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GULF OF MEXICO NUMERICAL MODEL

-- PROJECT SUMMARY --

MASTER

Alan F. Blumberg
George L. Mellor
H. James Herring

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20 Nassau Street

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TABLE OF CONTENTS

	<u>Page</u>
I. INVESTIGATIVE OBJECTIVES	1
II. ACCOMPLISHMENTS AND RECOMMENDATIONS	2
III. PUBLICATIONS	7
APPENDIX A: SIGNIFICANT MILESTONES	8
APPENDIX B: DELIVERABLES	9
APPENDIX C: PROGRAM TO READ CIRCULATION PREDICTION TAPES	14
APPENDIX D: PROGRAMS TO READ CLIMATOLOGICAL DATA TAPES	17

I. INVESTIGATIVE OBJECTIVES

The objective of this investigation is to develop and assess the skill of a three-dimensional, prognostic numerical model of the Gulf of Mexico and to identify the thermal impact of operating OTEC (Ocean Thermal Energy Conversion) power plants on the physical environment. The investigation consists of the following technical elements:

- a. Adaptation and refinement of an existing multi-layer numerical model to the Gulf of Mexico basin, including realistic boundary conditions and bottom topography, to predict the time dependent circulation and temperature distribution in the Gulf throughout the year.
- b. Comparison of the model predictions with the observed features of the Gulf.
- c. Application of the model to the case of OTEC power plants in the Gulf to estimate the physical perturbations to the environment.

II. ACCOMPLISHMENTS AND RECOMMENDATIONS

An efficient three-dimensional, time dependent prognostic model of the Gulf of Mexico has been developed. The model is driven by winds and surface heat flux derived from climatological, atmospheric surface data, the result of an intensive data analysis study. Mean velocity, temperature, salinity, turbulence kinetic energy and turbulence macroscale are the prognostic variables. Lateral boundary conditions for temperature and salinity and geostrophically derived velocity at the Straits of Yucatan and Florida are obtained from climatological ocean data. An analytical second moment turbulence closure scheme embedded within the model provides realistic surface mixed layer dynamics. Free surface elevation distributions are calculated with an algorithm which calculates the external (tidal) mode separately from the internal mode. The external mode, an essentially two-dimensional calculation, requires a short integrating timestep whereas the more costly, three-dimensional, internal mode can be executed with a long step. The result is a fully three-dimensional code which includes a free surface at no sacrifice in computer cost compared to rigid lid models.

A full year's simulation has been obtained. Along the way many problems have been overcome. In particular one problem of major proportion arose; when initialized with climatological temperature and salinity fields the model developed a very large gyre in the region of the Loop

Current. The recirculating gyre transport was 120 Sverdrups over and above the transport of 30 Sverdrups specified at the Straits of Yucatan and Florida and persisted while migrating westward for the 60 day length of the run. After considerable effort the problem associated with the standard method of computing baroclinic forcing and associated with the large bottom topographic variability in the Gulf was identified and remedied. The model is now capable of initialization with real data in regions of large topographical variation without resorting to a large horizontal eddy viscosity.

The results from the one year calculation appear, subjectively, to be a rather good simulation. The Loop Current does not shed but our understanding of Loop Current dynamics is not sufficient to generate a priori expectation of shedding in the model. The ability of the model to reproduce the large scale features of the circulation such as the variability, intensity and areal extent of major current systems has been established from comparisons with observational data. The seasonal variation of the mixed layer and thermocline compares well, but not perfectly, with climatology. Most important, however, is the fact that we are now able to identify detailed deficiencies and probably eliminate most of them.

Subject to quantitative diagnosis (heat and salt balances), the following model deficiencies can now be identified:

- 1.) Further development to reduce simulation costs for a given grid resolution is indicated. On the other hand grid resolution ideally should be refined which, however, automatically increases cost.

