density driven flow that is geostrophically balanced across the Gulf, though it may be modified by surface and bottom Ekman layers.

Current pattern in certain local areas of the Gulf have been studied and modelled by organizations in the region. Three areas in particular are the coastline industrial areas of Saudi Arabia, (Tetra Tech, 1977; Williams, 1983) the west coast of Qatar (Beltagy, 1980) and the Kuwait offshore areas, (Mathews and Lee, 1983). Galt et. al. (1984) showed that fresh water runoff had a significant impact on the residual currents in the Northern Gulf region.

Murty and El-Sabh (1983) have examined the effects on the current patterns in the Gulf and northern Arabian Sea during storm conditions.

5. OIL SPILL STUDIES:

As the world center of the oil industry, the Gulf region is constantly subject to environmental damage posed by oil spills as the Nowruz spill amply demonstrates.

Excluding disastrous spills such as Nowruz, different researchers have come up with different estimates of the amount of oil which will be spilled in the Gulf over the coming decade. Taking a 5% annual increase in oil production over the next ten years, Hayes and Gundlach (1977) have estimated that 3 million tons will be spilled. Golub (1980) using a more realistic production increase estimate of 1.7% annually, predicts that 1.5 million tons of oil will be spilled. In both predictions, the major source is seen to be related to tanker transport with offshore production and discharges by coastal refineries and other industries being the next major contributors.

Examining vessel reported slicks in the Gulf in 1978, Ootsdam (1980) has concluded that its spill rate is less than half of the world rate because risk due to human error is less at the start of outward bound journeys and most oil from ballast water on inward bound voyages would have been released before the vessels reached the Gulf. Nevertheless he calculates spilled oil in the Arabian Gulf in 1978 to be over 150,000 tons, a figure which may be too high since he uses too large a thickness estimate for oil spill sheen. A study by the Research Institute (Belen et. al., 1983) concluded that the average annual oil spillage from marine transport is 45,000 to 60,000 tons. Another study (Lehr and Cekirge, 1981) concluded that the shoreline impacts from this spilled oil is seasonally sensitive. Surveys of oil on the shore have been conducted for particular regions in the Gulf (Al-Hamri and Anderlini, 1979).

Several computer models have been used to simulate oil spills in the Gulf. The SLIKFORCAST model developed by the Continental Shelf Institute and Det Norske Veritas and widely used in the North Sea was applied to the 1980 oil spill in the Hasbah offshore oil field (Krogh, 1980) with satifactory results. Global Weather Dynamics Incorporated, under contract to the Saudi Arabian Meteorology and Environmental Protection Administration (MEPA) has conducted simulation studies on the Nowruz Oil Spill. Unfortunately the author has not been able to get any details of the predictions of the model. The National Oceanic and Atmospheric Administration (NOAA) applied its model, OSSM, to the same spill (Galt, et al., 1984) with the conclusion that the southern coastline of Saudi Arabia, Bahrain and Qatar would suffer the heaviest impact of Nowruz pollution mainly in the form of tar balls. A third model applied to the Nowruz spill was developed by Murty and El-Sabh (1983) with the determination that the southern Iranian coastline was the area of greatest pollution risk.

The Research Institute has developed an oil spill simulation package, GULFSLIK (Figure 5), specifically for the Gulf region. The first model developed for the package, GULFSLIK I (Lehr and Cekirge, 1979) was a simple trajectory model based on seasonal average winds and currents and is perhaps a good illustration that usefulness is not synonymous with complexity. Not only did it provide at least as good a prediction of the Hasbah oil spill path (Figure 6) as the more complicated

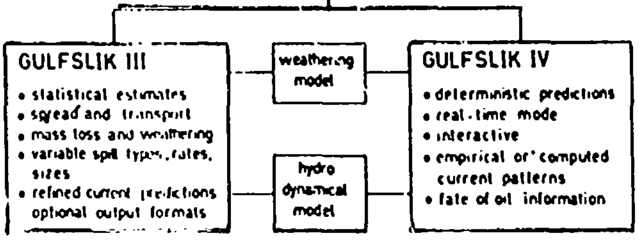

Figure 5. Diagram of GULFSLIK oil spill modelling package.

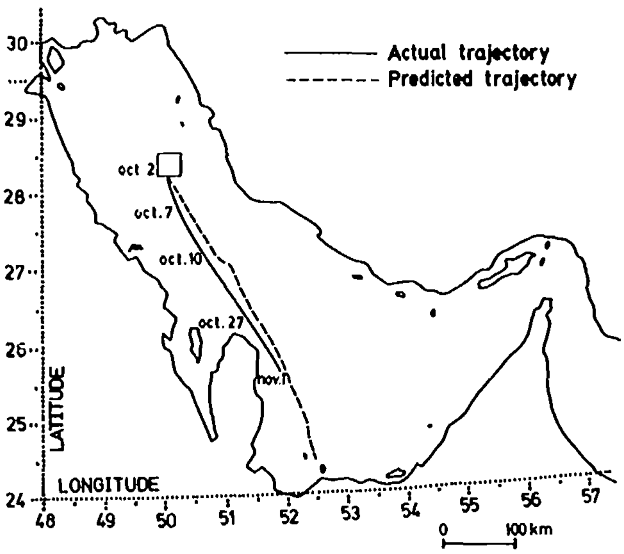

Figure 6. Predictions of Hasbah oil spill trajectory by GULFSLIK I.

SLIKFORCAST model, but also has been used to provide information about the possible source of a large (40,000 barrel) spill which impacted Bahrain in the summer of 1980 (Lehr and Belen, 1983). In early March of 1983 GULFSLIK I was applied to the Nowruz oil spill (Lehr, 1983) with the conclusions that the most at risk shorelines were the Saudi coastline near Abu Ali Island, Bahrain, Northern Qatar and Souther Iranian coastline near Hendorabi Island. Comparison of these predictions, as well as the predictions of the other models mentioned with the actual results of the Nowruz spill has been difficult, due in part to the nature of the spill and the lack of slick observation information from the eastern part of the Gulf.

Trajectory models designed for the whole Gulf are of limited use for near shore spills. The OSSM model of NOAA has the capabilities to be applied to a smaller area of interest within a larger region and was thus used on the nearshore areas of Kuwait (Galt, et. al. 1984). Certain coastal industrial sites have developed simplified models as part of their oil spill contingency plans. Under contract to the Arabian American Oil Company, the Research Institute developed GULFSLIK II, a spread and transport model for certain near shore areas of the Saudi Arabian coastline. It provides a good example of the type of information such models can provide.

GULFSLIK II receives as input data the initial volume of spilled oil, oil density, statistical tables of historical current and wind patterns and shoreline coordinates. To simulate a spill incident, the model divides the slick into nine Lagrangian elements located 40° apart on the edge of the spill. For each Lagrangian element a transport vector is constructed from a percentage of the wind vector at 10 meters, the residual current, and a spread vector. Spreading in the model was originally based on the well known Blokker formula (Blokker, 1964), with the spread vector for each spill edge element assumed to be radially outward from the center of mass of the slick.

Initial values for the transport vectors are chosen using Monte Carlo simulation as are subsequent vectors with a time interval of three hours. Details on the simulation and the approximation used to construct the conditional probabilities for the transport vectors are provided in Lehr et. al., (1981).

For a particular spill site, the model is run 100 times with the spill edge element locations recorded for each run on a grid appropriately chosen for the geography of the spill site. Then the grid block occupation numbers for some specified time after initial spill occurence are plotted on a map to provide an overall picture on the expected behavior of the spill. The block occupation numbers relate to the probability that the edge of the slick would be found in the corresponding grid block. Figure 7 shows a typical output for a simulated 1000 barrel 30 API spill at the Sea Island offshore loading platform at Ras Tanura.

Movement of oil is only one factor in oil spill simulation. Equally important is the mass loss and alteration of the oil due to weathering. While oil spill weathering models exist for the Gulf (Belen et. al., 1981) a recent series of four test spills carried out by the Research Institute and the Arabian American Oil Company suggest that many common assumptions of such models may have to be modified to Gulf conditions. In particular, widely used spreading formulas such as the Blokker formula or the Fay formula (Fay, 1971) compared quite poorly with the actual measured results (Lehr et. al., 1983). Figure 8 shows the contrast between the area predicted by the Blokker formula and the actual area for a 51 barrel spill of Arabian light oil.

Work on the GULFSLIK package and its applications has pointed out the requirements for a useful and usable oil spill modelling program for the KAP region. Basically, the need for oil spill models falls into two categories; (1) contingency planning for oil pollution, and (2) combat strategy in the case of an actual spill. The first category is suitable for models that do not operate in real-time and include sophisticated hydrodynamical packages requiring the use of a main-frame computer. Such models may need highly skilled and experienced operators to operate the package and interpret the results into a form useful for contingency planning. In the second category however, the users may not

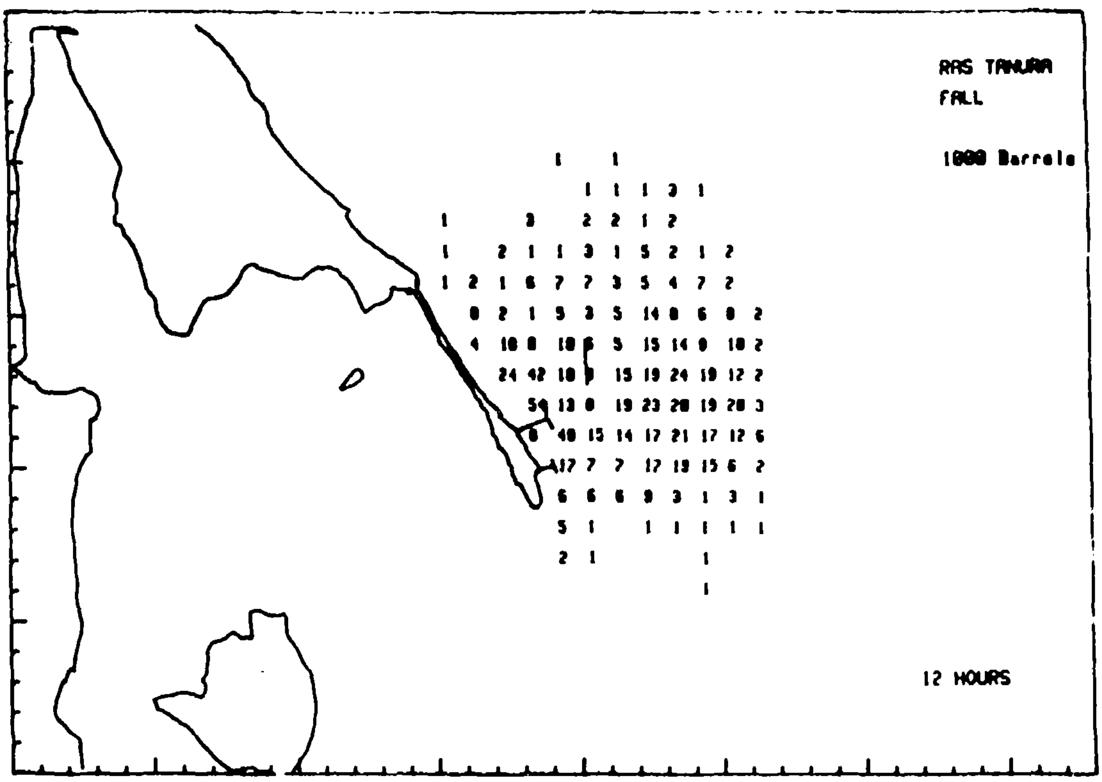

Figure 7. Sample output for GULFSLIK II model, twelve hours after simulated spill at Ras Tanura Sea Island.

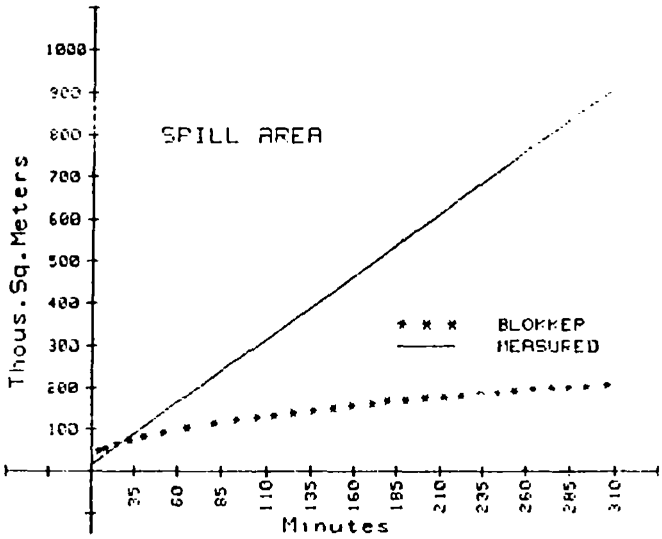

Figure 8. Area predicted by Blokker Formula Compared to actual area for 51 barrel spill.

be computers experts. Such programs should be interactive, providing simple prompts for necessary imput data, and should display output in an easily understood manner. A minicomputer is probably more suitable for such a program.

In either category, however, it is essentail that the model be calibrated to and preferably initially designed for, the conditions of the KAP region.

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Storm tracks, storm surges and sea state in the Arabian Gulf, Strait of Hormuz and the Gulf of Oman.

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ABSTRACT

The Arabian Gulf is mainly influenced by extra-tropical weather systems, whereas the Gulf of Oman is mostly under the influence of tropical weather systems. The west-to-east directed extra-tropical cyclone tracks and the generally east-to-west directed tropical cyclone tracks converge near the Strait of Hormuz. The shallower parts of the Arabian Gulf are subjected to major storm surges, whereas in the deeper Gulf of Oman, the storm surge threat is somewhat less.

1 INTRODUCTION

The K.A.P. (Kuwait Action Plan) region consists of the following water bodies: the Arabian Gulf, the Strait of Hormuz and the Gulf of Oman. There are eight nations bordering these water bodies (Figure 1): Iraq, Kuwait, Saudi Arabia, Bahrain,

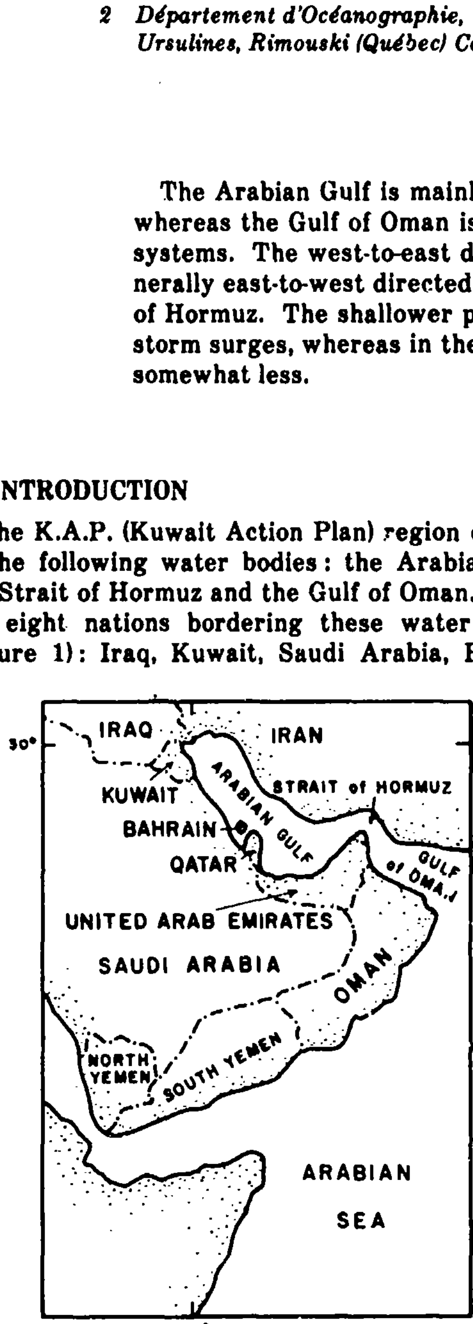


Figure 1. The Kuwait Action Plan region.

Qatar, United Arab Emirates (U.A.E.) Oman and Iran. The deeper Gulf of Oman joins the Arabian Sea towards east and south and is connected to the shallower Arabian Gulf through the Strait of Hormuz. Since the climate of the region is influenced strongly by orography, a brief description of the geography of the area is useful.

The region under discussion consists of low-lying central areas enclosed by mountains (Perrone, 1981): the Taurus family of mountains in southern Turkey, the Pontic mountains in northeast Turkey, the Caucasus mountains of Iran, and the Hajar and Hejaz mountains of the Arabian Peninsula. The Arabian Gulf and the Tigris-Euphrates Valley are at low elevations.

The Arabian Gulf is mainly affected by the extra-tropical weather systems, whereas the Gulf of Oman is at the northern edge of the tropical weather systems. Thus the Strait of Hormuz region forms the boundary between the generally west-to-east travelling extra-tropical weather systems and the east-to-west travelling tropical weather systems.

2. EXTRA-TROPICAL WEATHER SYSTEMS AFFECTING THE ARABIAN GULF

Figure 2 shows the extra-tropical cyclone tracks across Asia (Haurwitz and Austin, 1944). It can be seen that the tracks more or less follow the axes of the Arabian Gulf and the Gulf of Oman. One of the interesting weather phenomenon in the Arabian Gulf region is the so-called "Shamal" which is a sub-synoptic scale wind phenomenon that occurs in this region with sufficient frequency and influence on the local weather that it is significant operatio-

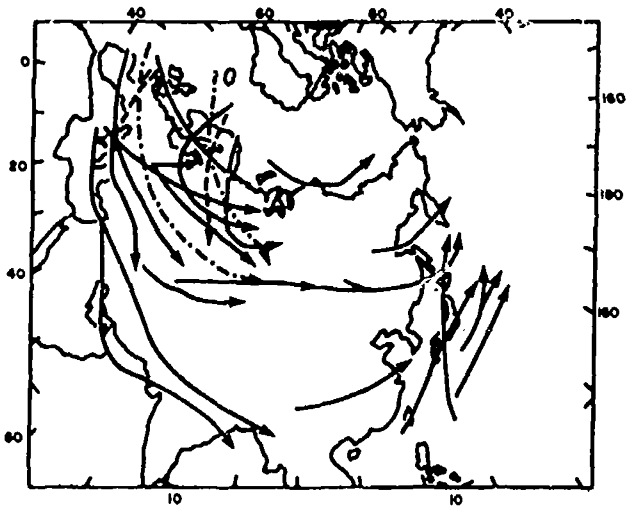


Figure 2. Extra-tropical cyclone tracks across Asia (from Haurwitz and Austin, 1944).

nally (Peronne, 1981). Shamal is an Arabic word meaning "north". It is used in the meteorological context to refer to seasonal northwesterly winds that occur during winter as well as summer in the Arabian Gulf region. In the following discussion, our source of information is the excellent technical report by Perrone (1981).

The Winter Shamal occurs mainly during November to March and is associated with mid-latitude disturbances travelling from west to east. It usually occurs following the passage of cold fronts and is characterized by strong northwesterly winds (mainly during December to February). Perrone (1981) mentions that only for less than 5% of the winter duration, the winds at most locations in the Arabian Gulf exceed 20 knots. Although it is infrequent, the winter Shamal is not insignificant (the March 1983 oil spill event in the Arabian Gulf occurred during a winter Shamal) from an operational point of view, because it sets in with great abruptness and force.

The summer Shamal occurs with practically no interruption from early June through July and is associated with the relative strengths of the Indian and Arabian thermal lows. When viewed from the point of the strength of the wind and the associated weather conditions, the summer Shamal is not as important as the winter Shamal. In the discussion to follow we restrict ourselves to the winter Shamal only. Based on duration, one can distinguish between two types of Shamal: (1) those which last 24 to 36 hours (2) those that last for three to five days.

The intense winter Shamals are preceded by movement of cold air from north into the Arabian Gulf region. Except the most intense of such incursions, the others are stopped by the mountains of Turkey, Georgian U.S.S.R. and Iran. However cold air can arrive in the Arabian Gulf area by at least two indirect routes: one of these is via the Aegean Sea. In the other indirect route, the cold air moves over the shorter mountain chain in western Turkey, then across the eastern part of the Mediterranean Sea, then travels either over or around the low mountains in Syria and Lebanon (with heights ranging from 914 to 1,829 m) and finally into the Tigris-Euphrates Valley. The orography also affects the airflow within the Arabian Gulf region. The sharply rising mountains to the north and east, and more gently rising to the west and southwest renders the airflow at low level from northwest to southeast.

Although the winter Shamal is a relatively rare event, typically occurring only once or twice each winter, it brings some of the strongest winds and highest seas of the season to the Arabian Gulf region. Next we will consider shorter duration Shamals (24 to 36 hours) which are more frequent. For these Shamals also the synoptic situation described above generally applies with one important exception. The upper air trough does not stall over the Strait of Hormuz, but travels fast to the east.

Shamal conditions rarely occur over the northern part of the Arabian Gulf in September. In association with the movement of cold fronts or mid-latitude lows either over or to the north of the Arabian Gulf, the onset of Shamal may happen at any time of the day. Before the onset of the Shamal, winds in the area ahead of the approaching cold front blow from the south to southeast. These southerly winds (called "Kaus" in Arabic or "Shakki" in Persian) slowly increase in intensity as the front approaches, and may reach gale force before the passage of the front (Perrone, 1981). Due to the channeling effect of the low level air flow by the Zagros mountains, in western Iran the strongest of these southerly winds occur on the eastern side of the Arabian Gulf.

Usually the Shamal occurs first in the northwest part of the Arabian Gulf and then spreads south and east behind the advancing cold front. It takes about 12 to 24 hours for the Shamal to spread from the northwest corner of the Arabian Gulf to the southern part. The onset of a typical mid-winter Shamal is associated with the advection of a cold, intense, upper air trough at 500 mb to a location over Syria and Iraq (East of the Taurus mountains of Turkey). A surface low usually forms to the east of the upper trough, in the area of strongest positive vorticity advection. The relatively warm waters of the Arabian Gulf act as a sensible heat source and the cyclogenesis is also due to the mechanical uplifting of the low level westerly or southwesterly flow by the Zagros mountains. The strong southwesterly airflow over the Zagros mountains further enhances this upward motion. The release of latent heat of condensation from the uplifted Arabian Gulf air further helps the cyclogenesis.

The onset of the Shamal is difficult to predict, mainly because of the difficulty in forecasting the associated upper air pattern. Once the Shamal has begun, it may subside within 12 to 36 hours after the passage of the cold front or it may persist for three to five days. The relationship between the surface and upper air patterns determines which duration sequence is most likely to occur. Once the Shamal is onset, the wind direction is strongly influenced by the coastal orography. In the northern part of the Arabian Gulf the Shamal winds generally blow from any direction between north and west-northwest. In the middle parts of the Gulf, Shamal winds tend to be from a direction lying between west-northwest to northwest. On the southeast coast of the Gulf the winds are westerly. In the Strait of Hormuz area the Shamal winds are generally from the southwest. In general the speed of the Shamal winds ranges from 20 to 40 knots.

For the longer duration Shamals, the upper air trough stalls over the Strait of Hormuz. The Shamal winds persist for three to five days with gale force and blow from northwest over the whole Arabian Gulf. Because of the large pressure gradient between the low over the Gulf of Oman and the high over Saudi Arabia, the Shamal winds are strongest in the southern and southeastern parts of the Arabian Gulf. Average wind speeds in the southern and southeastern parts of the Arabian Gulf range from 30 to 40 knots, with peak winds in excess of 50 knots not uncommon in this type of Shamal. Winds over the northern part of the Arabian Gulf tend to be 5 to 15 knots less than the above values, on the average.

According to Perrone (1981) two areas of the Arabian Gulf appear to experience stronger than average Shamal conditions. These are shown in Figure 3. One area is near the Qatar Peninsula,

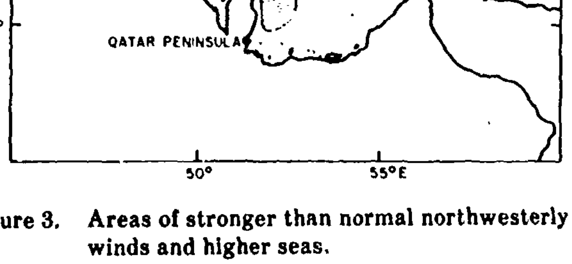


Figure 3. Areas of stronger than normal northwesterly winds and higher seas.

and another is near Lavan Island. The Shamal which is due to interaction between the synoptic scale and the meso-scale extra-tropical weather systems, is subject to modification by local conditions.

3. TROPICAL WEATHER SYSTEMS THAT AFFECT THE GULF OF OMAN

The specifications of the tropical cyclone disturbances in general use are: (a) Depression, when winds reach up to 33 knots (Beaufort 7); (b) Moderate Storm, when winds are from 34 to 47 knots (Beaufort 8 to 9); (c) Severe Cyclonic Storm, when winds are from 48 to 63 knots (Rao, 1981). Table 1 lists the monthly and annual number of depressions and storms which formed in the Arabian Sea during 1930 to 1969.

The Arabian Sea is in the area of the Monsoon, which signifies a seasonal wind regime in which surface winds blow persistently from one general direction in summer, and just as persistently from a markedly different direction in winter (Brody, 1977).

The following information is taken more or less directly from Brody (1977). Although tropical cyclones do not usually occur in the Arabian Sea area, they do have a significant effect on the local weather. In spite on the low frequency of their occurrence along the Arabian Coast, where they influence the weather on an average of only once in three years, their associated torrential rains make up a significant portion of the total rainfall. During the 25-year period 1943 to 1967, a quarter of the total rainfall at Salalah was associated with tropical cyclones. In addition, their winds and associated sea conditions make the tropical cyclone a dangerous meteorological event in the Arabian Sea region.

The Arabian Sea is the least active of the various tropical cyclone development regions on the globe. Only about 1% of the world's tropical cyclones of at least tropical storm intensity develop in the Arabian Sea, in contrast to 5% in the Bay of Bengal, which is somewhat smaller in area than the Arabian Sea. During a seventeen year period (1951 to 1967), no tropical storms were observed in the Arabian Sea for seven years, whereas only a maximum of three were observed in two of the 17 years. However, more recent satellite data appears to suggest that the occurrence of tropical storms in the Arabian Sea might be more frequent than believed earlier, especially in the southwestern areas where virtually no data were available earlier.

In the Arabian Sea region, the tropical cyclones develop mainly during the spring and fall transition seasons. The same bimodal distribution is applicable for tropical cyclones that reach hurricane intensity. The rarity of tropical storms in the

Table 1. Monthly and annual number of depressions and storms in the Arabian Sea, 1930-1969 (from Rao, 1981)

Year	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1930						2				1			3
1931													0
1932					2					1			3
1933					1		1						2
1934						1			1				2
1935	1					1							2
1936						1					1		2
1937						1				1			2
1938					1						1		2
1939										1	1		2
1940										1	1		2
1941					1					1			2
1942				1									1
1943											1		1
1944						1		1					2
1945											1		1
1946						1							1
1947				1					1				2
1948						2				2	1		5
1949					1								1
1950							1		1				2
1951				1		1					1		3
1952												1	1
1953													0
1954				1		1	1						3
1955													0
1956						1				1			2
1957					1				1	1			3
1958													0
1959					1	1	1			1			4
1960					1		1				2		4
1961					1	1	2						4
1962					1		1						2
1963					1					1	2		4
1964						1		1			1		3
1965												1	1
1966									1	1			2
1967													0
1968													0
1969						1							1

Arabian Sea region can be seen from the fact that only 92 tropical cyclones reached storm intensity during the 80-year period 1891 to 1970. Slightly more than half of these reached hurricane intensity.

Occasionally tropical storms generated in the Bay of Bengal cross the peninsular part of India and develop in the Arabian Sea. Figure 4 shows the tracks of two tropical storms that developed in the Arabian Sea in the spring of 1974. Figures 5 and 6 show tropical cyclone tracks for the Arabian Sea including the region of the Gulf of Oman. It can be seen that tropical storms south of about 15°N usually move towards the northwest quite far from the west coast of India. North of 15°N this track splits, with some of the storms moving westward while the others move northward.

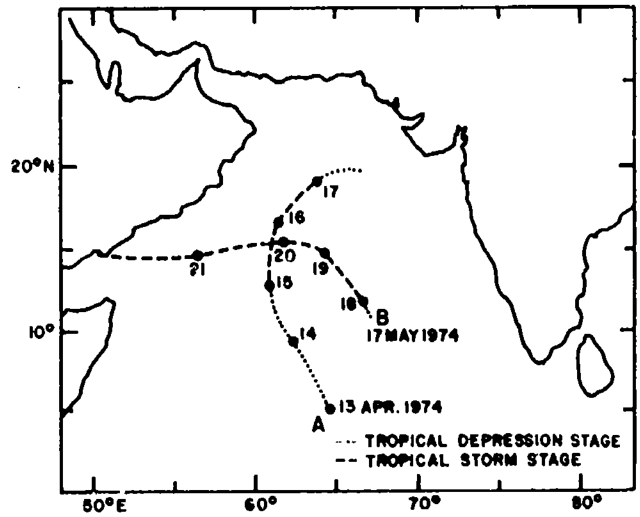


Figure 4. Tropical storms that originated in the Arabian Sea during the spring transition of 1974. Storm A : 13-17 April; Storm B : 17-21 May.

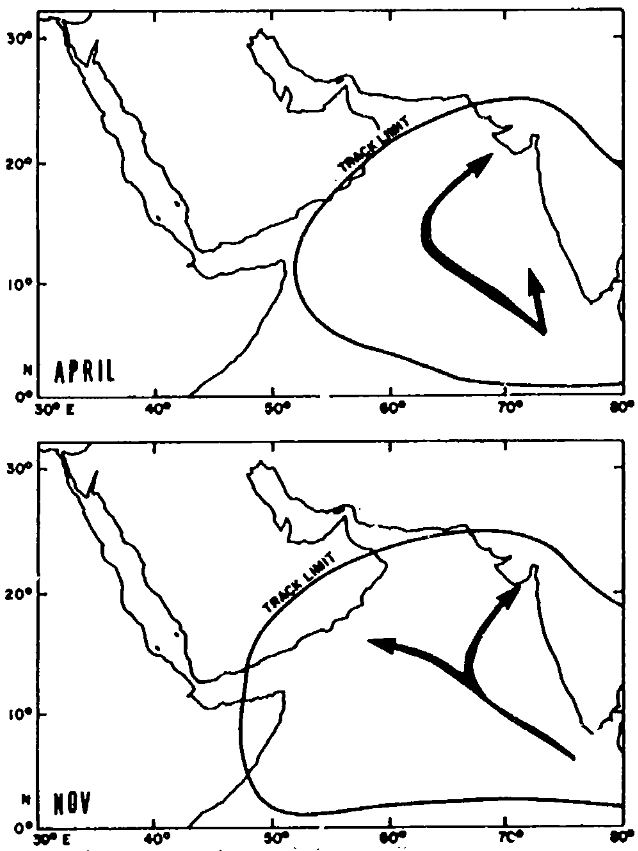


Figure 5. Mean tropical storm tracks for the Arabian Sea for the months of April and November (from U.S. Naval Weather Service Command, 1974).

