Wave Modeling New Orleans - Mississippi River Gulf Outlet

Hurricane Katrina August 2005

FINAL REPORT

C. Gautier, M. Kok, and J.K. Vrijling

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Preface

This report describes numerical modeling of the waves in the Lake Borgne vicinity of New Orleans (Figure 1.1) during hurricane Katrina on August 29th, 2005. This report also describes model runs using varying scenarios of the MRGO configuration. This project was a joint effort by the Delft University of Technology and Svašek Hydraulics of the Netherlands and undertaken January-May 2008. The Client is the Law Offices of Joseph M. Bruno, New Orleans, Louisiana.



Contents

Preface **3**

Contents **4**

1 Introduction **6**
1.1 General introduction 6
1.2 Objectives 6
1.3 Description of the area 7
1.4 Approach 8

2 General set up SWAN simulations **9**
2.1 Introduction 9
2.2 Computational grids, bathymetry and boundary conditions 10
2.3 Wind and water levels 11
2.4 Physical and numerical settings 12
2.5 Output 13

3 SWAN Scenario 1 ..... **15**
3.1 Introduction 15
3.2 Input Scenario 1 15
3.3 Results Scenario 1 15

4 SWAN Scenario 2C **17**
4.1 Introduction 17
4.2 Sensitivity tests for influence of vegetation on waves 18
4.3 Input Scenario 2C 21
4.4 Results Scenario 2C 23

5 Conclusions **25**

6 References **26**

Tables

Figures

list of figures

1.1 Location of the study area (within text)
2.1 Position of computational grids and bathymetry for A-grid
2.2 Scenario 1: Bathymetry for C, M, F and G grids [feet relative to NAVD88]
2.3 Scenario 1: Wind fields [knots] 04:00, 05:00, 06:00, 07:00, 08:00 and 09:00am
2.4.a Scenario 1: Water level fields grid A 4:00, 5:00, 06:00, 7:00, 8:00 and 9:00am LT
2.4.b Scenario 1: Water level fields grid M 4:00, 5:00, 06:00, 7:00, 8:00 and 9:00am LT based on ADCIRC data from Robinson experts and FINEL (de Wit, 2008).
2.5.a WAM output locations (red dots);
2.5.b WAM spectra on incoming wave boundary
2.6 Output locations
3.1.a Scenario 1: SWAN results Hs [ft] and wave direction, 4:00 and 5:00 am on grid A
3.1.b Scenario 1: SWAN results Hs [ft] and wave direction, 6:00 and 7:00 am on grid A
3.1.c Scenario 1: SWAN results Hs [ft] and wave direction, 8:00 and 9:00 am on grid A
3.2.a Scenario 1: SWAN results Hs [ft] and wave direction, 4:00 and 5:00 am on grid M
3.2.b Scenario 1: SWAN results Hs [ft] and wave direction, 6:00 and 7:00 am on grid M
3.2.c Scenario 1: SWAN results Hs [ft] and wave direction, 8:00 and 9:00 am on grid M
3.3.a Scenario 1: SWAN results Hs [ft] and wave direction, 4:00 and 5:00 am on grid MFG
3.3.b Scenario 1: SWAN results Hs [ft] and wave direction, 6:00 and 7:00 am on grid MFG
3.3.c Scenario 1: SWAN results Hs [ft] and wave direction, 8:00 and 9:00 am on grid MFG
3.4.a Scenario 1: SWAN results peak wave period Tp [s], 4:00 and 5:00 am on grid A
3.4.b Scenario 1: SWAN results peak wave period Tp [s], 6:00 and 7:00 am on grid A
3.4.c Scenario 1: SWAN results peak wave period Tp [s], 8:00 and 9:00 am on grid A
3.5.a Scenario 1: SWAN results peak wave period Tp [s], 4:00 and 5:00 am on grid M
3.5.b Scenario 1: SWAN results peak wave period Tp [s], 6:00 and 7:00 am on grid M
3.5.c Scenario 1: SWAN results peak wave period Tp [s], 8:00 and 9:00 am on grid M
3.6.a Scenario 1: SWAN results peak wave period Tp [s], 4:00 and 5:00 am on grid MFG
3.6.b Scenario 1: SWAN results peak wave period Tp [s], 6:00 and 7:00 am on grid MFG
3.6.c Scenario 1: SWAN results peak wave period Tp [s], 8:00 and 9:00 am on grid MFG
3.7 Scenario 1: Wave energy spectra t3 (8am).
3.8.a Scenario 1: SWAN computed wave spectra on rays 1-6, 4:00 and 5:00 am
3.8.b Scenario 1: SWAN wave spectra for rays 1-6, 6am till 9am
3.9.a Output locations for additional spectra
3.9.b: Scenario 1: SWAN wave spectra for 8 locations and 6 time steps
3.10.a-l: Scenario 1: SWAN wave parameters on rays
4.1 Decay of incident wave height as function of propagation distance through light vegetation (SWAN results and analytical model)
4.2 Friction coefficients applied in SWAN tests (within text)
4.3 Results SWAN tests for influence friction on waves
4.4 Scenario 2C: Bathymetry for C, M, F and G grids
4.5 Impression of cypress trees in swampy areas (within text)
4.6 Scenario 2C: Applied friction coefficient for SWAN computations
4.7 Scenario 2C: Example reduced wind field [knots] 7 am for version g
4.8 Scenario 2C: Surge water level fields based on data from FINEL and ADCIRC
4.9.a Scenario 2C version i: SWAN results wave height [ft] and wave dir 4-5am grid MFG
4.9.b Scenario 2C version i: SWAN results wave height [ft] and wave dir 6-7am grid MFG
4.9.c Scenario 2C version i: SWAN results wave height [ft] and wave dir 8-9am grid MFG
4.10 Scenario 2C version g&h: SWAN results wave height [ft] and wave dir 8am grid MFG
4.11.a Scenario 2C version i: SWAN results peak wave period [s] 4-5am grid MFG
4.11.b Scenario 2C version i: SWAN results peak wave period [s] 6-9am grid MFG
4.12.ab Scenario 2C version g: SWAN wave parameters on rays at 8 am
4.12.cd Scenario 2C version h: SWAN wave parameters on rays at 8 am
4.12.ef Scenario 2C version i: SWAN wave parameters on rays at 8 am

1 Introduction

1.1 General introduction

On the morning of August 29, 2005, Hurricane Katrina struck southeast Louisiana and triggered what would become one of the worst disasters ever to befall an American city. The storm overtopped levees and floodwalls throughout southeast Louisiana and also caused the levees and floodwalls in the New Orleans area to fail or breach in more than 50 locations. Water rushed into New Orleans and flooded over 80 percent of the city - more than ten feet deep in some neighborhoods.

Flooding of the city of New Orleans originated from several sources (or causes): breaches, overtopping (of the levees and flood control structures) and rainfall. The breaches were, among others, caused by waves. This is the topic of this report. The complex wave field generated during Hurricane Katrina in Lake Borgne that would have impacted the Mississippi River Gulf Outlet (MRGO) would have consisted of two basic kinds of waves reflecting their source; one group being the ocean swells generated offshore that would have long periods and could possibly have reached the MRGO Reach 2; and the second type waves generated locally in Lake Borgne as a result of the wind blowing across the lake. The ocean swells would have periods of up to 16 seconds between crests, while the wind generated waves would have expected periods between 3 and 7 seconds. The ocean swells would be somewhat reduced in height and possible totally assimilated by the wind-generated waves as they crossed the wetlands between the coast and Lake Borgne while the wind waves heights would be related to the fetch (distance over which the wind blows) and wind direction. Both wave types would have a limiting maximum height based on the depth of water the waves would be traversing (frictional drag of the bottom).

What is lacking in Louisiana is real wave data during the passage of major hurricanes. During Katrina, other than some questionable wave data collected in Lake Pontchartrain, no data exists in the nearshore and especially in water bodies such as Lake Borgne. This necessitates the use of wave simulation models to try to decipher what happens in the MRGO during passage of major hurricanes.

Additionally, one of the main factors which was not known until now was the influence of waves on the erosion of the levees along the Mississippi River Gulf Outlet (MRGO). This present report describes model runs for two different scenarios each depicting a variation on the configuration of the MRGO and funnel area. The main body of the report covers runs performed with surge surfaces generated by a combination of ADCIRC data from the Robinson experts, and FINEL data from de Wit (2008). Additional runs are presented in the appendices.

The numerical wave model SWAN is used to characterize the wave hydrodynamic conditions along the GIWW and MRGO during Hurricane Katrina. The flow simulations of the surge (Kemp 2008) and currents (De Wit et al, 2008) are described elsewhere in the Levee Litigation's Team submissions to the court.

1.2 Objectives

The SWAN model was used to derive wave spectra on Lake Borgne and more specifically along the MRGO Reach 2 that were generated during hurricane Katrina, August 2005. The

wave spectra are being used to assess the impact of the presence of the deep, wide and unmaintained MRGO channel during hurricane Katrina on the Lake Pontchartrain and Vicinity (LPV) flood protection structures along the MRGO.

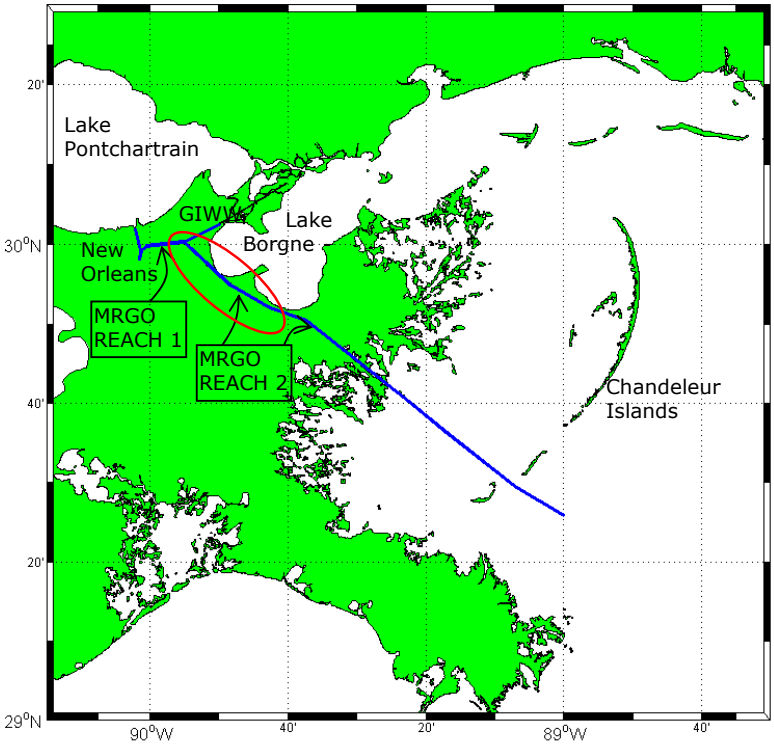


Figure 1.1: Location of the study area.

1.3 Description of the area

The MRGO is situated in Louisiana (USA) and connects New Orleans with the Gulf of Mexico, just east of the Mississippi River. The area of interest, indicated by the red oval in Figure 1.1, is Reach 2 of the MRGO. This is an area where the LPV levees were extensively damaged by waves and some miles destroyed during hurricane Katrina.

The MRGO, excavated in the 1950's and early 1960's is approximately 2000 ft wide (Van Heerden et al, 2007) and has a water depth of circa 40 ft (relative to NAVD88). The land between New Orleans and the Gulf mainly consists of swamps. During Katrina the high surge water levels associated with levee breaches inundated large areas.

As pointed out earlier the waves developed in the MRGO are a combination of locally generated wind waves and deep ocean swell penetrating from the Gulf onto the canal. The latter is strongly dependent on the distance from the Gulf and the strength and direction of the wind field during the storm.

1.4 Approach

The SWAN wave model is used to simulate the waves during Katrina. SWAN computes on a grid how waves generate, dissipate and propagate under the influence of wind, bathymetry, water levels, currents and incoming waves. See Appendix A for a brief explanation on SWAN. The input data provided by the client was converted into a SWAN compatible format. Output is given for a number of pre described output locations in the area of interest.

For this study, SWAN version 40.51AB is used in the stationary mode. The assumption was made that the winds and surge vary slowly enough for the waves to reach equilibrium. IPET in their Volume IV, appendix 4 (page IV-4-31) [ref 1] come to the same conclusion. It is concluded that the steady-state solution is adequate for the simulations.

In the main body of this report two scenarios are presented:

Scenario 1: Katrina real run (base case)

Scenario 2C: Katrina "neutral MRGO" conditions
This scenario is simulated in three different ways to assess the sensitivity for various vegetation options

In the appendices the following additional runs are presented:

Scenario 2A: Katrina "neutral MRGO" without levees, 40 Arpent levee at 6.5ft (App B)

Scenario 2B: Katrina "neutral MRGO" without levees, 40 Arpent levee at 17.5ft (App C)

Scenario 3: Katrina "neutral MRGO" with original dimensions (Appendix D)

2 General set up SWAN simulations

2.1 Introduction

In setting up SWAN a computational grid needs to be developed represented by a geographical domain (X and Y) and a spectral domain (frequency and direction). Next, bathymetry/topography, surge levels, currents, wind and wave conditions are input. Also numerical settings are entered including grid sizes and location and any nesting of grids as well as the required output.

The following times on August 29th, 2005 were simulated:

4:00 am local time (=9:00 UTC, simulation code t6). Surge on the rise pre landfall.

5:00 am local time (=10:00 UTC, simulation code t7). Surge on the rise pre-landfall

6:00 am local time (=11:00 UTC, simulation code t1)
The surge is starting to build up along MRGO, the winds are directly blowing across Lake Borgne at the MRGO levees and the eye is just short of the landfall

7:00 am local time (=12:00 UTC, simulation code t2)
The eye of the hurricane is just south of the MRGO.

8:00 am local time (=13:00 UTC, simulation code t3)
Close to the peak of the surge

9:00 am local time (=14:00 UTC, simulation code t4)
After the peak of the surge and the wind starts to switch to the west.

The SWAN simulations are identified with unique names existing of 5 characters, for example F3aS1. The explanation is as follows:

1) Grid identification (see Paragraph 2.2), either A, C, M, F or G
2) Time step identification (see above), either 1, 2, 3, 4, 6 or 7
3) Version of SWAN model used.
4) "S" for scenario
5) Scenario identification

The coordinate system used in the simulations is UTM (zone 15 R). Input data that was received in US State Plane Coordinate System [longitude; latitude] was transposed accordingly.

The SWAN code utilized the metric system. However, for this report the metric data was converted to feet. One meter equals 3.281 ft.

2.2 Computational grids, bathymetry and boundary conditions

Computational grids

In order to balance resolution (that is sufficiently fine to include major bathymetric variations) and scale (an area that is large enough to translate the offshore waves to the area of interest), a train of nested runs was used (see Table 2.1 and Figure 2.1).

The first grid (A-grid) has its south eastern boundary as the output locations of the WAM simulations carried out by USACE (IPET Appendix page IV-3-51) so that the WAM results can be used as up-wave input for the SWAN simulations. So in this way the IPET STWAVE and our SWAN model runs have the same outer deep water boundary and utilized the same WAM deep ocean wave outputs. The main output of the A-grid is the waves at the boundaries of the C-grid, which is input for the C-run. The C-run provides wave boundary conditions for the M-grid, and the M-grid makes the boundary conditions for both the F-and the G-grid. So as one progresses from A to F and G the grid covered gets less and less while the resolution increases. Therefore, for one particular time step, five simulations are carried out.

In the computations the full circle is considered (waves from all directions), divided into 36 directional bins of 10° each. This would be equivalent to a full plane run in the STWAVE nomenclature. This is the area where IPET ran a half plane version of their STWAVE model and therefore did not capture all the waves impacted the MRGO. The frequency domain goes from 0.0314 Hz to 1 Hz (=1-32 seconds) and is divided into 36 non-uniform frequency bins.

grid	name	area [m^2]	area [ft^2]	resolution [m]	resolution [ft]	number of cells	X0, Y0 [m]	rotation X-axis [+ = counter clockwise]
A	Base	160000 x135000	524933 x 442912	500 x 500	1640 x 1640	320 x 370	885000; 3217500	52°
C	Coast	75000 x 85000	246062 x 278871	200 x 200	656 x 656	375 x 425	794000; 3319500	-38°
M	MRGO	55000 x 20000	180446 x 65617	100 x 100	328 x 328	550 x 200	794000; 3319500	-38°
F	Fine	16000 x 3000	52493 x 9842	20 x 20	66 x 66	800 x 150	797000; 3322000	-38°
G	GIWW	4000 x 16500	13123 x 54134	20 x 20	66 x 66	200 x 825	796000; 3324000	-65°

Table 2.1: Characteristics computational grids

Bathymetry

The bathymetry consists of a combination of data from several sources. GEODAS (http://www.ngdc.noaa.gov/mgg/geodas/geodas.html) is the main source. Between the mainland and the Chandeleur Islands, high resolution bathymetric data was provided by the Robinson experts. LIDAR data was used for the land and the levee heights as supplied by the client's experts. In the finest bathymetry grids (F and G) the elevation of the land just southwest of the levees has been set at 20 ft to be sure that the waves do not pass the levees. No breached levee profiles are included in the bathymetry.

The MRGO and IHNC bathymetry is that as acquired from the Robinson experts. The GIWW has the dimensions of 150 ft wide and 12 ft deep, as provided by the Robinson experts. The resulting water depths in the model area are shown in Figure 2.1 and 2.2 for Scenario 1.

Boundary conditions

Boundary conditions for the nearshore wave modeling were provided by the client as acquired from the Corps of Engineers attorneys. They exist of WAM output spectra (28 frequency bands and 24 directional bands) on 60 locations along the 100 ft depth contour, at every 15 minutes from 28 Aug 00:30 UTC tot 30 Aug 00:00 UTC, 2005.

For the SWAN simulations, WAM spectra at locations 21, 24, 29, 33, 37 are used (see Figure 2.5.a). At sea the waves were very large during Katrina. Table 2.2 gives a few wave parameters for WAM location 33 (roughly X=913500 m; Y=3254300 m). Figure 2.5.b displays the spectra used. Since the frequency and the directional distribution of WAM and SWAN are not identical, interpolation between these two is required, resulting in small differences in boundary conditions.

For all scenarios the same boundary conditions are applied.

local time on 29 Aug	Hs [ft]	Tpeak [s]	Tmean [s]	wave direction coming from[°N]
4:00	41	14.8	13.2	148
5:00	44	14.8	13.4	155
6:00	46	14.8	13.4	163
7:00	47	14.8	13.3	170
8:00	44	14.8	13.0	175
9:00	39	13.5	12.7	181

Table 2.2: Wave parameters from regional WAM Cycle 4.5, location 33, as part of the boundary conditions for SWAN

2.3 Wind and water levels

The wind data consist of non-uniform data fields, based on ADCIRC S08 simulations Advisory 31 by the Robinson experts as modified from Van Heerden et al, 2007. The wind is considered as u10, being 10 m above the surface. Figure 2.3 shows the wind fields on the six simulation times. The eye of the hurricane moves from the Gulf in north-north easterly direction. At 4:00am and 5:00am the winds are blowing across Lake Borgne directly at the MRGO levees. Wind velocities at Lake Borgne are 50-70 knots. At 6:00am the eye is just short of its landfall. At 7:00am the wind velocities are highest, and reach over 90 knots (>45 m/s). At 8:00am as Katrina is crossing the land, wind velocities are reduced. At 9:00am the eye is right over Lake Borgne, and wind velocities at sea are circa 75 knots. The resolution of the wind field is 3281 ft x 3281 ft and was used as such for all computational grids, since the spatial variation in wind is limited.

The water levels are based on a combination of the ADCIRC S08 simulations and the FINEL simulations (De Wit et al, 2008). The FINEL simulations have a high resolution and fully cover the F-grid. Since the area covered by FINEL is smaller than required for the wave simulations, the FINEL surge data is completed with the ADCIRC fields. For the largest A-grid, only the ADCIRC data is used. Plots of the surge water levels for Scenario 1 can be found in Figure 2.4. At 8:00 am the surges in the area of interest (F-grid) are highest, and

reach over 17 feet. The resolution of the surge water level fields is adjusted to fit the resolution of the various computational grids.

2.4 Physical and numerical settings

The simulations are performed with the third-generation wave model SWAN, which was developed by Delft University of Technology, the Netherlands. The most recent version 40.51AB is used for the SWAN simulations. For details see the SWAN User Manual [ref 2].

Physical settings

The following physical settings are applied:

GEN3 WESTH
The computations run in third-generation mode for wind input, quadruplet interaction and whitecapping. Whitecapping is simulated according to the formulation proposed by Van der Westhuijsen et al. (2007), with nonlinear saturation-based whitecapping (Alves and Banner, 2003) combined with wind input of Yan (1978).

QUAD
The non-linear quadruplet wave-wave interactions are activated in the computations, which is the default formulation in SWAN (DIA).

TRIAD trfac=0.05
The wave-wave interaction is activated in the computations using the Lumped Triad Approximation (LTA method). The default values of Triad are used.

BREAKING alpha=1 gamma=0.73
The depth-induced wave breaking is modelled according to Battjes and Janssen (1978), which is default in SWAN

FRICTION JONSWAP
For Scenario 1, the bottom friction is activated in the computations using the JONSWAP formulation. For most grids the default value (CFJON=0.067, recommended for wind sea conditions) is used. The A-grid is the exception. Here CFJON=0.038 is used since this value is more suitable for long waves which occur on the A-grid.
The other scenarios have been carried out with the bottom friction expression of Collins, allowing the friction coefficient to vary over the computational region.

Numerical settings

The convergence criteria are set as follows:
NUM STOPC 0.00 0.01 0.005 98 STAT mxitst=50 alfa=0.0 which means that SWAN stops the iteration process if the relative change in the local significant wave height from one iteration to the next is less than 0.01 m and the curvature of the iteration curve of Hm0 normalized with Hm0 is less than 0.005 m:

$$\frac{\left|H_{m0}^{n}(i,j) - H_{m0}^{n-1}(i,j)\right|}{H_{m0}^{n-1}(i,j)} < 0.01$$

and

$$\frac{\left|H_{m0}^{n}-(H_{m0}^{n-1}+H_{m0}^{n-2})\right|+H_{m0}}{2H_{m0}^{n}}<0.005, \qquad \text{n=3, 4,.....}$$

These conditions must be satisfied in at least 98% of all wet grid points before the iterative process stops or the maximum number of iterations is achieved. The maximum number of iterations is set to 50, which is never reached. Under-relaxation is not applied (alfa=0), because this could stop the process too early.