2.) At the 200-500m depths the Gulf is warming by as much as 2°C over the year and salinities at these depths are becoming saltier. This may be related to incorrect specification of the inflow/outflow boundary conditions at the two Straits and possibly to the subsurface downwelling produced by a stronger than observed anticyclonic western gyre. The problem should be identifiable via heat budget studies.

3.) The surface temperatures exhibit cooler than observed distributions. This may partly be the result of excessive upwelling and may partly be related to the imprecise imposed heat flux. The feedback heating mechanism does correct significantly for the latter, presumed data analysis error but not for a residual timing error in the delicate transition period.

4.) The neglect of surface mass flux and river inflow should be reconsidered. Their inclusion will probably eliminate almost homogeneous salinity distributions in the upper layer.

5.) The atmospheric climatology yields mean vector component stresses needed to drive the general circulation and the mean of the stress vector modulus needed, it is thought to drive mixed layer deepening. A simple time dependent wind model incorporating these statistics now drives the numerical Gulf model. The wind model is probably too simplistic because actual surface layer mixing is dominated by wind events and averaging over the event time scale may inhibit mixed layer deepening in the numerical model.

6.) The model requires empirical stipulation of horizontal coefficients of viscosity and heat and salt diffusivity. Although required

for numerical stability, we do not yet know the sensitivity of these quantities on the computed results. "Background" vertical coefficients of viscosity and diffusivity are also stipulated; they are not required numerically and those used in the model ($1 \text{ cm}^2 \text{ s}^{-1}$) are small compared to that generated by the turbulence model ($\sim 100 \text{ cm}^2 \text{ s}^{-1}$). Over a period of 12 months, however, the model results are sensitive to the background diffusivity. We believe, however, that a value of zero is incorrect. More science is needed here.

7.) The dynamics of the eddy shedding by the Loop Current needs further investigation. Recent efforts by another research group have made a significant contribution. One of their, somewhat surprising, results is that an eddy may only develop after 2-3 years of model integration. However, their model is a two-layer one with no thermodynamics and their results, while suggestive, may not have direct quantitative relevance to the present results.

While the results of the model appear quite meaningful, the predicted distributions require further diagnoses and analysis to identify and quantify the sources of error and to prescribe changes to improve further simulations. Studies are needed to determine in detail how sensitive the results are to the assumptions built into the model and to the numerical representations of the imposed boundary conditions.

Exploratory one dimensional simulations to assess the thermal impact of OTEC operation on the Gulf have been conducted. The simplified model, driven by the same meteorological forcing as the three-dimensional model, produces results which indicate that for an even distribution of plants

the Gulf-wide impact of operating a reasonable number of plants is probably small. However, a concentration of plants may produce large local changes and perhaps have a noticeable Gulf-wide impact. Further studies must include running the three-dimensional model with appropriate distributions of OTEC plants to assess any local effects.

III. PUBLICATIONS

1. Blumberg, A.F. and G.L. Mellor, 1979: A whole basin model of the Gulf of Mexico. Proceedings of the 6th Annual Conference on OTEC, Department of Energy, Washington, D.C. (also Report No. 61, Dynalysis of Princeton).
2. Blumberg, A.F. and G.L. Mellor, 1981: A numerical calculation of the circulation in the Gulf of Mexico. Report No. 66, Dynalysis of Princeton, Princeton, NJ 08540.

APPENDIX A: SIGNIFICANT MILESTONES

September 1978: Reformulation of numerical model to accommodate the physical characteristics of Gulf of Mexico.

October 1978: Receipt of oceanographic data tapes from NODC.

November 1978: Receipt of atmospheric surface data tapes from NCC.

December 1978: Meeting with technical manager and outside consultants.

January 1979: Completion of oceanographic climatology data sets.

May 1979: Completion of model recoding effort which produced "slabbed" model.

June 1979: Attendance at 6th OTEC conference in Washington, D.C. and presentation of a paper.

August 1979: Completion of climatological atmospheric data sets.