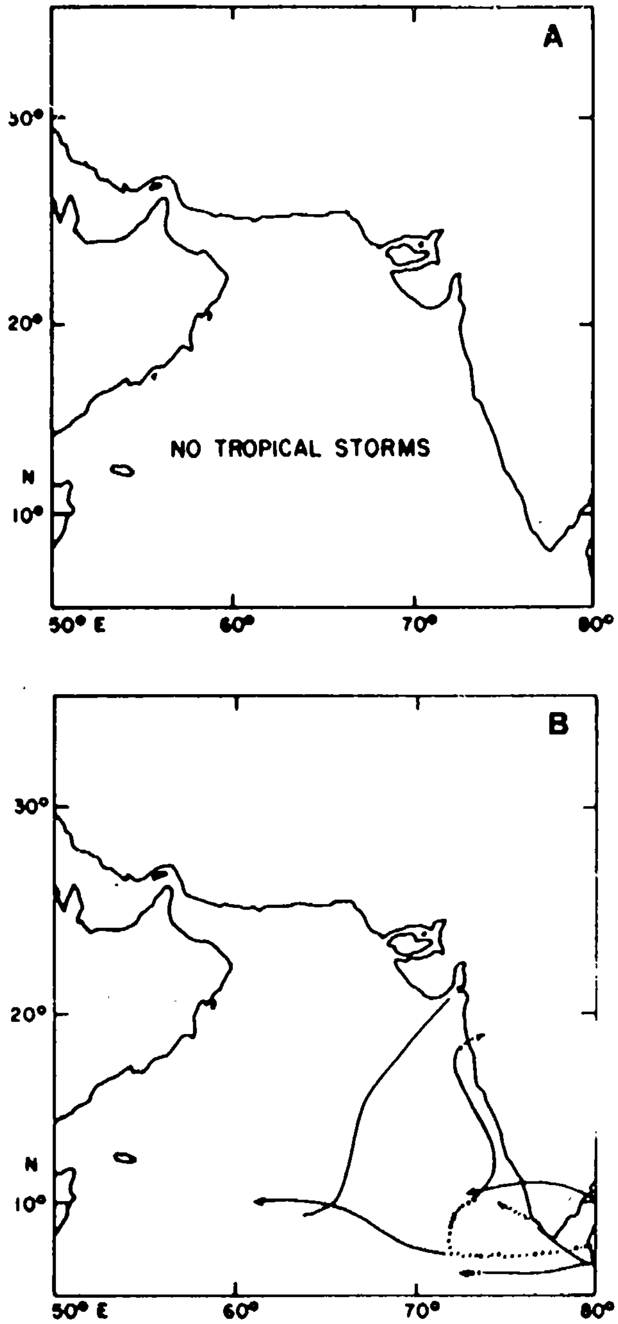


Figure 6. Tracks of tropical cyclones which reached tropical storm intensity in the Arabian Sea (dotted line indicates depression stage). The period of record is 1891 to 1970. These tracks tracks are for (A) the months of January, February and March, (B) for the month of December.

Tropical cyclones are extremely rare during the winter monsoon, and the few recorded ones occurred during December (Brody, 1977). The major meteorological events of the spring and fall transitional seasons are the tropical storms. According to Brody (1977), as long as the near-equatorial trough remains over the sea, and the farther it moves from the equator (as during spring), the more often tropical cyclones will develop in the sea.

The Arabian Sea Summer Monsoon is firmly established usually by June. Surface winds reach a maximum during July. During June, the near-equatorial trough occasionally re-intensifies over the Arabian Sea and this gives rise to tropical cyclones. Tropical cyclones reaching storm intensity in June generally develop off the west coast of India and move northwestward and cause high winds at Karachi, Pakistan.

4. STORM SURGES AND SEA STATE IN THE ARABIAN GULF

In considering the sea state, it is useful to understand the diurnal variations in the surface wind field. Detailed wind measurements at Ahmadi Sea Island and Das Island showed that maximum winds occurred during night time. This appears to be true for the case of Shamal winds of short duration. However, for Shamal winds lasting three to five days, the atmospheric surface pressure gradients and winds tend to increase during the day and weaken somewhat during the night, sometimes by as much as 5 to 10 knots (Perrone, 1981).

According to Perrone (1981) the usual relationship between wind speed and wave heights that are developed for deep water may not hold for the shallow Arabian Gulf whose maximum depths is only 73.3 m. According to him, the shallowness of the Gulf, as well as its stratification will make the wave heights much larger than thoso that are inferred from the deep water relationships. Observations made from oil rigs suggest that persistent gale force winds blowing for up to 12 hours can generate wind waves with amplitudes up to 4 m. Sometimes waves up to 5 m height could be generated in a few hours.

In the northern part of the Arabian Gulf wind wave amplitudes are usually smaller because of limited fetch and also due to the fact that this area is affected by short duration Shamals. According to Perrone (1981), the following three factors combine to generate waves up to 5 m height in the southern part of the Arabian Gulf during Shamals of three to five days duration: (i) the increase in the wind speed in the southern gulf; this contributes to locally generated seas; (ii) the longer duration of gale force winds over the whole Gulf; the northern part of the gulf generates swell which travels into the southern part; (iii) the lack of fetch limitation; the entire gulf experiences at least gale force winds, with the strongest winds in the southern part of the gulf. It may take several days for the swell to decay following Shamal winds.

Next we will consider storm surges in the Arabian Gulf and the general geography of the region. Figure 7 shows the bathymetry of the Arabian Gulf and the general geography of the region.

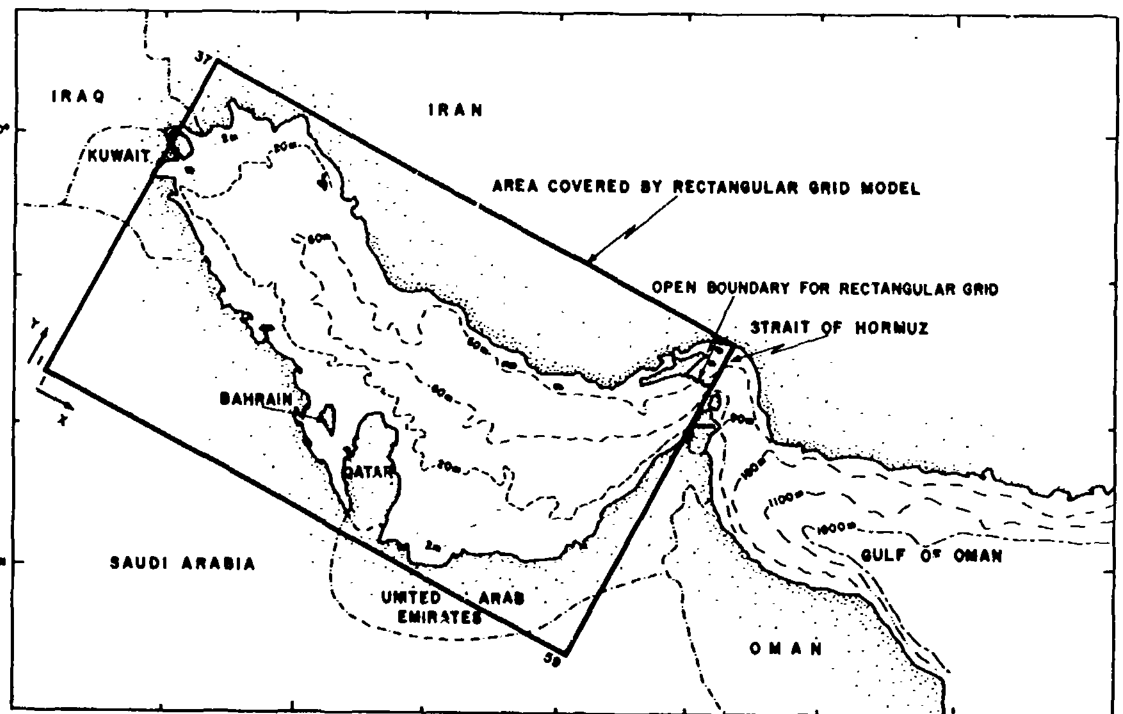


Figure 7. Bathymetry and geography of the Arabian Gulf area.

The linearized versions of the shallow water equation are where the subscripts in equations (1) to (3) denote differentiation with that variable. One can either use a linear form for the bottom friction as in equation (4) or a quadratic form as in (5), where r is a linear friction coefficient and k is a dimensionless quadratic friction coefficient.

$$\eta_t = -(du)_x - (dv)_y \qquad (1)$$

$$u_t = -g\eta_x + fv - F^{(u)} + G^{(u)} \qquad (2)$$

$$v_t = -g\eta_y - fu - F^{(v)} + G^{(v)} \qquad (3)$$

where

$\eta(x,y,t)$ = elevation of water surface above mean level

$u(x,y,t)$ = depth-averaged velocity in x-direction

$v(x,y,t)$ = depth-averaged velocity in y-direction

$d(x,y)$ = mean water depts

x,y = Cartesian coordinates in horizontal plane

f = Coriolis coefficient (assumed constant)

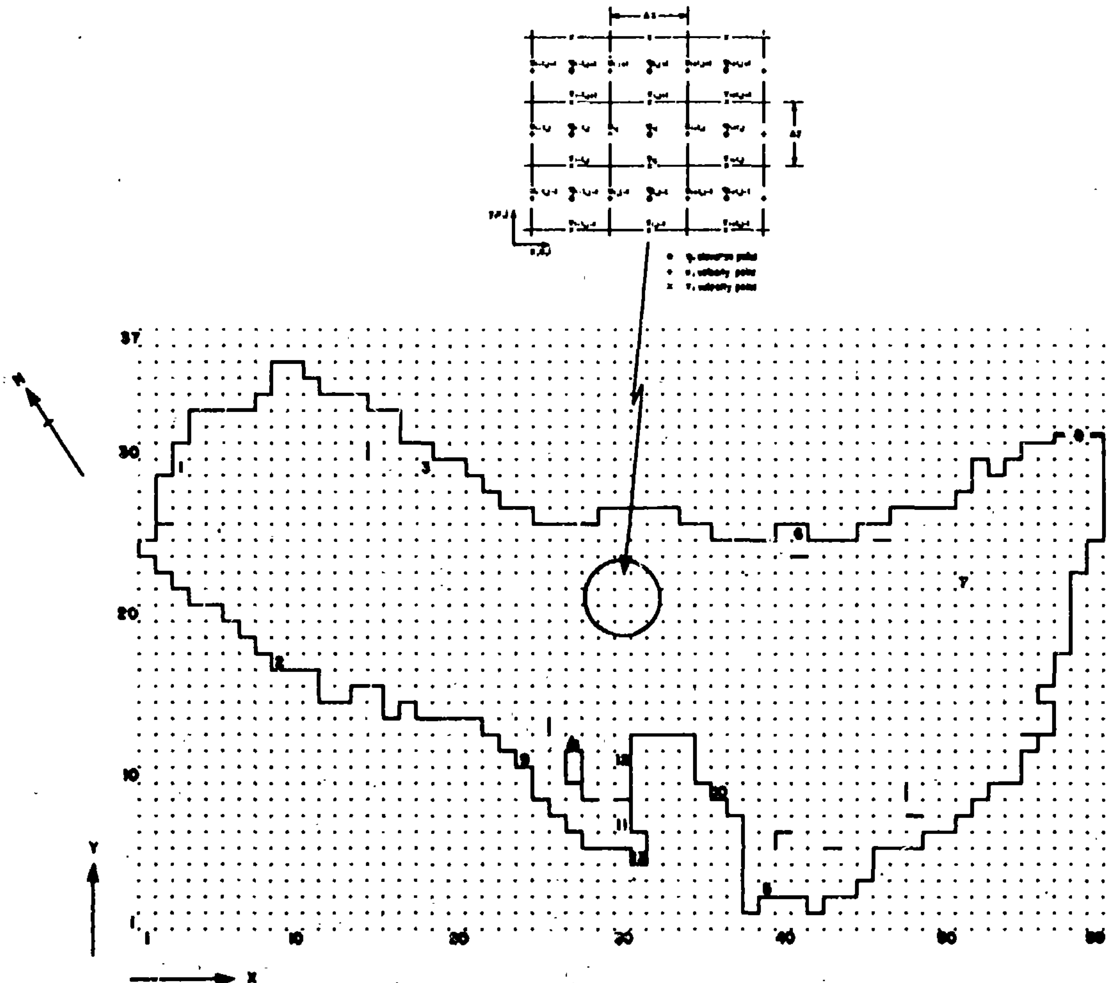
g = acceleration due to gravity

t = time

$F^{(u)}$ and $F^{(v)}$ = represent friction terms.

$$F^{(u)} = ru \;; \quad F^{(v)} = rv \qquad (4)$$

$$F^{(u)} = ku(u^2+v^2)^{\frac{1}{2}}/d; \quad F^{(v)} = kv(u^2+v^2)^{\frac{1}{2}}/d \qquad (5)$$



LEGEND

Station 1. Shat Al Arab Bar, Iran
Station 2. Ras Al Mishaab, Saudi Arabia
Station 3. Bushire, Iran
Station 4. Mina Salman, Bahrain
Station 5. Jazirat Ghagha, U.A.E.
Station 6. Jazirat Shaikh Shuaib, Iran
Station 7. Jazirat, Sirri, Iran
Station 8. Strait of Hormuz
Station 9. Dammam, Saudi Arabia
Station 10. Doha, Qatar
Station 11. Janan, Qatar
Station 12. Ras'Ashairiz, Qatar
Station 13. Al Hamlah, Qatar

Figure 8. The square grid used in the computations. The inset shows the finite-difference scheme.

Figure 8 shows the square grid used in the computations, and the inset shows the finite-difference scheme. The Strait of Hormuz is taken as an open boundary. At the interior points of the grid, equations (1) to (3) have the following finite difference forms.

$$\frac{\eta'_{ij} - \eta_{ij}}{\Delta t} = - \frac{(d_{ij}+d_{i+1,j})u_{i+1,j} - (d_{i-1,j}+d_{ij})u_{ij}}{2\cdot\Delta x} - \frac{(d_{ij}+d_{i,j+1})v_{i,j+1} - (d_{i,j-1} + d_{ij})v_{ij}}{2\cdot\Delta y} \quad (6)$$

$$\frac{u'_{ij} - u_{ij}}{\Delta t} = - g\,\frac{\eta'_{ij} - \eta'_{i-1,j}}{\Delta x} + f\bar{v}_{ij} - F^{(u)}_{ij} + G^{(u)}_{ij} \quad (7)$$

$$\frac{v'_{ij} - v_{ij}}{\Delta t} = - g\,\frac{\eta'_{ij} - \eta'_{i,j-1}}{\Delta y} - f\bar{u}'_{ij} - F^{(v)}_{ij} + G^{(v)}_{ij} \quad (8)$$

where

Δt = time step

$\Delta x, \Delta y$ = grid interval sizes in in x,y directions respectively

d_{ij} = mean water depth at elevation point η_{ij}

$$\bar{u}_{ij} = \frac{1}{4}\,[u_{i,j-1}+u_{i+1,j-1}+u_{ij}+u_{i+1,j}] \quad (9)$$

$$\bar{v}_{ij} = \frac{1}{4}\,[v_{i-1,j}+v_{ij}+v_{i-1,j+1}+v_{i,j+1}] \quad (10)$$

The following stability criterion is used in determining the optimum time-step.

$$\Delta t \le \frac{\Delta x\cdot\Delta y}{[gd_{max}(\Delta x^2 + \Delta y^2)]^{\frac{1}{2}}} \quad (11)$$

Figure 9 shows schematically the spatial structure of the storm as it advances one grid space in the x-direction in one time-step. This storm thus has a life of about one day and is supposed to represent a short duration winter Shamal. Figure 10 shows the wind directions as simulated for a winter Shamal. Figure 11 shows for selected locations the computed profiles of tide (with three semi-diurnal and three diurnal constituents included), tide plus storm surge and storm surge alone.

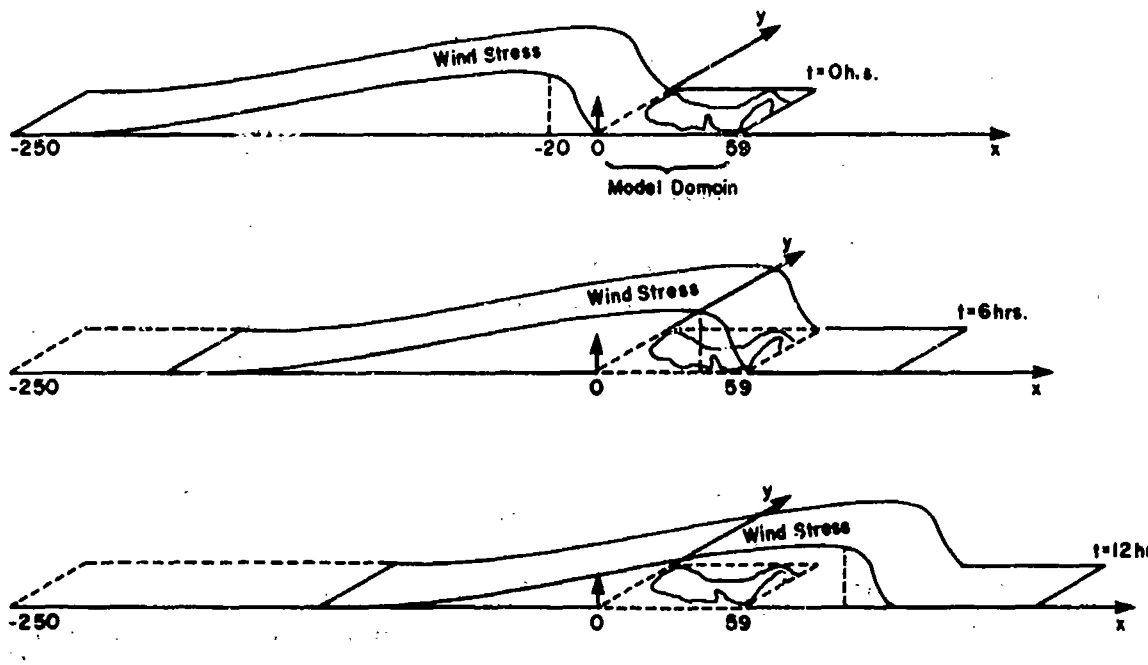


Figure 9. Schematic of the wind field used.

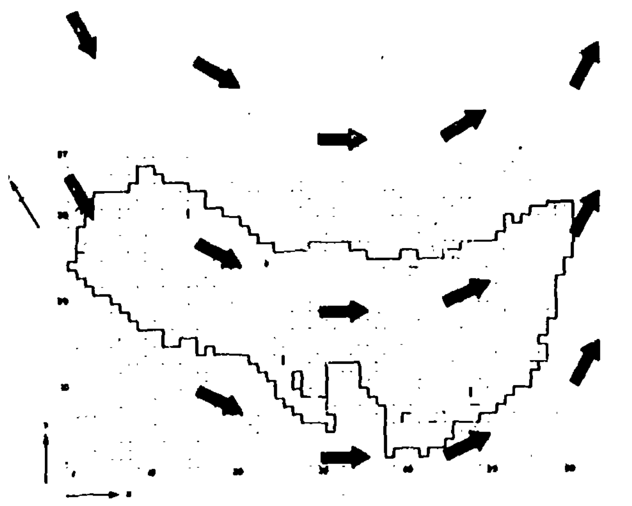
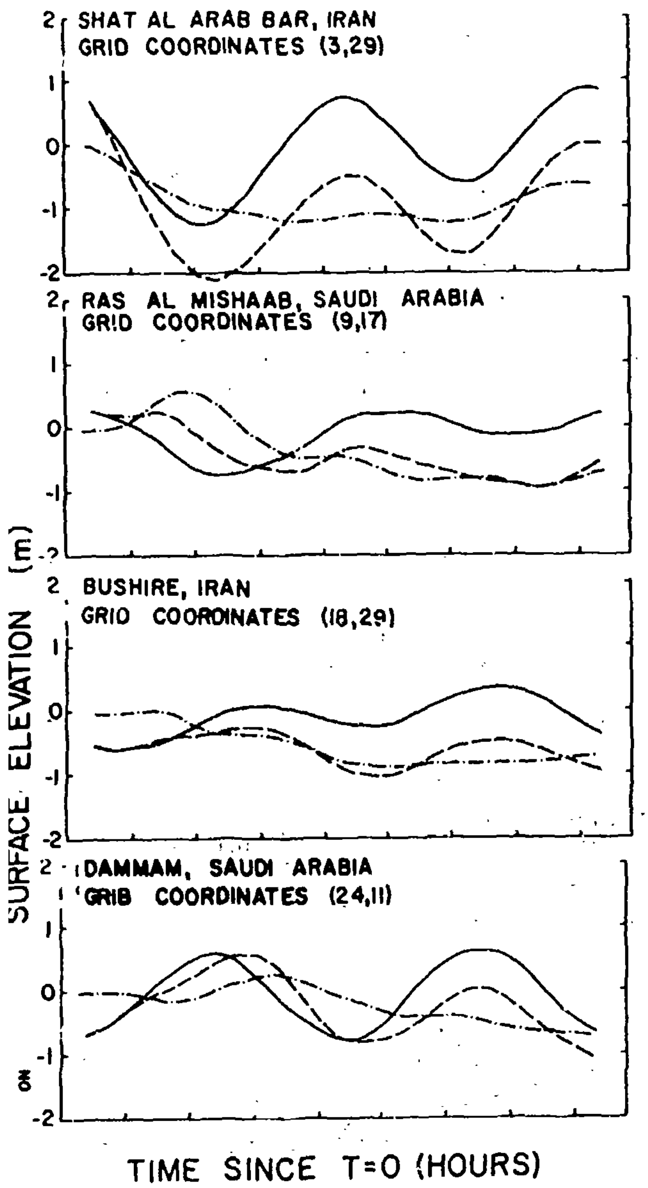


Figure10. Wind directions used in the numerical simulation.



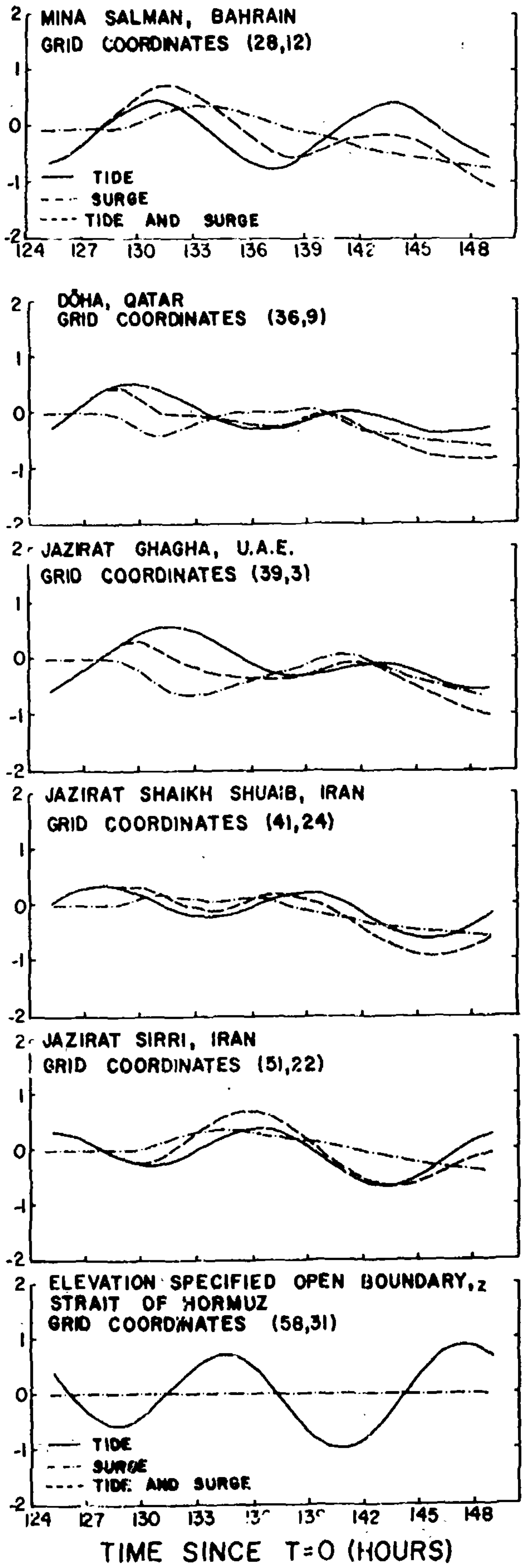


Figure 11. Computed profiles of the tide (six constituents M2, S2, N2, K1, 01, P1 are included), surge plus tide and surge only at selected locations.

Next we made additional simulations with the same wind directions, but for a longer duration (4 to 5 days) Shamal. Figure 12 shows the results of the simulations when the wind constantly blows from the positive y direction while, Figure 13 shows plots at four different times of the horizontal distribution of the storm surge heights. From these various types of plots it can be seen that significant positive and negative storm surges can occur in the Arabian Gulf. The tide is also important.

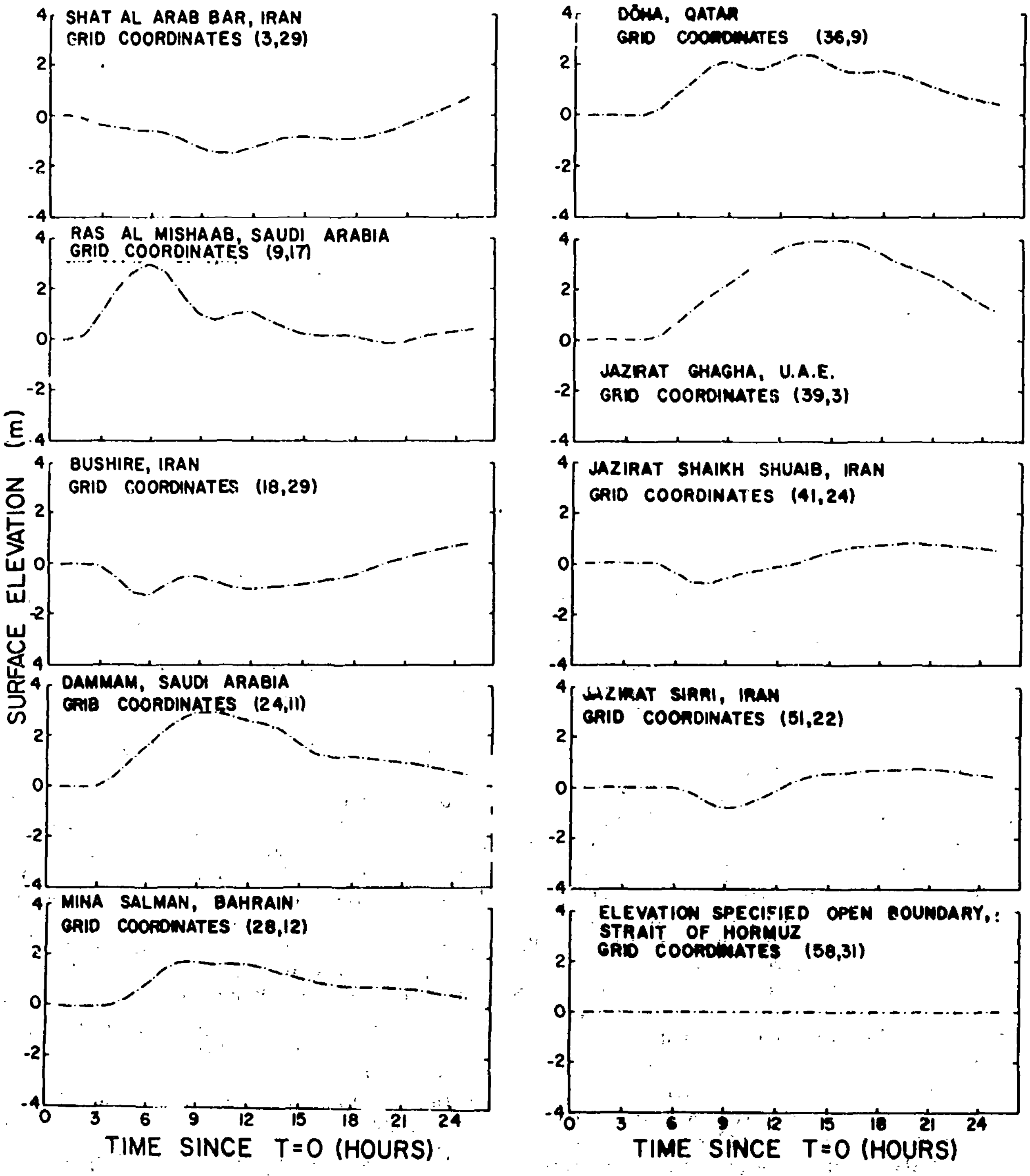


Figure 12. Results of simulations for long duration Shamal. The wind blows constantly from the positive y direction.

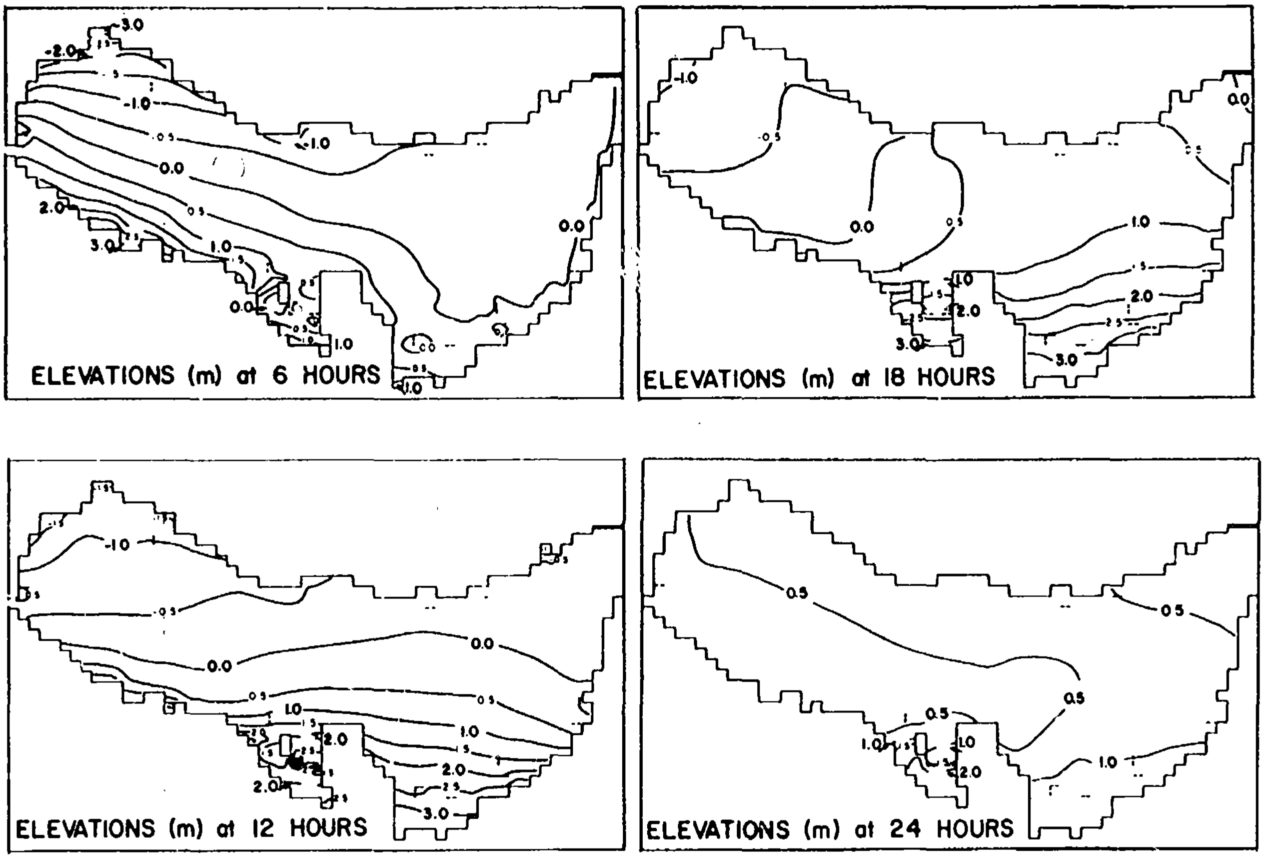


Figure 13. Distribution of storm surge heights.