2.5 Output

The SWAN output exists of block files of several parameters on each entire computational grid (a.o. Hs, Tp, Tm01, Tm-1,0, wave direction). Furthermore, rays are defined where various wave parameters are required as output. Also, a number of points are defined where SWAN gives the 1d and 2d wave energy spectra. A series of points are derived from levee to channel to wetlands (see Table 2.3) for a better understanding of the simulations.

Because small variation in local elevation can have significant influence on wave height, period and direction, a number of output points were chosen varying from levee to toe to the deeper center of the MRGO channel, see Figure 2.6.

Table 2.3 lists the pre described output locations. The lower right hand plot in Figure 2.2 shows the rays on which these points are located. Table 2.4 gives the elevation of the bottom surface of the output locations. Table 2.5 lists the coordinates.

The mean wave direction is the direction in degrees, where waves originate, relative to true North. Thus waves going from east to west would have a direction of 90°, waves going from north to south would have a direction of 0°, and so on.

Loc	Name	lat [N]	lon [W]	UTC [m]	UTC [m]
1	B. Bienvenue	29°59′ 54.51″	89°54′ 55.54″	797576.80	3322623.69
2	Station 430	29°59'12.29"	89°54' 03.80"	798999.25	3321360.77
3	Loc I	29.97368°	89.884833°	800604.59	3319954.56
4	MRGO Halfway	29°58′ 5.11″	89°52′ 40.14″	801298.90	3319352.25
5	Station 540	29°57'58.19"	89°52' 32.15"	801519.03	3319145.08
6	B. Dupre	29°56′ 5.52″	89°50′ 12.26″	805366.68	3315777.24
7	GIWW@BackB	30° 01.597'	89°52.291'	801729.81	3325859.37

Table 2.3: Pre described output locations

Loc	Name	L (levee)	T (toe)	D (deeper part)
1	B. Bienvenue	4.32	-12.91	-42.28
2	Station 430	6.81	0.79	-40.83
3	Loc I	8.60	0.65	-41.31
4	MRGO Halfway	5.88	-1.35	-42.46
5	Station 540	5.89	1.64	-42.96
6	B. Dupre	1.28	-10.42	-12.50
7	GIWW@BackB			-11.37

Table 2.4: Bottom elevation of output locations in feet relative to NAVD88 (positive upwards). For location 1-6 the "L-column" refers to the pre described output locations see Table 2.3. For location 7, the pre described output location is in the deeper part of GIWW and hence mentioned in the "D-column"

Loc	L (levee)		T (toe)		D (deep)	
	X [m]	Y [m]	X [m]	Y [m]	X [m]	Y [m]
1	797577	3322624	797642	3322692	797765	3322849
2	798999	3321361	799062	3321455	799185	3321613
3	800605	3319954	800662	3320027	800797	3320201
4	801299	3319352	801374	3319445	801498	3319603
5	801519	3319145	801586	3319229	801722	3319402
6	805367	3315777	805457	3315900	805482	3315932
7					801730	3325859

Table 2.5: Output locations

3 SWAN Scenario 1

3.1 Introduction

This chapter contains a selection of the SWAN results of Scenario 1: Hurricane Katrina and the physical bathymetry and topography as it existed immediately prior to Hurricane Katrina's landfall. This is called the "Katrina real run".

3.2 Input Scenario 1

Since this scenario should be considered as the base case, input data such as bathymetry, water levels etc is presented in Chapter 2.

3.3 Results Scenario 1

Scenario 1: SWAN results at output locations

Table 3.1 gives the significant wave height (Hs), peak wave period (Tp), wave direction and surge water level for the seven pre-described output locations. At time 8:00 am the wave heights, periods and water levels have the following maximums at the levee, respectively 7.3 ft (location 6), 5.6 s (locations 2,3,5) and 17.8 ft (location 3,4,5). Across the MRGO the wave direction changes slightly due to refraction so that the waves attack the levees more or less perpendicular.

2d-overview of significant wave height - Hs

Figures 3.1.a, b and c give an overview of the significant wave height and the wave direction on the entire computational domain, for the six time steps at the overall Grid A scale. On this scale the differences between the six times are small. The large incoming ocean swells and waves on the south-eastern side of the A-grid with heights above 40 feet are discernable. The Chandeleur Islands, however, cause a lot of wave dissipation and west of these islands the wave heights are considerably reduced. On Lake Borgne the wave direction follows more or less the wind direction. The time steps 06:00 am, 07:00, and 08:00 show the MRGO as a line with higher waves than the surroundings.

The significant wave height on the M-grid can be found in Figure 3.2.a-c (Results of the C-grid are not presented in this report as they contain no additional information on this scale). The waves in the area of interest are locally generated by the severe wind. Of the simulated times, t3 (8:00am local time) shows the highest waves on the south western bulb of Lake Borgne (8-9 ft). By 9:00am LT the eye of Katrina is located over Lake Borgne hence both wind velocities and wave heights are smaller. Note again the much higher waves in the MRGO.

Figures 3.3.a-c show the significant wave height on the high resolution grids F and G. The black dots indicate some of the Robinson experts required output locations. The waves that exist in Lake Borgne diminish in size as they travel west from the Lake due to limited water depth and high bottom friction over the wetland between the Lake and MRGO, which induces some wave breaking. In the MRGO where the depths (including surge water level) are greater than 50 ft, waves increase again up to more than 9 ft.

Scenario 1: 2d-overview peak wave period - Tp

Figures 3.4, 3.5 and 3.6 show the computed peak period for grids A, C and F&G respectively. On the A-grid we see that the peak period is considerably reduced where the water gets shallower, west of Chandeleur Islands. The SWAN model reveals that the longer offshore periods do not penetrate far towards the MRGO. At 06:00 and 09:00am LT there is minor penetration of ocean swells with peak periods of ca 10 seconds (Figure 3.4).

Scenario 1: Wave energy spectra

The wave energy spectra show how the wave energy is divided over the frequencies (1d wave spectra) and over the directions (2d wave spectra). As an example, Figure 3.7 presents the 2d and 1d spectra of the pre described output locations 1, 2, 3, 4, 5, 6 on the F-grid for 08h00 LT close to the peak of the storm. The 2d plots only show the frequencies below 0.4 Hz (circles). Wave energy in the south western quadrant of the plot indicates energy traveling to the south west. Note that the values shown in the headers of each of the 1d-spectra plots are only estimates. The correct values are given in Table 3.1.

Figures 3.8.a and b show the wave spectra on the output locations of the six rays along the MRGO (Table 2.3). Additional spectra further away from the area of interest (Figure 3.9.a) were chosen to determine the impact of wetlands on the wave regime (Figure 3.9.b). The left hand plots are just east and west of Breton Island. The island seems to block the low frequent wave energy (higher periods). The middle and right hand column show three locations from Chandeleur Sound (loc 3 resp 4), via the wetlands (loc 8 resp 9) to Lake Borgne (loc 11 resp 10). The wetlands definitely knock down the wave energy. The waves at Lake Borgne are often higher than offshore except for 8 am and 9 am. The wind direction on times 4am- 7am is such that the fetch is at a maximum for Lake Borgne, so the local wind generated waves are actually bigger than those in Chandeleur Sound.

Scenario 1: Wave parameters along the rays

Figure 3.10 shows the wave height, peak period, wave direction and water depth (including surge level) along rays through the pre described output locations, perpendicular to the MRGO. The location of the rays can be found in Figure 2.6. The Figure 3.10 plots show the variation in wave parameters and water depth (which includes surge). What is very striking is the increase in significant wave height where the waves reach the wide, deep channel of the MRGO. At the levees - at the end of each ray - the wave height is again reduced due to shoaling and wave breaking which causes some of the levee erosion.

4 SWAN Scenario 2C

4.1 Introduction

This chapter deals with Scenario 2C. In order to interpret the full impacts of the MRGO we decided to run a Katrina storm with a scenario run modified to a condition as if the MRGO had never existed but with pre-Katrina levees present. For this, we added the pre-Katrina levees to the situation similar to the late 1950s.

Accordingly, we simulate surge along the shores of Lake Borgne in a model in which we change the current model input in the following ways:

(1) MRGO Reach 2 is removed and replaced with land at normal marsh or swamp elevations;

(2) The influence of the vegetation originally present between Lake Borgne and the 40 Arpent levees is taken into account in the spatial roughness field.

Like Scenario 1, the six time steps 4a, 5am, 6am, 7am, 8am, 9am (local time on August 29th, 2005) are considered.

The position and resolution of the computational grids is equal to those in Scenario 1. Also the wave boundary conditions, numerical settings, output locations and most physical settings are the same. Since the difference between this Scenario and Scenario 1 is limited to the area within computational grid C, the Scenario 1 results on the base grid (A) are valid for Scenario 2C.

Input for Scenario 2C that differs from Scenario 1:
- Bathymetry
- Bottom friction
- Wind
- Water levels

In Scenario 2C the original dense marsh vegetation that was present in the area before the MRGO was constructed is taken into account. Since the original vegetation patterns are not exactly known, three different options are presented here, reflecting the influence of vegetation on the waves. Scenario 2C-i is considered most likely. In addition, Scenario 2C-g presents an upper bound for the potential roughness effects and Scenario 2C-h a lower bound.

In Paragraph 4.2 additional model tests are presented to show the influence of vegetation on the waves.

Besides Scenario 2C there are also SWAN results available for Scenario 2A and 2B in which both the MRGO and its levees are absent. The elevation of the 40 Arpent levee is respectively 17.5 and 6.5 ft for these scenarios. They are presented in Appendix C and D.

4.2 Sensitivity tests for influence of vegetation on waves

Wave decay by propagation through vegetated areas

A SWAN test was performed with a simple pool, 5 ft deep, Hs0=2 ft and T=3 s in order to see how the results correspond to analytical models by a.o. Dalrymple as included in Bea, 2008. The friction coefficients Cfr considered are 0.015 (default, no vegetation), 0.46 2.0 and a rather extreme 6.0. Cfr=0.46 corresponds with the light vegetation characterized by average diameters of 0.1 ft, clear spacings of 1.0 ft (10 trees per m^2) and heights of 5 ft.

The Collins friction coefficient entered in the SWAN model is calculated based on the following equation (Appendix B): $C_{fr} = C_w * d * n * h_{veg}$

C_w = measure of stem rigidity
d = plant diameter in meters
n = number of plants per m^2
h_{veg}= stem height of the vegetation

Figure 4.1 shows the wave decay as function of propagation distance through vegetation in terms of Hs0/Hs. Compared with the analytical results SWAN tends to overestimate the wave height in these situations. However, still a considerable reduction in wave height can be recognized. Note that the tests have been done without wind. When wind growth is considered, the large reduction in wave height due to vegetation will be far less.

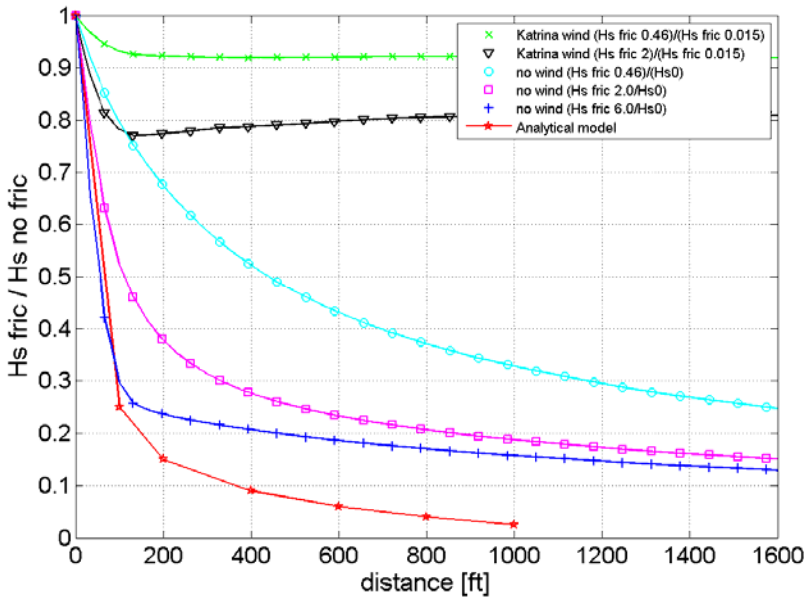


Figure 4.1: Decay of incident wave height as functuion of propagation distance through light vegetation (SWAN results and analytical model)

SWAN test results Scenario 2C

Some SWAN tests were performed to check the sensitivity of vegetation for the waves in Scenario 2C for time step 8:00 am local time on 29 August 2005. Only the F-grid is

considered. The runs are based on Scenario 2C. The area and type of vegetations has been varied resulting in the following runs:

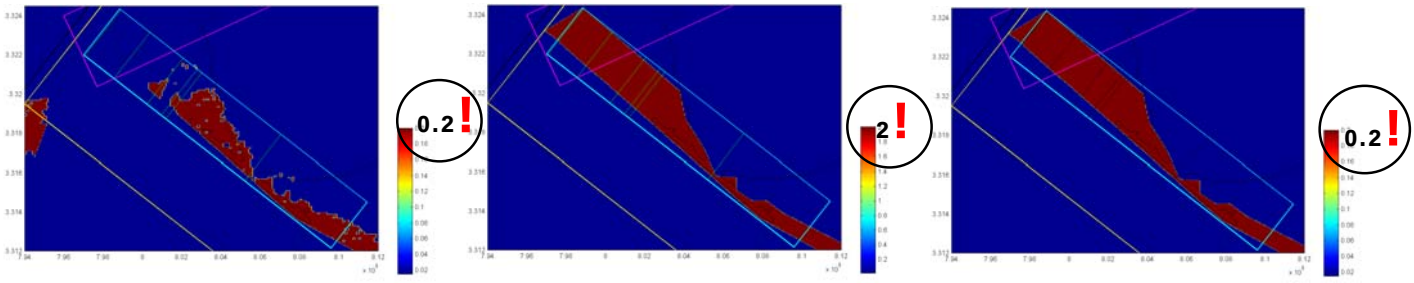
S: less dense small cypress forest resulting in:
wind reduction on small area
friction due to vegetation on small area and Cfr=0.2

T: dense cypress forest on entire F-grid excpet Lake Borgne and levee resulting in:
wind reduction on larger area
increased friction coefficient Cfr=2.0
increased friction coefficient on larger area

U: wind reduction on large area (wind as T)
friction due to vegetation on large area, but Cfr=0.2

V: wind reduction on large area (wind as T)
friction due to vegetation on small area and Cfr=0.2 (friction as S)

W: wind reduction on small area (wind as S)
increased friction coefficient on large area, Cfr=2.0 (friction as T)



Friction S & V:

small area vegetation Cfr=0.2

0.9 * 0.4 m * 0.11/m^2 * 5 m
rigidity * diam * # * h

Friction T & W:

large area vegetation Cfr=2.0

1.0 * 0.4 m * 1/m^2 * 5 m
rigidity * diam * # * h

Friction U:

large area vegetation Cfr=0.2

0.9 * 0.4 m * 0.11/m^2 * 5 m
rigidity * diam * # * h

Figure 4.2: Friction coefficients applied in SWAN tests

Figure 4.3 presents the resulting significant wave height of the five runs and some input parameters like friction, surge and bottom elevation. The zero on the x-axis is the north eastern end, and the 8000 (ft) is somewhere on the levee. The pink lines refer to the friction coefficient (times 10, so 0.2 and 2.0). One can see its higher value in run T and also the larger stretch where it is applied.

The blue line is the significant wave height of run S with limited vegetation and hence little wave decay. The red line presents the extreme situation that the cypress forest covered almost entirely grid F and were very dense (one rigid tree with diameter 0.4 m per m^2). In between the red and the blue line, the results of runs U, V and W can be found.

U (black): Run U gives the influence of the friction coefficient. We had hoped that the wind reduction would be so important that the value of the friction coefficient would not make a difference and that T and U would lay on top of each other. The only difference between run T and U (red and black) is the friction coefficient of respectively 2.0 and 0.2. The difference between these runs is maximum (ca 2 ft) at circa X=1000-2000 ft. In the vicinity of the output locations D, T and L, the difference is about 1 foot. So the value of the friction coefficient does matter.

V (cyan): This runs gives the influence of the wind reduction on the waves on ray 3. The input is similar to Scenario 2C except for the larger area of wind reduction (cyan vs blue). The difference in wave height is maximum between X= 2000 ft and 5000 ft and circa 2 feet. At locations D, T and L the difference is approximately 1 foot. Comparing run V and U (cyan and black), one can see the influence of the larger area of the increased friction (U and V have similar wind). This is about one foot in the area of the levee.

W (green): Comparing W and T (green and red), the influence of the wind reduction in combination with large friction can be seen. The friction coefficient is high both for W and for T. In run W, on most part of ray 3 the wind is still severe. The reduced wind of run T has considerable influence from X=0 to X=5000 ft. Closer to the levee, the wind in run W reduces too, and the difference in Hs between run T and W is reduced to a little over 1 foot. Note that the wind has more influence on small waves (with the increased friction, red and green) than on larger waves (with the friction of Scenario 2C, cyan and blue).

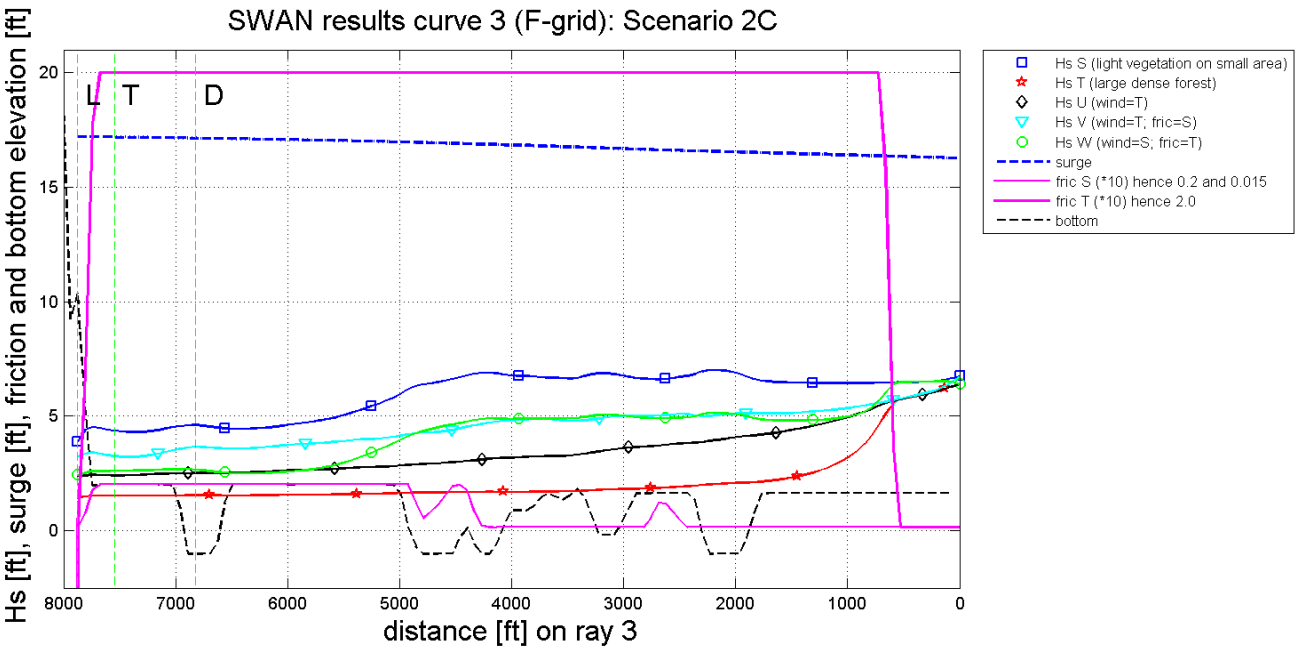


Figure 4.3: Results SWAN tests for influence friction on waves

Conclusions SWAN tests

When waves propagate through vegetation, they will dissipate. According to analytical models the reduction in wave height through vegetation with 0.1 ft diameter, 1 ft spacing and 5 ft height (and water depth) can be as high as 85% in only 200 ft. SWAN - as applied here - computes ca 60% which is the same order of magnitude.

A number of tests were performed simulating Katrina waves near the current levees (MRGO absent) under influence of various types of vegetations. Near the levee on ray 3 the significant wave height would be 4.1 ft when the vegetation was not so dense and only present on a small area. But if a dense forest were present covering a large area between Lake Borgne and the levee, the wave height may have been reduced till only1.5 ft according to the SWAN simulations.

4.3 Input Scenario 2C

Bathymetry Scenario 2C

The bathymetry for Scenario 2C is modified to represent the conditions prior to the construction of the MRGO but with the levees present. Reach 2 of the MRGO is filled up to the height of the surrounding marshes and swamps in the bathymetry, being at 2ft NAVD88 in the western part, and 1.5 ft NAVD88 in the eastern part. A land-water map provided by the Robinson experts has been used to construct the original small water streams in the marshes (elevation set at -1ft NAVD88). Where the levees of Scenario 1 are above 4ft they have been added to the bathymetry of Scenario 2C. The resulting depths in the model area are shown in Figure 4.4.

The adjusted bathymetry for Scenario 2C is only included in computational grids C, M, F and G.

Bottom friction Scenario 2C (version g, h, i)

Originally, the area between the MRGO and the 40 Arpent levees was covered with vegetation which would considerably reduce wave propagation. For the remaining vicinity of Lake Borgne, the marsh vegetation was much denser than it is now. The influence of the vegetation on the waves is included by locally enlarging the friction coefficient.

SWAN has three options for the bottom friction. For Scenario 2C, Collins is most appropriate since it allows for a spatially varying friction coefficient which may be modified to represent vegetation characteristics. In SWAN the default value of C_{fr} is 0.015. The model of Turner (Appendix B) makes it possible to express the friction coefficient in terms of vegetation as follows: $C_{fr} = C_w * d * n * h_{veg}$

C_w = measure of stem rigidity
d = plant diameter in meters
n = number of plants per m^2
h_{veg}= stem height of the vegetation

Since the original vegetation patterns are not exactly known, three different options are presented here, reflecting the influence of vegetation on the waves. Scenario 2C-i is considered most likely. In addition, Scenario 2C-g presents an upper bound for the potential roughness effects and Scenario 2C-h a lower bound.