November 1979: Meeting with outside consultants on surface heat flux calculations.

December 1979: Meeting with technical manager and outside consultants.

January 1980: Prognostic 60 day model results depicted unrealistic eddy event.

March 1980: Completion of constant-level numerical model.

June 1980: Attendance at 7th OTEC conference in Washington, D.C.

July 1980: Investigation of and solution to anomalous eddy behavior.

October 1980: Operational Gulf model.

November 1980: Achievement of full year simulation of Gulf circulation.

December 1980: Presentation of results (written and oral) to contracting officer and technical manager.

APPENDIX B: DELIVERABLES

The following products from this investigation are being transmitted to the Department of Energy:

1. Gulf of Mexico circulation model
 - a. initial condition program -- Tape DYN001, File=1
 - b. prognostic model -- Tape DYN001, File=2
2. Input data for circulation model
 - a. initial oceanic conditions -- Tape DYN001, File=3
 - b. topography -- Tape DYN001, File=4
 - c. atmospheric boundary conditions -- Tape DYN001, File=5
 - d. oceanic boundary conditions -- Tape DYN001, File=6
3. Circulation predictions -- Tape DYN002 and DYN003
4. Climatological data base
 - a. oceanic -- Tape DYN004, File=1-4
 - b. atmospheric -- Tape DYN004, File=5-16
5. Technical report entitled, "A whole basin model of the Gulf of Mexico" -- Dynalysis of Princeton Report No. 61.
6. Technical report entitled, "A numerical calculation of the circulation in the Gulf of Mexico" -- Dynalysis of Princeton Report No. 66.
7. A fully integrated vector and contour graphics package.
8. Specially formatted circulation prediction results at 30 day intervals compatible with graphics package.

The magnetic tapes included in the technological transfer have 9 tracks, no labels and a density of 6250 bpi. The tapes are:

1. Tape = DYN001

a. File = 1 -- initial condition program

File characteristics are:

LREC = 80

BKSZ = 4000

RCFM = FB

b. File = 2 -- prognostic model

Same file characteristics as File = 1, Both files are in card image format.

c. File = 3 -- initial oceanic conditions

Read on unit 40 by initial condition program, File characteristics are:

LREC = 32767

BKSZ = 4000

RCFM = VBS

d. File = 4 -- topography

Read on unit 9 by initial condition program, File characteristics are

LREC = 80

BKSZ = 1600

RCFM = FB

e. File = 5 -- atmospheric boundary conditions

Read on unit 30, first file, by prognostic model. File characteristics are same as File = 4.

f. File = 6 -- oceanic boundary conditions

Read on unit 30, second file, by prognostic model. File characteristics are same as File = 4.

2. Tape = DYN002

This tape contains the model predictions for day 0-180 at 2 day intervals. The file characteristics are:

LREC = 32767

BKSZ = 4000

RCFM = VBS

for all the files. A program to read the tape is included in Appendix C along with a glossary defining various quantities. The files contain:

<u>File</u>	<u>Day</u>
1	2-30
2	32-60
3	62-90
4	92-120
5	122-150
6	152-180

3. Tape = DYN003

This tape is similar to tape DYN002 except that it contains the model predictions for day 182-360. The files contain:

<u>File</u>	<u>Day</u>
1	182-210
2	212-240

<u>File</u>	<u>Day</u>
3	242-270
4	272-300
5	302-330
6	332-360

4. Tape = DYN004

The files on this tape contain oceanic and atmospheric climatological data sets. Both the oceanic data from the National Oceanographic Data Center (NODC) and the atmospheric data from the National Climatic Center (NCC) have been carefully edited to remove erroneous data entries. The data are sorted by 1°x1° squares for the entire Gulf. The ocean data is seasonal and has been divided into 29 vertical levels while the atmospheric data represents monthly mean surface conditions. Programs to read the data and glossaries describing the fields are included in Appendix D. The file characteristics are:

LREC = 80

BKSZ = 1600

RCFM = FB

The files contain:

<u>File</u>	<u>Contents</u>
1	January-March ocean data
2	April-June ocean data
3	July-September ocean data
4	October-December ocean data
5	January atmospheric data

<u>File</u>	<u>Contents</u>
6	February atmospheric data
7	March atmospheric data
8	April atmospheric data
9	May atmospheric data
10	June atmospheric data
11	July atmospheric data
12	August atmospheric data
13	September atmospheric data
14	October atmospheric data
15	November atmospheric data
16	December atmospheric data

APPENDIX C: PROGRAM TO READ CIRCULATION

PREDICTIONS TAPES

```

COMMON/COR/CORR(24)
COMMON/CONS/ISPLIT,ISTART,IEND,ISPI,ISP2I,SMOTH,UMOI,DAYI
COMMON/PMASK/DUM(34,24),DVM(34,24),FSM(34,24)
COMMON/PINTE/E(34,24),ET(34,24),ETB(34,24),EG(34,24,2)
COMMON/IO/KUNIT1,KUNIT2,KUNIT3,LEN,JROW,INT
COMMON/PUVRD/VRD(34,24,2),VRD(34,24,2)
COMMON/AID1/Z(16),ZZ(15),DZ(15),DZ2R(15),DZ4R(15),PHIL(5)
COMMON/PHA/H(34,24),AAM(34,24),AAH(34,24),HU(34,24),HV(34,24)
COMMON/AID2/DX,DY,DT,DI,DT2,DT4,DI2R,DI4R,COR4(3),
2      DX2R,DY2R,DX4R,DY4R,DX8R,DY8R,DXDXR,DYDYR,DXDYR,GDX2R,
3      GDY2R,GDX4R,GDY4R,GDX8R,GDY8R,GDX16R,GDY16R
COMMON/PSURF/PWUSUR(34,24),PWUSUR(34,24),PWTSUR(34,24),
2      PWSSUR(34,24),PUTAUS(34,24),PUTAUB(34,24)

C
  DIMENSION U(34,16),V(34,16),Q2(34,16),Q2L(34,16),T(34,16),
2  S(34,16),RHO(34,16),TBM(34,16),WBM(34,16),KM(34,16),
3  I(34,16),W(34,16),URM(34,16),VRM(34,16),KH(34,16),
4  D1(136,16),D2(136,16)

C
  COMMON/PEXTL/FF(34,24,3),FN(34,24,3),FP(34,24,3),
2  TRNU(34,24),TRNV(34,24)
  COMMON/RDRY/TRF(4,15,5),TRB(4,15,5),SRE(4,15,5),SRB(4,15,5),
2  DIDX,DIDY,UGEO(4,5),VGEO(4,5),UGS(4,15,5),VGS(4,15,5)
  COMMON/PWUVRT/PWURROT(34,24),PWURROT(34,24)
  COMMON/BINDEX/KBU(34,24),KBV(34,24),KBT(34,24),KBW(34,24)
  COMMON/BERIC/FRICX(34,24),FRICY(34,24)
  REAL ISPI,ISP2I,KM,KH,L
  DOUBLE PRECISION RHO,T,B

C
  DIMENSION RB1(2448),RB2(4080),RB3(81),RB4(24),RB5(28),
2  RB6(1842),RB7(8),RB8(8976),RB9(4080),RB10(3264),
3  RB11(6),RB12(1632),RB13(4896),RB14(3264)
4  ,RB15(1632)

C
  EQUIVALENCE (RB1,DUM),(RB2,H),(RB3,Z),(RB4,CORR),(RB5,DX),
2  (RB6,TBE),(RB7,ISPLIT),(RB8,FF),(RB9,E),(RB10,VRD),
3  (RB11,KUNIT1),(RB12,PWURROT),(RB13,PWUSUR),(RB14,KBU)
4  ,(RB15,FRICX)

C
  EQUIVALENCE (T,D2(1,1)),(S,D2(69,1)),(U,D1(1,1)),
2  (V,D1(35,1)),(Q2,D1(69,1)),(Q2L,D1(103,1))

C