5. SEA STATE AND STORM SURGES IN THE GULF OF OMAN

Brody (1977) mentions that local winds can generate wind waves up to 3m amplitude in the western part of the Arabian Sea and waves with even greater amplitudes in the northern part of the Arabian Sea and the Gulf of Oman area. Figure 14 shows the distribution of the wave heights in the Arabian Sea, Gulf of Oman and Arabian Gulf.

Next we will consider briefly the storm surge problem in the Gulf of Oman. Since the Gulf of Oman is deeper than the Arabian Gulf, one would expect the storm surge threat in the Gulf of Oman to be somewhat less than the threat in the Arabian Gulf, and the few available observations appear to suggest the same result. Most of the tropical cyclones of the Arabian Sea either travel westward or recurve and thus rarely they travel over the Gulf of Oman. This is not to say that significant surges do not occur in the Gulf of Oman; rather the frequency of their occurrence is small.

The Strait of Hormuz lies in the boundary region between the west to east travelling extra-tropical cyclones and the east to west travelling tropical cyclones. One could expect significant surges in the Strait of Hormuz, either from tropical cyclones or from extra-tropical cyclones.

Finally no storm surge forecasting in real time can be made without taking the tides into account. Since the Indian Ocean tide enters the Arabian Sea, travels into the Gulf of Oman, then into the Arabian Gulf through the Strait of Hormuz, for a better understanding of the tides one should make measurement of the tides at the junction of the Arabian Sea with the Indian Ocean.

6. SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

The extra-tropical cyclones that affect the Arabian Gulf were discussed with particular emphasis on the so-called "Shamal." The Gulf of Oman is affected by tropical cyclones from the Arabian Sea. The wind waves and storm surges from these weather systems are considered. The following studies should be made to obtain a detailed knowledge of the sea-state and storm surges in the Arabian Gulf and the Gulf of Oman.

i) Better observations are needed on the tracks of the extra-tropical cyclones that affect the Arabian Gulf.

ii) Detailed studies of the winter and summer Shamals.

iii) Understanding the differences between Shamals of shorter and longer durations.

iv) Better observations of the tracks of tropical cyclones that affect the Gulf of Oman

v) An understanding of the weather systems in the Strait of Hormuz area which forms the boundary between west to east travelling extra-tropical cyclones and east to west travelling tropical cyclones.

vi) Better and detailed measurements of the wind waves in the Gulf of Oman, Strait of Hormuz and the Arabian Gulf.

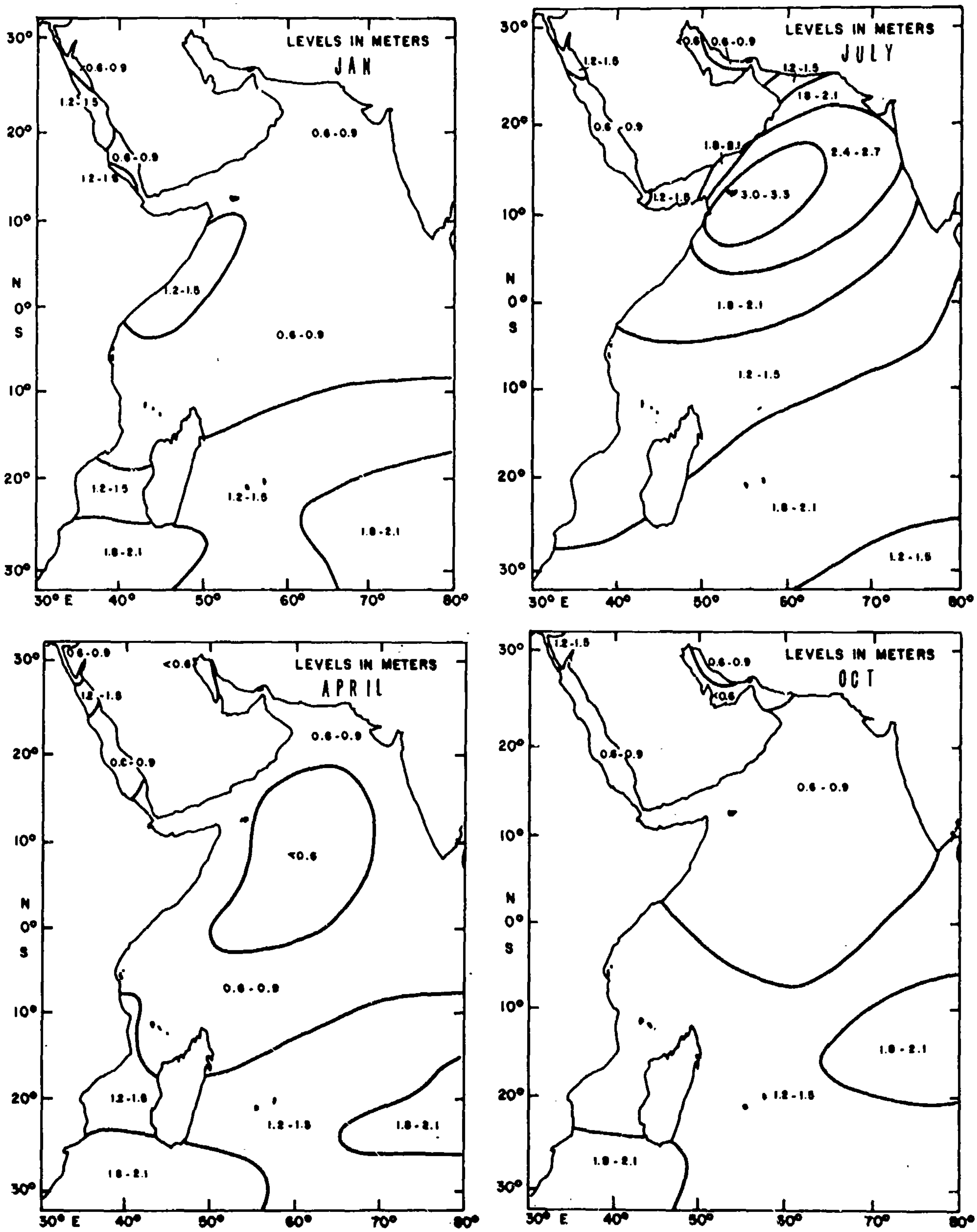


Figure 14. Wind wave amplitudes in the Arabian Sea and Gulf of Oman for January, April, July and October.

vii) Development of theoretical relationships between wind speed and wave height in shallow water.

viii) Development of an irregular triangular grid numerical model for the Arabian Gulf-Strait of Hormuz-Gulf of Oman system to compute storm surges, tides and tide-surge interaction.

ix) For better understanding of the tides in the system, measurement of the tides in the Arabian Sea that enter from the Indian Ocean should be made

ACKNOWLEDGEMENTS

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Models for tides in the KAP Region

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ABSTRACT :

A synthetic analysis of the available harmonic constituents of the tides for the Arabian Gulf and the Gulf of Oman is presented in a preliminary section, in order to precise the actual knowledge of the tides in the KAP region. That description is not restricted to the major constituents but extended to the non linear constituents which are not negligible in some particular places. The second part of this paper is devoted to the presentation of the classical numerical modelling technics applied for tidal problems, illustrated by references to three models of the Arabian Gulf fully documented in the literature. The performances of these models and their limitations are pointed out. In the last section, some recommendations are given for future works to improve and achieve our present knowledge of the tidal properties over the KAP region : complementary in situ observations of offshore tidal elevations and principally tidal currents, and new numerical modelling experiments based on methodology successfully applied to the resolution of similar problems in other coastal areas over the world.

1. INTRODUCTION

Tides in the Kuwait Action Plan region, including Arabian Gulf and Gulf of Oman must be considered as more or less well known, depending on the physical variable concerned, and on the expected precision on the phenomenon. In the present paper, we shall see that tidal elevations have been quite well observed and analysed, at least along the coast of the Arabian Gulf, leading to a satisfying picture of the components of tidal elevations all over the region. That empirical knowledge has been confirmed and completed, to some extent, by several numerical models which will be examined in the following. However, even for the tidal elevations, we shall see that some problems are still to be solved, if precise predictions are expected. It must also be pointed out that tides in the Gulf of Oman are less observed and identified, partly because of the oceanic characteristics of that area. But the main lack of data is on the velocity field : very little is known from observations about the water velocities; some global view has been produced by numerical models for the main tidal components; however, these informations have to be checked by a minimum set of in situ observations. In this paper, a brief description of the tides in the region will be first given, based on the observed sea surface elevations along the coasts. Anticipating the results of numerical models, a classification of the different tidal types (diurnal or semi-diurnal) for elevations and currents will be presented in this section, because of the exceptional variety of tidal regimes effectively present in that region. The second part of this paper will be devoted to the presentation of some numerical models produced in the literature for the KAP region; we shall point out their main characteristics, analogy or differences, and present a compared analysis of their results. The last section will give a summary of the different unsolved problems, and some recommendations for future works based on methodology successfully applied to the resolution of similar problems in other coastal areas over the world.

2. THE PHYSICAL CHARACTERISTICS OF TIDAL MOTIONS OVER THE KAP REGION.

Tidal motions are typically pseudo periodic phenomena, with notable variations along with time. Dominated by some main semi-diurnal and diurnal components, they constantly evolve between quite different situations with semi monthly, monthly, semi annual, annual modulations, and even more, since the strict periodicity of the tides is 18,6 years. Such a complexity can however be described rather simply through the harmonic theory of tides.

THE HARMONIC THEORY OF TIDES. BACKGROUNDS

DOODSON (1921) was the first to give a full expansion of the tide generating potential in terms of harmonic series based on Brown's expansions of the Moon's parallax, longitude and latitude; these series have been recomputed by Cartwright and

Tayler (1971) and Cartwright and Edden (1973) with modern astronomical constants and greater accuracy. It appears from these expansions that the energy in the tidal spectrum is localised in four narrow bands, said "species": (0) long period, (1) diurnal, (2) semi-diurnal and (3) third diurnal. Some hundred terms are necessary in that harmonic expansion to define the potential to about 1% accuracy, but a few of them are practically important. Figure 1 is an illustration of the shape of that spectrum which indicates the location of the main constituents with their symbols originally allocated by Darwin (1883); the characteristics of these constituents are also presented on table 1.

Following the dynamic theory of tides, it can be assumed that, to each constituent of this generating potential, corresponds a wave in the ocean; consequently, the sea surface elevation due to tides in the ocean can be written as:

$$H(x,y,t) = H_0(x,y) + \sum_{i=1}^{N_p} f_i A_i(x,y) \cos[\omega_i t + (V_0+u)_i - g_i(x,y)] \quad (1)$$

$H_0(x,y)$ = mean sea level at point (x,y)

$A_i(x,y)$ = amplitude of the constituent i at point (x,y)

$g_i(x,y)$ = phase lag, related to the phase of the corresponding constituent in the tidal

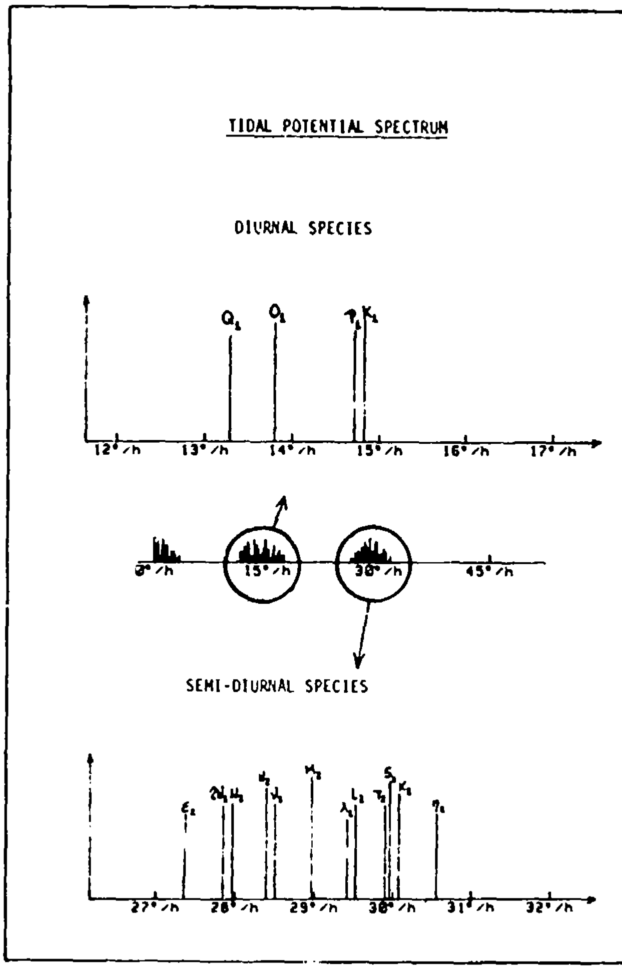

Figure 1. Tidal potential spectrum.

Table 1. Characteristics of the main tidal constituent potential.

	Name of partial tides	Symbol	Period in solar hours
Long-period components	Lunar fortnightly Lunar monthly	Mf Mm	327.86 661.30
Diurnal components	Principal lunar diurnal Luni-solar diurnal Large lunar elliptic Principal solar diurnal	O_1 K_1 Q_1 P_1	25.82 23.93 26.87 24.07
Semi-diurnal components	Principal lunar Principal solar Large lunar elliptic Luni-solar semi-diurnal Smaller lunar elliptic Variational Large lunar evectional Lunar elliptic second order Smaller lunar evectional Large solar elliptic	M_2 S_2 N_2 K_2 L_2 μ_2 ν_2 $2N_2$ λ_2 T_2	12.42 12.00 12.66 11.97 12.19 12.87 12.63 12.91 12.22 12.01

potential, the reference being taken on the Greenwich meridian.

v_{oi} = phase of that generating constituent at t = 0.

f_i and u_i = nodal correcting factor and nodal phase correction slowly varying with a basic period of 18.61 years.

N_P = number of significant constituents.

In shallow water areas, the development (1) can still be used, but new frequencies must be introduced in the spectrum, because of non linear effects governing the dynamic of propagation of the different astronomical tidal waves coming from the ocean. The frequencies of these non linear components are easy to deduce from the frequencies of their generating waves: they correspond to harmonics or interactions and are distributed in new species (quarter diurnal, sixth diurnal, ...) or superimposed to already existing astronomical species (long period, diurnal, semi diurnal, third diurnal).

Thus the harmonic theory of tides assumes that the variation of the sea surface elevation can be de-

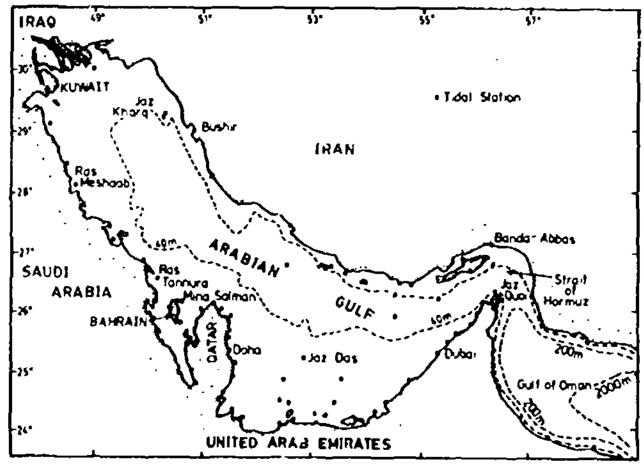

Figure 2. Location of observed tidal data.

veloped under a form similar to (1), with a number of constituents NR bigger than NP; the parameters A i (x,y) and gi (x,y) are typical parameters of the tidal spectrum at point (x,y), constant in time, and completely defining the time varying quantity H (x,y,t). Classicallly, these parameters Ai (x,y) and gi (x,y) are deduced from harmonic analysis of time series of *in situ* observations (notice that such analysis need long time series, because of the closeness of some frequencies). And the definition of

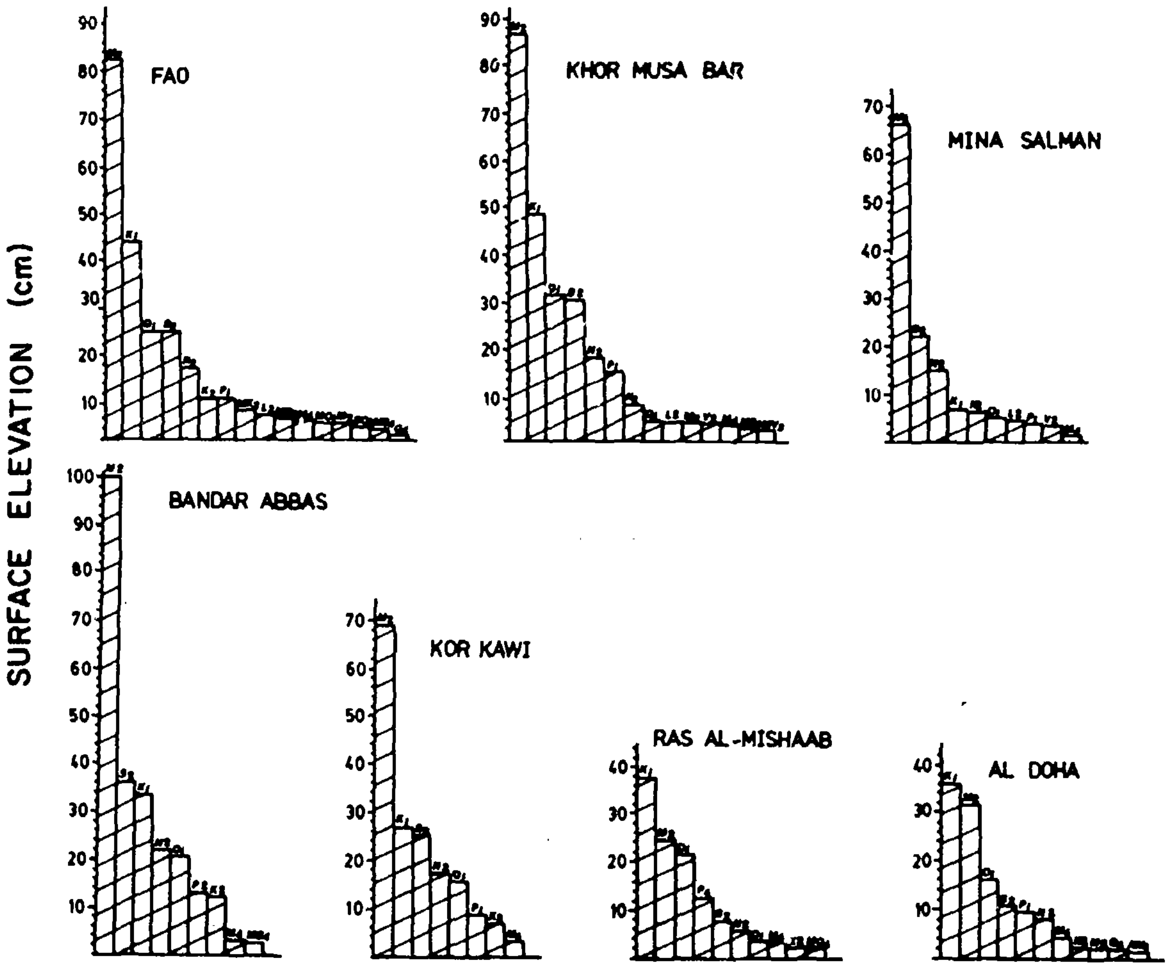

Figure 3. Observation points of maximum amplitude for the main tidal constituents.

A i and g i allows then the prediction of H (x,y,t) for any time t.

HARMONIC TIDAL DATA OVER THE KAP REGION

Tidal elevations have been rather well observed along the coasts of the Arabian Gulf. The locations where a set of harmonic constituents exists (B.H.I. source) are presented on Figure 2: more than fifty points can be noticed, which is quite sufficient to allow a correct knowledge of the tides over the area. The density of observation points is particularly high along the western coast of Saudi Arabia, Qatar and United Arab Emirates. On the otherhand, very little exists for the Gulf of Oman.

On figure 2, we can notice that the Arabian Gulf is a shallow area, with a deeper channel on the Iranian side, and that the Gulf of Oman is, on the contrary, very deep, with a continental shelf quite narrow, and depths greater than 2000 m in its eastern part. Consequently, we must expect that the tides in the Gulf of Oman are in fact part of the Indian Ocean cotidal system, and that in the Arabian Gulf, on the contrary, the tides are locally induced by the limits, i.e. the Strait of Hormuz.

The main tidal constituents

It is well known that the Arabian Gulf is a coastal area when the semi-diurnal and the diurnal tides can give rise to resonance oscillations; given its geometry (about 850 km long, and 250 km wide, and a mean depth of 50 m) Defant (1961) estimated that the free oscillation period of that basin is within 21,7 h and 22,6 h. And, effectively, important semi-diurnal and diurnal tides are observed. We have checked on Figure 3, and table 2, the maximum values of the main constituents observed along the coasts. The bigger values are located in the Strait of Hormuz (Bandar Abbas, and Khor Kani) and at the end of the Gulf (Fao, and Khor Musa Bar). Important semi-diurnal amplitudes are also observed in the vicinity of Bahrain. From the whole set of observed data, empirical cotidal charts have been produced for the main constituents by the Hydrographic Department of the British Admiralty: on Figure 4 the three dominant constituents M_2, S_2 and K_1 are presented. And we can observe that the semi-diurnal constituents present effectively areas of maxima in that three regions, resulting from a system of two amphidromic points, and the diurnal K1, one amphidromic point in the middle of the Gulf.

Such systems are well known, as Kelvin-Taylor amphidromes mathematically described by Taylor (1921) for co-oscillating waves in rectangular frictionless channels closed at one end, and situated in a rotating frame. In the Arabian Gulf, the energy is entering through the straight of

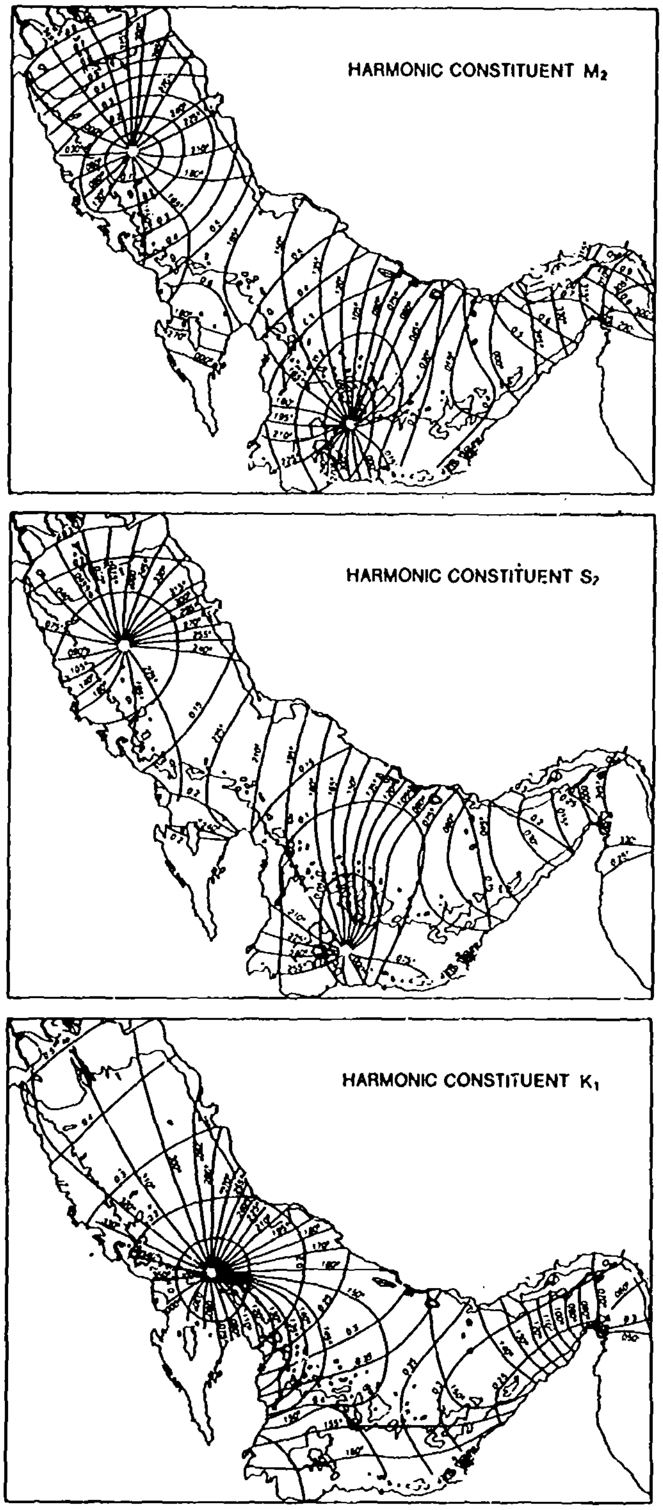

Figure 4. M_2, S_2 and K harmonic constituents (from British Admirality). g = time zone - 4, H in meters.

Hormuz and propagates for each constituent as a Kelvin wave sloping up towards the Iranian coast; these waves are reflected at the end of the Gulf, and come back along the other side of the channel; the resultant of these two opposite Kelvin waves forms a set of amphidromes with a first amphidromic point of zero amplitude at a quarter of a wave length from the end of the channel for each constituent. If the incident and reflected waves have the same amplitude, the amphidromic points are situated at mid distance from the two lateral coasts of the channel; but here, because of frictional damping, the outgoing wave is weaker, and the amphidromic points are consequently moved from the axis of the channel towards the Arabian coast.

The M_2 and S_2 cotidal charts presented on Figure 4 look very similar, and an evident question arises about the possibility of deducing the cotidal maps of any constituent from the knowledge of one of them in each species. And if possible, how to compute the ratio between them, and their phase lag? In table 2, these ratio and phase lags are given for all the significant constituents. For the semi-diurnal constituents, related to M2, we observed effectively quite constant ratio for the different noted points:

S_2/M_2 : 0.31 to 0.37
N_2/S_2 : 0.20 to 0.25
K_2/M_2 : 0.10 to 0.13
L_2/M_2 : 0.05 to 0.08
μ_2/M_2 : 0.02 to 0.07

$gS_2 - gM_2$ = 36° (at the entrance) to 62° (at the end)
$gN_2 - gM_2$ = - 18° (at the entrance) to - 34° (at the end)
$gK_2 - gM_2$ = 34° (at the entrance) to 50° (at the end)
$gL_2 - gM_2$ = 9° to 25°
$g\mu_2 - gM_2$ = 89° to 110°

These ratio are closed to those of the components of the tide generating potential, except for S2, because of the radiational contribution to the tides; similar values have been observed for the English Channel (Le Provost, 1974). The same observations can be made for the diurnal constituents, if related to K_1:

O_1/K_1 : 0.58 to 0.64
P_1/K_1 : 0.24 to 0.32
Q_1/K_1 : 0.07 - 0.10

$gO_1 - gK_1$ = - 3° (at the entrance) to - 47° (at the end)
$gP_1 - gK_1$ = 0° (at the entrance) to - 10° (at the end)
$gQ_1 - gK_1$ = - 51°, - 61°

the corresponding ratio for the tidal potential are quite similar for P_1, but bigger for O_1 and Q_1 because of the radiational contribution to K1 and P_1, which do not affect O_1 and Q_1.

The secondary constituents

We can notice on Figure 3 and table 2 that some significant non linear third diurnal and quarter diurnal constituents exist in the observed spectra.

It is difficult to conclude about the third diurnal non linear constituents, as significant amplitudes are observed only at the end of the Gulf, at Fao and Khor Musa Bar: they must result from non linear interactions between semi-diurnal and diurnal constituents: M_2 and K_1 = MK_3, M_2 and O_1 = MO_3, S_2 and O_1 = SO_3 (but why not SK_3?). If these interactions are real, one must take care of the non linear similar contribution to the diurnal constituents: M_2 and K_1 = O_1, M_2 and O_1 = K_1, S_2 and K_1 = P_1, which can perhaps explain the smallness of the O_1/K_1 and P_1/K_1 ratio at Fao.

Quarter diurnal probably exists in the Gulf, as the areas of maxima appear to be located in the areas of minimum of semi-diurnal amplitudes (except the end of the Gulf), as expected from the theory of non linear constituent generation (Le Provost, 1974). Significant amplitudes can be noticed at Ras Al-Mishaab and Al Doha. Moreover the amplitude ratio MS_4/M_4 seems quite constant, very close to the theoretical value $(2M_2 \cdot S_2)/M_2^2$ expected from the theory, and the phase lag equal to the one of the generating constituents $gS_2 - gM_2$.

All these secondary considerations are justified for precise predictions, because all the significant constituents have to be taken into account in the harmonic method. Moreover, higher order constituents can contribute to interprete the complexity of tidal currents, when differences are observed between ebb and flow.

CLASSIFICATION OF TIDAL TYPES

As we have just noticed, tides in the KAP region present typical semi-diurnal and diurnal amphidromes which must lead to various kind of tidal cycle, owing the location in the domain. Evans-Roberts (1979) has recently produced two maps for classification of tides, for elevations and currents, established from numerical simulations. We shall present later the numerical procedure used by E.R., but it is interesting to present here, on Figure 5, that classification, dividing the Arabian Gulf in areas when tides are either semi-diurnal $(M_2 + S_2) / (K_1 + O_1) < 0.5$, predominantly semi-diurnal (0.5 - 1.0), predominantly diurnal (1.0 - 1.5) and diurnal (>1.5). The diurnal character of the tide appears of course around the amphidromic points of the semi-diurnal cotidal maps. That classification is particularly interesting for the currents, as very little is known actually from observations about this essential parameter: in the limit of validity of the E.R. numerical results, it can be considered that diurnal characteristics for currents may arise in the central part of the Arabian Gulf; over an area where tidal elevations are semi-diurnal, and vice-versa for the semi-diurnal. This is evidently due to the amphidromic shape of these tides, where maximum amplitudes of currents are located in the areas of minimum of amplitude of sea surface elevations.