The following vegetation patterns are considered:

2C		C_{fr}	C_w	d [m]	n [1/m^2]	h_{veg} [m]
version g	marsh	0.49	0.5	0.01	49	2
	Cypress trees	2.00	0.9	0.5	0.9	5
version h	moderate dense marsh	0.49	0.5	0.01	49	2
version i	dense marsh	0.98	0.5	0.02	49	2

The levees are thought to be grown with marsh vegetation too. Lake Borgne and the ocean have the default friction of 0.015. The larger bottom friction is only included in computational grids M, F and G. Figure 4.6 shows the friction coefficient as input for the SWAN computations.



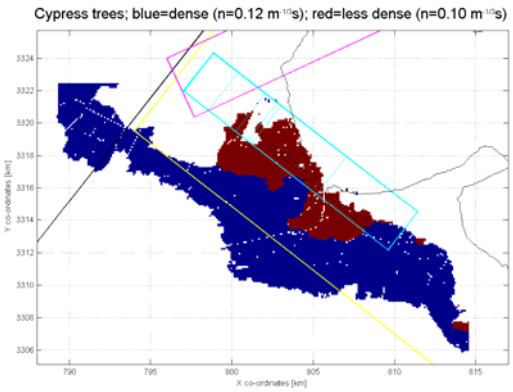


Figure 4.5: Impression of cypress trees in swampy areas (provided by the Robinson experts) for version g

Wind Scenario 2C

Inside the cypress forest the influence of the wind is reduced by the trees. Here a reduction factor of 80% (percentage provided to us by the Robinson experts) is applied for version g.

The marsh vegetation is thought to have no influence on the wind velocities.

The reduced wind is only included in computational grids M and F. Figure 4.7 shows the wind velocities as input for the SWAN computations. The resolution of the wind file for Scenario 2 is 500 m x 500 m (1640 ft x 1640 ft) which is twice as fine as in Scenario 1.

Water levels Scenario 2C

The computed water levels resulting from the FINEL Scenario 2C-runs (de Wit, 2008) have been used to locally modify the water level fields of Scenario 1 to Scenario 2. The FINEL simulations have a high resolution and cover fully the F-grid. The water level field for the M-grid has been completed with the ADCIRC Scenario 1 data.

The water levels for Scenario 2C are only included in computational grids M, F and G. Figure 4.8 shows the water levels as input for the SWAN computations.

4.4 Results Scenario 2C

General

In this scenario we simulate the situation before the MRGO was constructed, with dense vegetation and with MRGO-levees.

The absence of the deep and wide MRGO prevents the waves growing as they did in Scenario 1. Furthermore, the vegetation suppresses the waves. Also, the water levels of Scenario 2C are less, and in shallower water the waves will be smaller. The general outcome of the SWAN simulations of Scenario 2C is that the waves on the location of the present levee would be lower if there were no MRGO.

Scenario 2C: SWAN results at output locations

The significant wave height, wave direction and peak period as computed by SWAN on the output locations for the six time steps are presented in Table 4.1, 4.2 and 4.3 for respectively version g (forest and marsh vegetation), h (moderate dense marsh vegetation) and i (dense marsh vegetation). The water levels are also included in these tables. Note that the output locations "L", "T" and "D" have the same name and location as in Scenario 1, although "D" is not so deep since there is no MRGO in Scenario 2C.

Time step 8 am shows the largest wave heights and periods. If we consider the levee output location of ray 3, the significant wave height varies between 2.4 ft (version g) and 4.7 ft (version h) and 4.3 ft (version i). On ray 1 the wave height on the levees are highest, respectively 5.4 ft, 5.3 ft and 4.9 ft. In general, the difference between version h and i is about 0.5 ft. The peak period varies between approximately 3 and 4 seconds. Both periods and wave heights are considerably lower than in Scenario 1.

Rays 1 and 2 of version g have no limiting influence of Cypress woods and reduced wind and show therefore much higher waves than on the other rays.
The water levels of Scenario 2C are slightly lower than in Scenario 1.

Scenario 2C: 2d-overview of significant wave height - Hs

Figures 4.9.a-c reflect the significant wave height of version i on the six time steps in 2d-plots. One can see the higher waves on Lake Borgne (up to 9 ft on 8:00am), and smaller waves on the marshes. When comparing these plots with the ones from Scenario 1, the main difference is the absence of the MRGO. For the time step with maximum waves, also the results of version g and h are presented, see Figure 4.10. In version g one can recognize the Cypress forest as the area with lower waves.

Scenario 2C: 2d-overview of peak wave period - Tp

Figures 4.11.a-c present the peak wave period in 2d-plots. The peak period is a measure of how the wave energy is divided over the wave frequencies, rather than a measure for the amount of energy (which would be the significant wave height).

Scenario 2C: Wave parameters along the rays

Figures 4.12.a-c show the wave height, peak period, wave direction, water depth (including surge level) and friction coefficient along rays through the pre described output locations, perpendicular to the MRGO. These plots show the variation in wave parameters and water depth. The location of the rays can be found in Figure 2.6. The colored dots have the same position as the ones in Scenario 1, but since the MRGO has been removed in Scenario 2, the vertical elevation is almost the same now for the first four locations. Figure 4.12.a presents version g, Figure 4.12.b version h and Figure 4.12.c version i. Only time step 8am is presented.

Due to the absence of the MRGO, the variation in depth is less than in Scenario 1. The variation in friction coefficient depends on the presence of the vegetation causing additional friction. One can see that the wave height reduces as the friction coefficient increases (especially in version g).

5 Conclusions

General

SWAN was used to simulate waves during the Katrina event for the area of interest, being the northern end of Reach 2 of the MRGO, near New Orleans. Six time steps were considered on 29 August 2005; namely 4 am, 5am, 6am, 7am, 8am, and 9am (local time). Two scenarios are taken into account, Scenario 1 with and Scenario 2C without the MRGO channel. In the latter one also the original dense vegetation is taken into account.

Five computational grids were required in order to cover an area that is large enough to translate the offshore waves to the area of interest with a resolution sufficiently high to include major bathymetric variations.

The large offshore swells (Hs≈45 ft, Tpeak≈15 s) dissipate dramatically as they reach the Chandeleur Islands and for the most part do not reach the MRGO.

According to the SWAN model the waves in the area of interest are locally generated by the severe wind that blew over Lake Borgne with maximum fetch, straight at the levees.

The waves attack the levees almost perpendicular due to the normal wind direction and additional refraction.

According to the SWAN simulations of Scenario 1, at 8:00 am local time on August 29th 2005, wave heights, periods and water levels reached their maximum in the area of interest, whereas the maximum wind occurred at 7:00 am. In the deeper parts of MRGO, maximum Hs was about 9 - 10 ft, at the toe 8 - 9 ft and at the levee 6 - 7 ft. Periods were circa 5 s. Surge levels were approximately 18 ft above NAVD88.

Scenario 2C

In Scenario 2C the situation without the MRGO but with the levees has been simulated. The absence of the deep and wide MRGO prevents the waves to grow as they did in Scenario 1. Furthermore, the vegetation suppresses the waves. Since it is hard to know the exact vegetation patterns now if the MRGO would not have been constructed, three versions have been simulated with more or less dense vegetation. Additional SWAN tests indicate that the vegetation - included in the friction coefficient - has considerable effect on the waves. The general outcome of the SWAN simulations of Scenario 2C is that the waves on the location of the present levee would be lower if there were no MRGO.

6 References

1 IPET Volume IV The Storm - Technical Appendices by US Army Corps of Engineers
Appendix 3 Offshore Waves
Appendix 4 Nearshore Waves

2 SWAN team (Booij, N. IJ.G.Haagsma, L.H.Holthuisen, A.T.M.M. Kieftenburg, R.C.Ris, A.J.van der Westhuysen, M.Zijlema): SWAN Cycle III version 40.51A user manual 2007, http://www.fluidmechanics.tudelft.nl/swan/index.htm

3. Van Heerden, I.L., Ph.D. – Lead, G. Paul Kemp, Ph.D., Hassan Mashriqui, Ph.D. & PE, Radhey Sharma, Ph.D., Billy Prochaska, PE, Lou Capozzoli, Ph.D. & PE, Art Theis, PE, Ahmet Binselam, M.S., Kate Streva B.S. and Ezra Boyd, M.S., 2007, *The Failure of the New Orleans Levee System during Hurricane Katrina*, A report prepared by TEAM LOUISIANA for Secretary Johnny Bradberry, Louisiana Department of Transport and Development, Baton Rouge, Louisiana

4 Wit, L.de, Maaskant, Kok, Vrijling - Flow Modeling New Orleans - Mississippi River Gulf Outlet, Hurricane Katrina August 2005, dd June 2008 ref 1474/08202

TABLES

Hs [ft]	4am (local)				5am (local)		
loc	L	T	D		L	T	D
1	2.6	4.8	4.8		3.5	5.7	5.7
2	1.7	4.0	5.1		2.6	4.8	6.1
3	-	4.1	4.8		2.1	4.9	5.8
4	2.1	4.3	4.6		3.0	5.2	5.6
5	-	3.8	4.6		3.3	4.6	5.5
6	3.6	4.6	4.6		4.4	5.6	5.5
7			3.7				4.5

dir come from [°N]	4am (local)				5am (local)		
loc	L	T	D		L	T	D
1	43	56	61		45	54	59
2	52	52	57		53	51	56
3	-	52	60		51	52	59
4	47	55	61		47	54	59
5	-	54	61		60	54	60
6	46	50	50		46	49	49
7			53				51

Tp [s]	4am (local)				5am (local)		
loc	L	T	D		L	T	D
1	3.8	3.8	3.8		4.2	4.2	4.2
2	3.8	3.8	3.8		4.2	4.2	4.2
3	0.0	3.8	3.8		4.2	4.2	3.8
4	3.8	3.8	3.5		4.2	4.2	3.8
5	0.0	3.8	3.5		4.2	4.2	3.8
6	3.5	3.5	3.5		3.8	3.8	3.8
7			3.5				3.5

wl [ft]	4am (local)				5am (local)		
loc	L	T	D		L	T	D
1	9.1	9.1	9.0		10.8	10.8	10.7
2	9.2	9.1	9.1		10.9	10.9	10.8
3	-	9.2	9.2		11.0	11.0	10.9
4	9.3	9.3	9.3		11.0	11.0	11.0
5	-	9.3	9.3		11.1	11.0	11.0
6	9.4	9.4	9.4		11.1	11.1	11.0
7			8.2				9.7

Table 3.1a: Results SCENARIO 1 SWAN simulations 4am and 5 am on output locations (Hs, Direction, Tp, Water level; for output locations, see Paragraph 2.5; L=levee, T=toe, D=deeper parts)

Hs [ft]	6am (local)				7am (local)				8am (local)				9am (local)		
loc	L	T	D		L	T	D		L	T	D		L	T	D
1	4.5	6.8	6.9		5.7	8.3	8.4		6.8	9.1	9.4		4.3	5.3	5.4
2	3.7	5.9	7.3		5.0	7.2	8.9		6.1	8.2	9.9		3.9	5.0	5.5
3	3.3	6.0	7.1		4.9	7.4	8.6		6.0	8.4	9.6		3.6	4.7	5.1
4	4.0	6.3	6.8		5.3	7.8	8.4		6.3	8.6	9.3		4.0	4.5	5.0
5	4.3	5.7	6.8		5.5	7.0	8.3		6.6	8.0	9.2		3.6	4.3	4.9
6	5.5	6.9	6.8		6.8	8.5	8.3		7.3	8.8	8.7		3.2	4.1	4.1
7			5.3				6.4				7.5				4.6

dir come from [°N]	6am (local)				7am (local)				8am (local)				9am (local)		
loc	L	T	D		L	T	D		L	T	D		L	T	D
1	45	51	56		45	51	56		47	51	57		34	32	32
2	52	50	54		52	50	54		53	51	56		38	26	19
3	51	50	56		51	50	56		52	52	59		28	22	9
4	47	52	57		47	51	57		49	54	61		22	19	7
5	58	52	57		57	52	57		59	55	61		35	20	6
6	46	46	47		47	48	49		49	54	55		23	6	5
7			49				49				52				34

Tp [s]	6am (local)				7am (local)				8am (local)				9am (local)		
loc	L	T	D		L	T	D		L	T	D		L	T	D
1	4.7	4.7	4.2		4.7	4.7	4.7		5.1	5.1	5.1		4.2	4.2	4.2
2	4.7	4.7	4.7		5.1	5.1	4.7		5.6	5.6	5.1		4.7	4.7	4.7
3	4.7	4.7	4.2		5.1	5.1	4.7		5.6	5.6	5.1		4.7	4.7	4.7
4	4.7	4.7	4.2		5.1	4.7	4.7		5.1	5.1	4.7		4.7	4.7	4.7
5	4.7	4.7	4.2		5.1	5.1	4.7		5.6	5.1	4.7		4.7	4.7	4.7
6	4.2	4.2	4.2		4.7	4.7	4.7		5.1	4.7	4.7		4.2	4.2	4.2
7			3.8				3.8				4.2				4.2

wl [ft]	6am (local)				7am (local)				8am (local)				9am (local)		
loc	L	T	D		L	T	D		L	T	D		L	T	D
1	12.7	12.6	12.6		15.0	14.9	14.9		17.2	17.2	17.1		14.3	14.3	14.2
2	12.9	12.8	12.8		15.2	15.2	15.1		17.6	17.5	17.5		14.3	14.3	14.3
3	13.0	13.0	12.9		15.4	15.4	15.3		17.8	17.7	17.7		14.3	14.3	14.3
4	13.1	13.0	13.0		15.5	15.4	15.4		17.8	17.7	17.7		14.3	14.3	14.2
5	13.1	13.0	13.0		15.5	15.5	15.4		17.8	17.8	17.7		14.3	14.2	14.2
6	13.1	13.1	13.1		15.6	15.5	15.5		17.5	17.5	17.5		14.2	14.2	14.2
7			11.2				13.0				15.8				13.8

Table 3.1b: Results SCENARIO 1 SWAN simulations 6-9am on output locations (Hs, Direction, Tp, Water level; for output locations, see Paragraph 2.5; L=levee, T=toe, D=deeper parts)

Hs [ft]	4am (local)				5am (local)		
loc	L	T	D		L	T	D
1	1.9	2.3	2.3		2.6	3.0	3.0
2	-	2.7	2.5		2.2	3.5	3.3
3	-	1.1	1.2		0.8	1.4	1.5
4	1.2	1.2	1.1		1.7	1.5	1.4
5	-	1.1	0.8		1.6	1.4	1.1
6	1.0	1.2	1.2		1.3	1.5	1.6
7			3.0				3.7

dir come from [°N]	4am (local)				5am (local)		
loc	L	T	D		L	T	D
1	43	49	49		40	46	45
2	-	49	54		47	46	50
3	-	59	63		54	57	59
4	30	28	35		28	26	32
5	-	46	42		52	42	38
6	47	51	51		46	49	49
7			49				47

Tp [s]	4am (local)				5am (local)		
loc	L	T	D		L	T	D
1	2.6	2.6	2.6		2.9	2.9	2.9
2	-	2.6	2.9		3.2	3.2	3.2
3	-	2.0	2.0		2.4	2.2	2.4
4	2.2	2.2	2.0		2.4	2.4	2.4
5	0.0	1.8	2.0		2.2	2.2	2.2
6	2.0	2.2	2.2		2.4	2.4	2.4
7			2.9				3.2

wl [ft]	4am (local)				5am (local)		
loc	L	T	D		L	T	D
1	8.6	8.6	8.5		10.4	10.4	10.3
2	-	8.9	8.8		10.8	10.7	10.6
3	-	9.0	9.0		10.8	10.8	10.7
4	9.0	9.0	8.9		10.8	10.7	10.7
5	-	8.9	8.9		10.7	10.6	10.6
6	9.1	9.1	9.1		10.8	10.8	10.8
7			7.9				9.4

Table 4.1a: Results SCENARIO 2C version g SWAN simulations 4am and 5 am on output locations (Hs, Direction, Tp, Water level; L=levee, T=toe, D=deeper parts)

Hs [ft]	6am (local)				7am (local)				8am (local)				9am (local)		
loc	L	T	D		L	T	D		L	T	D		L	T	D
1	3.5	3.9	3.8		4.6	4.9	4.9		5.4	5.8	5.7		3.3	3.5	3.5
2	3.1	4.4	4.2		4.3	5.5	5.3		5.2	6.3	6.1		3.0	3.5	3.5
3	1.4	1.8	1.9		2.0	2.3	2.4		2.4	2.7	2.8		1.4	1.5	1.7
4	2.3	2.0	1.9		3.0	2.6	2.5		3.4	2.9	2.8		1.9	1.9	1.9
5	2.1	1.8	1.4		2.8	2.3	1.9		3.1	2.5	2.2		1.6	1.6	1.5
6	1.6	2.0	2.1		2.2	2.6	2.7		2.3	2.8	2.9		1.2	1.4	1.4
7			4.5				5.5				6.3				3.6

dir from [°N]	6am (local)				7am (local)				8am (local)				9am (local)		
loc	L	T	D		L	T	D		L	T	D		L	T	D
1	37	41	41		37	39	39		37	39	39		24	21	22
2	45	42	45		43	40	43		43	40	43		28	18	19
3	50	54	54		50	52	51		52	53	52		18	15	14
4	25	22	29		24	20	27		26	23	29		9	6	7
5	44	36	34		39	33	32		40	36	34		14	7	11
6	45	46	46		44	46	46		49	51	52		22	17	17
7			43				41				43				28

Tp [s]	6am (local)				7am (local)				8am (local)				9am (local)		
loc	L	T	D		L	T	D		L	T	D		L	T	D
1	3.2	3.2	3.2		3.5	3.5	3.5		3.8	3.8	3.8		3.5	3.5	3.5
2	3.5	3.5	3.5		3.8	3.8	3.8		4.2	4.2	4.2		3.5	3.5	3.5
3	2.6	2.6	2.6		2.9	2.9	2.9		3.2	3.2	3.2		2.9	2.9	3.2
4	2.6	2.6	2.6		3.2	3.2	2.9		3.5	3.2	3.2		3.2	3.2	2.9
5	2.4	2.4	2.4		2.6	2.6	2.9		2.9	2.9	2.9		2.9	2.9	2.9
6	2.6	2.6	2.6		2.9	2.9	2.9		3.2	3.2	3.2		2.4	2.4	2.4
7			3.5				3.5				3.8				3.5

wl [ft]	6am (local)				7am (local)				8am (local)				9am (local)		
loc	L	T	D		L	T	D		L	T	D		L	T	D
1	12.4	12.4	12.3		14.8	14.7	14.6		17.0	17.0	16.9		15.3	15.3	15.3
2	12.8	12.8	12.7		15.2	15.1	15.0		17.4	17.3	17.2		15.2	15.2	15.2
3	12.8	12.8	12.8		15.2	15.2	15.1		17.2	17.2	17.2		15.0	15.0	15.0
4	12.8	12.7	12.7		15.2	15.1	15.0		17.1	17.1	17.0		14.9	14.9	14.9
5	12.7	12.6	12.6		15.1	15.0	15.0		16.9	16.9	16.9		14.9	14.9	14.9
6	12.8	12.8	12.8		15.2	15.2	15.2		16.5	16.5	16.5		14.1	14.1	14.1
7			11.0				12.7				15.1				14.1

Table 4.1b: Results SCENARIO 2C version g SWAN simulations 6-9am on output locations (Hs, Direction, Tp, Water level; L=levee, T=toe, D=deeper parts)

Hs [ft]	4am (local)			5am (local)		
loc	L	T	D	L	T	D
1	1.9	2.3	2.3	2.6	3.0	3.0
2	-	2.7	2.5	2.2	3.5	3.3
3	-	2.4	2.6	1.7	3.2	3.4
4	1.6	2.4	2.4	2.5	3.1	3.1
5	-	2.4	2.4	2.4	3.2	3.2
6	2.3	2.4	2.4	3.1	3.2	3.2
7			3.0			3.7

dir come from [°N]	4am (local)			5am (local)		
loc	L	T	D	L	T	D
1	43	50	50	40	46	46
2	-	49	54	47	46	50
3	-	51	52	42	47	48
4	42	50	50	41	46	46
5	-	55	56	60	51	53
6	48	50	50	46	47	47
7			49			47

Tp [s]	4am (local)			5am (local)		
loc	L	T	D	L	T	D
1	2.6	2.6	2.6	2.9	2.9	2.9
2	0.0	2.6	2.9	3.2	3.2	3.2
3	0.0	2.6	2.6	3.2	2.9	2.9
4	2.6	2.6	2.6	2.9	2.9	2.9
5	0.0	2.6	2.6	3.2	2.9	3.2
6	2.6	2.6	2.6	2.9	2.9	2.9
7			2.9			3.2

wl [ft]	4am (local)			5am (local)		
loc	L	T	D	L	T	D
1	8.6	8.6	8.5	10.4	10.4	10.3
2	0.0	8.9	8.8	10.8	10.7	10.6
3	0.0	9.0	9.0	10.8	10.8	10.7
4	9.0	9.0	8.9	10.8	10.7	10.7
5	0.0	8.9	8.9	10.7	10.6	10.6
6	9.1	9.1	9.1	10.8	10.8	10.8
7			7.9			9.4

Table 4.2a: Results SWAN Scenario 2C version h (friction marsh =0.49): 4am and 5 am on output locations (Hs, Direction, Tp, Water level; for output locations, see Paragraph 2.5; L="levee", T="toe", D="deeper parts")

Hs [ft]	6am (local)			7am (local)			8am (local)			9am (local)		
loc	L	T	D	L	T	D	L	T	D	L	T	D
1	3.5	3.9	3.8	4.6	4.9	4.9	5.3	5.6	5.6	3.3	3.5	3.5
2	3.1	4.4	4.2	4.3	5.6	5.3	5.0	6.0	5.9	3.0	3.5	3.5
3	2.6	4.0	4.3	3.9	5.1	5.4	4.7	5.6	5.9	2.6	3.1	3.1
4	3.4	4.0	4.0	4.6	5.1	5.1	5.1	5.6	5.6	2.8	2.9	2.9
5	3.3	4.0	4.1	4.4	5.1	5.2	5.0	5.6	5.6	2.6	2.9	2.9
6	3.9	4.1	4.1	5.0	5.2	5.2	5.0	5.3	5.3	2.2	2.4	2.5
7			4.5			5.5			6.3			3.2

dir come from [°N]	6am (local)			7am (local)			8am (local)			9am (local)		
loc	L	T	D	L	T	D	L	T	D	L	T	D
1	38	41	41	37	39	39	41	42	42	24	21	21
2	45	42	45	43	40	43	45	42	45	28	18	19
3	39	43	43	38	41	42	43	45	46	13	12	13
4	38	42	42	38	40	41	42	45	46	14	11	10
5	55	47	48	52	45	46	53	48	49	21	12	13
6	43	43	43	43	43	43	49	52	52	9	3	4
7			43			41			43			43