```

```

C      DIMENSION DATA(34,24,16)
C
C      IM=34
C      JM=24
C      KB=16
C      KR=KB-1
C
C      DO 100 NCOUNT=1,100
C
C      READ(50,END=110)
C      2 RB1, RB2, RB3, RB4, RB5, RB6, RB7, RB8, RB9, RB10, RB11, RB12, RB13, RB14, RB15
C
C      TIME=DAYI*FLOAT(INT)
C      WRITE(6,2) TIME
C      2 FORMAT(////20H THE RESULTS AT DAY ,F6.0////)
C
C      DO 120 J=1, JM
C
C      READ(50) D1, D2, RHO, TRM, WBM, KM, L, W, URM, VRM, KH
C
C      DO 130 K=1, KR
C      DO 130 I=1, IM
C      DATA(I, J, K)=U(I, K)
C      DATA(I, J, K)=V(I, K)
C      DATA(I, J, K)=W(I, K)
C      DATA(I, J, K)=Q2(I, K)
C      DATA(I, J, K)=Q2I(I, K)
C      DATA(I, J, K)=T(I, K)
C      DATA(I, J, K)=S(I, K)
C      DATA(I, J, K)=RHO(I, K)
C      DATA(I, J, K)=KM(I, K)
C      DATA(I, J, K)=KH(I, K)
C      DATA(I, J, K)=L(I, K)
C      130 CONTINUE
C
C      120 CONTINUE
C
C      PRINT OUT THIS DATA FIELD HERE ... THE LEVEL IS K
C
C      100 CONTINUE
C      110 CONTINUE
C
C      STOP
C      END

```

Notation

U, V, W	velocity components [east-west, north-south, vertical; all in m/s]
Q2	twice turbulence kinetic energy [m^2/s^2]
Q2L	product of turbulence kinetic energy and macroscale [m^3/s^2]
T	temperature [$^{\circ}\text{C}$]
S	salinity [$^{\circ}/\text{oo}$]
RHO	density -1 [gm/cm^3]
KM	vertical eddy viscosity [m^2/s]
KH	vertical eddy diffusivity [m^2/s]
L	turbulence macroscale [m]
E	surface elevation [m]
H	topography [m]
DX	east-west grid spacing [m]
DY	north-south grid spacing [m]
DZ	vertical grid spacing [m]
DT	external mode timestep [sec]
DI	internal mode timestep [sec]
DATA	storage array, work space
PWUSUR, PWVSUR	wind stress components [m^2/s^2]
PWTSUR	heat flux [$\text{m}^{\circ}\text{C}/\text{s}$]
PWSSUR	mass flux [m/s]
INT	number of the time step

APPENDIX D: PROGRAMS TO READ CLIMATOLOGICAL DATA TAPES

Ocean Data:

```

C      DIMENSION TV(18,12,29),DPTH(29)
C
C      DATA DPTH/0.,10.,20.,30.,50.,75.,100.,125.,150.,
2 200.,250.,300.,400.,500.,600.,700.,800.,900.,1000.,1100
3 1200.,1300.,1400.,1500.,1750.,2000.,2500.,3000.,3500./
C
C      TU=20
C
C      DO 100 K=1,29
C
C      READ(IU,25) ((TV(I,J,K),I=1,18),J=1,12)
C      READ(IU,25) ((TS      ,I=1,18),J=1,12)
C      READ(IU,25) ((TN      ,I=1,18),J=1,12)
C      READ(IU,25) ((SV      ,I=1,18),J=1,12)
C      READ(IU,25) ((SS      ,I=1,18),J=1,12)
C      READ(IU,25) ((SN      ,I=1,18),J=1,12)
C
C      100 CONTINUE
C
C      25  FORMAT(8E10.3)
C      STOP
C      END