Table 2 : Maximum of amplitudes for the main constituents.
- Ratio/biggest amplitude in the species
and phase lag by reference to that biggest constituent -

SEMI-DIURNAL

	M_2		S_2		N_2		K_2		L_2		μ_2	
FAO	82.7	337°	25.3	39°	16.7	303°	10.7	27°	6.9	351°	5.6	87°
	Ratio/M2 phase lag		0.31	62°	0.20	- 34°	0.13	50°	0.08	140°	0.07	110°
KHOR MUSA BAB	86.9	313	31.3	13°	18.8	289°	9.2	9°	4.5	322°	4.3	52°
			0.36	60°	0.22	- 24°	0.11	56°	0.05	90°	0.05	99°
MINA SALMAN	66.1	152°	21.8	213°	14.7	121°	6.9	195°	4.6	177°	1.3	241°
			0.33	61°	0.22	29°	0.10	43°	0.07	25°	0.02	89°
KHOR KANI	68.9	309°	25.3	347°	17.4	286°	6.7	347°				
			0.37	38°	0.25	- 23°	0.10	38°				
BANDAR ABBAS	100.0	298°	36.0	334°	21.9	280°	10.4	332°				
			0.36	36°	0.22	- 18°	0.10	34°				
Tidal Potential			0.47		0.19		0.12		0.04		0.03	

DIURNAL / **QUARTER DIURNAL**

	K_1		O_1		P_1		Q_1		M_4		MS_4	
FAO	43.8	315°	25.4	268°	10.6	312°	3.1	264°	6.0	258°	4.3	326°
			0.58	-47°	0.24	- 3°	0.07	- 51°			0.7	+ 68°
KHOR MUSA BAB	49.5	301°	31.7	253°	15.8	291°	4.7	240°	3.8	172°	3.0	241°
			0.64	- 48°	0.32	- 10°	0.10	- 61			0.8	+ 69°
KHOR KANI	26.2	70°	15.8	67°	8.5	70°			2.7	182°	2.1	261°
			0.60	- 3°	0.32	0°					0.8	+ 79°
BANDAR ABBAS	33.8	64°	20.7	52°	11	62°			3.7	156°	3.0	246°
			0.61	- 12°	0.33	- 2°					0.8	+ 90°
Tidal Potential			0.71		0.33		0.14					
RAS AL-MISHAAB									4.0	16°	2.0	86°
											0.5	+ 70°
AL DOHA									4.5	166°	3.5	226°
											0.8	+ 60°

THIRD DIURNAL

	MK_3		MO_3		SO_3	
FAO	8.1	224°	6.3	187°	4.6	233°
KHOR MUSA BAB	2.8	159°	2.1	140°	2.5	259°

$\frac{A_{M_2} \; A_{S_2}}{A_{M_2}{}^2}$	$\simeq$ .07

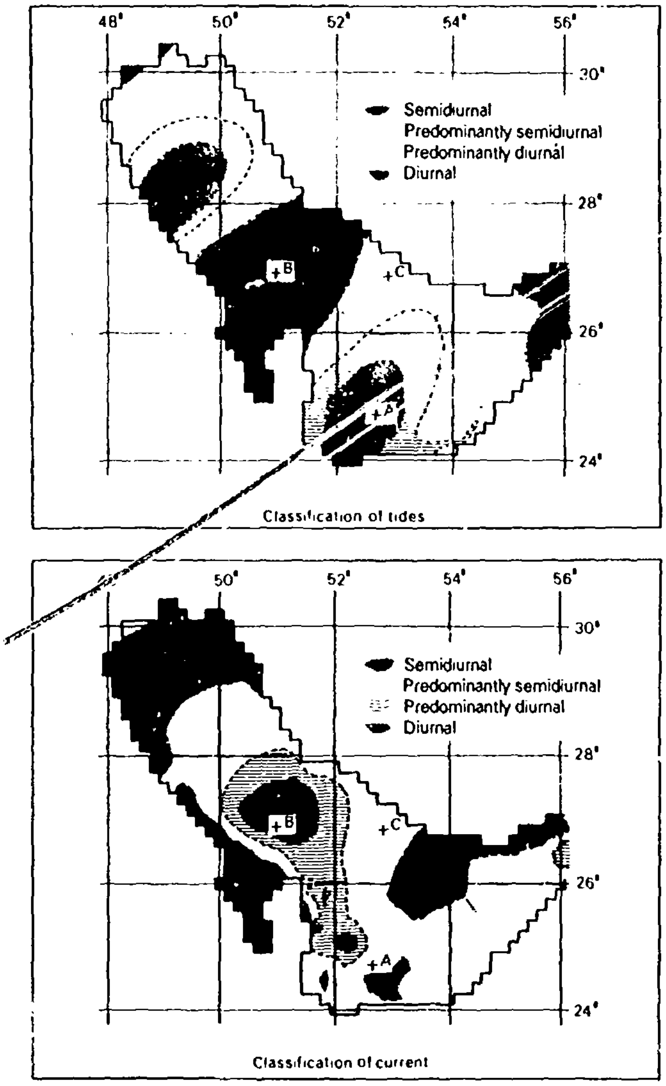

Figure 5. Classification of tidal types following Evans-Roberts (1979).

3. NUMERICAL MODELLING OF THE KAP REGION

During the last 20 years, in connection with the increase of computer facilities, numerical modelling of tides has been intensively developped and successfully applied to investigate tidal notions in many coastal areas. The number of such numerical models presented in the literature is enormous: even restricted to a particular area, a complete list of such models is difficult to achieve. In this paper devoted to the KAP region, we shall refer to three of the models developped for the Arabian Gulf: von Trepka (1968), Evans Roberts (1979), Lardner et al (1982), respectively noticed V.T., .E.R and LBC in the following; for the Gulf of Oman, it will be refered to one of the more recent ocean tide models published in the literature by Schwiderski (1979).

THE ARABIAN GULF

Equations and approximations in the formulation

The basic equations to any of these approachs, are the Navier-Stokes equations and the equation of continuity, written either in cartesian or polar coordinates, depending of the size of the domain investigated and the degree of approximation retained. But most of the tidal models practically used are restricted to an average version of these equations over the vertical, resulting from the so-called shallow water approximation, and reducing the problem to a two dimensional system involving u and v, the eastward and northward mean depth velocity components, and, the sea surface elevation :

$$\frac{\partial u}{\partial t} + \frac{u}{R\cos\phi}\frac{\partial u}{\partial \lambda} + \frac{v}{r}\frac{\partial u}{\partial \phi} - \frac{uv}{R}\tan\phi - 2\Omega\sin\phi\, v + Cu\,(u^2+v^2)^{\frac{1}{2}} + \frac{g}{R\cos\phi}\frac{\partial \zeta}{\partial \lambda} = \frac{g}{R\cos\phi}\frac{\partial P}{\partial \lambda} \qquad (2a)$$

$$\frac{\partial v}{\partial t} + \frac{u}{R\cos\phi}\frac{\partial v}{\partial \lambda} + \frac{v}{R}\frac{\partial v}{\partial \phi} + \frac{u^2}{R}\tan\phi + 2\,\Omega\sin\phi\, u + Cv\,(u^2+v^2)^{\frac{1}{2}} + \frac{g}{R}\frac{\partial \zeta}{\partial \phi} = \frac{g}{R}\frac{\partial P}{\partial \phi} \qquad (2b)$$

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R\cos\phi}\left(\frac{\partial}{\partial \lambda}(h+\zeta)u + \frac{\partial}{\partial \phi}(h+\zeta)\, v\cos\phi\right) = 0 \qquad (2c)$$

where we denote by

λ, ϕ = east longitude and latitude, respectively;

t = time;

ζ = elevation of the sea surface above the undisturbed level;

h = the undisturbed water depth;

R = the radius of the Earth;

Ω = the angular speed of the Earth's rotation;

g, the acceleration due to gravity;
u, v, eastward and northward mean depth components of current;
P, the generating tidal potential;
C, bottom friction coefficient.

In order to solve these equations, appropriate boundary conditions have to be specified along the boundaries. On any land boundary, the normal velocity component must be zero; along the open boundaries, the most appropriate boundary condition is to prescribe the flux of water, but such a condition is most of the time difficult to estimate, and it is easier to specify the sea surface elevation, deduced from observations at the coast.

Thus, the boundary conditions are generally of the form :

$$lu + mv = 0 \quad \text{on } \Gamma_1 \text{ (land boundary)} \qquad (3\ a)$$

$$\zeta = \zeta_0 \quad \text{on } \Gamma_2 \text{ (opon boundary)} \qquad (3\ b)$$

here (l, m) is the unit normal to the shore line, and ζ_0 is the prescribed values of the water height along the open boundary.

Some simplifications are applied to the system (2) for practical applications. For shallow water tides, the generating potential is generally neglected. For restricted areas, the equations (2) are written in cartesian coordinates, neglecting thus the earth curvature : this is the case for V.T. and LBC models, but not for E.R. who retains a spherical polar system; it must be noticed that, given the latitudinal extension of the Gulf, from 24° N to 30° N, it is better not to do that approximation. In order to save computational efforts, equations (2 a) and (2 b) are sometimes linearized; such a simplification is largely justified when the modelled area is not too shallow, and do not present important velocity gradients; V.T., following W. Hansen formulation (1956, 1962, 1966) used it, but the analysis of the data presented in section II has pointed out the existence of harmonic and interaction constituents in the spectrum which cannot be reproduced in the models if these non linear terms are excluded.

The bottom friction parametrisation is a very important factor for the efficiency of these models. Several laws are classically used, but they must all postulate at least a quadratic velocity dependance : thus, V.T. used a friction coefficient inversely proportional to the depth of the water column :

$C = r/(h+\zeta)$. In their model, LBC introduced a more complex formulation, following Leendertse (1967)

$$C = \rho g/k^2 \quad \text{with} \quad k = C_1 \ln (C_2 h + C_3)$$

where C_1, C2 and C3 are constant values depending on the nature of the bottom.

Finite difference approximations

The system (2) of differential equations is transformed into a set of finite difference equations for numerical integration. The precision of the numerical solutions depends of course of the properties of the finite difference scheme adopted.

V.T. used the well known Hansen scheme. LBC model is based on a splitted method developped by Leendertse which consists in dividing each time step into two half steps : during the first half time step equations (2 a) and (2 c) are solved to compute a new value of ζ and u, and the v new value is then computed from equation (2 b), using these new values of ζ and u. During the second half time step, the process is reversed.

With the finite difference technics, it is necessary to use constant grid spacing. As the size of the mesh greatly influences the precision of the results, it is often difficult to conciliate the fineness of the mesh size, with the volume of computational requirements. Regular mesh-size of 14 km was used by V.T. and of 10 minutes of latitude and longitude (approximately 9 by 10 nautical miles) by E.R. LBC developped a multi-block technic consisting of a relatively coarse mesh (approximatively 20 km) which covers the whole Gulf, including a secondary block of finer mesh (about 10 km) over the shallow coastal areas along the south-east, south-west and north-west shores.

Conditions of simulation and analysis of the results.
The LBC results

One of the main differences between the different simulations of V.T., LBC and E.R. is the way they have approximated the tidal forcing at the Strait of Hormutz. The simpler approach was done by LBC : they have studied separately the different constituents by forcing them at the open boundary. Starting from rest, they have carried on simulations during 75 hours of real time, considering that the dynamics has reached equilibrium after a spin up phase of about two days. They retained the last day of simulation to estimate the amplitudes and the phases of the simulated constituent all over the domain. They have thus produced cotidal maps for M2, S2 and K_1. We present on Figure 6 the charts of equal amplitudes for M2 and K_1. These maps must be compared to those presented earlier, based on extrapolations of observed values (Figure 4). Their solutions look quite good : the semi-diurnal tide exhibits two amphidromic points situated at the right place, and high tidal amplitudes at the entrance of the Gulf, in the region between Saudi Arabia, Qatar and the Iranian coast on the other side, and at the bottom of the Gulf; the diurnal tide presents a single amphidromic point correctly located, north of Bahrain, and large amplitudes at the bottom of the Gulf and off the eastern Qatar and Southern Emirates coast. However from a detailed analysis of the M2 solution, it appears that these amplitudes are too small in the central part of the Gulf, between Bahrain and the Iranian coast, by about 10%; the same remark arises for K_1 between Qatar and the Emirates coasts. One can think first that the bottom friction coefficient is not well adapted, and is too strong; but this argument is probably not the good one, because these cotidal charts are elsewhere in good agreement with the observations. In fact, we shall see later that the non linear damping interactions between M2 and

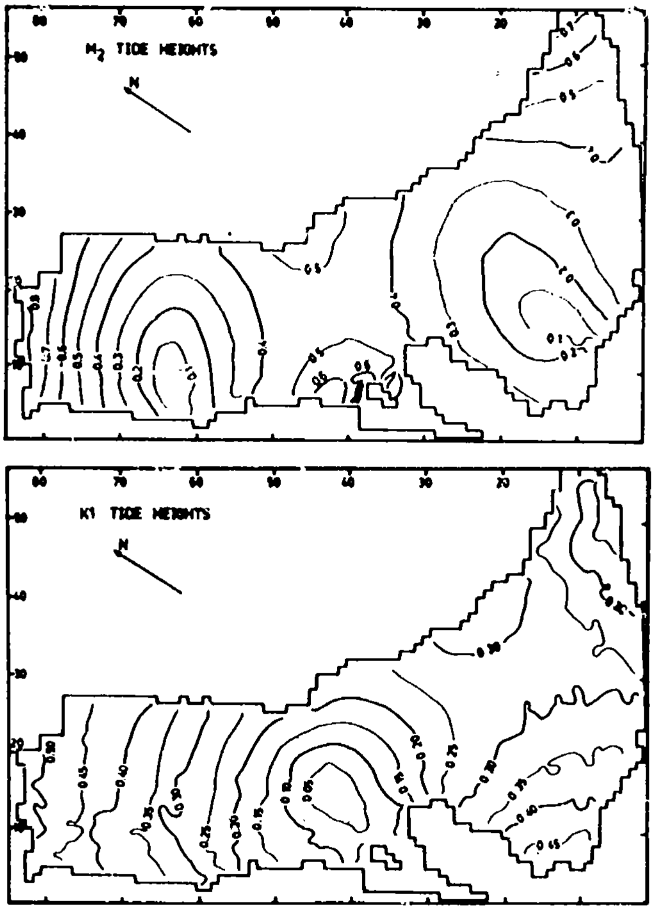

Figure 6. Amplitudes for M_2 and K_1 in meters simulated by Lardner et al (1982).

K1 cannot be neglected. The authors noticed also that their S_2 constituent, on the contrary, is too big; but it is here evident that a secondary wave like S_2 cannot be simulated alone : its damping is dominated by the velocity field of the dominant waves propagating together with it : at least M_2, but also probably K_1.

The V.T. results

V.T. has first investigated separately M_2 and K_1 . His M_2 solution is presented on Figure 7; globally, the amplitude seems to be better : in the central part of the basin, the solution is higher than for the LBC case, and the author noticed that even in the Bahrain area, with its complicated coastline and very shallow waters, his solution is very good. However, a careful examination of that solution shows that this M_2 wave is too strong all along the eastern coast of Qatar, and the southern coasts of Emirates : the discrepancies reach more than 20% in that area. And we come back to the same conclusion as precedently, about the impossibility of correctly representing even the dominant waves separately. V.T. itself arrived to that conclusion when trying to reproduce O_1 and S_2 : as for LBC simulations, the amplitudes of these waves were too big.

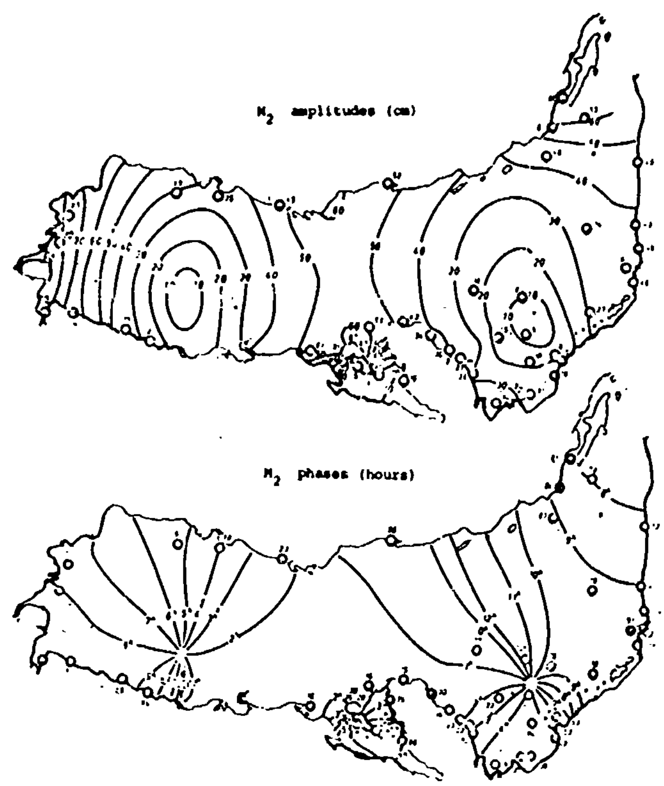

Figure 7. Amplitudes and phases for M_2 simulated by Von Trepka (1968).

In order to take into account the non linear interactions between the different constituents, V.T. realized an interesting experiment. He prescribed a real prediction of sea surface elevations at the entrance of his model, including seven constituents, during 40 days beginning on 5th August. To save computer time, a mesh size of 42 km was used. The results of that simulation were checked with the predictions of high and low water levels given in the tide tables. Typically, in Kuwait harbour, the differences in height were less than 10 cm, with a maximal difference of 36 cm; the mean deviation in time was about 20 minutes, and it was observed that these deviations were not cumulative. The author concludes that, with a finer grid net, and more than seven constituents, those difference would be reduced, and that harmonic analysis should then give the influence of tide-tide interactions. We shall come back to that idea in the last section of this paper.

The E.R. results

E.R. developped a low cost method to reproduce the $M_2 \cdot K_1$ interaction, by simulating the M_2 constituent together with an artificial diurnal tide (AM_1) having the amplitude and phase of K_1 but period exactly twice M_2. This produces a tide cycle which is repeated at intervals of 24.8 hours. The economy is evident : the main features of the tides can thus be studied without the need to generate and analyse vast quantities of results.

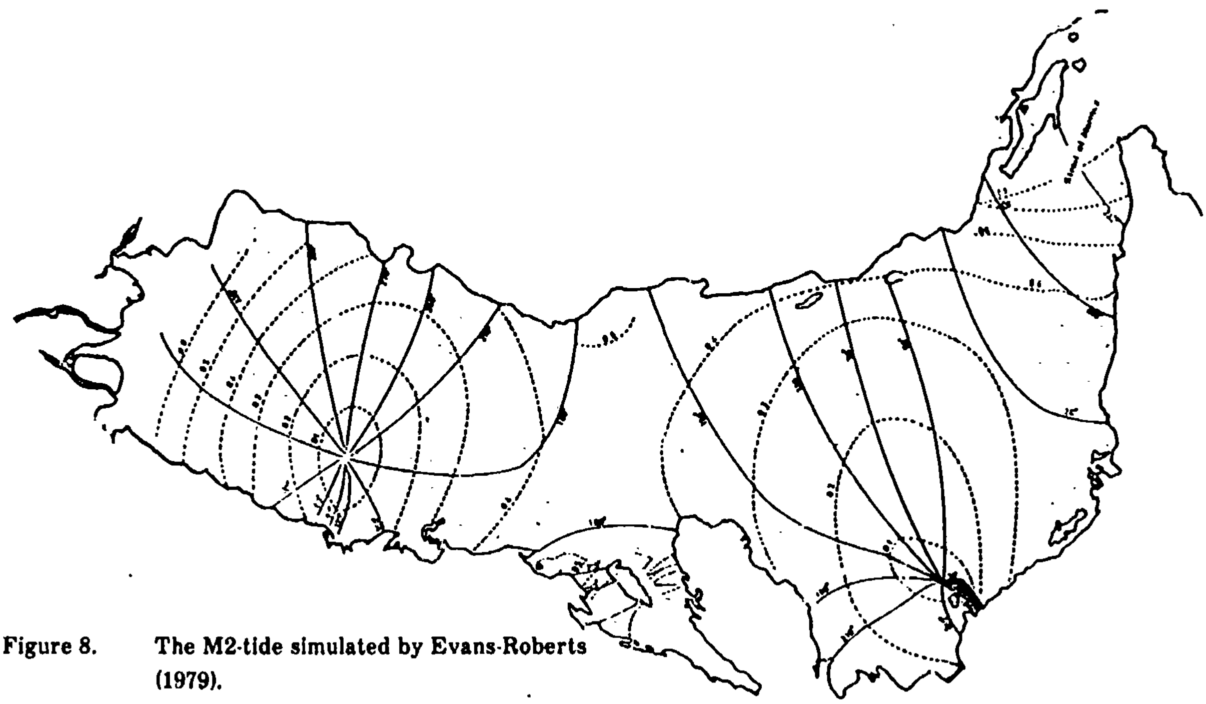

Figure 8. The M2-tide simulated by Evans-Roberts (1979).

However, that method do not allow to study the other constituents of the tides such as S2 and O1, or the non linear interaction that we have pointed out in section 2. The cotidal map of M2 produced by E.R. is presented of Figure 8. As noticed by the author, the amplitudes generated for M2 tended to be lower than those observed in situ, and those on the Admiralty co-tidal charts. This is a little surprising : is it due to the fairly coarse grid used? Here is one point which needs to be elucidated.

The velocity field

All these models produce also velocity fields corresponding to mean depth currents. But these informations are impossible to be checked because of the lack of observational data on tidal currents in the Gulf. However, similar models have been successfully applied throughout the world, and some confidence can be given to these results. As an example of what must be the currents in the Arabian Gulf, we present on Figure 9 a chart giving the magnitude and the direction of the maximum M2 velocity, obtained by V.T. We can notice that this field is quite complicated, and strongly influenced by the topography of the coast and of the sea bed. Typically, these mean velocities are of the order of 20 cm/s and do not exceed 0.4 m/s. But, as already noticed in section II.3, one must take care of the diurnal contribution which can produce diurnal currents in areas where semi-diurnal currents are weak, or alternatively increase and weaken these semi-diurnal velocity fields in particular areas.

LOCAL MODELS AROUND BAHRAIN

Because of the complexity of the topography around the Island of Bahrain, and its sensibility to environmental problems, local models have been developped for that region, which must be mentionned here, because of their practical importance.

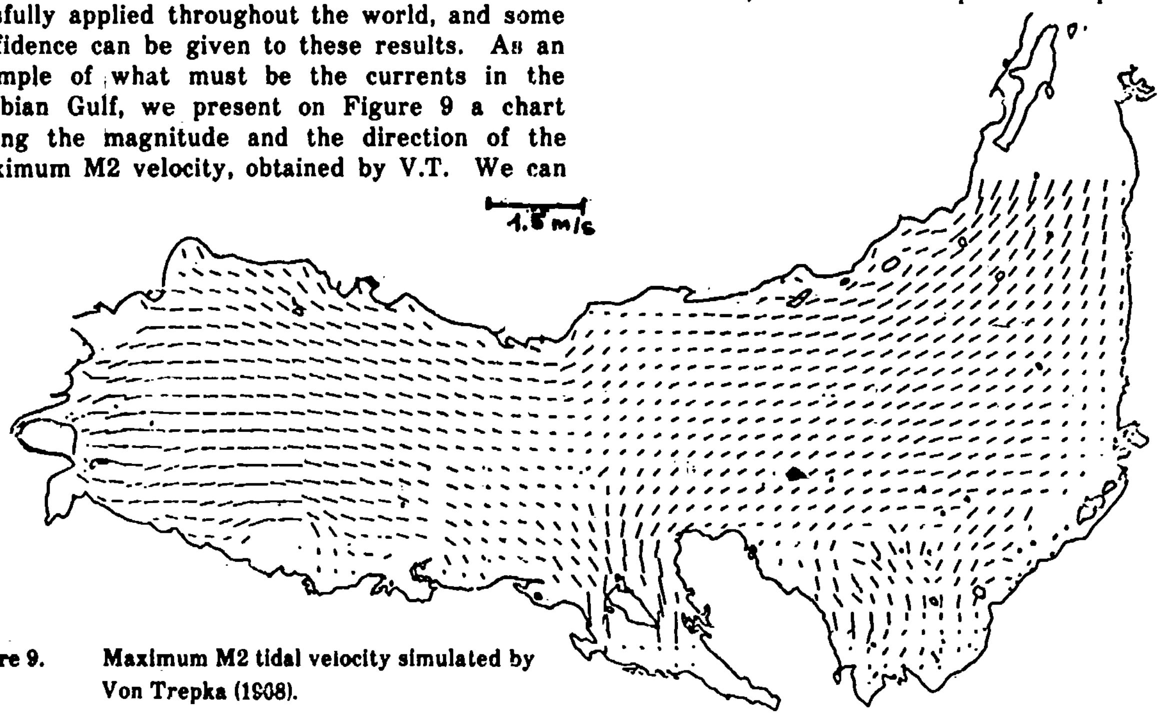

Figure 9. Maximum M2 tidal velocity simulated by Von Trepka (1968).

Danish Hydraulic Institute has developped four hydrodynamic models with successively finer grids focussing onto a particular studied area (Al Khobar in Saudi Arabia): a model of the Gulf, with 8 km grid, a secondary model (Dawhat Salwa) with a grid of 3 km, a regional model, between Bahrain and Saudi Arabia Coast, with a grid mesh of 740 m, and a local model going down to 247 m. Unfortunately, this system of models is not documented in the literature and it is thus impossible to analyse the corresponding results.

We present as illustration for this paragraph another example of local model produced by Lardner et al. (1982), as an extension of their multi block model precedently presented. This model covers the area between the Arabian coast south of Ras Tanura and the west coast of Qatar, see Figure 10. The grid mesh is here of 5 km. The simulated amplitudes for M2 and S2 are presented on Figure 10; if we compare these solutions with

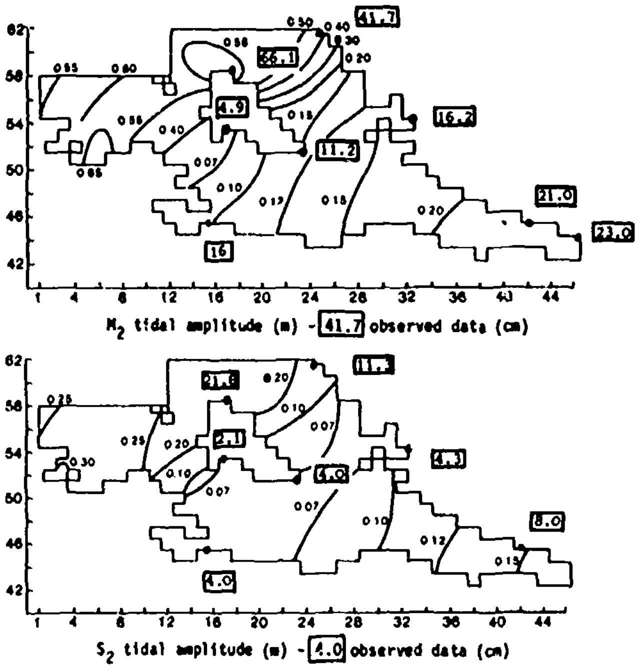

Figure 10. Example of local model. The Arabian Gulf between new coast of Qatar and the south of Ras Tanura with the Island of Bahrain (from Lardner et al., 1982).

observed data, we can see that the results are correctly representing the complex structure in that area.

THE GULF OF OMAN

As we have previously noticed, tides in the Gulf of Oman are of a different type, as that area is directly opened on the Indian Ocean, and the depth is important, more than 2000 m in its eastern part. Modelling, these tides are consequently depending of an other class of models, dealing with oceanic tides. As an example of this class of models, we can refer to Schwiderski (1979): these models generally include the tidal potential, the loading tide and the body tide; they compute the amplitudes and the phases of the main constituents of the tides over the globe as a whole: consequently, the space resolution of these models is very coarse. For Schwiderski, the resolution is of 1° x 1°: only a few number of values have thus be computed in our area of interest. The examination of these solutions in the Gulf of Oman brings to the conclusion that the tides must be quite homogeneous over all the area:

M_2 : amplitude varying from 63 cm to 72 cm
phase quasi constant : 160° TU

S_2 :	amplitude	: 22 cm to 24 cm
	phase	: 194° to 199° TU
K_1 :	amplitude	: 32 cm to 37 cm
	phase	: 339° to 348° TU

These values are fitting very well with in situ observations because Schwiderski model is conceived to adjust the computed solution to the data observed along the coasts.

4. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORKS

From the present review, tides in the Arabian Gulf and the Gulf of Oman appear to be rather well known and understood. Tidal elevations have been intensively observed along the coasts. And several models have been developped recently which give a quite satisfying overview all over the KAP area. However, some lack of observed data have been noticed, and some improvements are necessary in the modelling activities.

NEEDS FOR OBSERVATIONS

Long period observations taken offshore, such as from oil rigs would be interesting to enable more accurate co-tidal charts to be drawn. Some particular locations can be preferably recommended, such as in the middle of the Gulf, between Barhain Qatar and the Iranian Coast, to exactly evaluate the amplitude of the semi-diurnal constituents in that area of maximum values.

Of evidence, tidal currents need to be observed: as we have seen from model results, the intensity and the characteristics of that important physical parameter are very complicatly distributed over the region. With the help of these model results, it would be possible to choose a set of observation stations correctly distributed in order to precise our present knowledge and check the numerical solutions. It is important to have in mind that, given the complexity of the tidal spectrum, long-period of observations are needed, at least of the order of the month.

NEEDS FOR MODELLING IMPROVEMENTS

It clearly appears from the analysis of the different models presented that a more satisfying simulation needs to be done, combining all the positive properties of the previous models. An interesting framework would be as follows, if limited at least to a two dimensional classical model : that new model will be :

- formulated in spherical coordinates
- completely non linear, including the advective terms carefully treated in the finite difference scheme adopted
- applied with the highest possible space resolution
- driven along time in such a way that the non linear interactions between the main tidal constituents will be correctly reproduced.
- using improved bottom friction laws.

Such a simulation has been recently realized for the English Channel by Fornerino and Le Provost (1983 a). With a grid resolution of 10 km, a second order finite difference scheme and a simulation carried over a month including 22 constituents, a full synthesis of the tides over that area has been obtained, leading to a detailed description of all the significant tidal constituents fitting very well with the observations, in elevations and mean depth currents. And, based on these results, a model for prediction of tidal elevations and tidal currents have been developped, leading to very satisfying results. Comparisons with in situ observations, based on tidal gage data, or altimetric measurements from satellite for the sea surface variations, have confirmed the order of precision of the tidal elevation prediction model, within 15 cm for several meters of variability (up to 13 meters in the St. Malo Gulf), see Le Provost, (1981). Some comparisons with long period observations of tidal currents have shown that the model of tidal current prediction reproduce mean depth velocities with a mean square error of some 10 cm/s, for currents of the order of 1 or 2 m/s maximum amplitudes, see Fornerino and Le Provost, (1983 b).

These two dimensional models, however, are limited by their formulation for a better representation of the tidal flows, especially the vertical distribution of the velocity field. Three dimensional models are now available (see Davies, 1977). These models are more computer time consuming, and their simulation must probably be limited to some tidal cycles. It is consequently recommended to establish some combined project including long time simulations with 2D models, and shorter 3D simulations leading to a good knowledge of the vertical distribution of the tidal currents.

These global models will serve of course to provide boundary conditions for local models, which can be 3-dimensional, and of very fine resolution.

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A Review of the Residual Circulation and Mixing Processes in the Kuwait Action Plan Region, with Reference to Applicable Modelling Techniques.

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ABSTRACT

The available literature concerning the main aspects of the residual circulation and mixing processes in the KAP region is reviewed. Unfortunately, there are virtually no published reports of direct measurements of residual currents in the region, and estimates up until now have been based on the observations of ships' drifts and of the distribution of salinity, and on the modelling of the dynamics of the water movement. All three methods are prone to various errors, but it is shown that a reasonably consistent picture of the overall circulation pattern (an anti-clockwise density-driven flow, somewhat modified by the surface wind stress) can be obtained from them. It is noted that, whereas numerical hydrodynamic models have been very successful in accurately predicting tidal currents in the coastal sea areas of the World, their usefulness in predicting residual currents is rather limited - they are still primarily research tools, to be used with caution in conjunction with other techniques.

Estimates of the turn-over time (the time for all the water in the Gulf to come within the influence of the open sea boundary, at the Strait of Hormuz) and the flushing time (the time for all the water in the Gulf to be exchanged with water from the open sea) are made from our knowledge of the residual flow, from computations based on the water and salt balance of the basin and from our understanding of the physical processes operating in the region.