Tp [s]	6am (local)			7am (local)			8am (local)			9am (local)		
loc	L	T	D	L	T	D	L	T	D	L	T	D
1	3.2	3.2	3.2	3.5	3.5	3.5	3.8	3.8	3.8	3.5	3.5	3.5
2	3.5	3.5	3.5	3.8	3.8	3.8	3.8	3.8	4.2	3.5	3.5	3.5
3	3.5	3.5	3.2	3.8	3.8	3.8	3.8	3.8	3.8	3.2	3.2	3.2
4	3.5	3.2	3.2	3.8	3.8	3.8	3.8	3.8	3.8	3.2	3.2	3.2
5	3.5	3.5	3.5	3.8	3.8	3.8	3.8	3.8	3.8	3.2	3.2	3.2
6	3.2	3.2	3.2	3.5	3.5	3.5	3.5	3.5	3.5	2.9	2.9	2.9
7			3.5			3.5			3.8			3.2

wl [ft]	6am (local)			7am (local)			8am (local)			9am (local)		
loc	L	T	D	L	T	D	L	T	D	L	T	D
1	12.4	12.4	12.3	14.8	14.7	14.6	17.0	17.0	16.9	15.3	15.3	15.3
2	12.8	12.8	12.7	15.2	15.1	15.0	17.4	17.3	17.2	15.2	15.2	15.2
3	12.8	12.8	12.8	15.2	15.2	15.1	17.2	17.2	17.2	15.0	15.0	15.0
4	12.8	12.7	12.7	15.2	15.1	15.0	17.1	17.1	17.0	14.9	14.9	14.9
5	12.7	12.6	12.6	15.1	15.0	15.0	16.9	16.9	16.9	14.9	14.9	14.9
6	12.8	12.8	12.8	15.2	15.2	15.2	16.5	16.5	16.5	14.1	14.1	14.1
7			11.0			12.7		15.1				14.1

Table 4.2.b: Results SWAN Scenario 2C version h (friction marsh =0.49): 6-9am on output locations (Hs, Direction, Tp, Water level; for output locations, see Paragraph 2.5; L="levee", T="toe", D="deeper parts")

Hs [ft]	4am (local)			5am (local)		
loc	L	T	D	L	T	D
1	1.7	2.1	2.1	2.4	2.7	2.7
2	0.0	2.5	2.3	2.0	3.2	3.0
3	0.0	2.2	2.4	1.5	2.9	3.1
4	1.5	2.2	2.2	2.3	2.9	2.9
5	0.0	2.2	2.2	2.2	2.9	2.9
6	2.1	2.2	2.2	2.8	2.9	2.9
7			2.8			3.3

dir come from [°N]	4am (local)			5am (local)		
loc	L	T	D	L	T	D
1	43	49	49	40	45	45
2	-	49	54	47	46	50
3	-	50	52	42	47	47
4	42	50	50	41	46	46
5	-	54	56	58	50	52
6	48	50	50	46	47	47
7			50			47

Tp [s]	4am (local)			5am (local)		
loc	L	T	D	L	T	D
1	2.4	2.4	2.4	2.6	2.6	2.6
2	0.0	2.6	2.6	2.9	2.9	2.9
3	0.0	2.4	2.4	2.9	2.6	2.9
4	2.4	2.4	2.4	2.6	2.6	2.6
5	0.0	2.4	2.4	2.9	2.6	2.9
6	2.4	2.4	2.4	2.6	2.6	2.6
7			2.6			2.9

wl [ft]	4am (local)			5am (local)		
loc	L	T	D	L	T	D
1	8.6	8.6	8.5	10.4	10.4	10.3
2	0.0	8.9	8.8	10.8	10.7	10.6
3	0.0	9.0	9.0	10.8	10.8	10.7
4	9.0	9.0	8.9	10.8	10.7	10.7
5	0.0	8.9	8.9	10.7	10.6	10.6
6	9.1	9.1	9.1	10.8	10.8	10.8
7			7.9			9.4

Table 4.3.a: Results SWAN Scenario 2C version i (friction marsh =0.98): 4am and 5 am on output locations (Hs, Direction, Tp, Water level; for output locations, see Paragraph 2.5; L="levee", T="toe", D="deeper parts")

Hs [ft]	6am (local)			7am (local)			8am (local)			9am (local)		
loc	L	T	D	L	T	D	L	T	D	L	T	D
1	3.2	3.5	3.5	4.2	4.5	4.5	4.9	5.2	5.2	3.0	3.2	3.2
2	2.9	4.1	3.8	4.0	5.1	4.9	4.6	5.5	5.4	2.7	3.2	3.1
3	2.5	3.7	4.0	3.6	4.7	5.0	4.3	5.2	5.4	2.3	2.8	2.8
4	3.2	3.7	3.7	4.2	4.7	4.7	4.7	5.1	5.1	2.5	2.7	2.7
5	3.1	3.7	3.8	4.1	4.8	4.8	4.6	5.1	5.2	2.3	2.6	2.6
6	3.6	3.8	3.8	4.7	4.8	4.8	4.5	4.7	4.7	1.9	2.1	2.1
7			4.1			5.0			5.9			3.3

dir come from [°N]	6am (local)			7am (local)			8am (local)			9am (local)		
loc	L	T	D	L	T	D	L	T	D	L	T	D
1	38	41	41	37	39	39	40	40	40	24	20	20
2	45	42	45	43	40	42	44	42	44	27	18	19
3	40	42	43	38	41	41	42	44	45	12	12	13
4	38	42	42	38	40	41	42	45	45	13	10	10
5	53	46	47	50	44	45	51	47	48	20	11	12
6	43	43	43	43	43	43	48	52	52	7	0	0
7			43			41			42			28

Tp [s]	6am (local)			7am (local)			8am (local)			9am (local)		
loc	L	T	D	L	T	D	L	T	D	L	T	D
1	2.9	2.9	2.9	3.5	3.5	3.5	3.5	3.5	3.5	3.2	3.2	3.2
2	3.2	3.2	3.2	3.5	3.5	3.5	3.5	3.5	3.8	3.2	3.2	3.2
3	3.2	3.2	3.2	3.5	3.5	3.5	3.5	3.5	3.5	3.2	2.9	2.9
4	3.2	3.2	3.2	3.5	3.5	3.5	3.5	3.5	3.5	2.9	2.9	2.9
5	3.2	3.2	3.2	3.5	3.5	3.5	3.5	3.5	3.5	2.9	2.9	2.9
6	2.9	2.9	2.9	3.2	3.2	3.2	3.5	3.2	3.2	2.6	2.6	2.6
7			3.2			3.5			3.5			3.2

wl [ft]	6am (local)			7am (local)			8am (local)			9am (local)		
loc	L	T	D	L	T	D	L	T	D	L	T	D
1	12.4	12.4	12.3	14.8	14.7	14.6	17.0	17.0	16.9	15.3	15.3	15.3
2	12.8	12.8	12.7	15.2	15.1	15.0	17.4	17.3	17.2	15.2	15.2	15.2
3	12.8	12.8	12.8	15.2	15.2	15.1	17.2	17.2	17.2	15.0	15.0	15.0
4	12.8	12.7	12.7	15.2	15.1	15.0	17.1	17.1	17.0	14.9	14.9	14.9
5	12.7	12.6	12.6	15.1	15.0	15.0	16.9	16.9	16.9	14.9	14.9	14.9
6	12.8	12.8	12.8	15.2	15.2	15.2	16.5	16.5	16.5	14.1	14.1	14.1
7			11.0			12.7			15.1			14.1

Table 4.3.b: Results SWAN Scenario 2C version i (friction marsh =0.98): 6-9am on output locations (Hs, Direction, Tp, Water level; for output locations, see Paragraph 2.5; L="levee", T="toe", D="deeper parts")

FIGURES

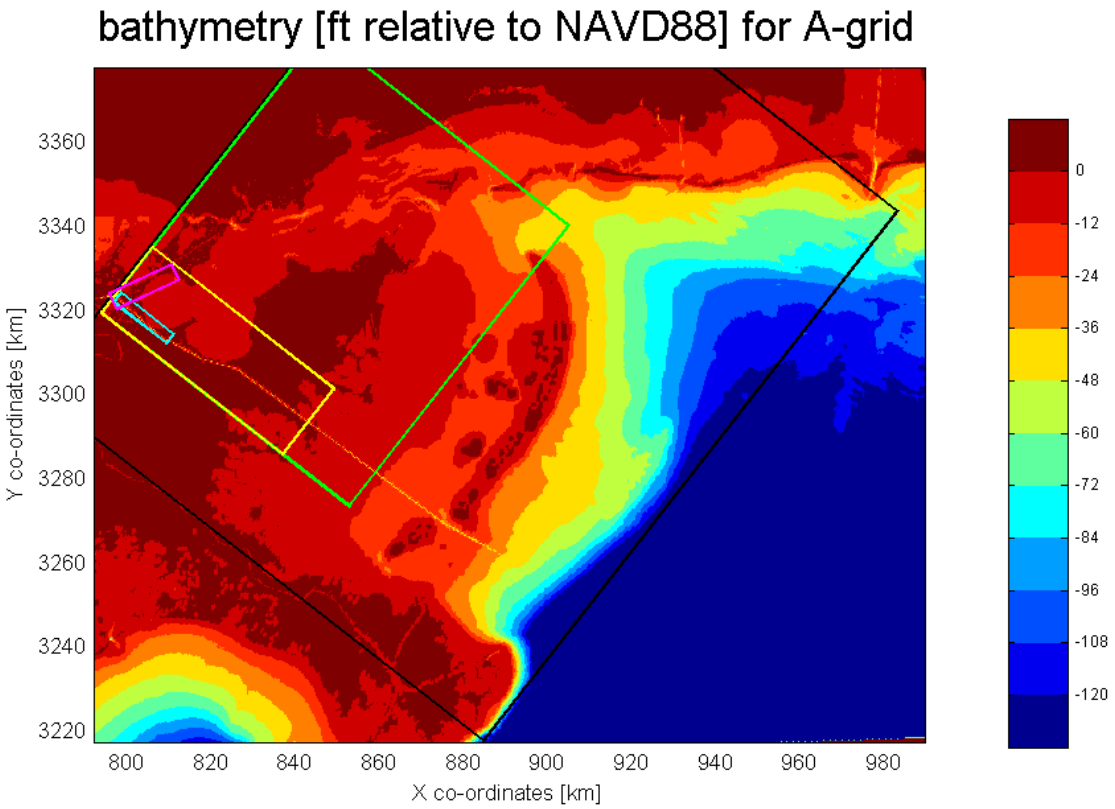
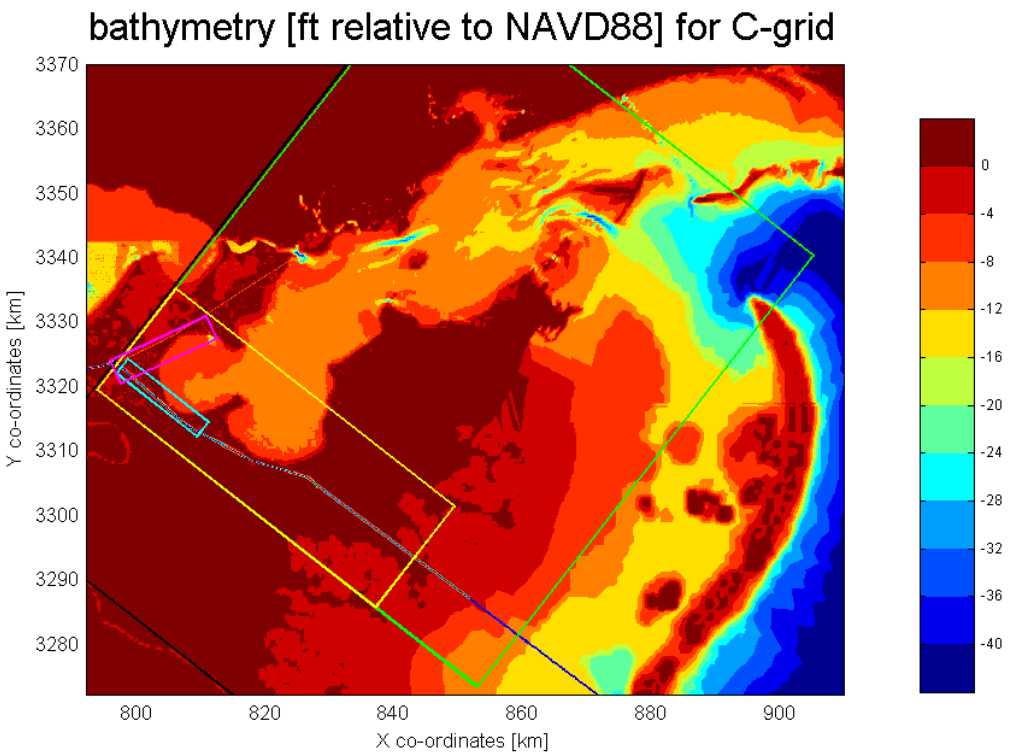
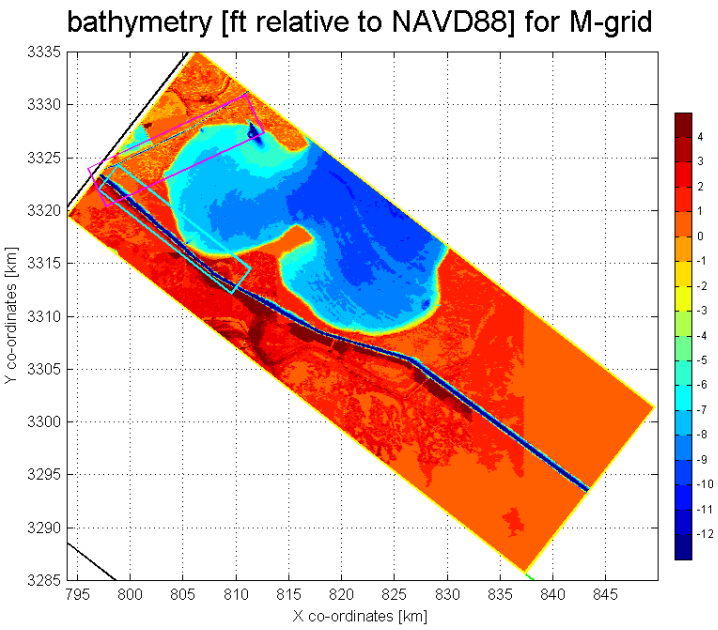


Figure 2.1: Position of computational grids and bathymetry for A-grid
Black: A-grid
Green: C-grid
Yellow: M-grid
Cyan: F-grid
Pink: G-grid





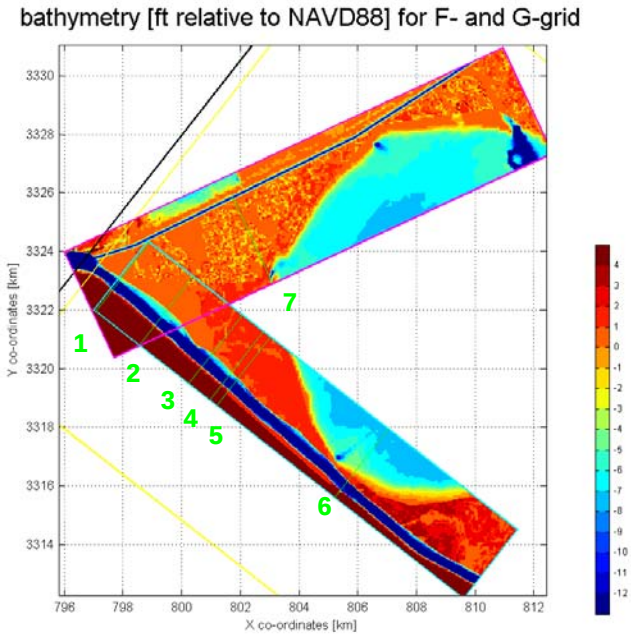


Figure 2.2: SCENARIO 1 Bathymetry for C, M, F and G grids [feet relative to NAVD88]

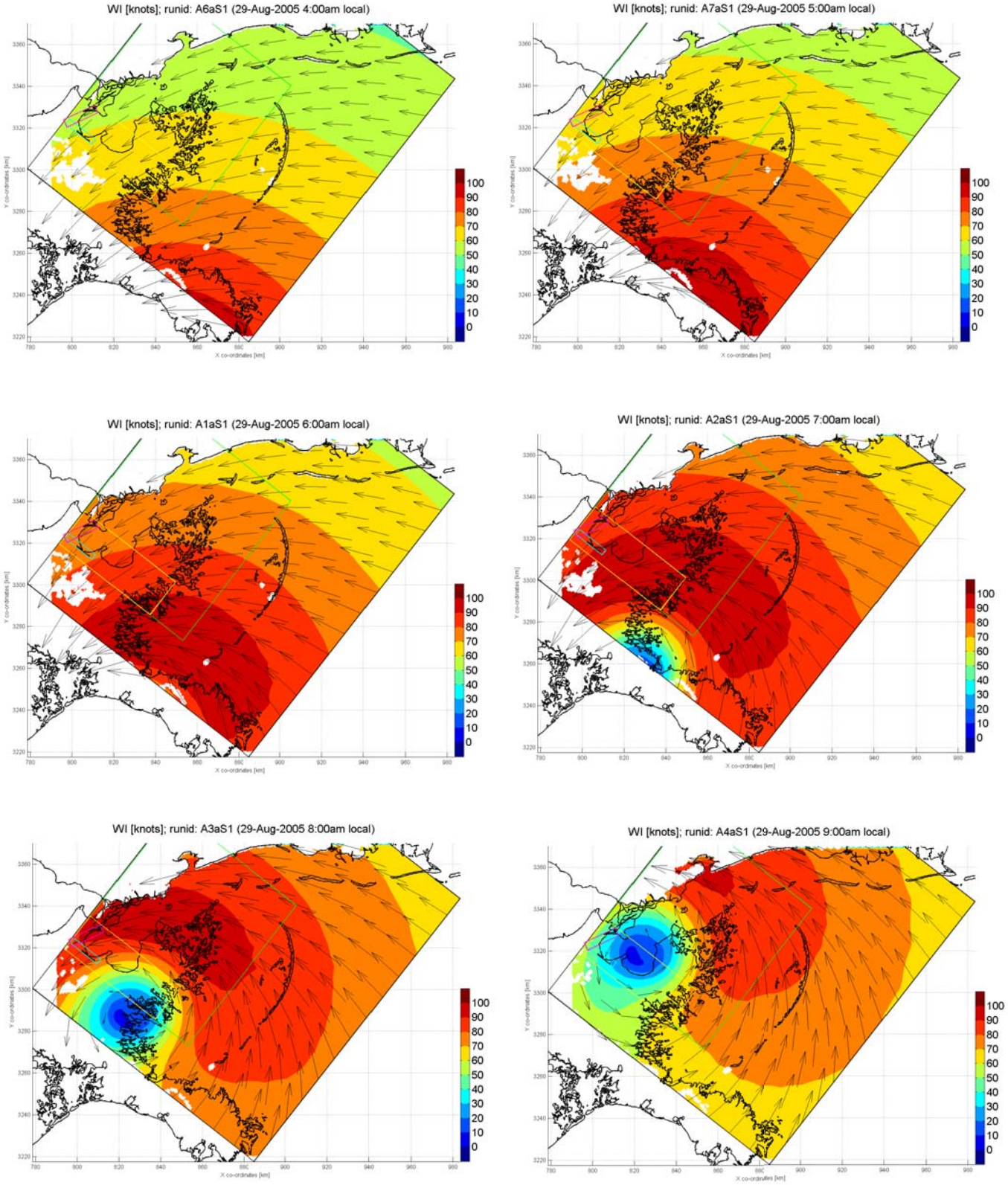


Figure 2.3: SCENARIO 1 Wind fields [knots] 04:00, 05:00, 06:00, 07:00, 08:00 and 09:00am LT based on data from the Robinson experts

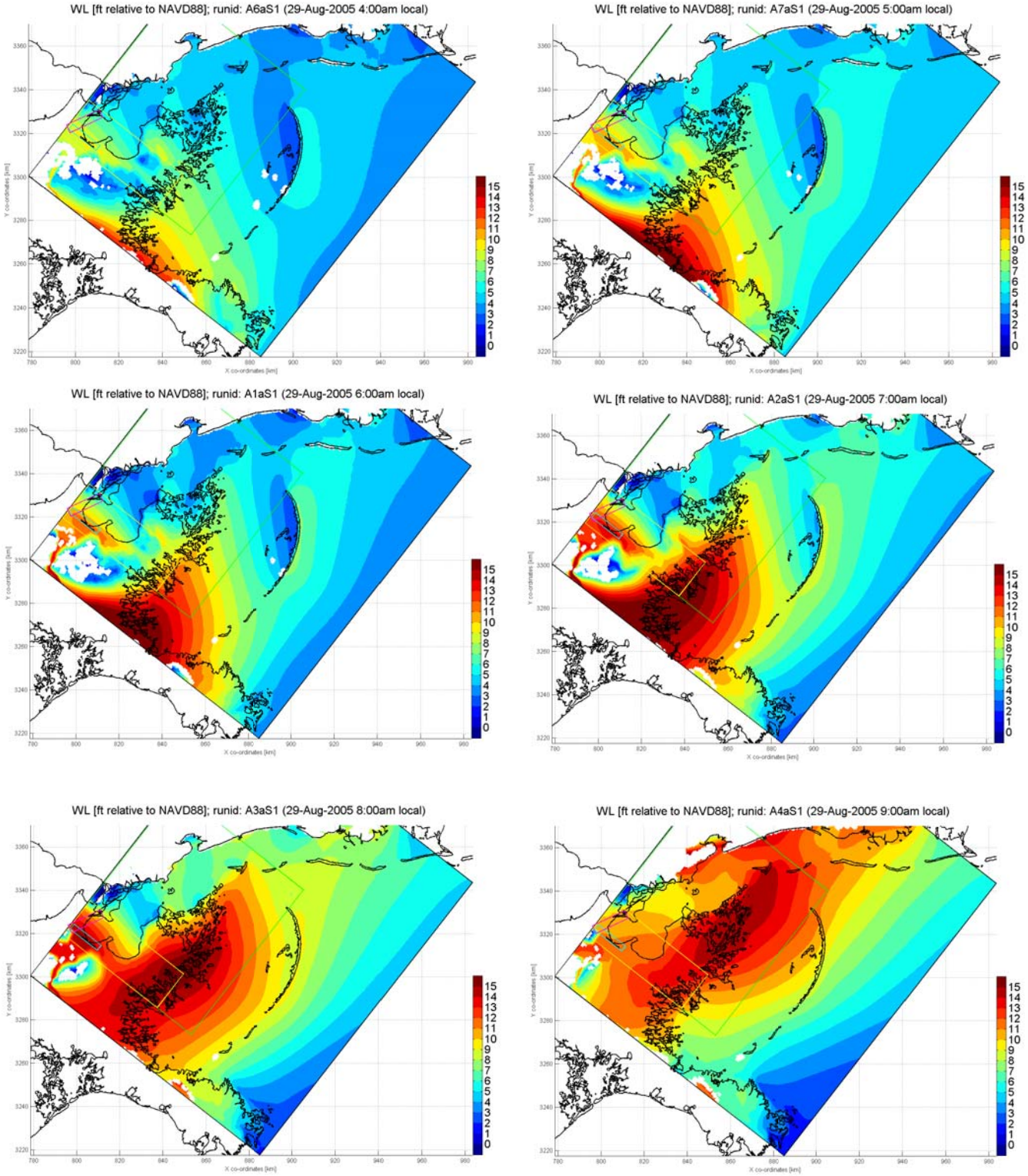


Figure 2.4.a SCENARIO 1 Water level fields [ft relative to NAVD88] grid A 4:00, 5:00, 06:00, 7:00, 8:00 and 9:00am LT based on ADCIRC data from Robinson experts.