```

Notation:

DPTH	depth [m] of standard ocean levels
TV	mean temperature [°C]
TS	standard deviation [°C] of temperature
TN	number of observations for temperature
SV	mean salinity [°/oo]
SS	standard deviation [°/oo] of salinity
SN	number of observations for salinity

Atmospheric Data:

```
DIMENSION NT(18,12), TXY(18,12), STXY(18,12)
DATA IXD, JYD/ 18, 12/
```

C

```
IU=30
```

C

```
READ (IU,52) ((NT(I,J), I=1, IXD), J=1, JYD)
READ (IU,53) ((TXY(I,J), I=1, IXD), J=1, JYD)
READ (IU,53) ((STXY(I,J), I=1, IXD), J=1, JYD)
READ (IU,53) ((TX, I=1, IXD), J=1, JYD)
READ (IU,53) ((STX, I=1, IXD), J=1, JYD)
READ (IU,53) ((TY, I=1, IXD), J=1, JYD)
READ (IU,53) ((STY, I=1, IXD), J=1, JYD)
READ (IU,53) ((TA, I=1, IXD), J=1, JYD)
READ (IU,53) ((STA, I=1, IXD), J=1, JYD)
READ (IU,53) ((TS, I=1, IXD), J=1, JYD)
READ (IU,53) ((STS, I=1, IXD), J=1, JYD)
READ (IU,53) ((WT, I=1, IXD), J=1, JYD)
READ (IU,53) ((SWT, I=1, IXD), J=1, JYD)
READ (IU,53) ((H, I=1, IXD), J=1, JYD)
READ (IU,53) ((SH, I=1, IXD), J=1, JYD)
READ (IU,53) ((E, I=1, IXD), J=1, JYD)
READ (IU,53) ((SE, I=1, IXD), J=1, JYD)
READ (IU,52) ((NR, I=1, IXD), J=1, JYD)
READ (IU,53) ((RS, I=1, IXD), J=1, JYD)
READ (IU,53) ((SRS, I=1, IXD), J=1, JYD)
READ (IU,53) ((RL, I=1, IXD), J=1, JYD)
READ (IU,53) ((SRL, I=1, IXD), J=1, JYD)
READ (IU,53) ((G, I=1, IXD), J=1, JYD)
READ (IU,53) ((SG, I=1, IXD), J=1, JYD)
READ (IU,53,END=300)
```

```
300 CONTINUE
```

```
REWIND IO
```

```
52 FORMAT (16I5)
```

```
53 FORMAT (8(1PE10.3))
```

```
STOP
```

```
END
```

Notation:

NT = N_T ; number of observations for TXY, TX, TY, TA, TS, TW, H and E.

TXY = $\frac{1}{N_T} \sum_{i=1}^{N_T} |\tau|$; shear stress magnitude $[\text{Nt/m}^2]$

TX, TY = $\frac{1}{N_T} \sum_{i=1}^{N_T} \tau_x$, $\frac{1}{N_T} \sum_{i=1}^{N_T} \tau_y$; X and Y components of mean shear stress $[\text{Nt/m}^2]$

TA air temperature at 10m above surface $[\text{°C}]$

TS sea surface temperature $[\text{°C}]$

TW wet bulb temperature $[\text{°C}]$

H sensible heat flux into sea surface $[\text{W/m}^2]$

E evaporation rate $[\text{Kg/m}^2/\text{s}]$

NR = N_R ; number of observations for RS, RL and G

RS shortwave radiant heat flux into sea surface $[\text{W/m}^2]$

RL longwave radiant heat flux into sea surface $[\text{W/m}^2]$

G net heat flux into sea surface $[\text{W/m}^2]$

ST = $\sqrt{\frac{1}{N} \sum_{i=1}^N \Gamma^2 - \bar{\Gamma}^2}$; standard deviation of variable Γ with number of observations N.