Applicable modelling techniques are reviewed, ranging from simple (but often very useful) single-box models to complex three-dimensional models of the momentum, water, heat and salt balance of the sea.

1. INTRODUCTION

The physical oceanography of the KAP region has been reviewed by Grasshoff (1976), Hughes and Hunter (1979), and Hunter (1982, 1983). More general reviews of the marine environment of the Region have been given by Hartmann et al (1971), Purser (1973), UNESCO (1976) and Kashfi (1979). A recent bibliography of the marine science of the Region has been given by Farmer and Docksey (1983).

It is evident that there are virtually no published direct measurements of residual currents (ie. the currents left behind after removal of tidal oscillations) or of mixing processes. The former could be obtained by a long (eg. one month) time series of observations using current meters or lagrangian drifters, while the latter could be obtained using a dissolved tracer such as dye. We hence have to resort to indirect methods, such as the analysis of the drifts of ships at sea, or of "conventional" oceanographic variables (such as temperature and salinity), in order to investigate these phenomena.

Our understanding of the physical processes at work in the sea may be furthered through the use of modelling techniques. These may range from simple equations defining, say, a one-box flushing model, to complex three-dimensional models of the momentum, water, heat and salt balance of the sea. The latter may at present be implemented only on the largest of modern computers. Modelling enables us to combine our present (limited) knowledge of mechanisms with observational data, and to give fresh insight into the relevant processes, or to predict observable parameters not previously measured. A particularly successful example has been in the use of vertically-averaged numerical hydrodynamic models to predict tidal elevations and currents in shelf seas. The physical processes which determine such tidal motions have been quite well understood for a long time, and there are also numerous records of tidal elevations from ports around the coasts. We are, however rather deficient in observations of offshore tidal elevations and currents in many shelf sea areas of the World, and numerical tidal models have served as useful, and verifiable, tools for the prediction of these variables from the data that we do have. Models are hence used in this way as "intelligent" (ie. they include information concerning our understanding of mechanisms at work in the sea) interpolators or observations that are sparse, in the sense that they come mainly from the coasts rather than from offshore areas. There have been three quite successful models of the tidal motions in the Region (von Trepka, 1968 and Evans-Roberts, 1979, Lardner et al, 1982).

Vertically-averaged hydrodynamic models of the type used to predict tidal motions have been used extensively in attempts to predict residual currents in shelf seas. While they have been quite successful in predicting "surge" events (ie. strong time-varying motions of time scales of order a few days, associated with moving meteorological systems) (eg. Davies and Flather, 1977), they have really been quite unsuccessful in predicting longer term variations of the residual currents.

There have been few attempts to model either residual currents or mixing processes in the Region.

2. OBSERVATIONS OF THE RESIDUAL CIRCULATION OF THE REGION

It has been known for a long time that evaporation exceeds precipitation in the Gulf, and so it would be expected that the more saline dense water would sink and pass out of the Strait of Hormuz, giving rise to a compensating surface flow of less dense water into the Gulf. The effect of the Earth's rotation would be to deflect these flows to the right, giving a surface flow West and North West along the Iranian coast, and a deep flow to the South East and East along the coasts of Saudi Arabia and the United Arab Emirates (the deep flow would be further contrained to these latter coastlines as it is in these regions that the shallow sea areas of high evaporation lie). This circulation pattern would undoubtedly be modified by forcing by wind and atmospheric pressure, but it has been generally supported by observations of drifts of ships at sea.

Evidence for this anti-clockwise residual circulation in the Gulf, driven predominantly by evaporation (giving rise to horizontal density and pressure gradients) has been described by Schott (1918), Barlow (1932a, 1932b, 1932c), the British Admiralty (1941), Emery (1956), Sugden (1963), Hartman et al (1971), Szekielda et al (1972), Purser and Seibold (1973), Grasshoff (1976), Szekielda (1976) and Brewer et al (1978).

Szekielda et al (1972) and Szekielda (1976) reported that data from ships' drifts indicated two separate anti-clockwise circulations, one in the Northern part of the Gulf and one in the Southern part. However, an analysis of all the ship drift data collected by the British Meteorological Office up to 1981 (Hunter, 1982) does not support this view. This latter data consisted of 1806 observations distributed over 28 "one degree" (latitude and longitude) squares, divided up both by month and by season. Simple statistical tests were applied to indicate if the vector average for a given "one degree" square represented a significant residual flow - if not, then that data set was rejected (this would not necessarily mean that the residual

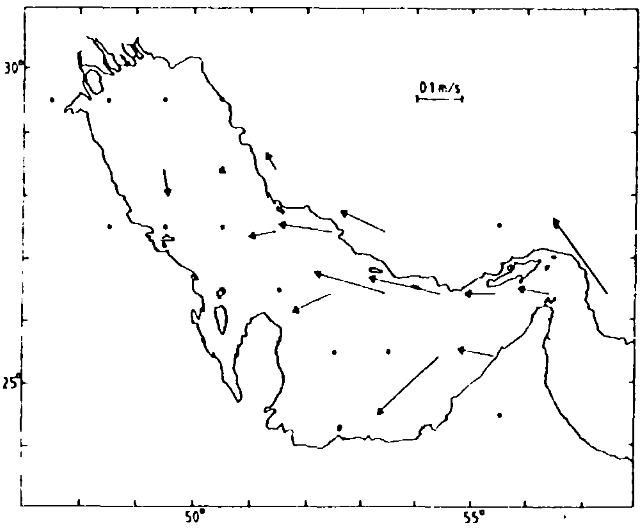

Figure 1. Selected ship drift data for whole year (after Hunter, 1982).

at that square was small, but rather that the variability was too large for a constant residual to be detectable). Figure 1 shows the resultant data for the whole year (reproduced from Hunter (1982)), after statistical selection (vector "tails" are centred on each "one degree" square, and a "o" indicates the centre of a square where the observed residual was not statistically significant). These vectors show considerably less spatial variability than the raw data (ie. including every observed drift), and generally indicate a surface flow Westwards into the Gulf along the Iranian coast (of magnitude about 0.1 m/s). There is also the suggestion of an anticlockwise circulation. The analysis was also carried out for the four seasons. The results did not differ markedly from those for the whole year, except that less "one degree" squares were accepted (since there were, on average, less observations per square), and the Westward flow into the Gulf appeared strongest in summer (about 0.2 m/s) and weakest in spring and autumn (about 0.1 m/s), and there was little evidence of an anti-clockwise circulation (ie. no Eastward return flow was present).

Current estimates based on ship drift observations may be subject to a number of errors (HMSO, 1977), one of the main ones being due to the ship's windage, tending to bias estimates in the direction of the prevailing wind if sufficient allowance is not made for this factor. However, the prevailing wind in the Gulf is from the North West and West (IMCOS, 1974) in opposition to the dominant inferred flow. It would hence appear that the ship drift observations are an indicator of the "long term" circulation pattern, namely a surface inflow towards the West along the Iranian coast, of strength between 0.1 and 0.2 m/s (strongest in summer). There is, unfortunately, little data on the currents in the South and South West regions of the Gulf, due to the absence of ships' observations in these areas.

The North Western part of the Gulf is undoubtedly influenced by the fresh water inflow of the Tigris, the Euphrates and the Karun (entering the Gulf via the Shatt Al-Arab). This inflow appears to be deflected to the right by Coriolis force to form a river plume of width approximately 20 km, flowing along the Iraqui coast into Kuwait waters (Mathews et al, 1979). This phenomenon is also indicated by observations at a somewhat larger scale by Dubach (1964) and Brewer et al (1978).

The inflow of water from the Gulf of Oman, near the Iranian Coast, and conditions in the Strait of Hormuz have been observed by Sonu (1979). In the Strait of Hormuz, the inflow was estimated to occupy the top 30 m of the water column, a mixing layer the middle 20 m and the outflow the bottom 30 m. Current observations were made from on board ship, near Kish Island, off the Iranian coast, but no effort was made to remove the tidal oscillations (which probably exceed the residual flow in this area), or even to report at what time in the tidal cycle the observations were made.

The deep saline outflow of water from the Strait of Hormuz into the Gulf of Oman has been observed by Sewell (1934a, 1934b), Emery (1956), Duing and Koske (1967), Duing and Schwill (1967) and Leveau and Szekielda (1968). Unfortunately, the time of year during which the observations were made is not clear from some of these reports. However, it appears that a tongue of saline water flows out of the Strait of Hormuz at a depth of about 100 metres, sinks to about 200 metres in the Gulf of Oman and finally sinks to about 500 metres in the South Arabian Sea. Duing and Koske (1967) reported a seasonal variation in the Northern parts of the Arabian Sea (and hence probably in the Gulf of Oman). Sewell (1934a) described a second tongue of saline water passing out of the Gulf of Oman from the surface to about 50 m depth (it is believed that these observations were made in the winter).

The residual circulation in the Gulf of Oman (and indeed in the Southern part of the Gulf) is undoubtedly influenced by the seasonal effect of the South West and North East monsoon. It has long been realised that these give rise to a seasonal reversal of currents in the North Indian Ocean (Warren, 1966) - the currents being generally to the West during the North East monsoon (winter) and to the East during the South West monsoon (summer). The surface currents observed from ship drifts in the Gulf of Oman do not appear to show a consistent seasonal pattern. Barlow (1932a) reported observations up until that time which indicated a surface outflow in the Gulf of Oman during the winter, and a surface inflow in the summer. Barlow (1932b, 1932c) then described later observations that indicated an outflow in the Gulf of Oman in the summer as well. Barlow also described the interesting phenomenon that between February and April the "South West monsoon" type of circulation is established in the Arabian Sea while the North East monsoon is still blowing. The current Admiralty Pilot (the British Admiralty, 1967) indicates, in winter, an inflow along the Northern coast of the Gulf of Oman and an outflow to the South of this, with a reversal of this situation in summer.

Published accounts of direct observations of currents in the Region are few. The observations of Sonu (1979) have been referred to above. British Admiralty charts report a few observations in the form of tidal stream "diamonds", but these are based on records of generally short duration, and the residual flow has usually been removed from the data before presentation. Peery (1965) probably gave the most complete set of direct current observations in the Region, but these were based on record durations of 3 days or less, and were made from on board an anchored ship. These results were hence probably contaminated by ship movement, and would not anyway be representative of any long-term residual flow. They do however serve as a useful data set, to be used with numerical model results, as indicators of tidal currents in the Region. Dubach and Wehe (1959) reported observations in Kuwait harbour, but these are only indicative of tidal flows.

There have undoubtedly been many observations taken by moored recording current meters in the Region, as part of commercial survey programmes. These data sets are difficult to obtain partly for the reason that they are presented only in the form of internal reports, and partly for reasons of confidentiality. Many of these would have been recorded in coastal regions and would hence not be of great value in indicating the overall features of the residual circulation in the Region.

3. SIMPLE MODELS OF THE RESIDUAL CIRCULATION

It would appear that the dominant forcing mechanism for residual currents in the Gulf is through pressure gradients arising from evaporation-induced density variations. Horizontal variations in water density give rise to horizontal pressure forces which vary with depth. These lead to vertically varying horizontal water velocities, which balance the density forces by the following mechanisms:

(1) By internal friction (ie. turbulent stresses).

(2) By a Coriolis force at right angles to the water flow.

Superimposed on the depth-varying currents may also be a baratropic flow balanced by a surface slope and Coriolis force, and a bottom Ekman layer (which probably exists in the Gulf, as the "Ekman depth" is in many places less than the water depth (Hunter, 1982)).

A technique used by the deep-sea oceanographer is to assume that between the surface and bottom Ekman layer (the former caused by the wind stress) - this is the bulk of the ocean - the dominant process determining the vertical variations in horizontal velocity is a balance between density forcing and Coriolis accelerations (mechanism (2)). This leads to the well-known geostrophic computation, which allows the oceanographer to determine velocity variations from estimates of sea water density made over two adjacent vertical profiles. Hunter (1982) considered four vertical density profiles on a transverse oceanographic section in the Southern part of the Gulf, reported by Brewer et al (1978), and performed geostrophic computations for two pairs of these profiles. He showed that the density structure was consistent with a velocity difference from surface to bottom of between 0.1 and 0.2 m/s. As the density data were recorded in the winter, this result is in approximate agreement with the estimate of surface inflow obtained from ship drift data (Hunter, 1982). Hence it would appear that (in winter at least) the the inflow and outflow passing along the axis of the Gulf is *geostrophically balanced (ie. balanced by Coriolis force)* *across the channel*. It is probable that similar agreement would be found for geostrophic computations carried out on data collected in the summer (the only comprehensive set of summer oceanographic data is due to Emery (1956), who unfortunately gave little density information).

However, if we postulate that the Coriolis force *at right-angles* to the current is balanced by pressure forces due to density variations and surface slopes, we must also satisfy a force balance *parallel* to the flow. Internal friction in the fluid due to vertical shears in the horizontal velocity must *also* be balanced by density and surface slope driven pressure forces. Unfortunately, our present understanding of the internal "viscous" stresses due to turbulence in a stratified fluid is poor, and it is difficult to make reliable predictions of the "estuarine-type" circulation due to this balance of forces. Hence Hughes and Hunter (1979) concluded that the density-induced forces would not be sufficient to sustain the observed circulation pattern, while subsequent computations of Hunter (1982) indicated that they would.

On the basis of a geostrophic force balance across the Gulf, and a frictional balance along the Gulf, Hunter (1982) indicated the circulation schematically by the diagram shown in Figure 2. Eva-

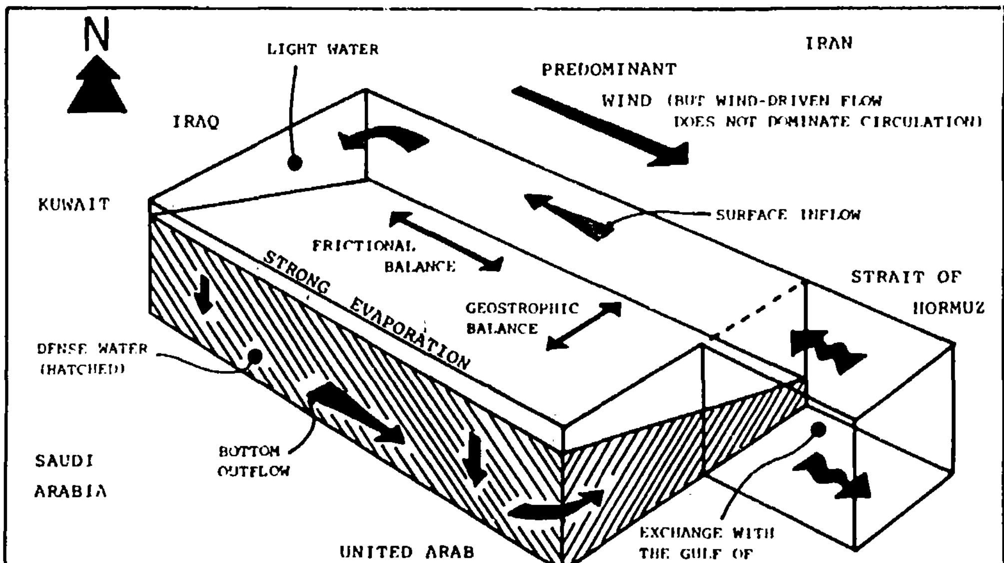

Figure 2. The probable circulation pattern in the Gulf (after Hunter, 1982).

poration in the shallow areas of the South Western and Southern Gulf lead to a sinking of dense water, that is deflected to the right by Coriolis force, to flow out at the bottom of the Strait of Hormuz. This flow is compensated by a surface inflow along the Iranian coast. This circulation will be modified by the effect of surface wind stress, especially in shallow areas where the effect of density forcing will be small.

4. A NUMERICAL MODEL OF THE RESIDUAL CIRCULATION

It is clear that the circulation of the Region is complex and three-dimensional. The only numerical three-dimensional model of the overall residual currents in the Region, known to the author, is that due to Hunter (1983). The model was used to to simulate the steady-state response of the Gulf to a specified density distribution (derived from the winter observations of Brewer et al (1978)) and a uniform wind stress. Specific features of the model were:

(a) The computation was on a flat Earth, using the beta-plane approximation and variable topography.

(b) The equations were time-dependant and linearised, with the damping effect of the tides included through appropriate bottom friction.

(c) "Sigma coordinates" were used in the vertical (ie. the vertical axis wrs scaled by the local depth).

(d) A quadratic law was used to relate wind stress to wind velocity.

(e) A fixed sea level was prescribed at the open boundary.

(f) The density data was not subject to modification by the model.

(g) The vertical eddy viscosity and linear bottom friction coefficient were "best guesses" from the available data, and were not "tuned" to obtain optimum model results.

(h) The model mesh consisted of 331 cells in the horizontal, each divided into 5 levels.

(i) The model was run to "steady state" (for the internal velocity field), which took about 23 days.

(j) Two model runs were implemented - one for the case of no wind, and one for the case of a typical wind.

Figure 3 shows the predicted surface and bottom currents under conditions of a 5 m/s wind from the North West (a typical wind for the Gulf). "Noise" present in the predicted velocities was attributed to the use of relatively sparse density data collected over a period of only one month. The predictions indicate a surface inflow of strength around 0.1 m/s along the Iranian coast, some evidence of river inflow at the North Western end of the Gulf, and an outflow of water along the bottom from the coastal areas off Saudi Arabia, Qatar and the United Arab Emirates. The wind stress generates clear Ekman rotation and a surface inflow into the region North of the United Arab Emirates.

5. MIXING PROCESSES IN THE REGION

Mixing processes in the Gulf were reviewed by Hughes and Hunter (1979). They showed, from simple analyses of the limited oceanographic data available that:

(a) The time to obtain 90% mixing of a contaminant over a water column in the Gulf would be around 16 days (longer in summer, due to the presence of vertical thermal density stratification, inhibiting mixing).

(b) Exchange of water in the horizontal direction is dominated by the residual circulation. In some sea areas of the World vertical mixing can interact with vertical shears in the tidal currents, but this is not an important mechanism in the Gulf. Horizontal turbulence is also not an important contributor to the transport processes.

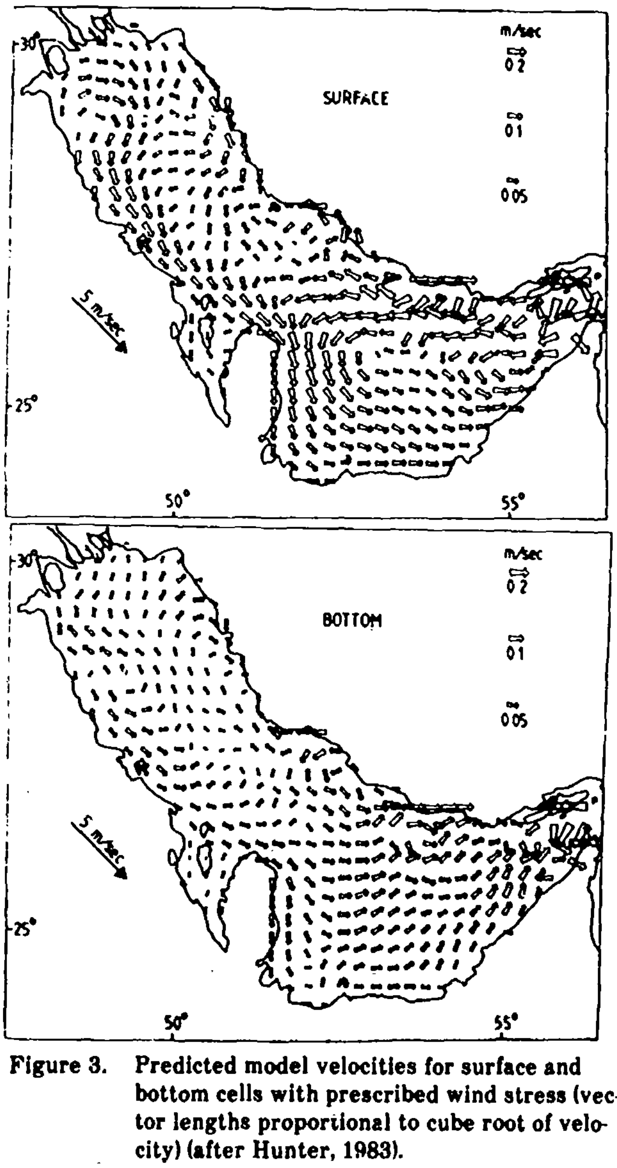

Figure 3. Predicted model velocities for surface and bottom cells with prescribed wind stress (vector lengths proportional to cube root of velocity) (after Hunter, 1983).

Two time scales may be defined for a basin such as the Gulf, in relation to the overall mixing processes :

(A) THE TURN-OVER TIME

This is the time for all the water in the basin to come within the influence of the open sea boundary. Consider a basin of volume, "V", and a surface current of total transport, "Q" flowing parallel to the basin axis. By continuity, this transport must be balanced by a return flow somewhere else in the basin cross-section. If there is no exchange of water with the open sea, and if the flow, "Q", is the dominant process "turning over" the basin, then we may define the turn-over time by : V / Q

From flow estimates from ship drift data, a typical current in the surface inflow is about 0.1 m/s (allowing for a somewhat reduced current near the head of the Gulf). If this current acts across half the average cross-sectional area of the Gulf, "A", then the transport, "Q", is defined by :

$Q = 0.1\ A / 2$

and the turn-over time is :

$2\ V / (0.1\ A) = 20 \times$ (length of Gulf in metres)

From Emery (1956), the length of the Gulf is 990 km, giving a turn-over time of 230 days. This estimate is however modified by vertical mixing processes, which effectively "short circuit" the flushing circulation described above, and increases the estimated turn-over time to about 2.4 years (Hughes and Hunter, 1979).

(B) THE FLUSHING TIME

This is the time for all the water in the basin to be exchanged with water from the open sea. This must clearly be longer than the turn-over time. The flushing time may be estimated by considering the conservation of water and salt, and the evaporation rate over the sea surface. Koske (1972), assuming the exchange in the Strait of Hormuz was due to shear flow, thus derived a flushing time of 3 years (at the same time, he deduced an outflow velocity of about 0.1 m/s for the bottom water in the Strait). Using a somewhat similar approach, but a less restrictive model of the exchange in the Strait, Hughes and Hunter (1979) derived a time for 90% flushing of 5.5 years.

As the spatial scales of the Gulf and the Gulf of Oman are so very different (their typical depths differ by an order of magnitude), the two areas must be considered as distinct oceanographic regimes, joined by the Strait of Hormuz. The Gulf is a shallow "inverted estuary" where tidal currents and wind effects exert an important influence (the latter especially in shallow areas) on circulation and mixing processes. Exchange of dissolved contaminants within the Gulf can be understood as a process of horizontal redistribution by residual currents, and vertical redistribution by turbulence (both processes being modified by the presence of vertical density stratification, which is strong in the summer). The time scales involved are of order tens of days for vertical mixing, and years for horizontal "turn over". Exchange between the Gulf and the Gulf of Oman does not appear to offer an overiding constraint on the total flushing of the Gulf, as estimates of the flushing time are not much larger than the estimate of the "turn-over" time - indeed, our estimates are clearly subject to quite large errors and it is probable that present evidence does not suggest any significant difference between the flushing time and the "turn-over" time. It is unlikely that the Gulf of Oman imposes any significant restriction on the flushing of the Gulf as it is basically an extension of the Arabian Sea (which itself forms part of the North Indian Ocean) - the majority of the Gulf of Oman is deeper than 1000 m and as wide as the Gulf.

The above estimates of turn-over and flushing of the Region relate only to gross features of a contaminant distribution, *once it has been transported significantly away from the shore.* There will, of course, also be local problems of removal of effluent (say, from small embayments, or from coastal discharges at places where the local currents are weak). This short review of mixing processes only relates to the exchange processes acting on "large-scale" (ie. of order the size of the sea basins involved) distributions of dissolved substances.

Contaminants that are predominantly associated with the sea surface (eg. floating oil) must also be considered separately. Advective processes at the air-sea interface are generally stronger than elsewhere (as a rule-of-thumb, floating substances travel at about 3% of the wind speed (typically .15 m/s in the Gulf), relative to the underlying water (ie. of order 10 m below the surface)). Further, a floating effluent is not subject to vertical mixing processes, so a "turn-over" time (in the absence of wind) of around 200 days would be appropriate.

6. RECOMMENDATIONS FOR MODELLING OF THE RESIDUAL CIRCULATION AND MIXING PROCESSES IN THE REGION

There can be no single model that will serve as a predictor of any required oceanographic parameter at all length and time scales over the whole Region. What is required is a suite of models varying from the very simple (eg. single-box models) to the very complex (eg. three-dimensional numerical models), covering different requirements (eg. some modelling the hydrodynamics only, others modelling flushing processes) and different spatial and temporal scales (e.g. some modelling local coastal processes, others modelling the gross features of exchange in the Region). For certain applications, it is not possible to divide up the effort into a number of discrete models, due to the interactions between oceanographic variables - for instance, the residual circulation of the Gulf can only be modelled successfully by considering the balances of momentum, water and salt, and we cannot omit any of these three components from the computations. However, it should be taken as a general rule that it is more computationally efficient to model separately those variables that do not "mutually" interact - by the latter term we include variables that interact in one direction only (eg. momentum and a passive contaminant, as the former affects the latter by advection and diffusion processes, but the latter does not affect the former), but not variables that interact in both directions (eg. momentum and salinity, as salinity also affects momentum through variations in density and hence in the generation of stable vertical stratifications, and of horizontal pressure forces).

The basic requirements for a model of the residual circulation of the Region are :

(a) The model should be three-dimensional if it is to adequately predict observed features of the circulation. It is however possible that models of less dimensions may be sufficient in certain local areas (eg. two-dimensional (in plan) models may be capable of describing the circulation in shallow areas, although applications of these types of models in other areas of the World have not been particularly successful).

(b) The model should include the effects of density and wind forcing, both of which are important in determining the circulation pattern. The former may be defined from observational data (eg. the model of Hunter (1983)), but for predictive purposes (rather than simply for use as a tool to understand the physical processes at work) it is preferable that the density distribution be a modelled variable.

(c) The model should include the effect of bottom friction, as the Gulf is effectively a shallow sea area, where bottom currents are a significant part of the total circulation.

(d) The model should include the effect of surface evaporation, runoff and precipitation.

The requirements described above correspond closely with three dimensional estuary-type models (with the inclusion of surface evaporation, which is quite simple). It may be thought that they also correspond with models of the deep ocean, but these generally use the "rigid lid" approximation, and ignore bottom friction (eg. Semtner, 1974).

Models of mixing processes in the Region may be based on the diffusion and advection schemes used in hydrodynamic models. However, many of these schemes lead to numerically-induced diffusion. An alternative is the use of particle-tracking techniques, utilising a random-walk method to simulate diffusion (eg. Bork and Maier-Reimer, 1977). These latter models are at their most computationally efficient when the contaminant exists as a relatively small patch in a larger sea area - they have hence been used successfully in oil slick modelling (eg. Ahlstrom, 1975, Hunter, 1980). When the contaminant covers the whole sea area (such as is the case with salinity), this technique is, however, rather inefficient.

An example of a simple single-box model has been given in the calculations of the flushing time of the Gulf earlier in this paper. Another quite successfull simple model is the cross-sectionally averaged one-dimensional model used to predict water quality variables such as biological oxygen demand and dissolved oxygen in an estuary (eg. Stommel, 1953, Tracor, 1971). These models are often time-averaged over a tidal cycle, and hence derive their advection velocity from the fresh water flow (in the case of the Gulf, this would be equivalent to the evaporation rate). The longitudinal diffusion coefficient (which describes many processes such as turbulence, and the interaction of this with the lateral and vertical shears in both the tidal and the mean flow) is generally obtained from observation of the salinity distribution in the estuary - this is probably the reason for the success of these highly parameterised models, in that they are very closely tied in with experimental data from the region under consideration.

Other simple yet successful models are those describing the nearfield plumes of buoyant effluent such as those due to outfalls of sewage, or the cooling water from thermal power stations. There exist a number of analytic and similarity solutions of both the two - and three dimensional problem, based on a mixture of theoretical reasoning and empirical results. The complexity of calculations required for these solutions range from the very simple to relatively uncomplicated numerical integration of a series of differential equations. These types of model have been reviewed by Agg (1978), Macqueen (1978) and Fisher et al (1979).

7. RECOMMENDATIONS FOR ASSOCIATED COLLECTION OF OBSERVATIONAL DATA

It is clear that there is a great lack of published observations of conventional oceanographic data, of current velocity data and of any mixing experiments (eg. using tracers such as dye to indicate factors such as the vertical mixing time for the water column) in the Region. There must exist a considerable quantity of such data that has been collected as part of the industrial development and oil exploitation in the area. It is considered imperative that a concerted effort be made to obtain this information by consultation with both the survey companies (who collected the data) and the clients (who commissioned the data collection). To the author's knowledge, there at present exist year-long records of current meter observations from the deep-water areas of the Gulf - an analysis of these would prove invaluable in furthering our understanding of the circulation processes. It will only be when a thorough inventory of such data has been made that it will be reasonable to plan any future large-scale oceanographic experiments in the Region. Collection agencies for oceanographic data exist in many countries (in the United Kingdom, it is the Marine Information and Advisory Service) and these serve as useful sources of conventional oceanographic observations (mainly collected by government organisations, however). It is only during recent years that current velocity measurements have been collected by these agencies, and then again, most of these come from government organisations. The situation as regards meteorological data is somewhat better, as co-operation exists both between governments (ie. the World Meteorological Organisation) and between commercial companies (ie. the Oil Companies Weather Co-ordination Scheme), so that meteorological observations in the Region are reasonably freely available.

The types of observation that are particularly required are :

(a) Long period (greater than one month) observations of current velocity over the whole Region.

(b) Large-scale conventional oceanographic observations over the whole Region.

(c) Smaller-scale conventional oceanographic observations in certain significant areas such as :

(1) The shallow areas of high evaporation in the South-Western and Southern areas of the Gulf.

(2) The area around the fresh water inflow of the Shatt Al-Arab.

(3) The Strait of Hormuz, as an aid to understanding exchange processes between the Gulf and the Gulf of Oman.

(d) Mixing experiments involving the use of tracers such as dye. A particularly important factor to measure is the vertical mixing time, as this, together with observations of current velocities, will yield estimates of the horizontal exchange rate.

(e) The rate of inflow of fresh water via the Shatt Al-Arab, which clearly has an important effect on the oceanographic conditions at the Northern end of the Gulf. There is much evidence that this has declined considerably during this century, due to irrigation schemes (Ubell, 1971). Discharge data for the Tigris, Euphrates and the Karun are published reasonably frequently by UNESCO (eg UNESCO, 1974), but these generally have to be corrected for downstream withdrawal of water for irrigation. There is hence a requirement for more accurate estimates of the quantity of fresh water actually entering the Gulf.

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Trajectory Analysis and Simulation of Oil Spill Movement

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ABSTRACT

A number of physical processes affect the movement and spreading of hydrocarbons in the marine environment. These processes typically include advection, spreading, turbulent diffusion, wave/oil slick interactions, weathering of the oil and beaching. This paper will discuss these physical phenomena and the various algorithms and procedures used to represent them. The sensitivity of the simulation results using these procedures will be examined relative to realistic geophysical data and operational constraints.

For many applied problems, such as *a priori* assessment studies, contingency planning, and tactical support for spill response, alternate model formulations or configurations may be useful. These alternate formulations will be examined and illustrated with examples.