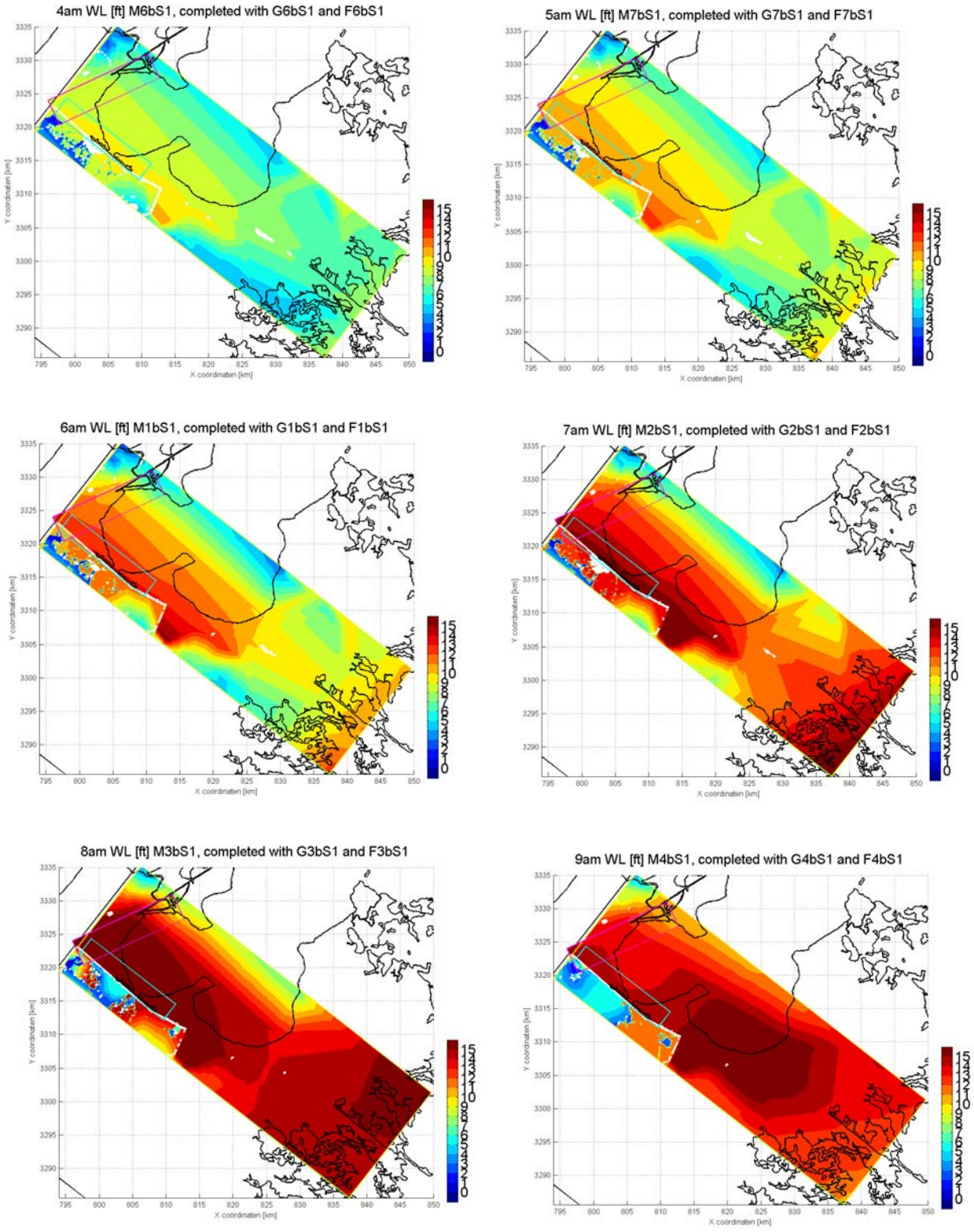


Figure 2.4.b SCENARIO 1 Water level fields [ft relative to NAVD88] grid M 4:00, 5:00, 06:00, 7:00, 8:00 and 9:00am LT based on ADCIRC data from Robinson experts and FINEL (de Wit, 2008).

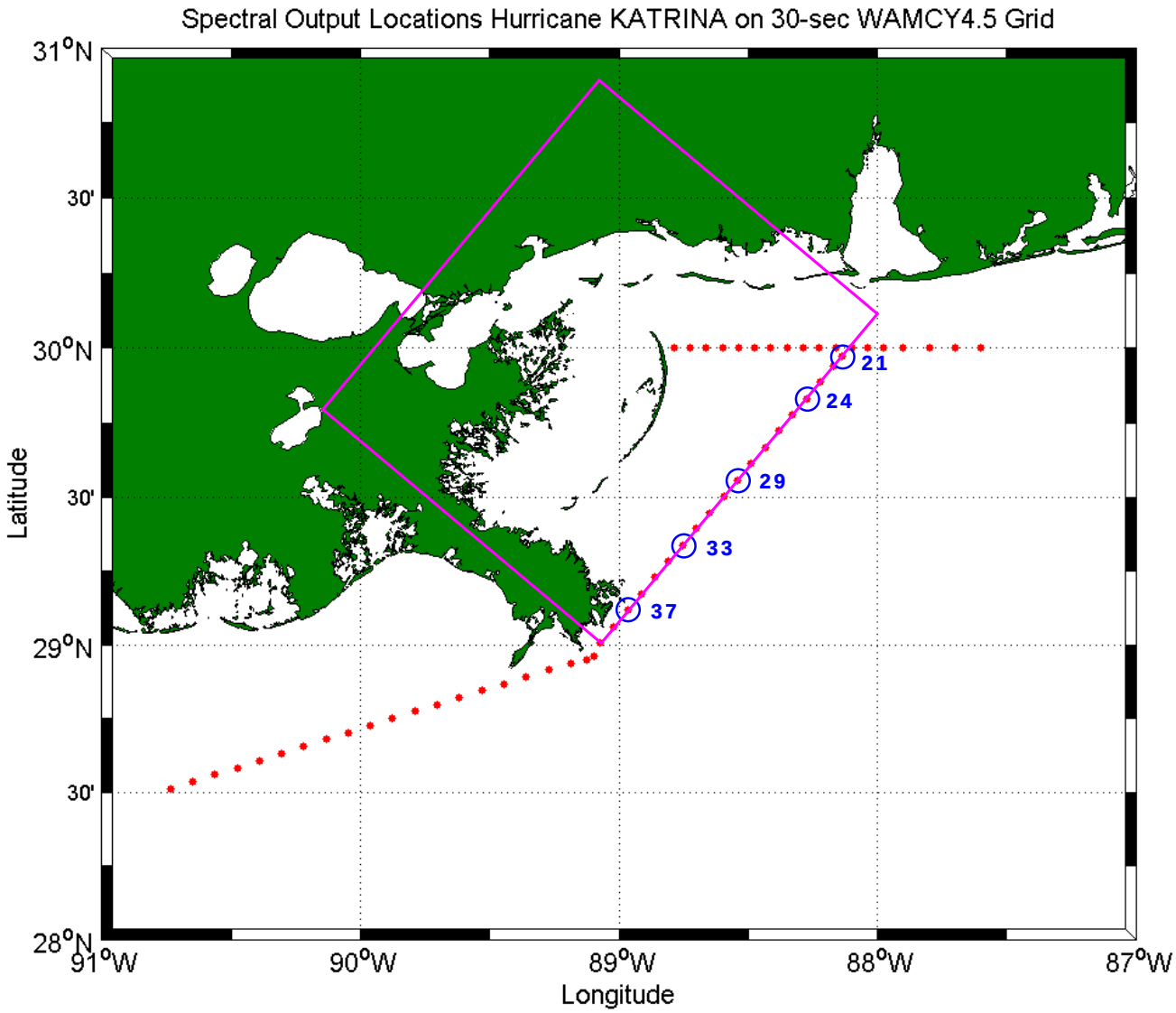


Figure 2.5.a: WAM output locations (red dots); the numbered locations have been used as input for the SWAN computations on the pink grid

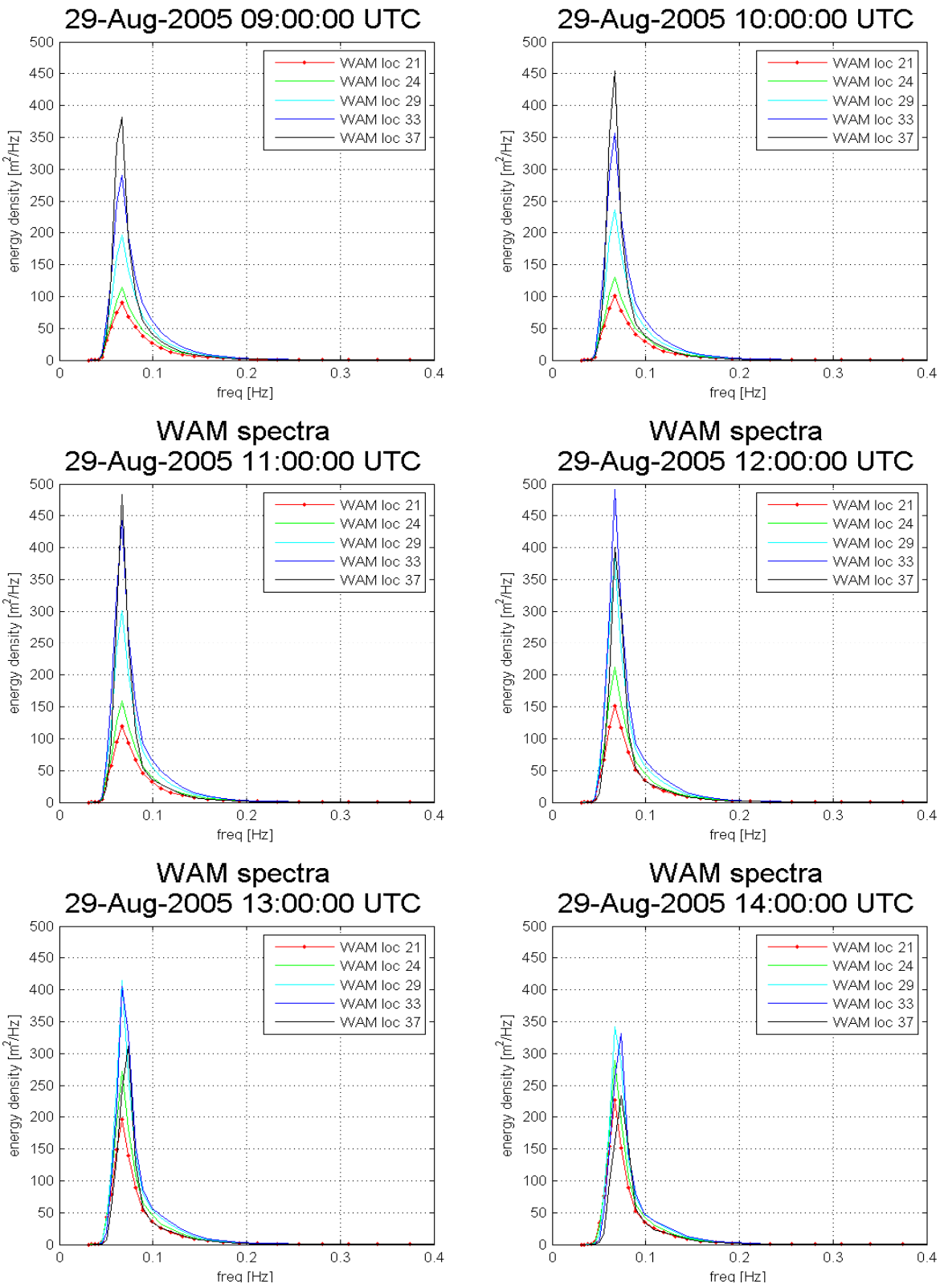
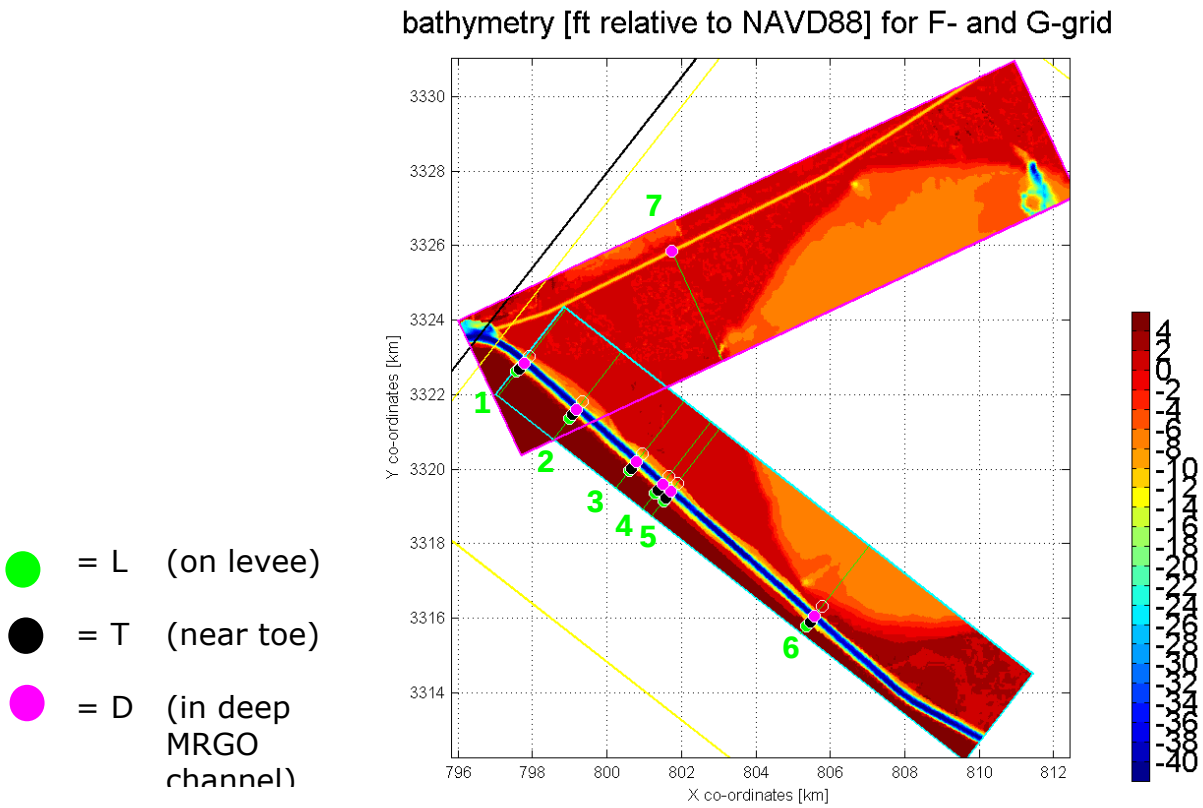


Figure 2.5.b: WAM spectra on incoming wave boundary



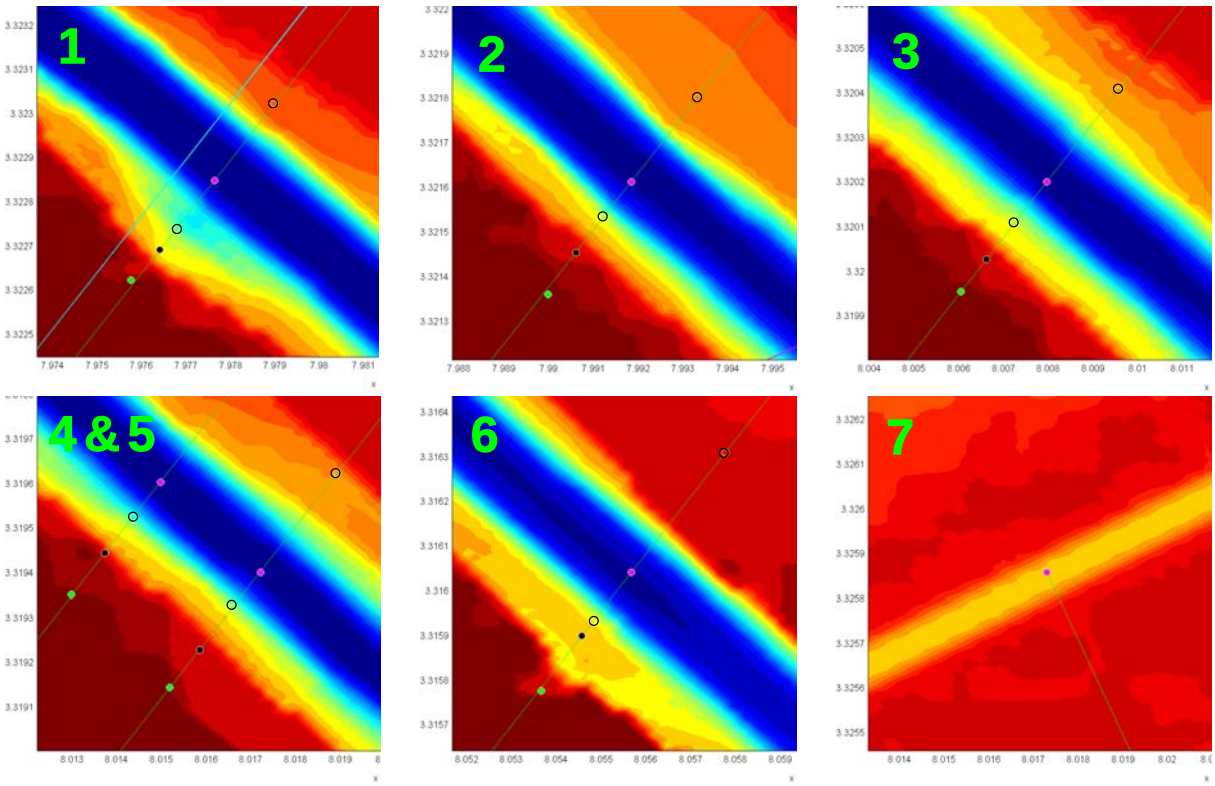


Figure 2.6: Output locations

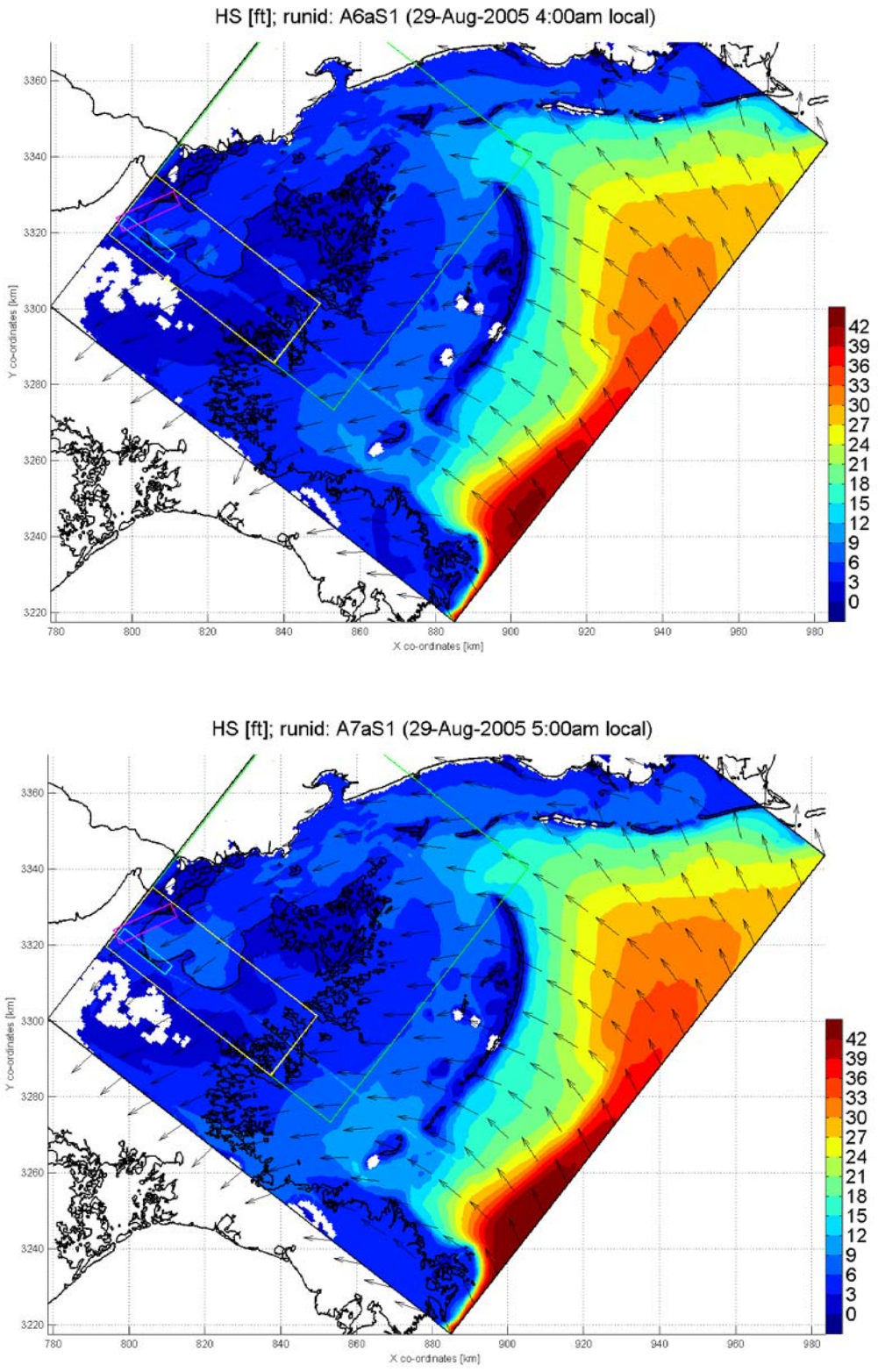


Figure 3.1.a: SWAN results Hs [ft] and wave direction, 4:00 am and 5:00 am on grid A.

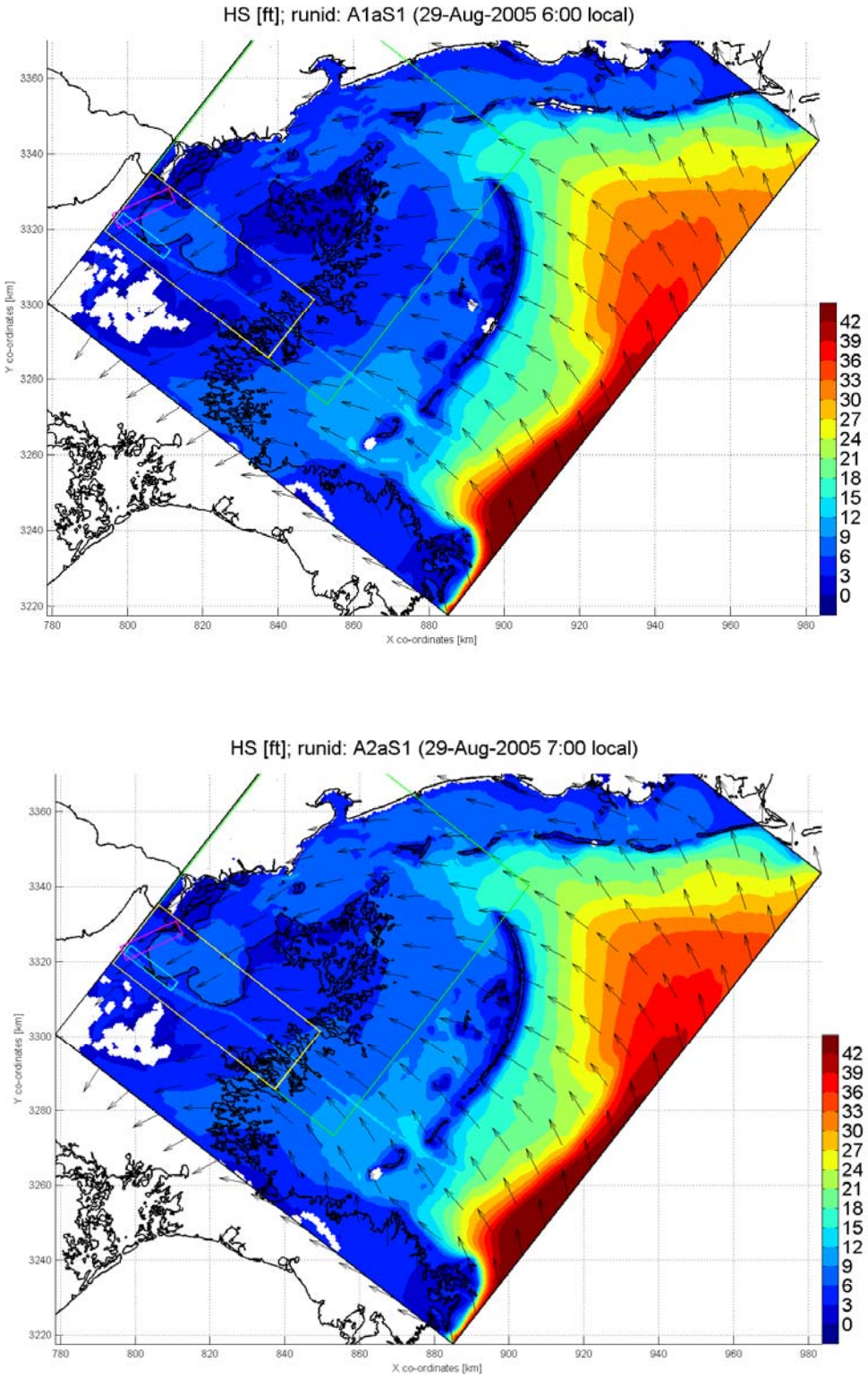


Figure 3.1.b: SWAN results Hs [ft] and wave direction, 6:00 am and 7:00 am LT on grid A

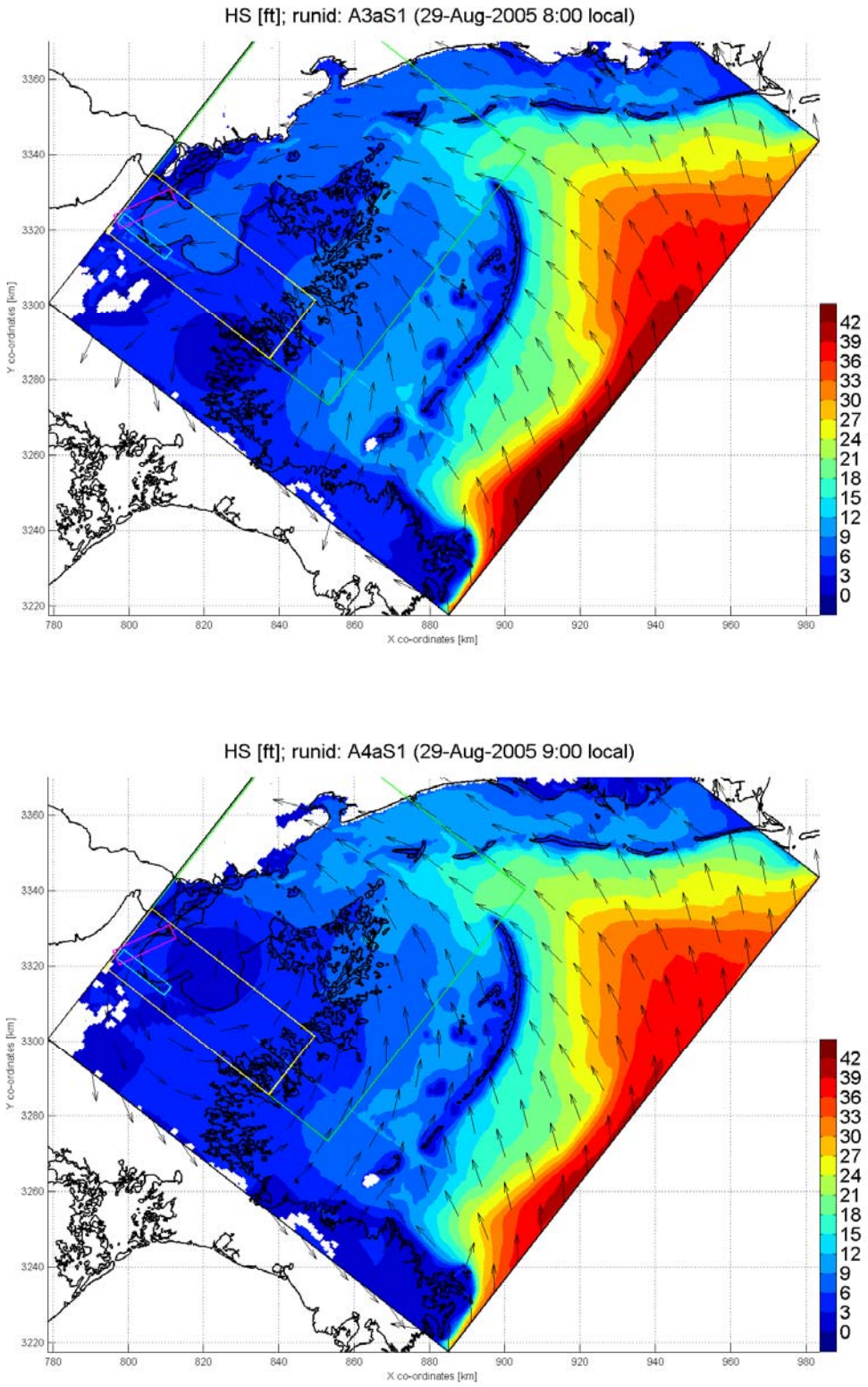


Figure 3.1.c: SWAN results Hs [ft] and wave direction, 8:00 am and 9:00 am LT on grid A

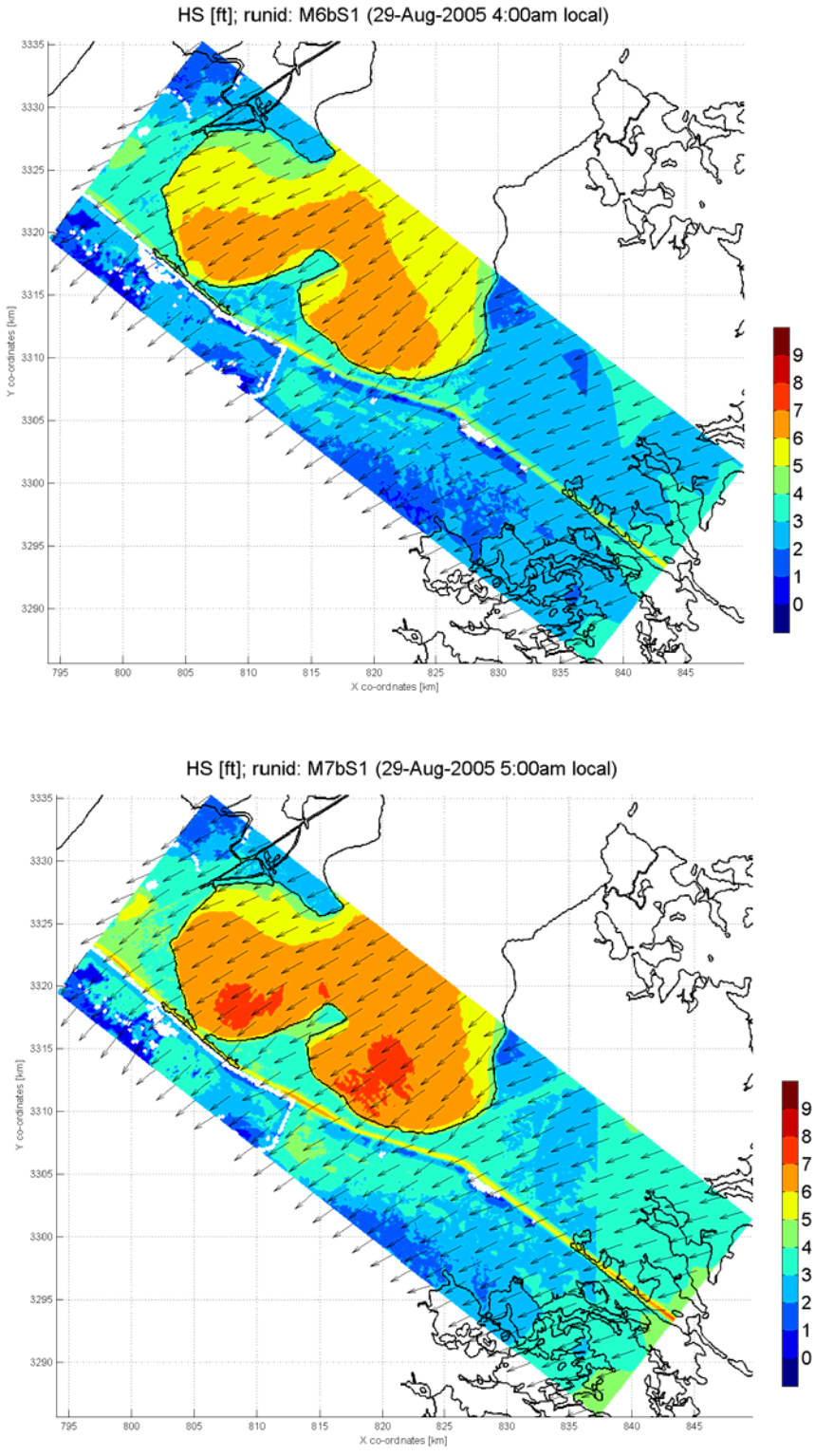


Figure 3.2.a SCENARIO 1 SWAN results significant wave height (Hs [ft]) and wave direction, 4:00 am and 5:00 am LT on grid M

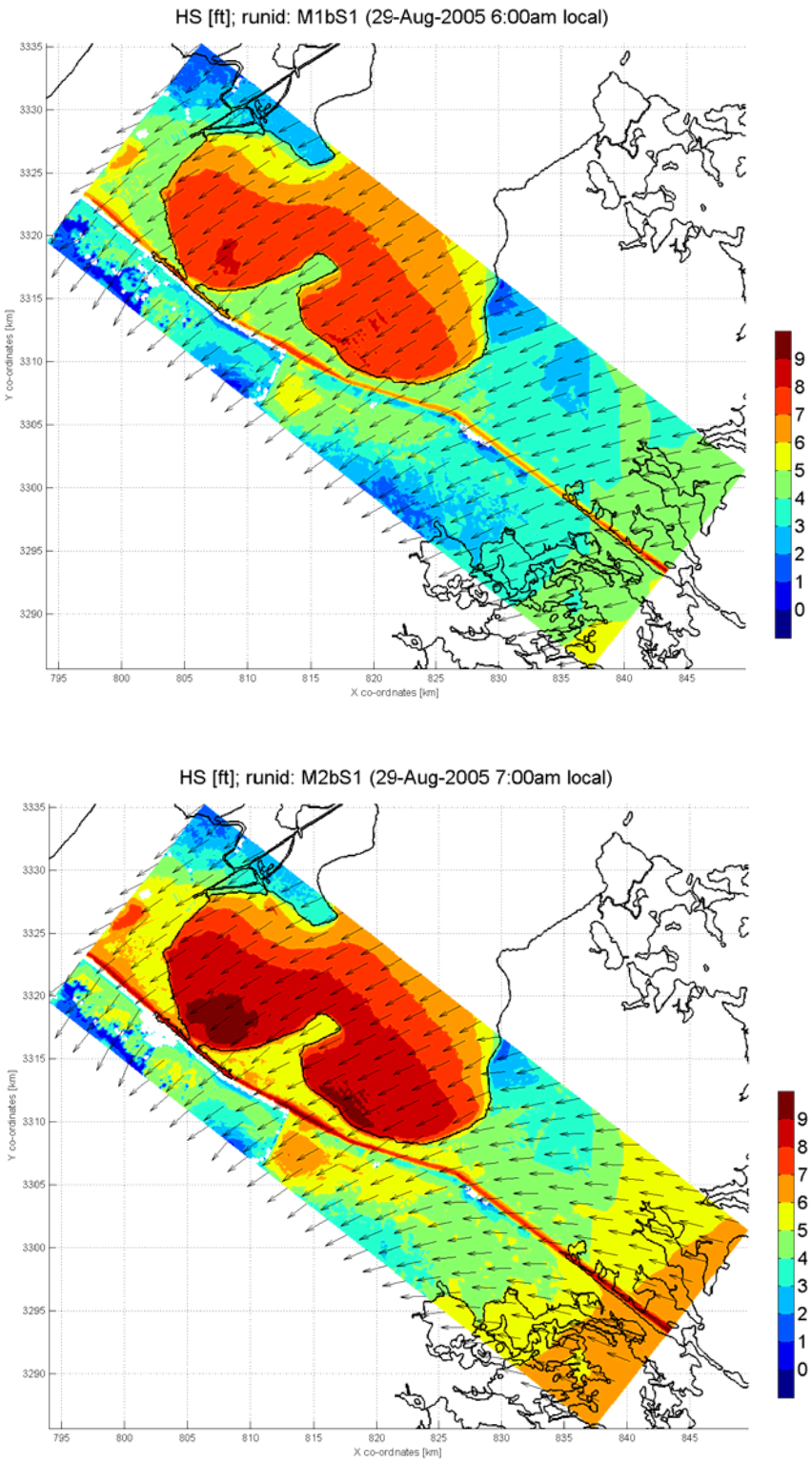


Figure 3.2.b: SCENARIO 1 SWAN results significant wave height (Hs [ft]) and wave direction, 6:00 am and 7:00 am LT on grid M

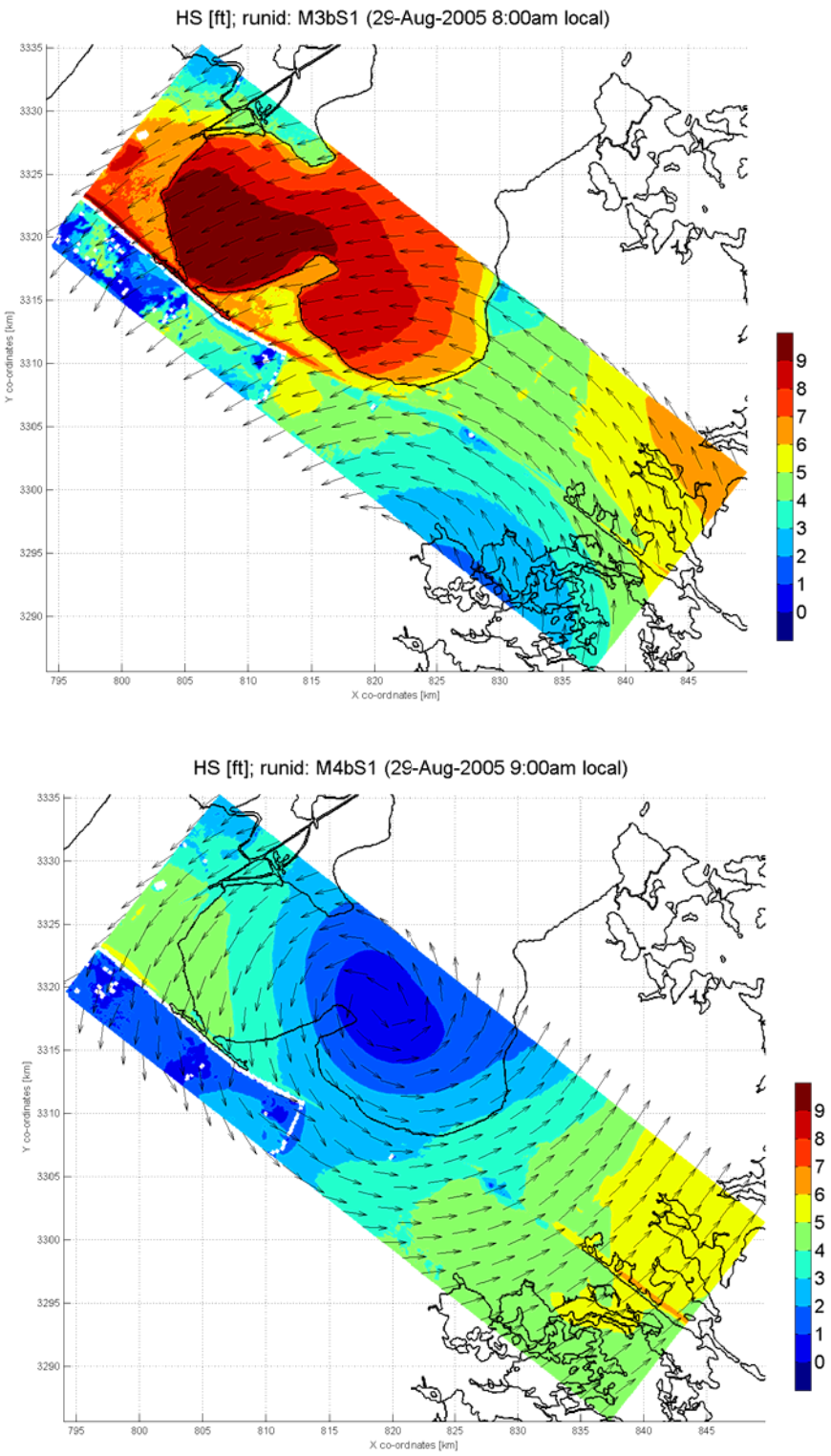


Figure 3.2.c: SCENARIO 1 SWAN results significant wave height (Hs [ft]) and wave direction, 8:00 am and 9:00 am LT on grid M

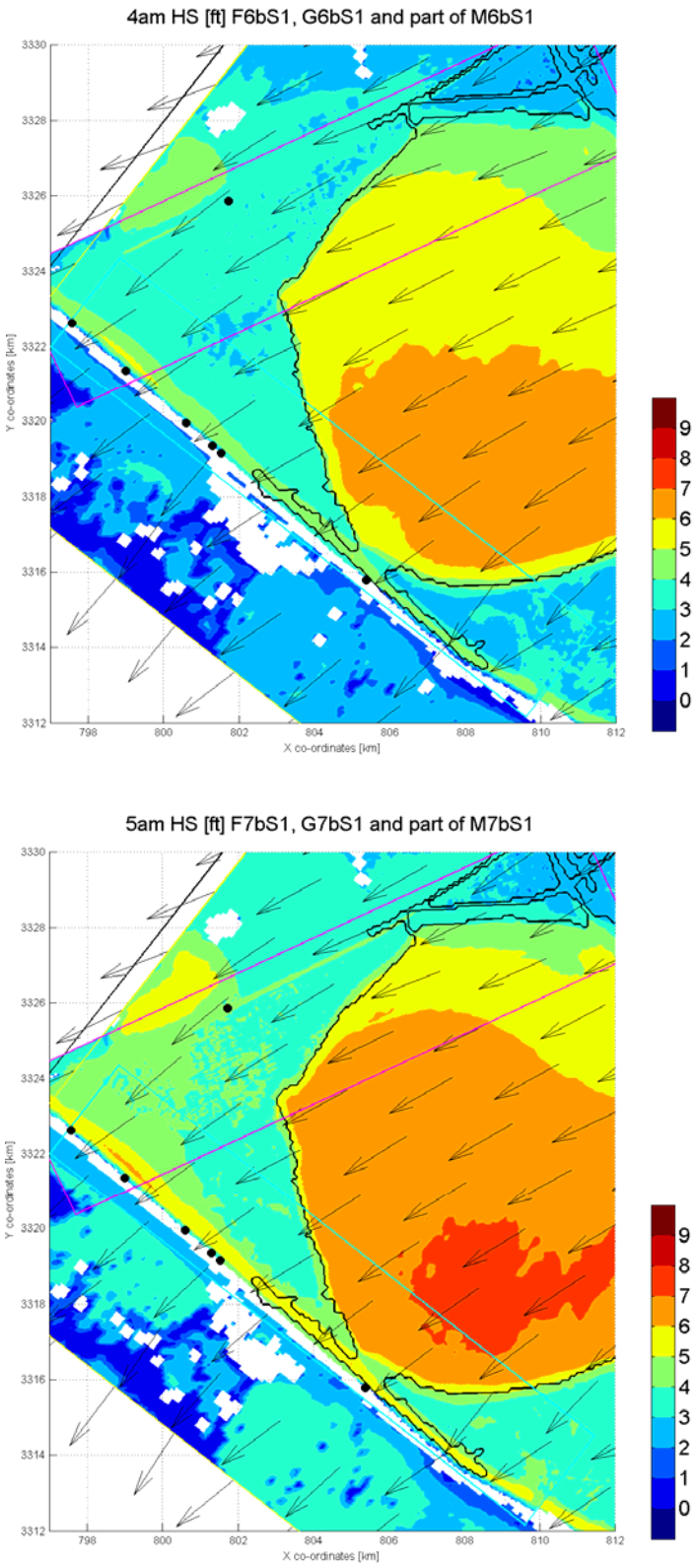


Figure 3.3.a: SCENARIO 1 SWAN results Hs [ft] and wave direction, 4:00 am and 5:00 am LT on grid F, G and part of M