1. INTRODUCTION

This work is intended to present a review of the physical processes and algorithms which affect the movement and spreading of oil slicks in the marine environment. The work will confine its attention to floating pollutants and will not attempt to cover the problems of how hydrocarbons mix down into the water column

The procedures and opinions presented in this work are based on experience gained during eight years of activity in a national spill response program. These studies have been carried out in direct support of spill response and contingency planning activities. This introduces a different set of conceptual biases than might otherwise be the case. I consider this approach to be one of applied science, somewhere between the empiricism that is traditionally associated with engineering and the esoteric realm of pure science.

The next section of this paper will outline the basic formulation of the spill trajectory problem. The third through sixth sections will address specific processess associated with advection, spreading and/or diffusion, weathering, and beaching. The seventh section of this paper will cover general computer requirements for real time trajectory modeling support. The final section will discuss alternate strategies for model use and possible future developments.

2. BASIC FORMULATION OF THE SPILL TRAJECTORY PROBLEM

The physical processes that affect the movement and spreading of floating oil can be categorized in a number of different ways. For this work I will group all the processes under the general categories of advection, spreading or diffusion, and weathering (sources and sinks). An additional process which represents boundary conditions (rather than the fundamental transport processes associated with the differential equation or initial conditions) is associated with beaching, and it will be discussed separately. This breakdown corresponds to the terms in the classical mass balance or distribution of variables equation that is the fundamental underlying principle addressed by all spill trajectory models. In differential form, this equation can be written :

$$\frac{\partial c}{\partial t} + \vec{\nabla} (c\vec{v}) = \vec{\nabla} (k \vec{\nabla} c) + S$$

where :

c = the pollutant concentration in an Eulerian sense (i.e. mass/volume or mass/area in the case of a floating pollutant).

$\vec{\nabla}$ = vector operator $\vec{i} \frac{\partial}{\partial x} + \vec{j} \frac{\partial}{\partial y}$

v = vector advective velocity

k = diffusion coefficient

The first term on the left-hand side of this equation gives the local time-rate change of the pollutant at a particular point. The second term on the left-hand side of the equation is the advection, or movement, of the pollutant due to the movement of the media itself. The first term on the right-hand side of this equation represents the diffusion, or sub-advection scale spreading, of the pollutant. Here it is written as simple Fickian diffusion. The final term in equation (1) represents the sources and sinks of the pollutant. These must include a description that specifies when, where, and how much pollutant enters the environment and how the pollutant is removed from the surface of the marine environment.

With this as our basic conceptual framework we will now discuss the individual terms in this formulation.

3. ADVECTIVE PROCESSES

A major and distinctive feature of the marine environment is its continual state of movement. The idea that pollutants introduced into water will move with the water is pretty well understood. Ocean currents can transport objects or pollutants very long distances. Perhaps the central factor in pollutant trajectory analysis for the marine environment will be to develop an understanding of ocean currents.

The understanding of ocean currents is an extremely ambitious undertaking and has held the attention of many physical oceanographers for a number of decades. The trajectory modeler will need to specifically address the questions: Exactly what do I need to know about the currents? and Where can I get the required information?

Currents cause a displacement of water elements, and consequently a displacement of any pollutants which are suspended in, or floating on, this water. This can easily be represented as a classical Lagrangian problem. Clearly, if we do not know which way the water goes, our trajectory analysis will be incorrect at the most primitive level. The very first question which a spill trajectory specialist will be asked is, "which way is the spill going to go?"

Looking back at equation (1) we note that advection is actually represented as a differential term and if we expand out the divergence of the mass flux term we get

$$\vec{\nabla}(c\vec{v}) = c\,\vec{\nabla}\cdot\vec{v} + \vec{v}\cdot\vec{\nabla}c \qquad (2)$$

The first term on the right-hand side of this equation indicates that the differential change associated with advection has a component associated with the divergence or convergence in the fluid flow. For the description of the surface distribution of a floating pollutant the two-dimensional divergence is not necessarily zero. Because of this, problems can easily arise in the representation of the advective fields. Consider, for example, flow in an irregular channel. Increases in depth must be compensated for by a stretching of the water column which causes a horizontal surface convergence. Variable layered depths can also cause convergences and divergences in the horizontal advective fields. Tidal circulation often causes convergent slick lines. Such interfaces typically accumulate floating pollutants. It is not uncommon for spill trajectories in estuarine areas to be dominated by the convergence patterns associated with these mixing fronts.

On a slightly smaller scale, irregularities in the wind-driven flow cause surface roll vortices referred to as Langmuir circulation (Assaf, et al., 1971). These patterns tend to accumulate floating material and cause linear features in the pollutant distribution associated with the convergence areas. These linear convergence lines are observed under moderate and strong wind conditions.

All of the effects mentioned above are readily observable in real spills. The advective currents that are used in a spill trajectory model should ideally be able to represent all of them. To the extent that they do not, then the trajectory analysis clearly cannot simulate or represent these distributions. We have identified some possible errors associated with the misrepresentation of realistic convergences or divergences in the marine environment. Unfortunately, the problem becomes more complicated when we consider the available data sources to represent advective flow fields.

Many spill trajectory models simply input a velocity field that is available from literature reviews, ship drift data, single point drift measurements, or current meter observations. The available data must be interpolated onto a continuum so that pollutants throughout the field can be advected. Often the interpolation procedures that are developed make no allowances for the two-dimensional divergence. A trajectory model that uses a uniform, spatially constant current vector will give a strong convergence along any shoreline where the dot product of the outward-directed normal and the current vector are positive. This clearly does not make good sense from a physical point of view, and the trajectory estimates derived from such a model are bound to show unrealistic concentrations in some areas and forbidden zones along some coastlines where it is impossible for oil to ever go. Another commonly used interpolation procedure is to take data from a number of sources and interpolate based on nearest neighbor considerations. Such schemes tend to distribute the divergences and convergences along line sources where the lines are bisectors between the given data points. The application of Laplacian filters tends to reduce the divergence in these fields but does not solve the actual problem associated with these kinds of misrepresentations.

It is important to develop a strategy for processing advective field data. Ideally, advective fields to represent ocean currents should be generated by mass-conserving, hydrodynamic flow models (Galt, 1980; Galt and Payton, 1981). If observed or historical data is used in a spill model then it is imperative that the interpolation functions used to transfer the data to the conceptual continuum conserve mass. Scales which are not represented, for example Langmuir scales or estuarine fronts, must be identified or flagged as missing. When the overall trajectory analysis is being carried out, these missing components must be included in the estimates of uncertainty and appear in the descriptive documentation that should be presented at all spill trajectory estimate briefings.

It is well known that at the air-sea interface, a number of physical processes are active that cause currents which are present in only the top meter or so, and these are typically not represented in any of the standard current estimates. One of the primary components of this drift is caused by surface gravity waves. This so-called Stokes drift is a non-linear effect which is associated with the steepness of the waves. An additional surface current can be caused by the wind stress acting directly on the ocean surface. In steady linear theory this gives an Ekman drift. More complex theories may include Langmuir circulation (Assaf, et al., 1971) or Prandtl layers. The net result is a downwind or nearly downwind surface current. During an oil spill any organized slicks are observed to move through the water in a downwind direction at a speed that is greater that the surface current. The actual mechanism for this differential oil-water velocity is associated with the absorption of surface gravity waves by the slick. The momentum that is present in the waves must then be transferred to the oil slick. This then pushes the oil in the direction of the dominant short gravity and capillary waves, which is downwind.

We note that all three of the surface active processes which have been described above are actually currents or momentum transfer, and that they are all well-correlated with the wind. Any floating hydrocarbons will be advected by these processes. When grouped together, these processes all make up what is referred to as the wind drift factor. Typical trajectory models take this to be a simple displacement at three percent of the wind speed.

In addition to the advective processes covering all the organized and well-defined displacements associated with classical ocean flows, such as tides, geostrophic currents, estuarine flows, and barotropic wind drift, we must add the specific surface phenomena which are correlated with the wind but not directly related to the stress-driven displacement of the oil. With this combination we will have a relatively complete description of advective processes.

Advective processes are central to trajectory analysis. They totally determine the center of mass of a spill and include the dominant effects of winds and currents. It is paramount that these fields not only represent appropriate directional information but they must also have realistic divergence properties if good results are to be obtained. To the extent that any of these advective characterizations are unresolved or poorly described, the resulting trajectory analysis will be degraded. Such uncertainties or degradations must be reflected in the non-deterministic portions of the trajectory analysis which will be covered next.

4. SPREADING AND DIFFUSION

Spreading and diffusion processes as envisioned in spill trajectory analysis encompass the effects of a number of different physical mechanisms and there is some ambiguity in how to classify them. There is, in fact, no clear distinction between advective processes and diffusive processes that can be invoked purely on physical grounds. In spite of this potential confusion there is a practical distinction which can be used to separate these processes. In particular, we think of advection as deterministic. Spreading and mixing are attributed to additional movement about which there is some uncertainty. This suggests that the more we know about advective processes, the less we would expect to represent as spreading or diffusion.

On the smallest scale, thermal kinetic energy causes Brownian movement with individual molecules exhibiting random motion. Statistical mechanics has been successful at describing this type of behavior and predicting the macroscopic properties of the resulting distribution. This leads to the classical notions of isotropic diffusion. With this, several features are evident which we will need to carry through for nearly all of the spreading and diffusion algorithms that are commonly used for trajectory analysis. First, the diffusive movements are not know in detail and secondly, as a result of these motions particles move apart such that areas of high concentration are reduced with a net transport of material down concentration gradients.

Considering slightly larger scales of motion, we find that the interactions depend on the macroscopic properties of the pollutant as well as the properties of the marine environment. The conceptual model used here is that of a pool of hydrocarbon floating on seawater. The formulation then uses dimensional analysis to consider balances between the various forces (gravity, viscosity, and surface tension) and a "three phase" spreading law is derived. From a practical point of view, three phase spreading is never seen to occur in real geophysical settings. This is because other dispersive and mixing processes always dominate and in experience with hundreds of real spills, three phase rules do not operate to yield useful improvements in simpler spreading and diffusion algorithms.

An examination of real geophysical flows in either the atmosphere or the oceans reveals that steady flows are rarely present. Winds always exhibit gustiness and ocean currents have eddies or vortices embedded in the larger scale flows. This geophysical turbulence is fundamentally related to the non-linear advective terms (Hinze, 1959) that occur in the Navier-Stokes equation. Pioneering work by Reynolds established the early recognition that turbulent processes act in a dispersive manner, and a powerful mixing length anology tied this much more complex turbulent diffusion back to the simpler molecular diffusion with the introduction of an eddy or turbulent diffusion coefficient. The use of eddy coefficients is extremely helpful in representing mixing and spreading processes in natural geophysical domains. The actual numerical values for eddy coefficients clearly depend on the scale that is being considered. For example, the small eddies behind a pier caused by tidal currents mix in qualitatively the same way as mesoscale eddies spawned off from instabilities in the Gulf Stream, but the appropriate diffusion coefficients will vary by many orders of magnitude. In practice, these diffusion coefficients can only be evaluated empirically. This requires a good deal of experience as well as a clear understanding of what processes the trajectory analysis is actually trying to represent.

To be a bit more specific, if we model flow along a smooth but highly developed coastline and represent the mean flow but do not resolve the eddies behind piers, jetties, and breakwaters, then our empirical eddy diffusion coefficient must represent the mixing associated with the turbulence induced by these "roughness elements". Alternately, while modeling a large estuary we may choose to include the thermohaline flow patterns but ignore tidal currents as part of the advection. In this case, the turbulent diffusion coefficients must represent mixing associated with the energy input of tidal oscillations and its associated dispersion.

Spreading and diffusive processes cover such conceptually different things as spreading and turbulent diffusion on the one hand, and uncertainty on the other. These alternate views lead to quite different interpretations of the trajectory analysis results. As long as this is kept clearly in mind, no particular problem arises from this dichotomy. If, for example, we model a single plume of oil emanating from a ruptured hull, the mean flow carries the oil away, and mixing or turbulence widens the plume. A suitable specification of the diffusion coefficient will result in a plume with the correct aspect ratio. When properly done, the trajectory results can be interpreted as actual oil concentrations. Now, if we were to address the same problem but were not sure about variations in the current or wind direction, then we could use the diffusive algorithms to represent uncertainty or measurement errors. The model would predict a similar plume but, in this case, the results would be interpreted quite differently. The plume distribution now represents a probabilistic distribution of the oil. Scatter shows possible locations for the pollutant, not actual concentrations. Such output is characteristic of trajectory analysis that is carried out for assessment purposes or which uses climatologically-based current and wind data. In any case, this dual use of diffusive algorithms must be carefully distinguished and the proper interpretation presented with the trajectory analysis results.

Given the actual difficulties associated with modeling spill events, it is generally unrealistic to develop elaborate diffusion or spreading algorithms when the observational data, initial conditions, and our understanding of geophysical processes will never be able to distinguish such subtle differences. A simple approach accompanied by careful interpretation and appropriate caveats seems to be the best. With a Lagrangian formulation, a random walk diffusion algorithm has proved useful and the diffusion operator in equation (1) is replaced with a Monte Carlo formulation.

Advective processes tell us where the pollutant is going to go, but spreading and diffusive processes tell us what it is going to look like when is gets there. In any real spill the small scale processes determine the form that the oil is going to appear in. Langmuir cells line the oil up in wind rows and thin linear features. Convergent zones trap and hold oil. Radiation stress from waves can actually compress pools of oil such that individual large pancakes or patches can exist hundreds of kilometers from the spill site. Weathered tar balls can obtain a density close enough to seawater so that wave induced turbulence mixes them down below the surface and throughout the upper mixed layer. Under these conditions they may be nearly invisible to observational aircraft or even ships. All of these observational details may be important to response personnel. Once again, any presentation of computer-generated trajectory analysis should include briefing documentation (oral or written) and it is here that the trajectory modeler must explain what the model includes and what it does not include.

5. WEATHERING

Weathering includes processes that remove floating oil or hydrocarbons as products of concern. This is obviously a somewhat restricted view but this work is focused on the trajectory modeling of floating hydrocarbons as pollutants so this framework will be maintained throughout the present discussion.

Oil and hydrocarbon products are combinations of thousands of molecular species. Additionally, sea water is a chemically complex mixture. It is not surprising, then, that many different types of reactions are possible. Evaporation, agglomeration to sediments, dissolution, micell formation, oxidation, and ingestion are some of the possibilities (Wolfe, 1977; Rosen, 1978). Each of these interactions has been studied in laboratory settings and, to a lesser extent, in the actual marine environment. With all of these potential interactions occuring simultaneously, it is not surprising that no operative trajectory model tries to parameterize all these processes in detail. Recent experience with the Nowruz oil spill suggests that sandfall may also provide a significant weathering mechanism, at least in the northern section of the Arabian Gulf.

Aggregate weathering algorithms have been proposed by a number of authors to represent many of these weathering processes (Kolpack, 1977; Mackay, 1980; Mackay and Leinonen, 1977). More recently, specific work has addressed how to best classify and parameterize hydrocarbons to describe their physical weathering properties (Mackay, 1983). In spite of major simplifications, most of the proposed aggregate algorithms still require more input data than is typically available during a short-term spill response. From a pragmatic point of view an even simpler approach is needed. It is known that some of the major weathering processes depend roughly on molecular weight. This then suggests that we should classify hydrocarbons by their molecular weight fractional distribution.

If each hydrocarbon is considered as being made up of a light, an intermediate, and a heavy fraction (i.e. three weight classes), useful results can be obtained.

A simplified algorithm can then be generated by assuming exponential loss (i.e. a half-life loss law) for each of the three fractional components. The lighter fraction will disappear quickly, the intermediate fraction more slowly, and the heavier fraction more slowly still. Although the exponential loss law behaves like a classical evaporation model, the evaporation rates are empirically derived and really represent a combination of evaporation, dissolution, and other forms of accommodation.

An obvious question related to weathering algorithms is how to handle non-natural weathering processes such as the use of dispersants (by our limited definition of weathering, effective dispersant use should be included in the trajectory analysis as a weathering process). Laboratory investigations of dispersant effectiveness have been presented (Mackay and Szeto, 1981) but I know of no large scale quantitative documentation for actual spills. For smaller spills and as more effective application techniques become available, the effects of dispersant use should certainly be included in spill trajectory analysis and weathering algorithms.

From a computational point of view, it should be noted that the three-part exponential weathering law described above can be implemented in a Lagrangian framework using a Monte Carlo formulation. If individual Lagrangian pollutant elements were allowed to be characterized by such additional descriptors as age and pollutant type, many other empirically-derived weathering algorithms can prove useful.

For example, while observing and tracking many spills at sea, experience has led to the idea that as oil concentrations get smaller and individual patches weather, observability goes down. In this case, overflights, even with trained observers, may return negative results. To represent these conditions in trajectory analysis, the following algorithms have been used : when oil concentrations become small and the average age of the pollutant Lagrangian particles goes beyond three of four half-lives of the intermediate weight class for the type of pollutant spilled then the spill trajectory output maps indicate a low probability of detection.

As scattered tarballs weather, their density increases and under rough wave conditions may will tend to mix down throughout the upper mixed layer of the ocean. This has the effect of making them extremely difficult to observe from the air or even from small boats, and has led in numerous spills to reports that the oil is sinking. Although it is not impossible for oil to sink in this fashion, it rarely happens and quantitative studies by divers (Hooper, 1981) have shown that tarballs are mixed down by wave energy bu remain buoyant and that as seas calm down and low energy conditions prevail, the oil refloats and reappears at the surface. This process has occurred at nearly every major spill and has led to considerable confusion and disagreement among observers who fly out and try to report the location of the oil. Most floating crude oil appears as black or brown, with occasional tinges of red in it. All of these colors and their observability in the visual range are dramatically affected by lighting conditions. Stormy or near-dusk conditions can seriously affect whether oil is observable or not, and overflights at mid-day and in the late afternoon can be expected to come back with significantly different reports on the amount of oil seen even if reported by the same observer.

All of the above-mentioned observability factors have the potential to degrade the observational data base required to verify and improve our weathering algorithms. In spite of this, the empirical, results based on observations with a modest reliance on the underlying processes is still useful and produces helpful insights on how spills will persist as surface problems.

6. BEACHING

As oil approaches the shoreline a number of different processes become operative. First, the regional currents are deflected by the shoreline itself. As one approaches the shoreline, turbulent diffusive processes may also be reduced due to decreased mixing lengths. Even nearer the shore, diffusion processes may increase again because of a focusing of energy in the surf zone. Atmospheric forcing is also modified by the presence of a coastline and variations in the winds are commonly seen. Coastlines with high relief show orographic effects and regions where high thermal contrasts exist between land and adjacent marine areas, often show adiabatic or drainage winds, as well as sea breeze phenomena. To the extent that any of these processes are known, they should of course be included in the advective and diffusive algorithms of the trajectory model.

Even closer to the shore, there are a number of boundary scale phenomena that affect the pollutant distribution for floating hydrocarbons. Steep shorelines reflect wave energy, and the resulting standing wave patterns have been observed to hold oil offshore (Hess, 1978). Wave refraction can also turn and channel pollutants as they near the shoreline. An important secondary offshoot of wave refraction is the generation of alongshore currents. These alongshore currents develop strongly within the surf zone and tend to propel a pollutant parallel to the beach with the net effect that as oil comes ashore, it tends to be distributed and moved along a broader section of beach face than it would be if it came directly ashore in the absence of these kinds of processes. Alongshore currents also feed what is referred to as "rip current systems" (Shepard, 1963). These rip currents are offshore-directed counter-currents which take the oil from the nearshore surf zone and reinject them out through the breakers into the offshore region, sometimes reaching as far as one kilometer from the beach. This phenomenon also has the net effect of distributing pollutants along a beach face and has been documented as operative in a number of spills.

All of the above-mentioned processes affect the oil or pollutant as it nears the shoreline. Once it actually comes in contact with the shoreline, what happens depends on a somewhat different complex set of conditions. The behavior of the oil will depend on the sediment size of the beach, the steepness of the beach face, the porosity and interstitial water pressure in the beach, and the amount of wave energy along the beach face. Climatic factors such as the amount of sunlight and air temperatures may also be significant. As with weathering, what is needed to incorporate all these processes into trajectory models is a simplified algorithm which recognizes the basic processes and is consistent with the rather large body of observational experience that is now available from studies that have taken place over the course of many spills. To develop a basic beaching algorithm, we must first classify beaches with regard to oil pollution (Gundlach and Hayes, 1978). In this system, low-scale values correspond to short residence times for stranded pollutants and high-scale values correspond to long residence times. To incorporate this scale into a beaching algorithm, we use the scale numbers to define the half-life probability that oil will remain on the beach if it could refloat. For example, rocky headlands (a scale value 1 beach) will rewash half of their hydrocarbon pollutants approximately every two days. On the other hand, salt marshes (a scale value 10 beach) will rewash half of their pollutant load only every six years.

The incorporation of a refloating half-life into a beaching routine requires that we also specify how oil actually adheres or sticks to the beach face in the first place. Theoretical considerations indicate that oil cannot contact the beach face due to currents alone (currents do not inundate the shoreline - with the exception of percolation into mangrove swamps or marshes). There must be an onshore component of the wind or waves to bring oil in actual contact with the beach face.

Observations point to the fact that oil will not stick to the beach face on a rising tide. A falling water level and onshore winds are the conditions under which oil will be stranded and stuck on the beach face. From this point on, the beached oil is subject to a probabilistic refloating (based on beach type) any time that the water level is sufficiently high to wet it. Once refloated or reinjected into the water, the oil is free to rebeach, sink, or be carried offshore to move to another region. This proposed beaching algorithm retains its simplicity while emulating some of the major available observational data.

7. COMPUTER REQUIREMENTS FOR TRAJECTORY MODELING SUPPORT

A fundamental underlying requirement of all spill trajectory modeling systems is that they be quick to implement and that they be user-friendly. No matter how much pre-planning and contingency planning has been done, nearly all spills occur as unexpected accidents. This means that input data must be set up rapidly and that the trajectory modeling team needs to have uncomplicated and straightforward communication links with the machines. Program codes should be interactive and interrogative. Wherever possible, input data should be automated. To input basically graphical information such as the shape of a region and its bathymetry by hand is not only archaic, it is also very prone to error. Digitizing marine charts with a light pen is an order of magnitude faster and much more accurate. There are also on the market television scanner-digitizers and it is quite likely that most major trajectory models will receive their basic geometry and topographic information in this format within a very short time.

Considering the rapid development of microcomputer technology and the dramatic cost reductions of these units it is obvious that spill trajectory models developed in the future should take advantage of this type of unit. Useful spill trajectory algorithms should be developed for stand-alone microcomputers that offer a high degree of portability. These will offer a field support capability that is presently unknown. In the near future, we will have spill trajectory models that are stored in cassette form that can be plugged into any number of standard micro-CPU units. Every terminal operator, platform superintendent, or port captain should have a spill trajectory model available for his local area on which he can play through alternate scenarios. A final requirement is that standardized terminology and graphical output should be developed. For the highly mobile oil industry and response personnel to be forced to learn an entirely new system when they move to a new area will

8. STRATEGIES FOR TRAJECTORY MODEL USE

A common and straightforward technique for the use of trajectory analysis is to simply respond in a tactical support mode when there is a spill. That is, when the modeler is informed of an accident in which oil was lost, a mad scramble is initiated to collect enough environmental data to feed all of the pre-assembled computational algorithms, a spill forecast is carried out, the results are output, and a briefing is prepared to inform response personnel of the probable track of the spilled pollutant. Hopefully, all of this can take place before the spill is over. Experience has led to the conclusion that it is seldom useful to go straight for a state-of-the-art spill trajectory product after the initial notification call. First, this will take too long, and secondly, initial reports are always sketchy and usually incorrect (much effort can be wasted going in the wrong direction). During a spill response, trajectory analysis should be continuous and the results applied like coats of paint. There will be something to work with right away and the results should get better as time goes on.

After the initial spill notification, the first trajectory estimates should be available within ten to thirty minutes. This product will probably not use any computer analysis routines, but will be based on a quick look at readily available environmental data. The briefing results for these trajectory estimates should be delivered over the telephone and will alert response personnel to major problems and give some indication of which way the pollutant is likely to head.

Within two hours after the initial spill notification, a second level analysis should be available. Maps should have been studied, key threatened resources should be identified, and potential time-of-impact estimated. For this, simple algorithms will suffice. At this stage, briefings are still probably being presented over the telephone, but teletype and telefax equipment may also prove useful.

By the fourth hour after initial spill notification, computer-generated current patterns should be available and graphic representations of tidal and wind forecasts should be ready for transmission. The briefing should include specific coastline sections that may be threatened, and enough current data to help in recommendations for boom placement and other containment or mitigation procedures.

By the second day of the spill, hindcasts should be made to check trajectory forecast accuracy. Recommendations should be available for routing of observational and monitoring overflights. Tactical spill trajectory support requires close ties between modelers and operational response groups, and involves a continual process of upgrading input, analysis, forecasting, and hindcasting. Experience, communication links, computers, and endurance are all needed for successful results.

Although most spills are unexpected, this is not universally true; many spills continue for a long time and may actually have some degree of choice as to when they occur. This suggests a second way in which trajectory analysis procedures can be used for spill response. Consider the following cases :

Case 1. A grounded ship may require relatively high risk operations to refloat the hull or lighter the cargo. When shall this be done?

Case 2. A crippled ship may need to be beached to carry out salvaging operations, but there is considerable choice as to which beach should be used. Where should it go?

These are real cases in which trajectory analysis was used as part of the overall planning and response strategy. In each case, the analysis centered around using the computer to run a series of scenarios. This is not a typical forecast, but rather an exploration of situation space. With these results, the consequences of alternate plans of action can be compared.

Large oil spills can assume oceanic proportions. In such spills it also usually becomes obvious that for most open ocean areas little can, or should be, done in the way of response. The questions then become "When should action be initiated?" "How long will response personnel have to respond?" "Which areas are threatened by particular hydrocarbon concentrations as they approach my coastline?" "How much equipment will I need and at what level of alert should it be kept ready?" All of these questions relate to subjects which will be covered in any good regional contingency plan. A third type of trajectory analysis, receptor mode analysis, is particularly useful to answer this type of question (Gilbert, 1983; Galt and Payton, 1983).

Receptor mode trajectory analysis starts by choosing a particular high value target site (i.e. marina, public beach, or high value fisheries resource) and the algorithms then proceed to calculate where the oil might have come from such that is could threaten this high value area. The output of receptor mode analysis is presented in the form of two distribution maps. The first map is a joint probability distribution map that shows the likelihood of a pollutant moving from any location to the high value target area. The second form of output will be time-of-travel maps. These time-of-travel maps indicate how long a response group would have to effect countermeasures or mitigation procedures. The use of receptor mode analysis results can dramatically decrease the number of false starts, unnecessary standby costs, and in general, focus scarce resources on the problem areas which are most likely to be affected.

9. CONCLUSION

Hopefully, this paper has pointed out that spill trajectory analysis is a combination of a number of different things. It must begin with a clear understanding of the physical processes which transport oil. In every case, these processes must be understood in terms of the local or regional marine environment. Some areas, for example, will be dominated by tides while others may have permanent oceanic currents that approach coastlines, while still a third region may be totally dominated by estuarine and thermohaline forcing. After the physical processes in the local marine environment are understood, it is then necessary to develop the appropriate analysis and computational algorithms to represent these processes. This, of course, will not be useful until the appropriate hardware and communication links are put together. Finally, sucessful strategies for the use of all these tools are required. It perhaps goes without saying that every situation will be slightly different and each of the spill trajectory analysis teams that are formed will turn out to be slightly different. Trajectory analysis is but one small piece of a larger response organization and thus each team will have to fit into a different national, industrial, or regional spill response organization.

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Applications of Trajectory Analysis for the Nowruz Oil Spill

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ABSTRACT

Early in the calendar year of 1983 an accident in the Nowruz oil field in the northern part of the Arabian Gulf began a spill that continues up to the time of this writing. This paper describes modeling and trajectory analysis procedures that were carried out to investigate the oil lost from these wells. These studies included a large-scale analysis of the entire Arabian Gulf region and a more detailed small-scale analysis of the northwest section of the Gulf centered on Kuwait. Four high-value areas in Kuwait were identified and a second type of trajectory study referred to as "receptor mode analysis" was investigated for these sites.

1. INTRODUCTION

The movement and spreading of oil on the surface of the sea is controlled by a number of complex processes including advection by currents, indirect wind forcing, turbulence, and weathering; these processes will not be discussed in detail in this paper. The reader is referred to Galt (1984) for a discussion of these topics.

The next section of this paper will discuss the initial Arabian Gulf modeling work and trajectory analysis. The third section discusses the higher resolution, more detailed development of trajectory analysis components for the northwest portion of the Gulf. The fourth section of this paper describes the use of receptor mode trajectory analysis for specific high-value sites along the Kuwait coast. The final section presents some conclusions based on this analysis, and makes some recommendations for the utilization of these trajectory studies in response and contingency planning activities.

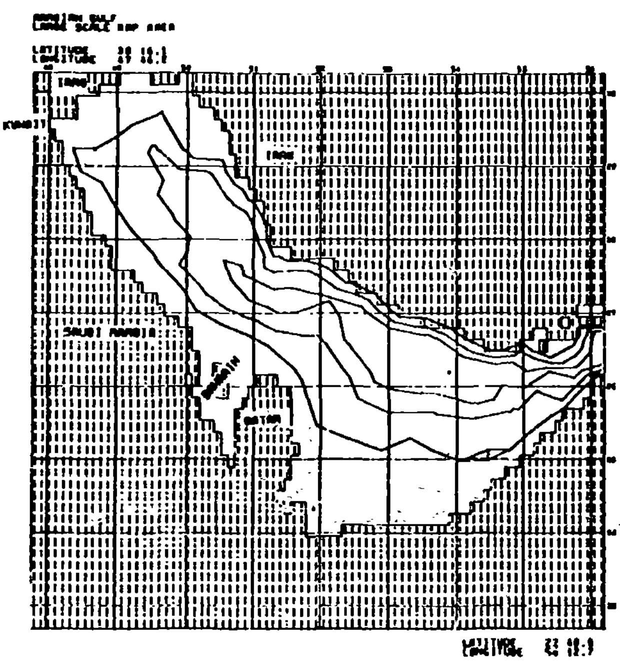

Figure 1. Large-scale map of the Arabian Gulf depth contours at 20, 40, and 60 m are shown.

2. LARGE-SCALE ANALYSIS

As an initial axiom, the data required for trajectory analysis will have to cover the area of concern with an appropriate scale to resolve the details of interest. Figure 1 shows the large-scale Arabian Gulf map used for this trajectory analysis study. The eastern basin and the northwest basin are clearly distinguishable.

Given the large-scale map it is next necessary to estimate the advective current fields. There are a number of sources for this data available for the Arabian Gulf. One such source of current estimates has been compiled by the U.S. Defense Mapping Agency. Oceanographic cruises in the Arabian Gulf (Ross and Stoffers, 1978) have mapped temperature and salinity distributions for various seasons. Quite detailed tidal flow models are also available to provide tidal height and current patterns. In addition, there are numerous site specific studies all along the Gulf where developmental activities have required local investigations.

Most of the available current data is empirically derived and there has been no particular effort during the subsequent analysis to examine the divergence of the composite velocity field. If these velocity patterns are then used for trajectory analysis, the potential divergence errors are a serious drawback (Galt, 1984). Faced with this problem, computational modeling procedures that ensure mass conserving advective patterns to describe the fundamental components of the advective field are used. The resulting patterns will then need to be scaled by the observed data to ensure that we have predicted currents which are scaled correctly and give plausible results.