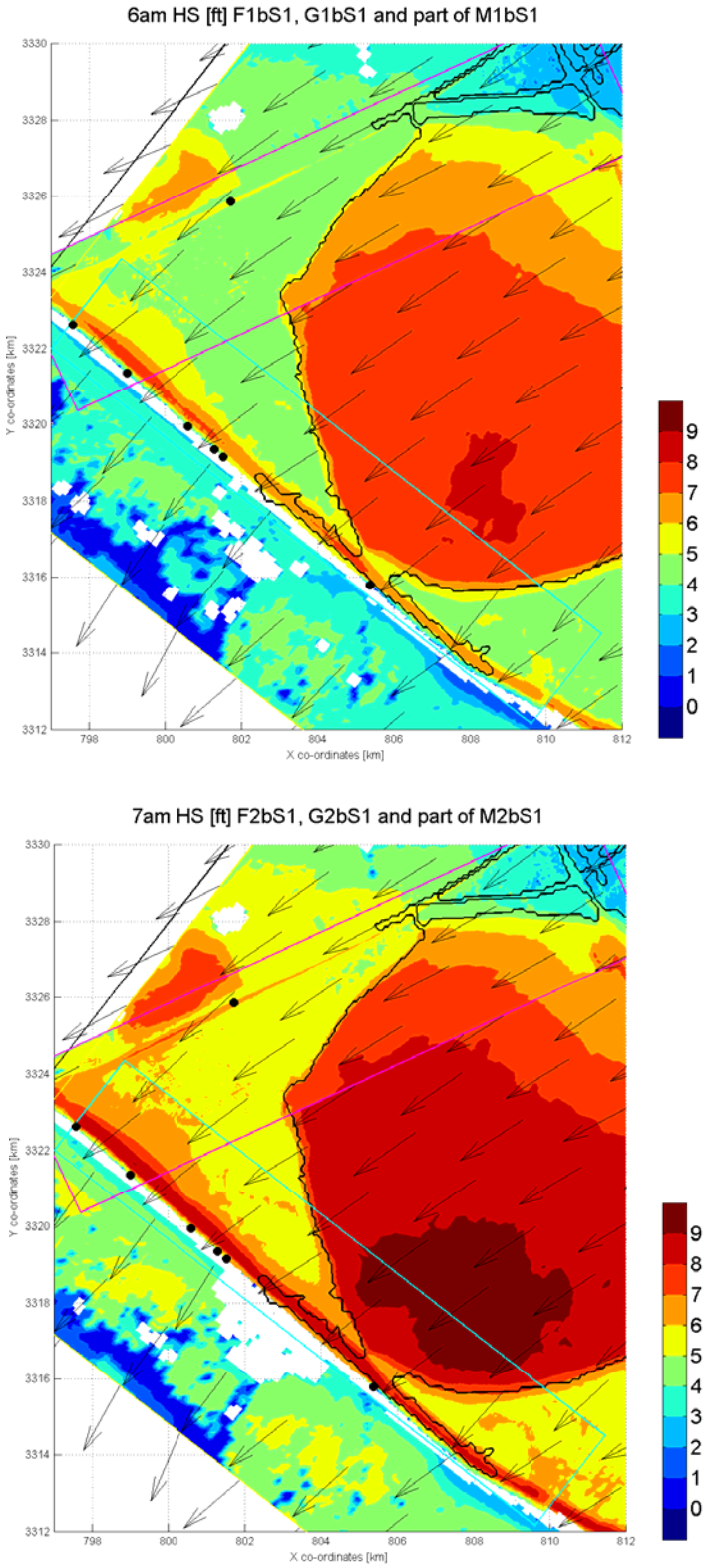


Figure 3.3.b: SCENARIO 1 SWAN results Hs [ft] and wave direction, 6:00 am and 7:00 am LT on grid F, G and part of M

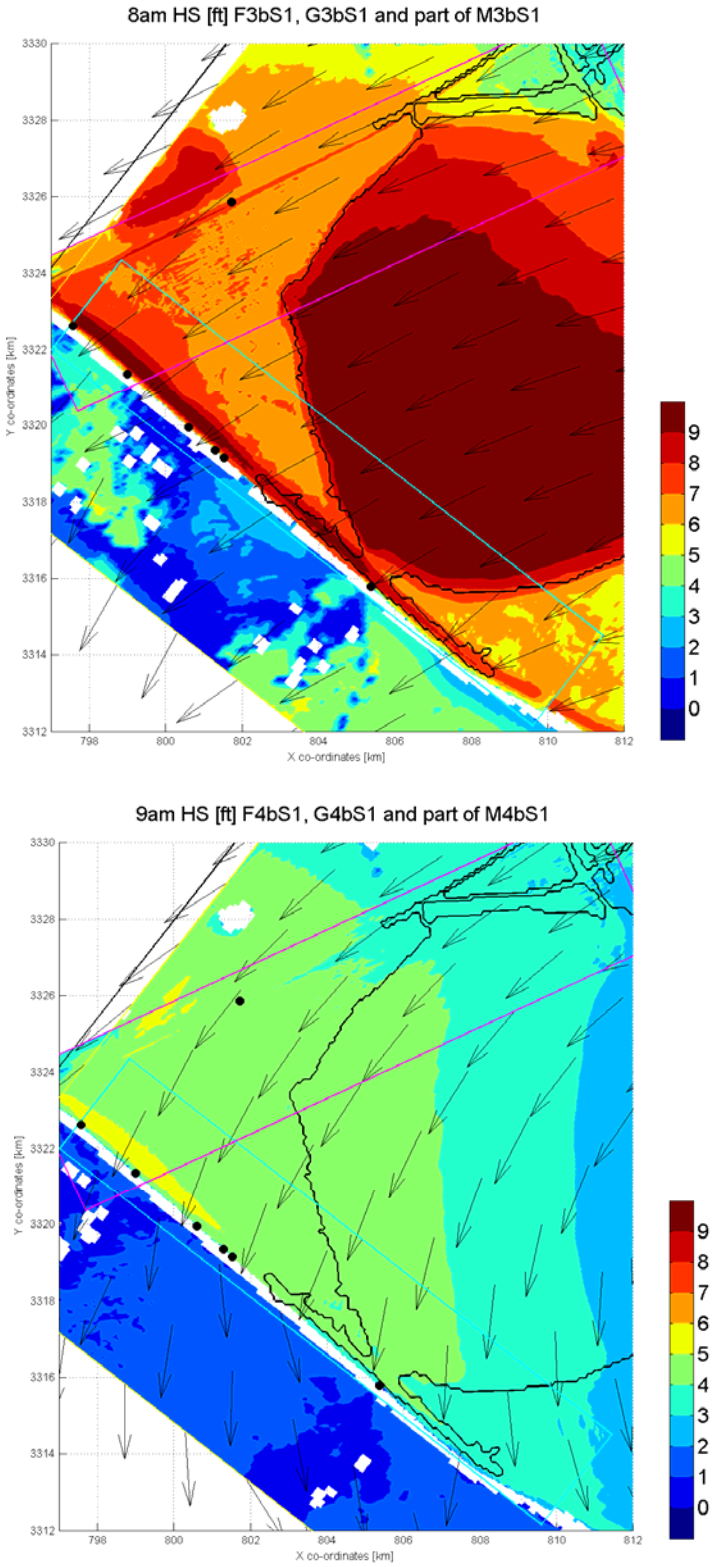


Figure 3.3.c: SCENARIO 1 SWAN results Hs [ft] and wave direction, 8:00 am and 9:00 am LT on grid F, G and part of M

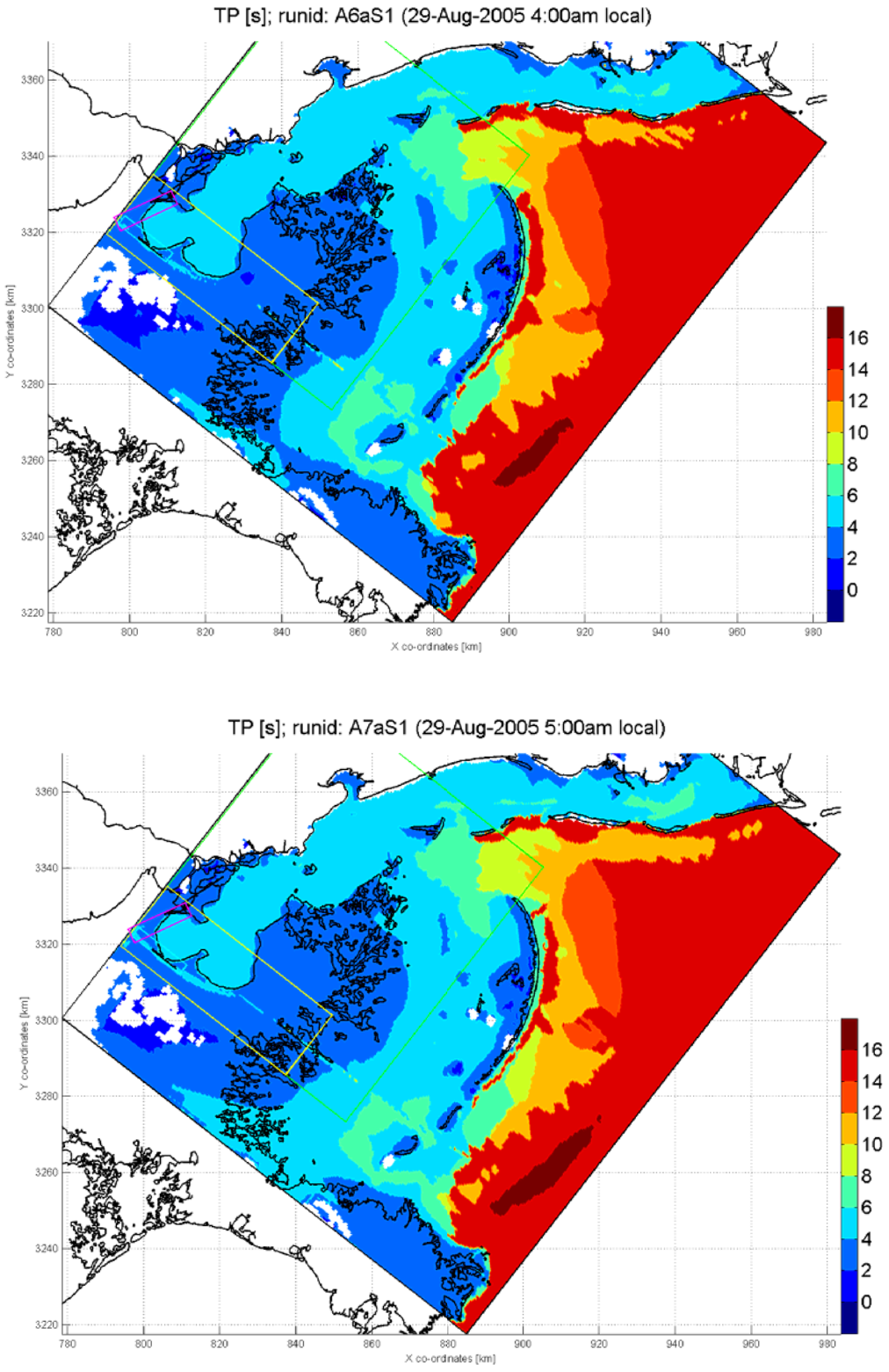
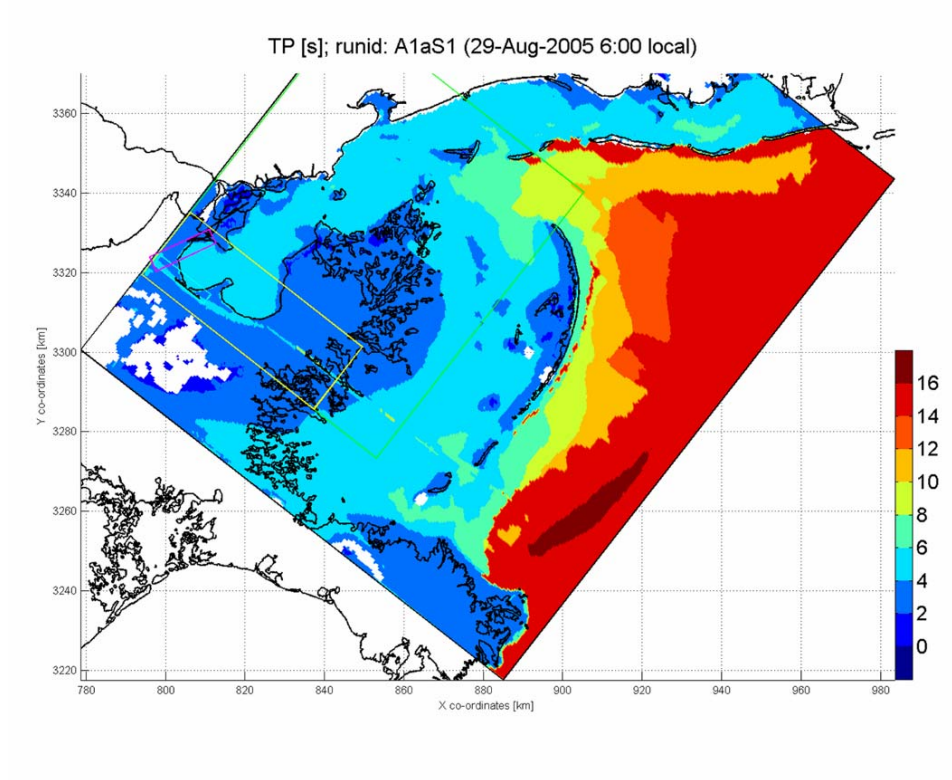


Figure 3.4.a: SCENARIO 1 SWAN results Tp [s] 4:00 am and 5:00 am on grid A



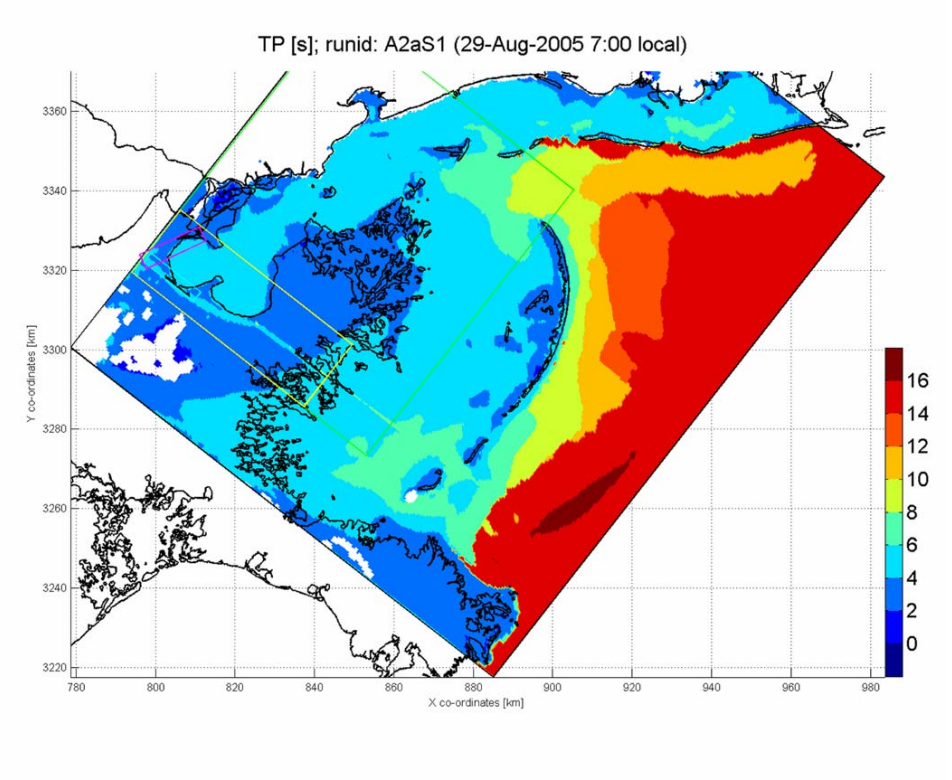
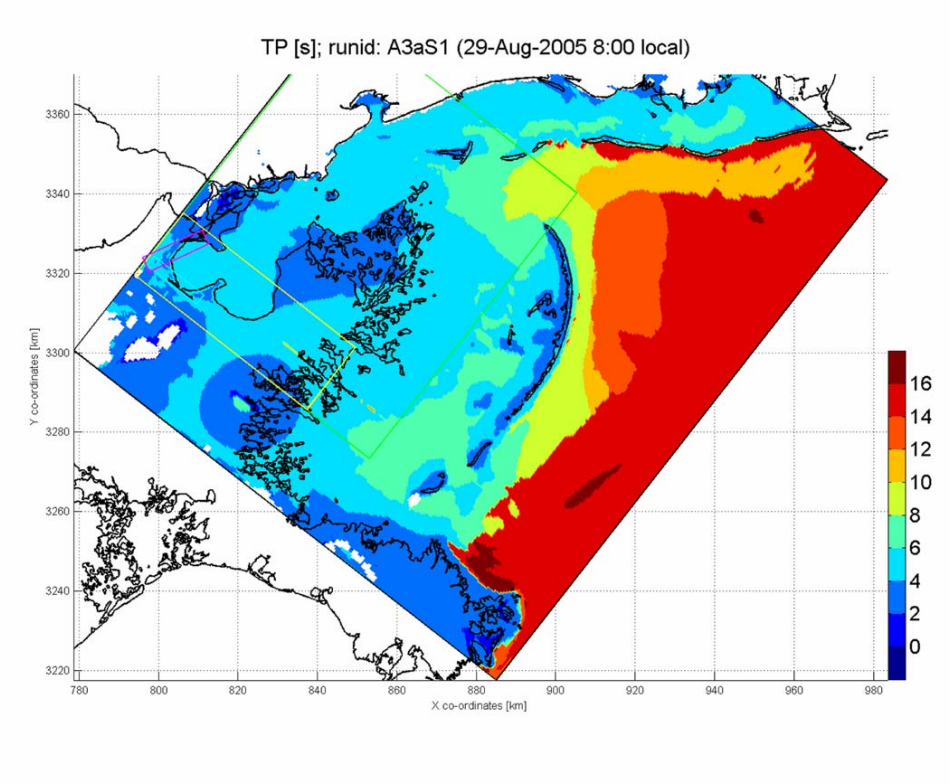