Since we are interested in the larger scale trajectory analysis problem, we will ignore advective processes caused by the tides. These will be oscillatory in nature and an examination of predicted tital flow fields suggests taht the pollutant excursion associated with these currents will be smaller than our map resolution.

A major component of the steady-state circulation in the Arabian Gulf is due to the prevailing winds. With much of the Gulf shallow, an integrated transport formulation is likely to prove useful. The particular form of the equations we use are:

$$\frac{\partial \vec{v}}{\partial t} + 2\vec{\omega} \times \vec{v} = -g\nabla\xi - \frac{c|\vec{v}|\vec{v}}{\vec{h}} + \vec{\tau}$$

$$\frac{\partial \xi}{\partial t} + \nabla (\vec{v}h) = 0$$

where:

$\vec{v}$ = is the horizontal vector velocity

$\vec{\omega}$ = rotation vector of the earth (Coriolis parameter)

ξ = free surface elevation

c = drag coefficient for bottom friction

h = undisturbed water depth

$\vec{\tau}$ = wind stress vector

These equations were solved using a finite element time-stepping procedure. Quasi-steady solutions were obtained by applying a steady, uniform wind and running the model for 48 hours from an initial condition of rest. The major spin-up of the model is related to the natural seiche period of the basin which is on the order of 24 hours. Thus, by 48 hours the time-dependent oscillations are quite small.

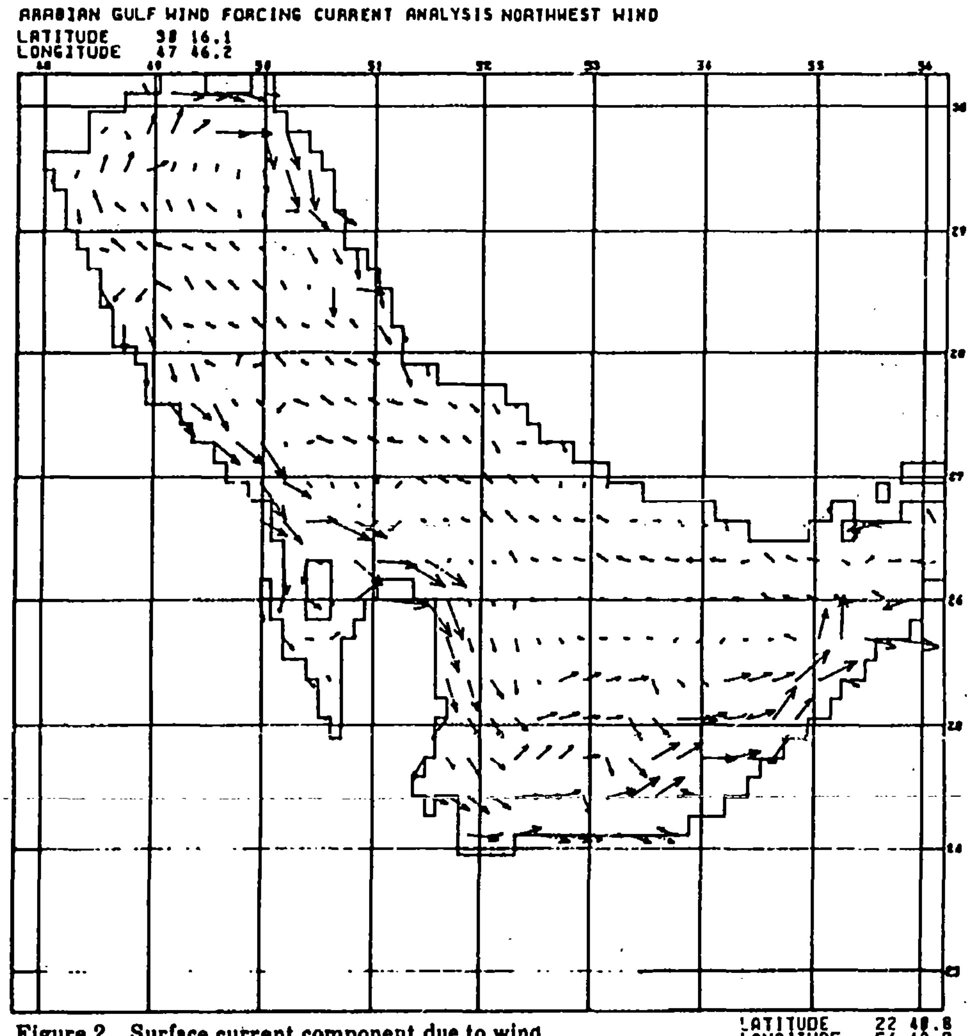

Figure 2. Surface current component due to wind stress using a 5m/s wind from the northwest.

A number of alternate scenarios were investigated with this model. The first test case hypothesized was for a five meter/second wind from the northwest. The results of this case can be seen in Figure 2.

Examination of patterns derived from the wind forcing to the south and east imply currents for any wind direction can also be approximately represented by the sum of these two basic component patterns.

A second current component identified for the Arabian Gulf is caused by surface waters that come in through the Strait of Hormuz to replace the evaporative losses that take place over the entire Arabian Gulf. The distribution of this current (Figure 3) can be estimated by an examination of salinity distribution data (Dubach, 1964; Grice and Gibson, 1978) and the use of another finite element circulation analysis routine (Galt and Payton, 1981). At the northern end of the Arabian Gulf a small amount of fresh water runoff comes in from the major river systems. The flow pattern associated with this can also be estimated using the same analysis techniques.

Each of these components to the current can now be scaled and linearly added together to best represent the observational data available for the Arabian Gulf. Figure 4 presents the results of this combination. The major features of the predicted Gulf-wide current system can now be examined.

One major feature of the circulation is a current moving to the southeast along the western shore. This is seen to develop first in southern Kuwait and then to move south along the Saudi Arabian coast, gaining strength as it moves. By the time it reaches the Gulf of Bahrain, some of it moves south along the western shore of Bahrain, but the majority of the flow is bathymetrically steered to the south and east over towards the northern tip of Qatar where some small fraction of it rounds the Qatar coast and moves into the eastern basin of the Gulf. Some re-circulation north of Qatar can also be seen. The maximum speed associated with this current is on the order of a half-knot along the southern coast of Saudi Arabia and north of Bahrain and Qatar.

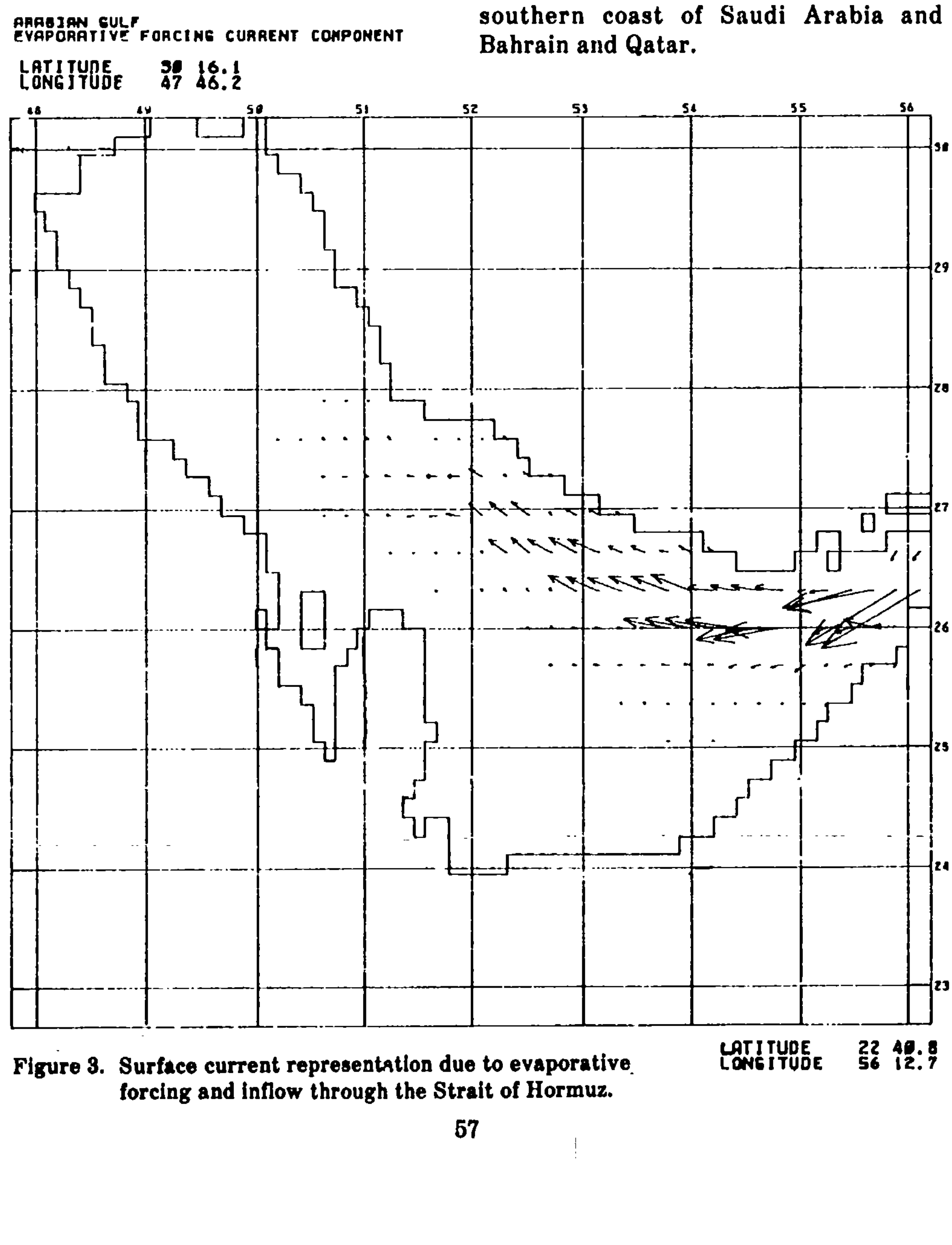

Figure 3. Surface current representation due to evaporative forcing and inflow through the Strait of Hormuz.

A second major feature of the derived current pattern is coastal flow along the eastern shore or the southwestern coast of Iran. This current is seen to be both weaker and more narrow than the one along the Saudi Arabian coast. Suspended sediment patterns seen in satellite pictures of the Arabian Gulf clearly indicate the position and width of this current. Throughout the center of the northwestern basin there is seen a weak return flow that covers the deeper segments of the Gulf. This continues towards the northwest where it approaches the shoreline and bifurcates about midway down the Kuwait coast. This is the basic advective field used in the large-scale trajectory analysis. Given this, we now consider available wind data.

Wind statistics are available from a number of stations around the Gulf (IMCOS, 1976). Actual wind observations are reported from a number of stations around the Gulf every six hours. From this and pressure field data the Marine Environmental Protection Agency (MEPA) in Saudi Arabia has carried out a regional analysis which estimates surface wind patterns for the entire area.

With this collection of wind data, current patterns, and the spill characteristics, a number of trajectory experiments were carried out.

Two experiments used mean the averaged currents with statistical winds from Kharg Island and Bahrain. A third and fourth test used the mean averaged currents and the actual or analyzed winds available from MEPA first for the Kharg Island region, and then for an area in the central Gulf north of Bahrain.

Since the wind-driven current analysis suggested that the Arabian Gulf takes more than six hours to come into even an approximate state of equilibrium with an applied wind stress, an additional series of trajectory experiments was carried out. In this set, various combinations of mean averaged currents and variable currents were keyed to the observed winds.

The results from each of these trajectory experiments were compared to the available observational sitings of oil that had been compiled by the Regional Office for Protection of the Marine Environment (ROPME). Figure 5 indicates the predicted distribution on May 5 and is an example of the

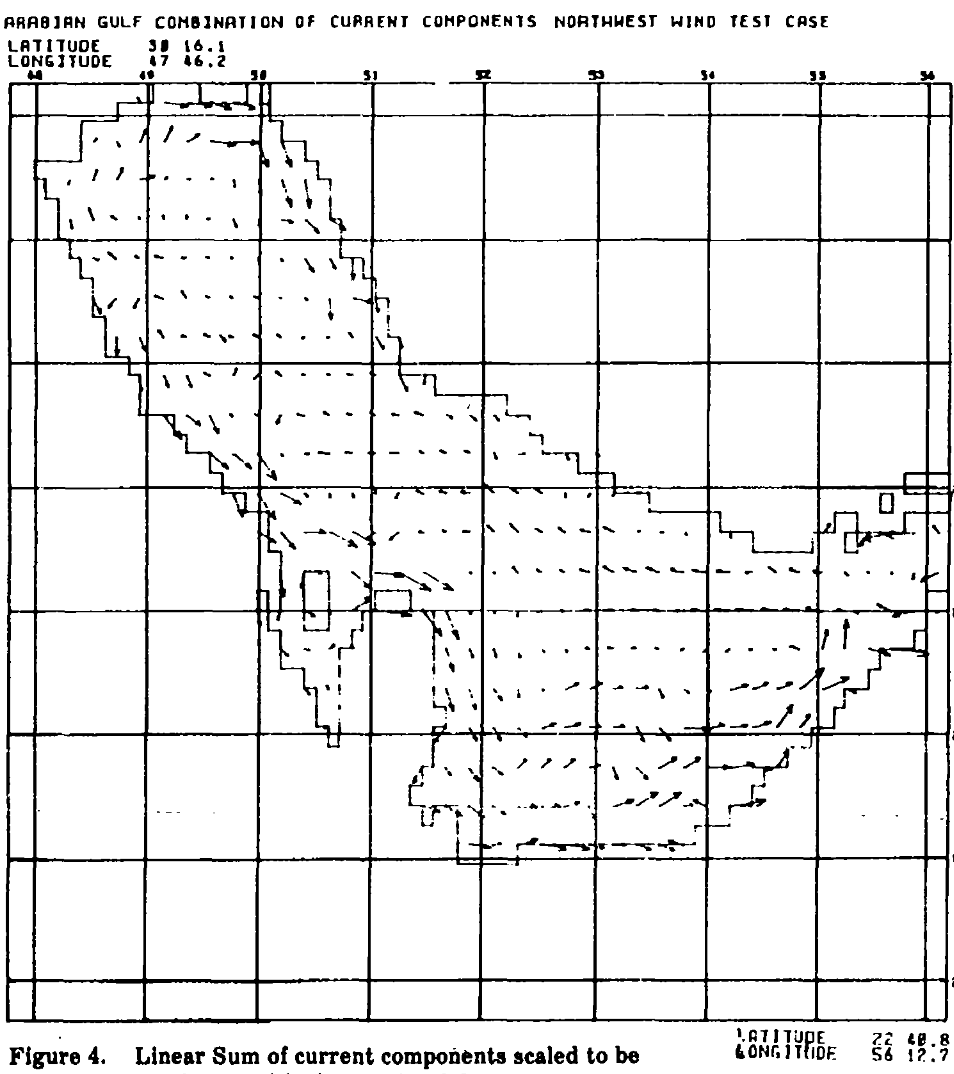

Figure 4. Linear Sum of current components scaled to be consistent with observational data.

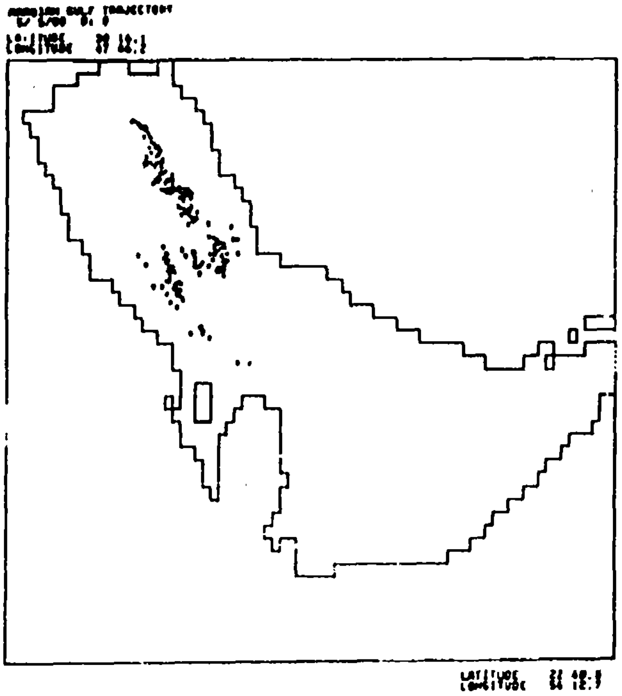

Figure 5. Example of trajectory analysis results for May 5, 1983.

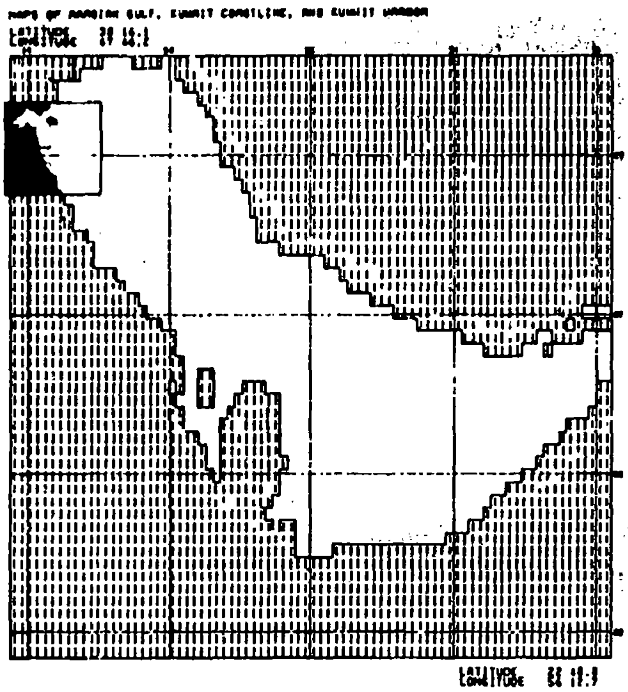

Figure 6. Representation of three maps used for the Kuwait Regional Study.

typical model results. The oil can be seen to move southeast down the center of the Gulf. By approximately the hundredth day of the spill, the heaviest part of the distribution is extending southeast to the vicinity of Qatar.

The distribution estimates include the primary effects of the major weathering processes. Sandfall data from Kuwait indicates that this may also be an effective weathering or sinking mechanism in the Arabian Gulf; however, this factor has not been included in these trajectories.

From experience gained in previous spills and reports of the observations made during the Nowruz spill, it is possible to describe what the surface pollution will look like in the areas covered by this trajectory analysis. Major concentration areas indicated by concentrations of dots can be expected to contain relatively large numbers of dense tarballs and small oil patches. In the northern sections some consolidated patches and larger pools of oil may be present. At the extremes of the distribution, one would expect to see widely scattered tarballs which will become ubiquitous as time goes on. These tarballs appear to be quite dense and contain highly weathered oil. In this form any mechanical mixing associated with wave activity can stir them below the surface where they are particularly difficult to observe from either aircraft or ships.

3. REGIONAL ANALYSIS - KUWAIT

The large scale analysis presented in the previous section gives a relatively low-resolution overview of the expected spilled oil distribution. Major threat areas are identified and the general characteristics of the floating pollutant have been described. We now focus our attention upon a higher resolution analysis. The region chosen for study is Kuwait. We begin the investigation by looking at higher resolution maps. Their relationship to the Arabian Gulf map is shown in Figure 6. From a trajectory analysis point of view, these higher resolution regions are thought of as a sequence of nested maps embedded in the next level higher resolution. The larger of the two maps covers the entire Kuwait coastline while the smaller, higher resolution map covers only the region of Kuwait Bay.

Figure 7a indicates the bathymetric contours that are resolved by the computer simulation in the larger of the two maps. Major bathymetric features are seen to be the large shoal area surrounding Failaka Island and the relatively deep submarine valley that leads along the coastline and up into the Kuwait harbor.

For this section of the Gulf, a dominant steady-state current caused by the wind stress is expected. We start out as before by an investigation of the vector wind components. With a wind from the north we can clearly identify southerly flow over the shoal region along Failaka Island, and along the shallow section adjacent to the Kuwait coast. A wind from the west presents a quite different circulation picture with easterly flow over the shoal area around Failaka Island and a relatively strong compensating flow up the submarine canyon and along the northern section of the Kuwait coastline.

A characteristic wind direction for the Kuwait region is from the northwest and Figure 8 indicates the expected current patterns associated with this kind of forcing. This pattern indicates a

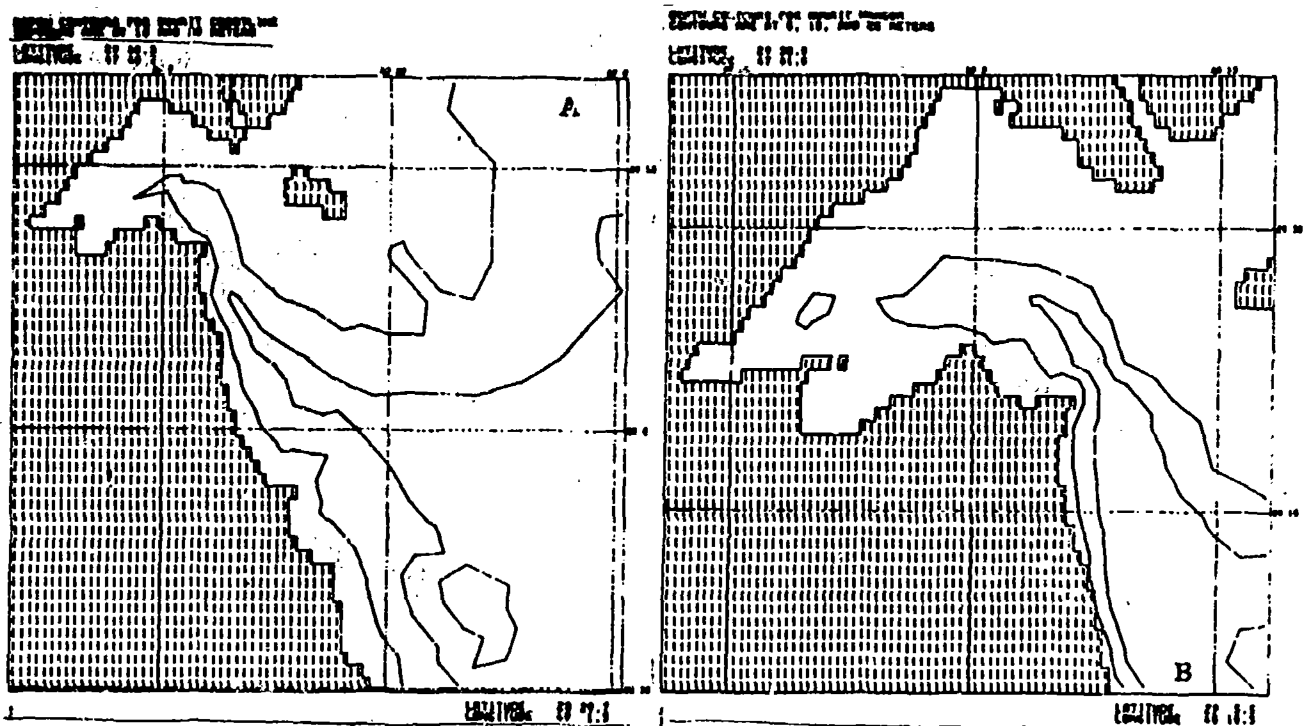

Figure 7. A) Map of Kuwait Coastal area. Contours at 10 and 20 m are shown.

B) Map of Kuwait Harbor area. Contours at 5, 15 and 25 m are shown.

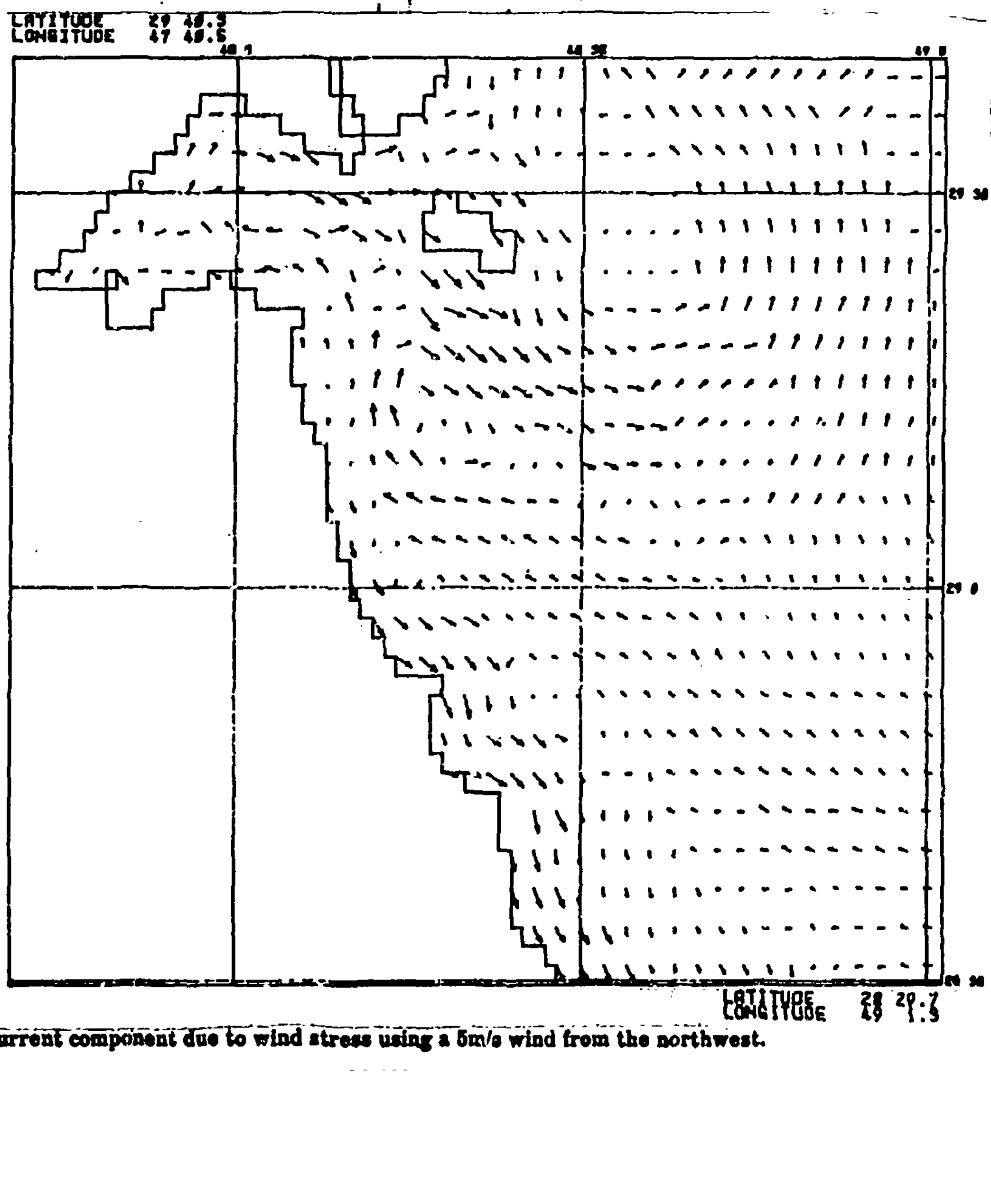

Figure 8. Surface current component due to wind stress using a 5m/s wind from the northwest.

number of interesting features. There is a clockwise gyre south of Failaka Island and slightly offshore. At the coastline in the vicinity of the Shuaiba industrial complex, the currents are seen to bifurcate with weak northerly flow north of that area and weak southerly flow south of the area. As we move south along the Kuwait coast, the current is seen to increase in magnitude and develop into a much more organized coastal current structure parallel to the shore. Although throughout the year in Kuwait a northwesterly or north-northwesterly wind is the most common, there are periods in the year when a bimodal wind direction distribution is present. In these cases, the secondary maximum in the wind direction indicates flow from the southeast. Examination of the expected current distribution for this type of wind forcing indicates that this pattern is very nearly the negative of the northwest wind pattern. This also reconfirms that we can represent the current patterns for any particular direction of wind forcing by a linear combination of the component currents that are derived from the west wind and north wind cases.

We now move to a consideration of our third level zoom map which focuses specifically on the Kuwait Harbor region. Figure 7b indicates the map used for this analysis and the bathymetric contours that are resolved in the computer analysis.

Once again, we expect one of the major components of the current to be the wind-driven flow. Figure 9 indicates the expected current pattern that would result from a northwest wind and thus represents the most common case expected in this region. Evident in this flow pattern is the northwesterly flow up the submarine canyon with easterly flow south of Failaka Island. Within the bay itself, the northern portion of the bay still exhibits a relatively well-defined counterclockwise circulation, while the eastern or inner bay segment shows a much more complex circulation with generally weaker flows. Comparison with the expected current pattern that would result from southeasterly winds once again be seen to be the negative of the previous case.

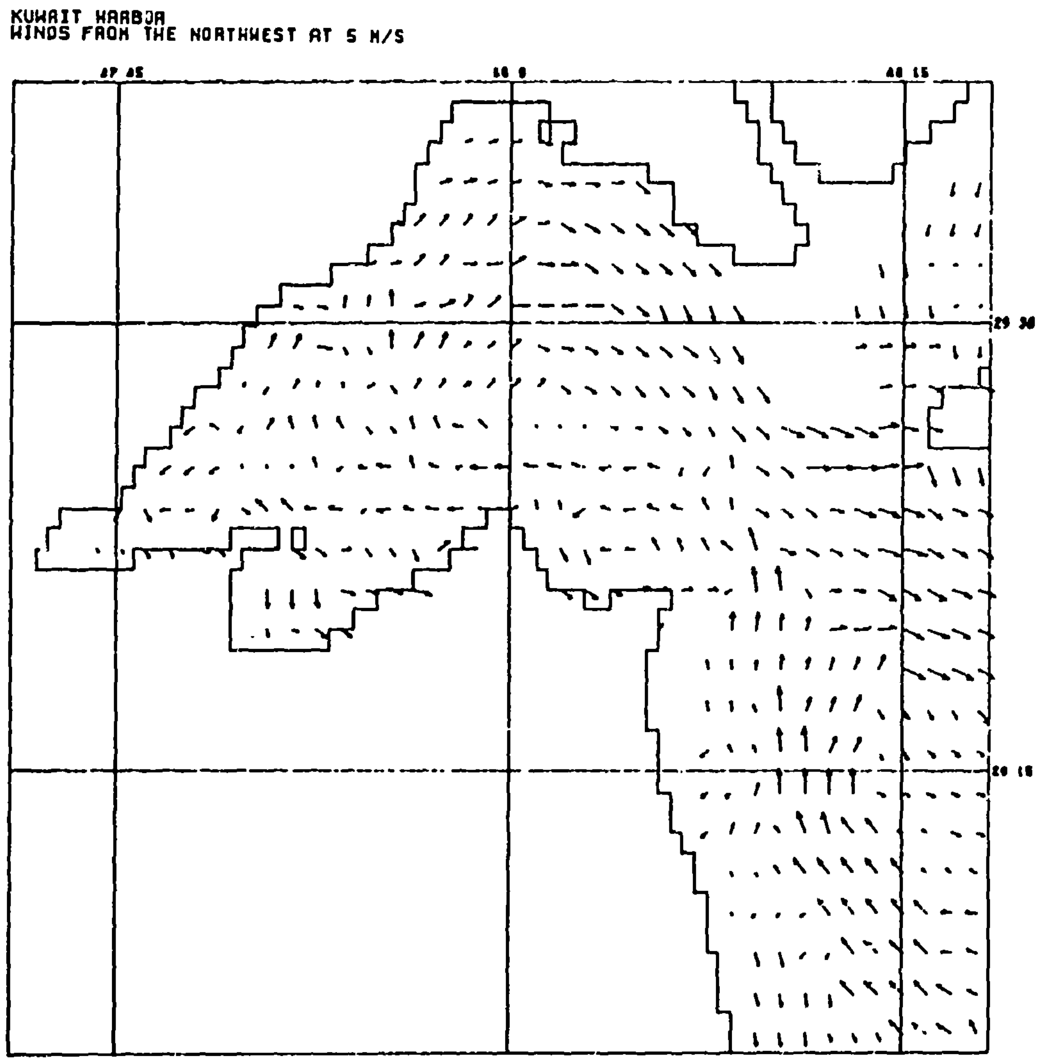

Figure 9. Surface current component due to wind stress using a 5m/s wind from the northwest.

Within Kuwait Harbor the tidal currents become significant. Near the mouth of the harbor, just off Ra's al Ard, the tidal currents can reach two knots in magnitude. For trajectory analysis at this higher resolution level, we can no longer ignore the tidal excursions compared to the other transport processes. To estimate the tidal current patterns a kinematic transport analysis is used (Galt and Payton, 1981). The results of this analysis are shown in Figure 10.

Given the advective current patterns described above, we must now consider wind forcing and wind forcing data for the higher resolution Kuwait studies. Regular wind reports are available from the Kuwait International Airport and Mina al Ahmadi. Long statistical records are available from the airport, Mina al Ahmadi, and south at Ra's al Khafji. A close examination of the statistical wind distribution indicates that the coastal stations show evidence of sea breeze phenomena which are typically not present in the data from the Kuwait International Airport. For offshore trajectory analysis the coastal stations probably provide a more realistic statistical distribution of winds.

Now that we have developed the current pattern distributions and possible wind data sources it will be useful to look into a comparison of the modeled processes and available observational data. This will provide a strategy for the actual set-up and use of the model computations.

Looking first at the tidal current in Kuwait Bay, we may calculate the tidal prism associated with the predicted tidal elevation changes. This gives the volume of water that must be carried into the Bay by the flood currents. The volume flow in is directly proportional to the time rate of change of the surface elevation. This yields a "keying strategy", i.e. a way to predict real-time currents using available geophysical data (predictions from the Tide Table).

Lacking current data from the southern Kuwait coast, our keying strategy will be to use wind data as the independent forcing variable. To do this, we divide the wind into north and west components

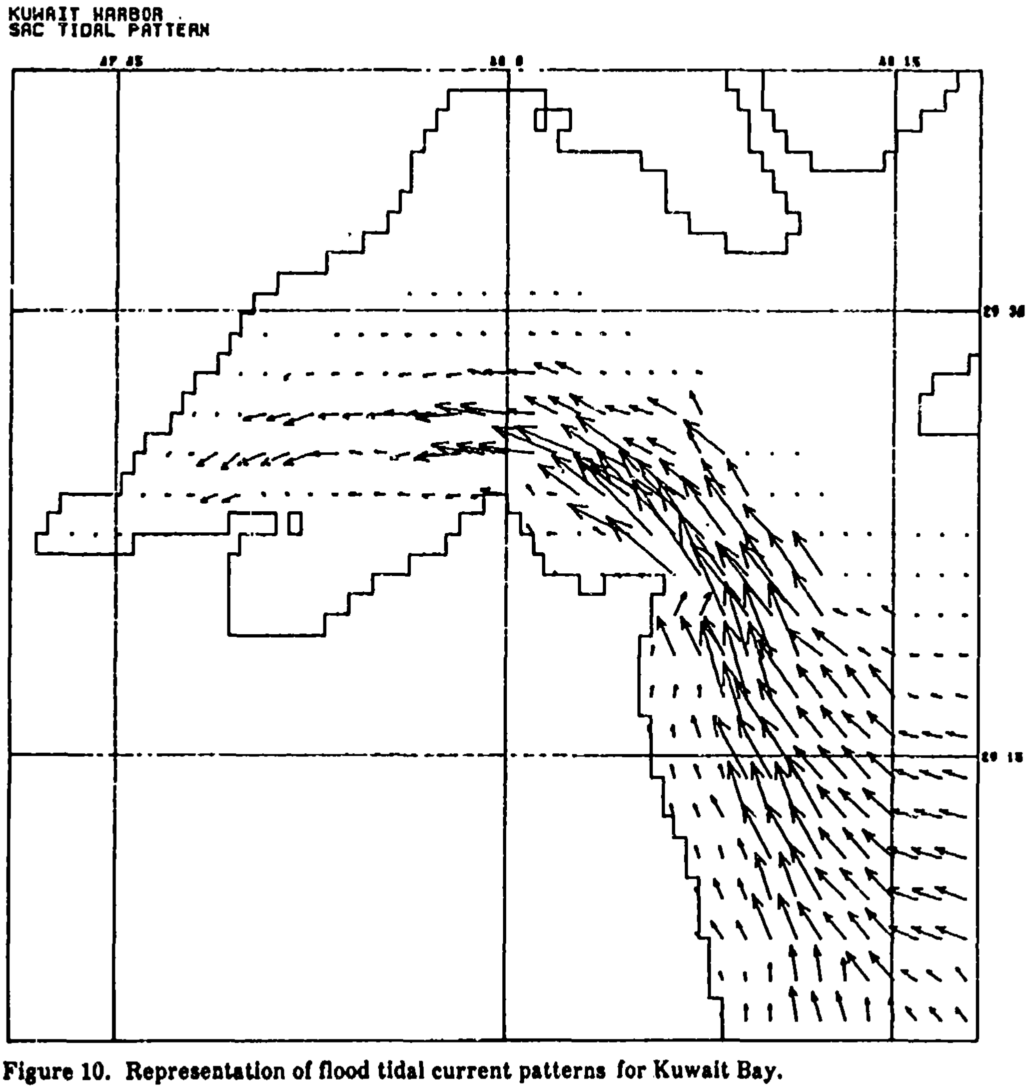

Figure 10. Representation of flood tidal current patterns for Kuwait Bay.

and use these, along with a steady mean component, to represent the flow which is not balanced by the instantaneous wind. A linear dependence is hypothesized which is the appropriate formulation for shallow regions where the bottom stress is the major dissipation process.

Our proposed keying strategy for the wind-driven currents is admittedly empirical but it does preserve a number of circulation features that can be seen in the area. For example, the predicted currents respond to variations in the wind but do not go to zero during short calm periods; currents in the vicinity of Shuaiba will be weak and variable with a slightly negative correlation to the wind variations; and a general southeasterly current is seen to increase in strength as one moves south along the coast towards Saudi Arabia. All of these are observed features and the predicted magnitudes of the current patterns are consistent with a much wider body of observational data that is available for the Kuwait coast.

To carry out the trajectory analysis, we must also specify the diffusion and spreading processes. Small-scale dye studies from power plant effluent studies provide some information for diffusion along the Kuwait coast. However, because of the slightly larger scale of resolution used in the model, larger diffusion coefficients will be necessary. Typical coastal values are on the order of 1-5 x 10^5 cm^2/second.

We now have all the components necessary to assemble a trajectory analysis model for the Kuwait region :

1) Three nested maps are considered (Figure 6);

2) North- and west wind current response patterns which can be linearly summed to predict all wind forcing cases are associated with each map
   a) Figure 2 is associated with the Arabian Gulf map
   b) Figure 8 is associated with the Kuwait coast map
   c) Figure 9 is associated with the Kuwait Harbor map;

3) The tidal current patterns (Figure 10) are associated with the Kuwait Harbor map;

4) The diffusion coefficient is set between 1 and 5 x 10^5 cm^2/second with the understanding that it should be adjusted during the course of the trajectory analysis study based on observations of the spill as it develops. (An iterative hindcast/forecast process is obviously suggested);

5) 25% of the long-term mean wind components are keyed to each of the wind-driven component patterns;

6) 75% of the variable six-hour averaged winds components are keyed to each of the wind-driven component patterns;

7) The six-hour averaged wind vectors are used to key the indirect surface transport processes; and

8) The time-dependence of the tidal height curve for Kuwait Harbor is associated with the tidal current pattern.

This now completes the description of the Kuwait regional trajectory analysis model. With a spill model configured as indicated above, and loaded into an iterative, interactive simulation program, we are in a position to perform trajectory analysis studies with a minimum amount of actual data input at run time. Tidal height predictions, forecasted winds, and monthly historical mean winds, along with the initial distribution and type data on the pollutant are sufficient input parameters to carry out real time trajectory analysis for support of spill response activities. If forecasted winds are replaced by observed winds it is possible to perform hindcast analysis with this same model configuration. When carrying out trajectory analysis for time or length scales longer than those dominated by tidal excursions for use in assessment or contingency planning modes, the only required input data will be the statistical wind distribution divided into speed and direction classes. These cases include the extremely important class of receptor mode trajectory analysis which we will now consider.

4. RECEPTOR MODE ANALYSIS

Trajectory analysis is most commonly carried out to support real time or tactical spill response. In this case, a spill is hypothesized, environmental data is entered, and the questions of "Where will the pollutant go?", "When will it get there?", and "What will it look like?" are all addressed. For the problems associated with spill response planning or contigency planning, an alternate formulation, referred to as receptor mode analysis, is particularly useful (Galt, 1984; Galt and Payton, 1983; Gilbert, 1983). In this mode of analysis, a high value receptor site is identified, and we then address the question of where a pollutant could come from such that it could reach the high value receptor site or target. To do this, a statistical ensemble of hypothesized spills are traced backwards in time and space. The output from this type of analysis is presented as two maps or distribution fields that can be graphically combined.

The first map is a probability distribution which indicates the chance that a pollutant would have of moving from any location in the marine environment to the high value receptor site. The second map shows the minimum time-of-travel contours. This data defines a threat zone for the high value target or receptor and indicates how long response personnel would have to set up and implement mitigation procedures.

To carry out this analysis for Kuwait, four high value receptor sites were identified. For these studies, statistical winds from Mina Al Ahmadi were used to key the indirect wind transport processes and the wind-driven current components. As an example, Figure 11 shows a contour plot of the statistical wind distribution for the month of November.

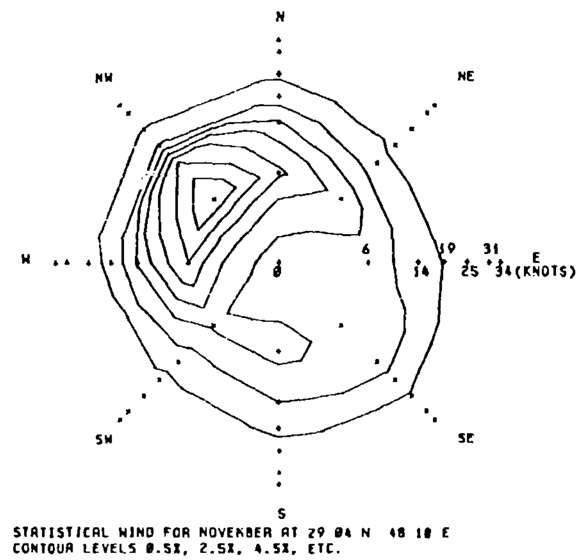

Figure 11. Contour map of the Statistical wind distribution for November from data collectes at Mina Al Ahmadi.

Because a statistical ensemble of spill trajectories is being considered, tidal currents were not explicitly included in the receptor mode analysis since the tidal phase would be random and the net effect would only be an increased scatter or uncertainty in the displacements. To compensate for this effect, a diffusion coefficient of 2.6×10^5 is used for all of the receptor sites. This diffusion coefficient value is well within the normal range for the offshore region but slightly higher than the norm for the inner bay.

For each site 250 spills were considered in the statistics and their displacements were traced for five days during the month of November. Figure 11 indicates the receptor mode analysis results for one of these sites for the month of November. The threat probability distribution is contoured with four solid, heavy lines. The inner contour surrounds the region where the receptor site has a greater than 40% probability of being impacted if the pollutant is found within this contour. The second contour surrounds the area with a greater than 10% probability of impacting the receptor site. The third contour surrounds the greater than 1% probability of threat area; and the fourth contour indicates the maximum extent of any possible threat zone to the receptor site.

Figure 12 shows the minimum time-of-travel contours with a contour interval of 24 hours. These contours are indicated by dotted lines.

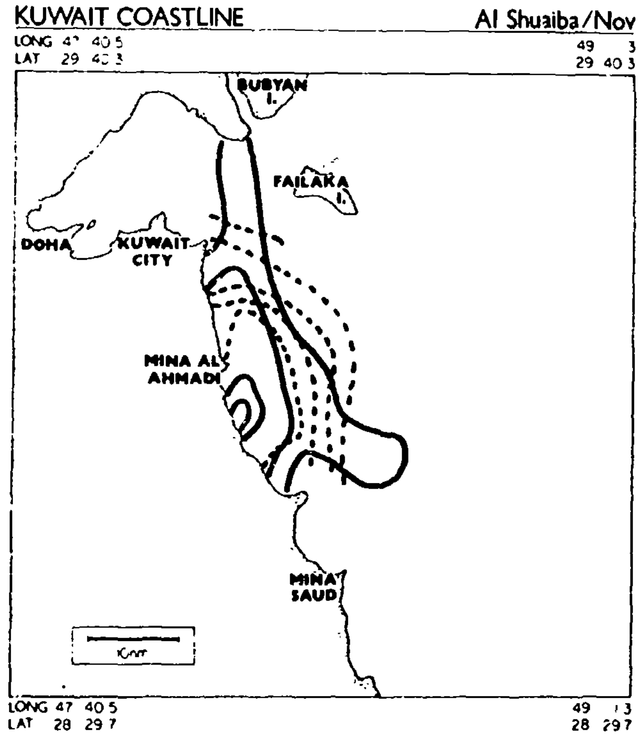

Figure 12. Example of reception mode analysis for November at Al Shuaiba Site. Probability contours are solid and correspond to areas of 40%, 10%, 1% and greater than 0% probability. Dotted contours indicate time of trowel in days.

These receptor mode maps now provide a basis for developing an efficient and cost-effective response plan for oil pollution protection for the four sites studied. Surveillance programs need only cover the threat zones indicated. Beyond that range, oil sitings are not likely to be relevant to the five-day problem. Once significant oil is identified within the threat perimeter, its relative seriousness can be ascertained. Pre-designated response personnel can be alerted and equipment moved to "ready to deploy" positions. At this point, modeling activity should shift to a tactical support mode and regular forecast/hindcast procedures started. The model, observation, and response components designated in contingency plans should all continue close cooperation and information exchange throughout the duration of the threat alert. After the threat passes, all units can return to the surveillance level program.

5. CONCLUSIONS

In order to investigate the significance of these impacts, estimate their time and space distributions, and to effectively plan defensive strategies, a number of environmental questions must be answered. Trajectory analysis has the ability to provide some of the required answers. In this particular case, the initial level of trajectory analysis focused on the entire Arabian Gulf. Major components of the advective flow were associated with, 1) wind-driven currents, 2) thermohaline or estuarine flow including evaporative and runoff effects, and 3) tidal currents. Based on time and space scales of the analysis, displacements due to tidal currents were seen to be insignificant so these processes were not considered further in the large scale analysis. Each of the relevant current factors was estimated using mass-conserving algorithms and the results were scaled to match available observational data. Wind data considered in the large-scale analysis came from statistical climatological data or real-time hindcast and local meteorological analysis. Combinations of keying strategies for wind and current data were investigated in a series of trajectory experiments. The model output was compared to observed oil siting data. Trajectory analysis results indicate that the primary threat area for coastal impacts covers the southeast coast of Saudi Arabia, Bahrain, Bahrain Bay, and the northern coast of Qatar. Time of travel to these impact areas will be between one to three months and thus pollutants will arrive in a highly weathered state and appear as stiff, dense, tarballs. The long transit times and basically closed nature of the Gulf means that outside of the major plume scattered tarball concentrations will also be likely.

In addition to the Gulf-wide trajectory studies, a regional investigation covered Kuwait waters and used two nested high-resolution maps (Figures 7a, 7b). For this study, wind-driven and tidal flow components were estimated. Alternate keying strategies considering the variations and the mean components of the wind were compared. The statistical wind distribution and similar current statistics for a location offshore of Shuaiba were compared. The current statistics showed a large amount of scatter and a week negative correlation with the wind statistics. Dynamic considerations suggest that this is associated with a coastal bifurcation in the current pattern that shifts up and down the northern half of Kuwait's open coast. On the average, its position appears slightly south of Shuaiba.

Climatological wind data available for Kuwait was used as forcing for a receptor mode analysis for four high-value sites in Kuwait. For each of these locations, threat zone and time-of-travel maps are developed for each month of the year. These maps indicate where offshore sitings of floating oil represent a significant threat to any of these high-value target areas.

With the analysis and experiments presented in this work, it is possible to make some general statements about the large-scale distribution of oil from the Nowruz field as a threat to Kuwait, and some recommendations for how to use these components for developing a modeling response strategy:

1) Given the general Gulf-wide circulation, location of the Nowruz spill, and the statistical winds for the Northern Gulf, the probability of large coherent patches of oil impacting Kuwait are slight. Coastal impacts are more likely going to be associated with peripheral scatter from the edges of the major plume and from impacts due to indirect and widely scattered divergent paths. Relatively long transit times will be associated with either of these pollutant routes.

2) The form of the pollutant reaching Kuwait will most likely be dense, heavily weathered tarballs. As these will have densities close to that of seawater, any turbulent mixing will distribute them down into the mixed layer and away from the surface. This situation often leads to observational reports of "sinking" or "disappearance" of the oil, neither of which may be true. Actual sinking is likely as the tarballs get into the surf zone where sediment can agglomerate onto the oil, and may result from sandfall at sea, but little is know about this process. Once these weathered tarballs are beached, high temperatures can cause them to melt, whereupon they can then flow together and form heavy tar mats.

3) Receptor mode analysis can form the basis for determining threat zones for the four selected high value targets along the Kuwait coast. These threat zones define where regular offshore surveillance would be required. Until significant concentrations are sited within these threat zones, no particular defensive response activities are warranted.

4) If significant oil concentrations are present within a designated threat area tactical modeling support should be initiated with forecast/hindcast activities and response or protection plans should be activated with the issuance of an alert to response personnel. As the probability of impact increases, continual modeling trajectory analysis should work closely with and support actual cleanup and protection procedures.

The overall approach outlined above is believed to offer a conservative and effective oil spill defense strategy for Kuwait waters. At the same time, it will minimize the demands on key scientific and response personnel by evaluating threats and discarding as false alarms sitings with a low probability of impact to the major areas of concern.

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Contributed papers
(abstracts only)

Hydrodynamic modelling : an overview

A'ALIM A. HANNOURA

ABSTRACT

The progressive developments which took place in the field of automated computations and numerical methods over the last three decades have made it possible to simulate a very wide range of hydrodynamic processes. Perhaps the most common problem involved in these processes is the determination of a free surface. Once the free surface is obtained; international flow phenomena such as velocity field and pressure distribution could be found from the solution of the internal flow governing equation.

In this paper a survey of hydrodynamic modelling techniques; governing equations; and different hybrid approaches for the solution of hydrodynamics and transport of foreign elements are presented. Specific case studies of wave-structure interaction are discussed to show numerical procedures as well as limitations.

Oipasipa - A powerful tool for contingency planning

J.W. DIPPNER

ABSTRACT

A new and powerful tool for quantitative oil spill contingency planning is presented in this paper. OIPASIPA (oil patch simulation package) is a deterministic numerical model for the simulation dynamical processes framework is done by a Lagrangian tracer technique. OIPASIPA includes drift by currents and wind, spreading and horizontal dispersion by turbulent diffusion and shear currents. Evaporation of different sorts of crude oil is calculated as a function of temperature and wind. Natural dispersion effects are simulated by an empirical relationship between wind speed and rate of natural dispersion. Comparisons with observation e.g. the Bravo Ekofisk blow out show excellent agreement.

The modular structure of OIPASIPA has a high flexibility and permits convenient implementation of new developments as well as universal application of different kinds of oil spills. The model is designed to fit the requirements of users. It permits risk assessment and sensitivity analysis. OIPASIPA may also be run in an interactive mode. Hence it is a powerful tool for quick decisions in clean-up strategy.

Tidal charts of the Arabian Sea North of 20°N

KHAWAJA ZAFAR ELAHI

ABSTRACT

A depth-averaged two-dimensional numerical model (20°N to 25°N, 56°E to 70°E) of the Arabian Sea, including Gulf of Oman is developed to reproduce the major diurnal and semi-diurnal tidal constituents. The model has resolution of 1/2° both latitude and longitude and has open boundary at latitude 20°N along which tidal input data, derived from the emperical co-tidal charts of the Arabian sea, is applied. The classical non-linear hyperbolic initial and boundary value problem of long wave propagation in shallow waters is solved by the explicit finite difference technique. The results regarding tidal elevation are used to develop detailed co-tidal and co-amplitude charts for principal tides. The charts provide the possibility to predict the tidal elevation at the coast and also in the open sea area with very higher accuracy. These can be used as the deriving force for development of numerical model to study the tidal dynamics in the Gulf of Oman and the Arabian Gulf.

Numerical modelling of tidal flows in estuaries using the vertically integrated equations for depth averaged motion

V. CARR

ABSTRACT

A numerical model of tidal structure in various channels is constructed. Reduction of the wave-forms into Fourier components is employed to determine the magnitude of the inherent non linearity in the vertically integrated equation for depth averaged motion at positions throughout the channel.

Illustration of tidal structure is given for pure lunar semi-diurnal forcing and for combined lunar-solar forcing.

Additionally, non linear interactions between luner and solar tides are presented.

The effects of imposed constrictions of the channel on tidal structures together with mean elevation profiles are shown and the net flow deduced.

Simulation models for pollutant transport in the marine environment - capabilities and limitations

J. POST

ABSTRACT

Industrial activities and antropogene near-shore pollution are two important reasons for the development of dispersal models. The physical processes of dispersal are given by the well known transport diffusion equa-

tion. The quality of a dispersal model depends strongly on the accuracy of the circulation model, since the advection is the most important part of the equation. The development of circulation models has a long history in the Institute of Oceanography at the University of Hamburg. During the last 30 years various one-, two- and three-dimensional baroclinic and barotropic models based on explicit or implicit finite difference schemes are designed. The models show reasonable agreement in comparison with measurements and seem to be a good basis for transport models. In the latest stage a three-dimensional baroclinic model based on a semi-implicit difference scheme is developed which is one of the quickest algorithm in the world. Beside the circulation models various dispersal models are constructed for transport and diffusion of heat, salt, radioactive waste, sewage.

Oceanographic modelling applications for industry in the Arabian Gulf

R.O. WILLIAMS

ABSTRACT

Modelling of meteorologic and oceanographic (metocean) processes have numerous applications for coastal and offshore industries for both design and operation bases.

Design of facilities typically requires extreme event and joint probability analyses based on modelling of long term continous metocean data. Major storm data are used for developing hindcast models of winds, waves, currents, and storm surge and the inter-relationships to arrive at, for example, the "100 year storm".

Industrial operations require metocean modelling for day-to-day activities such as vessel operation and berthing and emergencies such as oil spill tracking and clean-up.

Semi empirical method of estimating residual surface currents in the KAP region

WILLIAM J. LEHR AND ROBERT J. FRAGA

ABSTRACT

Ship drift data are combined with a streamline equation for steady state residual currents suggested by Nihoul. Two cases are considered : a closed Gulf case and a case where flow through the Strait of Hormuz is allowed. The solution for the steamline equation with the boundary conditions appropriate to each case is obtained numerically using finite element techniques.

A coupled numerical model for predicting storm-surge flooding extent

T.C. GOPALAKRISHNAN

ABSTRACT

Flooding of coastal areas due to storm-surge is an important problem re-

quiring predictive analysis. Such an analysis would enable the coastal communities to plan their coastal activities and construction so as to avoid damage to life and property. Several numerical models have been developed in the past to compute the storm-surge intrusion, given the storm parameters and coastal conditions. Most of these models do not consider the extent of flooding due to wave attack over storm-surge. The present study evaluates the coastal inundation due to both storm-surge and storm wave attack over the enhanced water levels.

Storm-surge some distance offshore from the coastline is computed using a two-dimensional finite element model. The governing equations are the momentum and continuity relations with due emphasis on Coriolis and wind forces. Using the values of storm-surge thus predicted, a one-dimensional moving boundary model is used to compute the extent of intrusion on land due to the surge at individual locations of interest. Over the water level thus produced, the storm wave is allowed to ride. Here again the one-dimensional moving boundary approach is relied on to compute the extent of flooding due to the storm wave. The governing equations for the wave computation will not include the Coriolis force, as the phenomenon is one of short duration.

The above model was applied to the North Caroline Coast, USA. The paper details this case study and gives sample results.

MEPA Marine Weather Services operational models

AL-DEGHAITHER, D BROWN*, R. CHAO*, R. LANGLAND*, H. LEWIT*
C. LOZANO*, V. PETERSON*, G. ROSENBERGER

ABSTRACT

MEPA Marine Weather Services include the routine production of sea level pressure, surface winds, singular waves, mean currents, water heights, and surface currents for both the Arabian Gulf and the Red Sea. These products support MEPA forecast services for the trajectory and evaporation spreading cil spill models.

In addition, MEPA has hydrodynamic models for the major harbord and ports in the Kingdom and the capability of rapid model deployment for a new area.

In this paper we give an overview of this set of models giving a critical appraisal of the data base input, the heuristics and physics used in the models, and a discussion of the reliability of the model output. Suggestions for further improvement are included.

An evaluation of Jubail meteorological data to provide wind parameters for oil spill movement predictions

KARL F. ZELLER AND ASSAD T. AMR

ABSTRACT

The Royal Commission for Jubail and Yanbu has been collecting meteorological and air quality data at eight locations in and around Madinat Al-Jubail Al-Sinaiyah since August 1978. Four of the eight sites are adjacent to the Arabian Gulf, and the other four sites are located several kilometers inland. One of the inland sites has a 90-meter tower and continually collects meteorological data at 10, 50 and 90 meters above ground. The other seven sites have 10-meter meteorological towers and also collect data continously.

Surface oil spill movement is dependent upon wind turbulence, wind speed and wind direction. Oil spill models require wind parameters as input. Computing surface wind fields over sea from sparse measurements obtained at coastal and inland stations has to be accomplished with great care because of the differences in surface roughness. This paper evaluates selected 5-minute meteorological data obtained at Jubail during homogeneous wind turbulence periods. Data from one of the coastal sites are compared to data from the inland 90-meter tower site. Values of friction velocity, u^*; roughness length, Z_0; coefficient of friction, C_d; and power law exponent are investigated. Wind speeds from these selected data periods are then correlated for subcategories of bulk Richardson number, vertical temperature lapse rate, and wind direction.

The fate of oil pollutants in the marine environment

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ABSTRACT

It's well known that oil spills in the marine environment can be responsible for the expansion of an improverished, altered coastal environment and the disappearance of sensitive types of organisms in the polluted areas. Similar effects can be observed in the immediate area around oil refineries in coastal regions. Many of the oil components are known to be toxic, carcigenic or mutagenic.

Part of the ongoing research in this laboratory concerning biological and chemical studies of marine organisms in the territorial waters of Saudi Arabia deals with asserting the effect of oil pollutants on marine life in these waters. To do so one must first determine the fate of oil components spilled onto coastal area. The samples chosen for this study comprised a crude oil and two oil residues collected from Abu Ali Island and Tarut Island shores. The samples were fractionated into their major components: saturates, aromatics and polars. Each of these fractions were then analyzed by infrared and ultraviolet spectroscopy and by high performance liquid chromatography. Several standard compounds were used for the identification of the major compounds in each fraction.

As would be expected the oil residues were devoid of the low molecular saturated hydrocarbons and the volatile aromatic hydrocarbons but enriched with the polar constituents. The biological implication of the data including examples of some oil compounds that accumulate in marine organisms will also be discussed.

Movement of oil slicks in the Arabian Gulf during stormy periods

T.S. MURTY AND M.I. EL-SABH

ABSTRACT

A time-dependent, two dimensional numerical model has been developed to simulate the movement of oil slicks in the Arabian Gulf. Initially, the oil is assumed to spread under the action of gravity, inertia and surface tension forces, but most of the movement is due to the currents in the water column

due to wind-driven circulation and tides. The output from tidal and storm surge numerical models for the Arabian Gulf are used as input for the oil slick model which computes the trajectory as well as the area covered by the oil slick, as a function of time. A two-dimensional square grid of 15 km size was used with 59 x 37 grid points and a time step of six minutes was used in the numerical integration. To approximately simulate the movement of the oil slick in the Arabian Gulf that occurred during March-April 1983 at the time of a meteorological situation known as "Shamal", realistic values for the amount of crude oil being discharged into the water (about one thousand metric tons per day) as well as appropriate values for the winds and tides were used. The numerically simulated results show reasonable agreement with the observations.

RECOMMENDATIONS

THE SYMPOSIUM/WORKSHOP,

Considering that the numerical modelling of oceanographic phenomena can provide a powerful tool for assisting in the decision-making processes leading to environmental management policy;

Considering that requirement for predictive models dealing with the dispersion of certain pollutants in marine environments;

Considering the importance of propagating the idea of oceanographic modelling among marine scientists in the KAP Region and the necessity to continue with such action;

Considering the enthusiastic response from marine scientists participating in this and former symposia and workshops;

Considering the lack of oceanographic data that exists in the KAP Region;

Recognizing that the acquisition of sufficient baseline data is a necessary prerequisite for any successful modelling effort;

Considering the need to update marine scientists in the methodology of modelling;

Recognizing the importance of maintaining continous interaction between regional research groups;

Being aware of the fact that the available data base for the Gulf of Oman was not adequate for a comprehensive numerical model;

MAKES THE FOLLOWING RECOMMENDATIONS :

1. Form a group from the region to inventory available oceanographic and atmospheric data pertaining to the KAP Region;

2. Reinforce the efforts made toward the establishment of a regional data center in order to archive and disseminate such data;

3. Collect additional data for use in specific modelling projects in the following fields :

(a) Tides and storm surges
(b) Residual currents and mixing processes
(c) Oil Slicks
(d) Ecosystems

For (a) and (b), data particularly required are :

(i) long-period current measurements taken at key sites and different depths throughout the KAP Region.

(ii) long-period measurements of sea-level variations taken simultaneously around the Gulf, offshore, and in the Gulf of Oman.

(iii) better and more detailed measurements of the wind waves and swell in the KAP Region.

(iv) development of theoretical relationships between wind speed and wave height in shallow water.

In addition, for (b) data include :

(v) large-scale conventional oceanographic observations over the KAP Region and, in particular, during the summer.

(vi) fresh water input to the KAP Region.

(vii) measurements of evaporation throughout the Gulf at different times of the year.

(viii) mixing experiments involving the use of tracers especially to determine vertical mixing time.

For (c), data required are :

(ix) characterization of the oil in particular with regard to properties like weathering, toxicity, dispersibility which bear directly on the environment.

4. Investigate the use of remote sensing techniques to augment, reinforce, and calibrate conventional observation programs in the KAP Region.

5. Establish a regional center for numerical modelling at a research institution in the region to act as a locus for the free exchange of ideas, develop a regional focus and avoid needless duplication of effort, making use of existing facilities in the region.

6. Hold a follow-up workshop/symposium in two years time to review progress and update recommendations.

7. Encourage training of young scientists in the KAP Region in the field of oceanographic modelling.

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