Figure 3.4.b: SCENARIO 1 SWAN results Tp [s] 6:00 am and 7:00 am on grid A



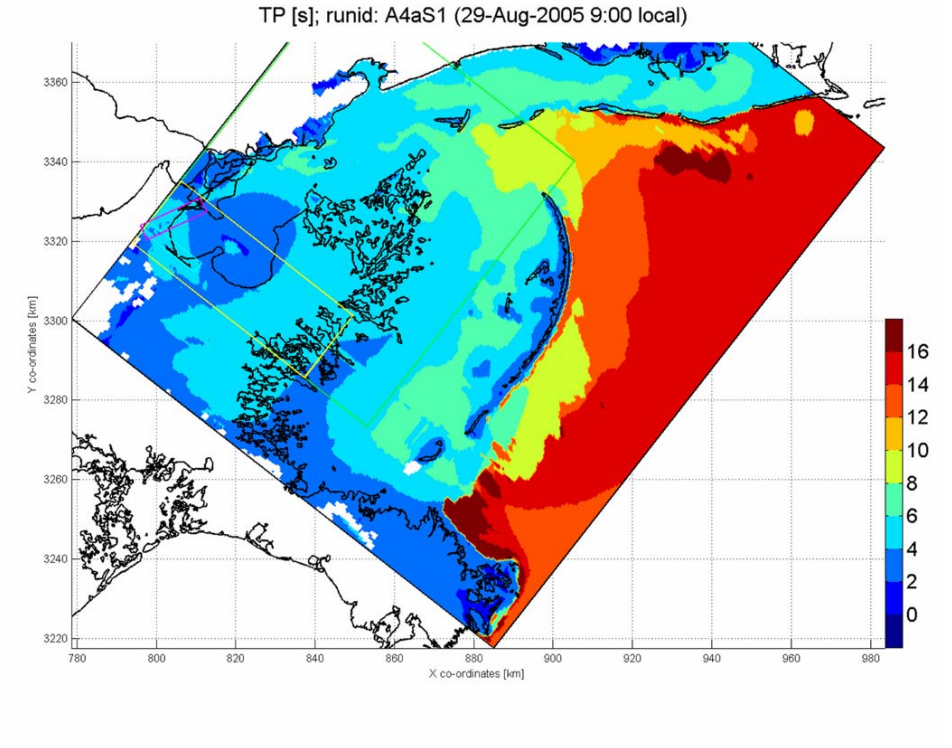


Figure 3.4.c: SCENARIO 1 SWAN results Tp [s] at 8:00 am and 9:00 am LT on grid A

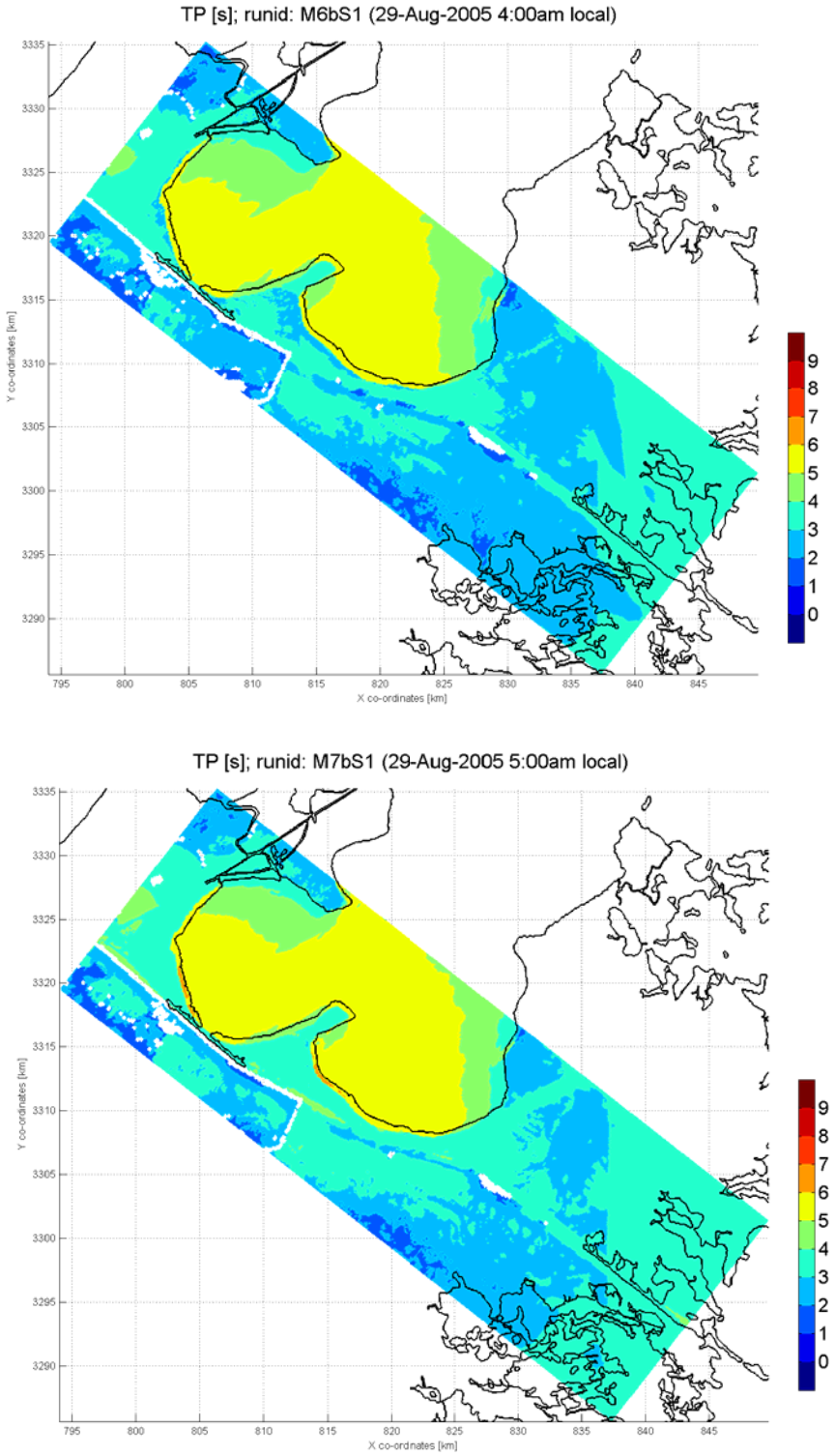


Figure 3.5.a: SCENARIO 1 SWAN results Tp [s] 4:00 am, 5:00 am on grid M

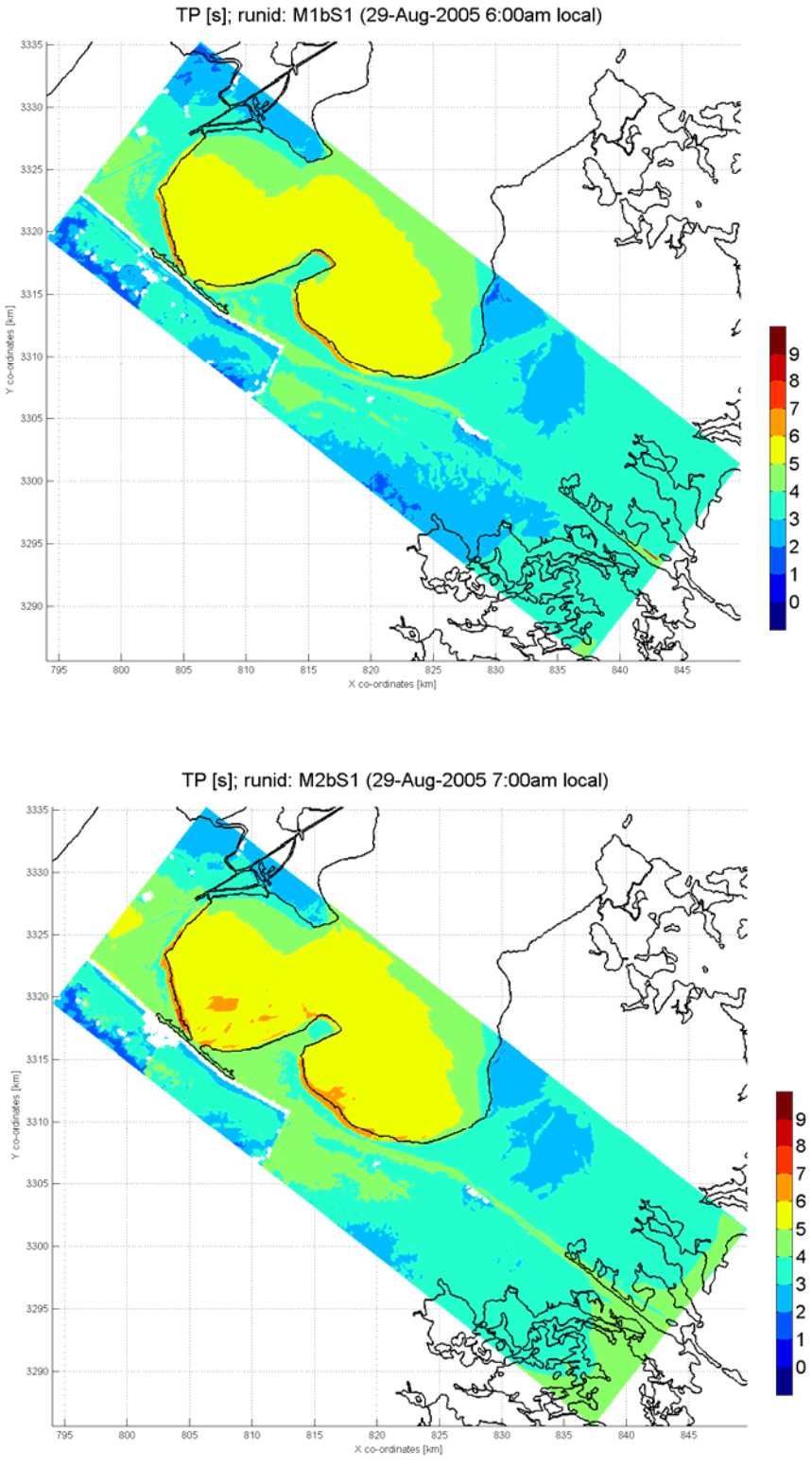


Figure 3.5.b: SCENARIO 1 SWAN results Tp [s] 6:00 am, 7:00 am on grid M

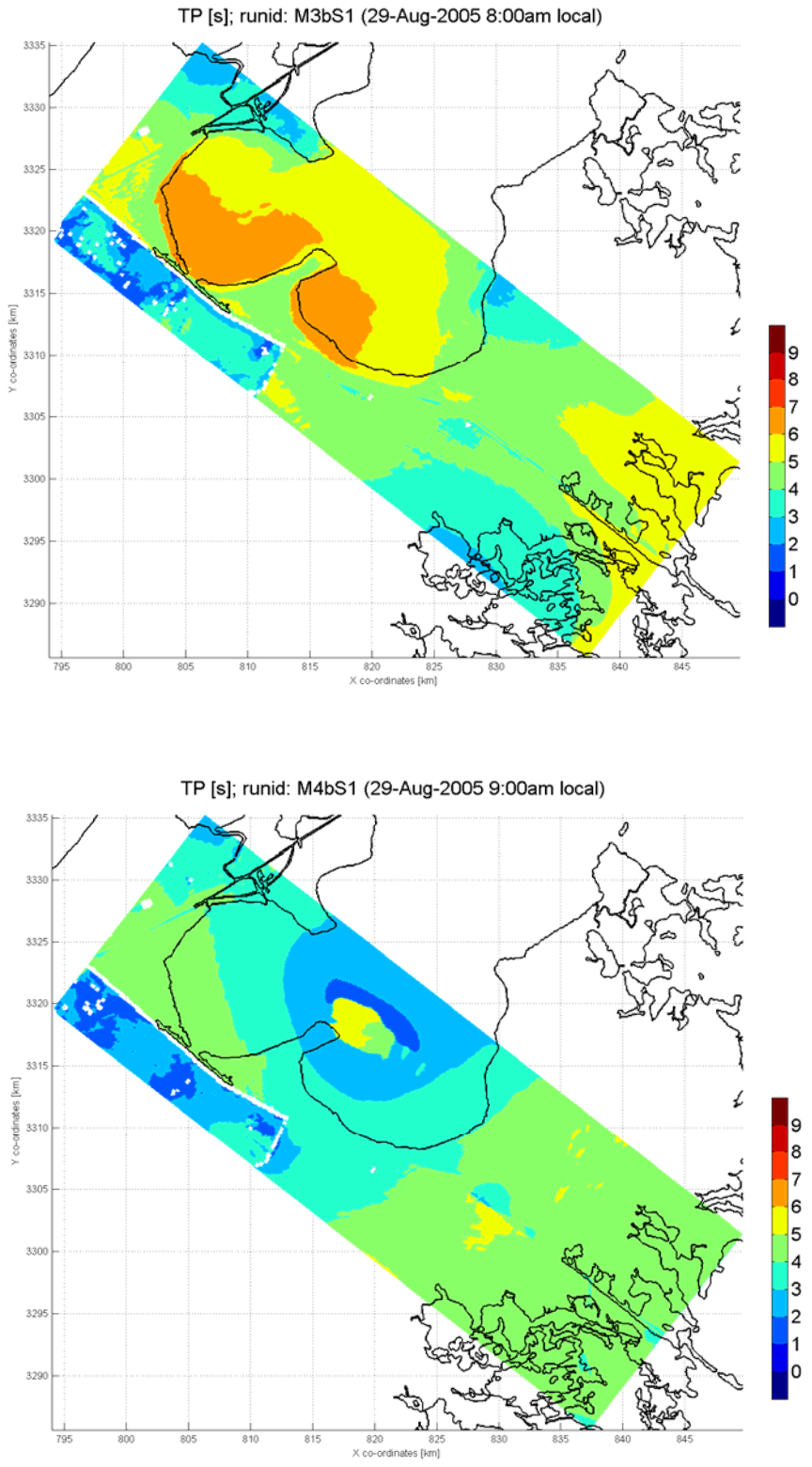


Figure 3.5.c: SCENARIO 1 SWAN results Tp [s] at 8:00 am and 9:00 am LT on grid M

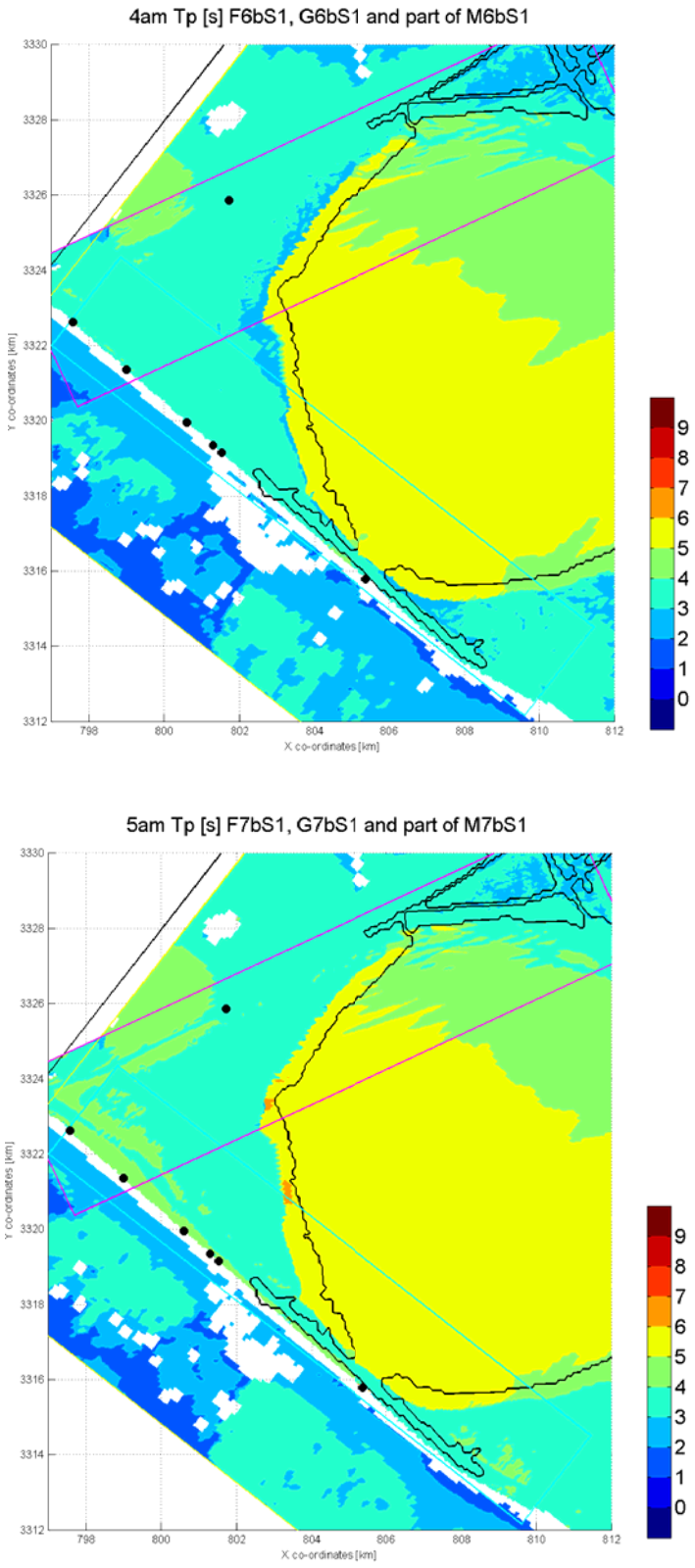


Figure 3.6.a: SCENARIO 1 SWAN results Tp [s] 4:00 am and 5:00 am on grid F, G and part of M

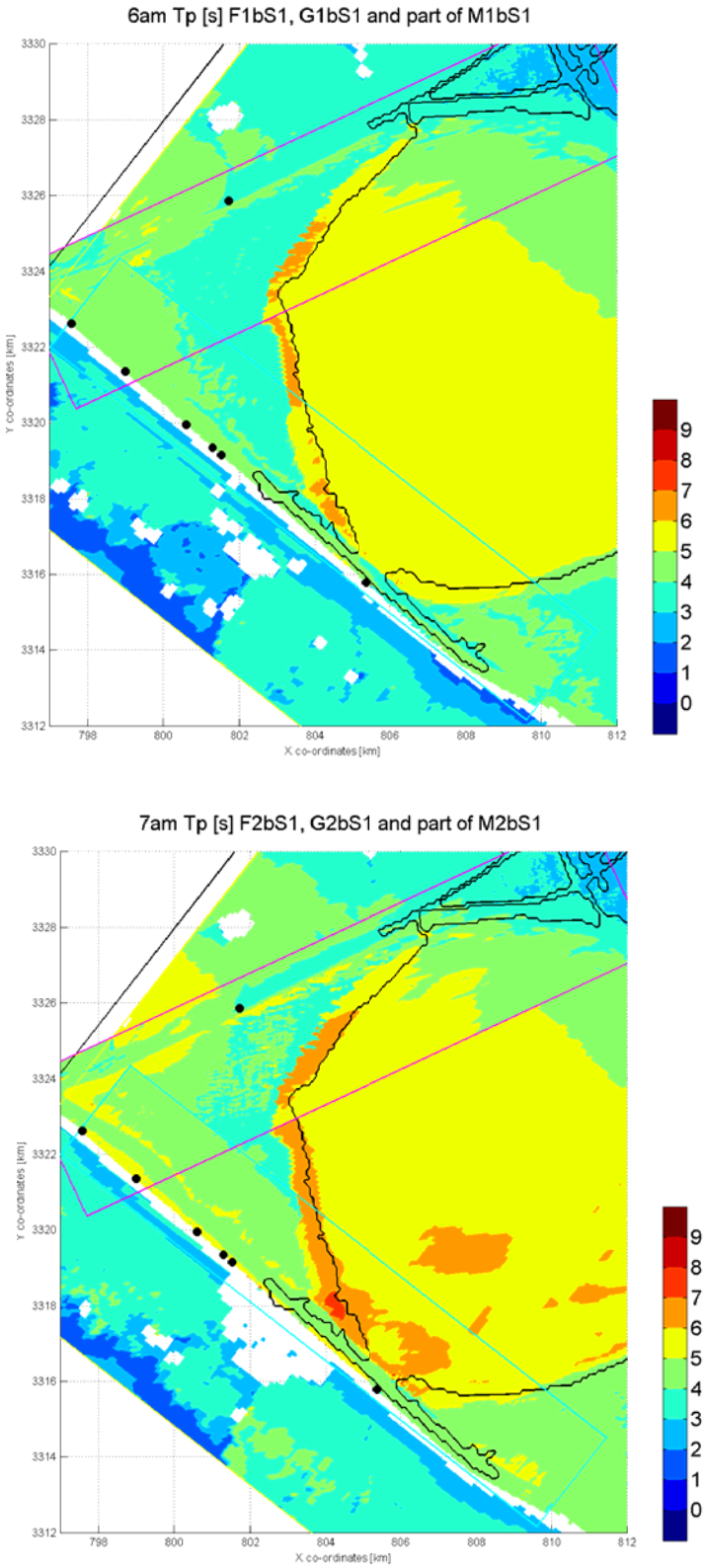


Figure 3.6.b: SCENARIO 1 SWAN results Tp [s] 6:00 am and 7:00 am on grid F, G and part of M

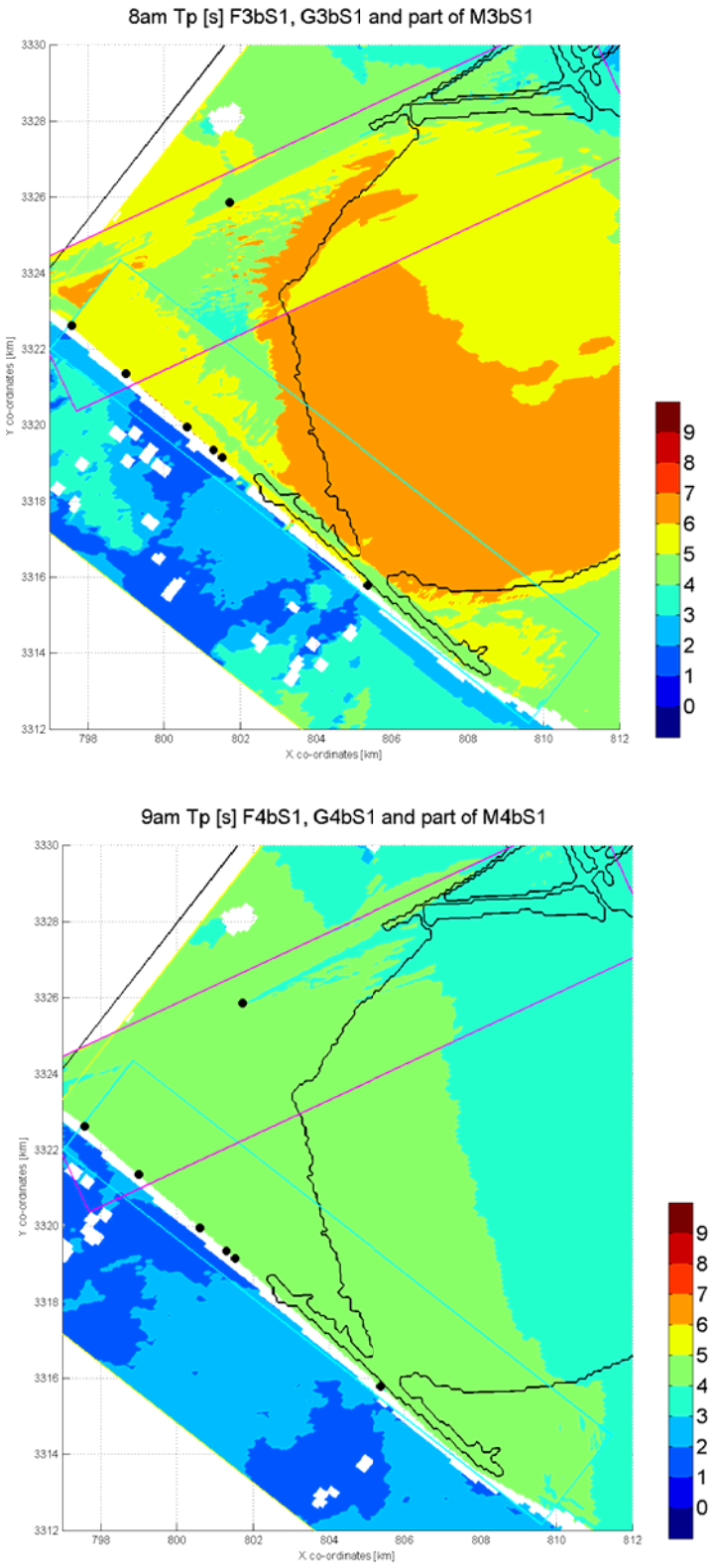


Figure 3.6.c: SCENARIO 1 SWAN results Tp [s] 8:00 am and 9:00 am on grid F, G and part of M

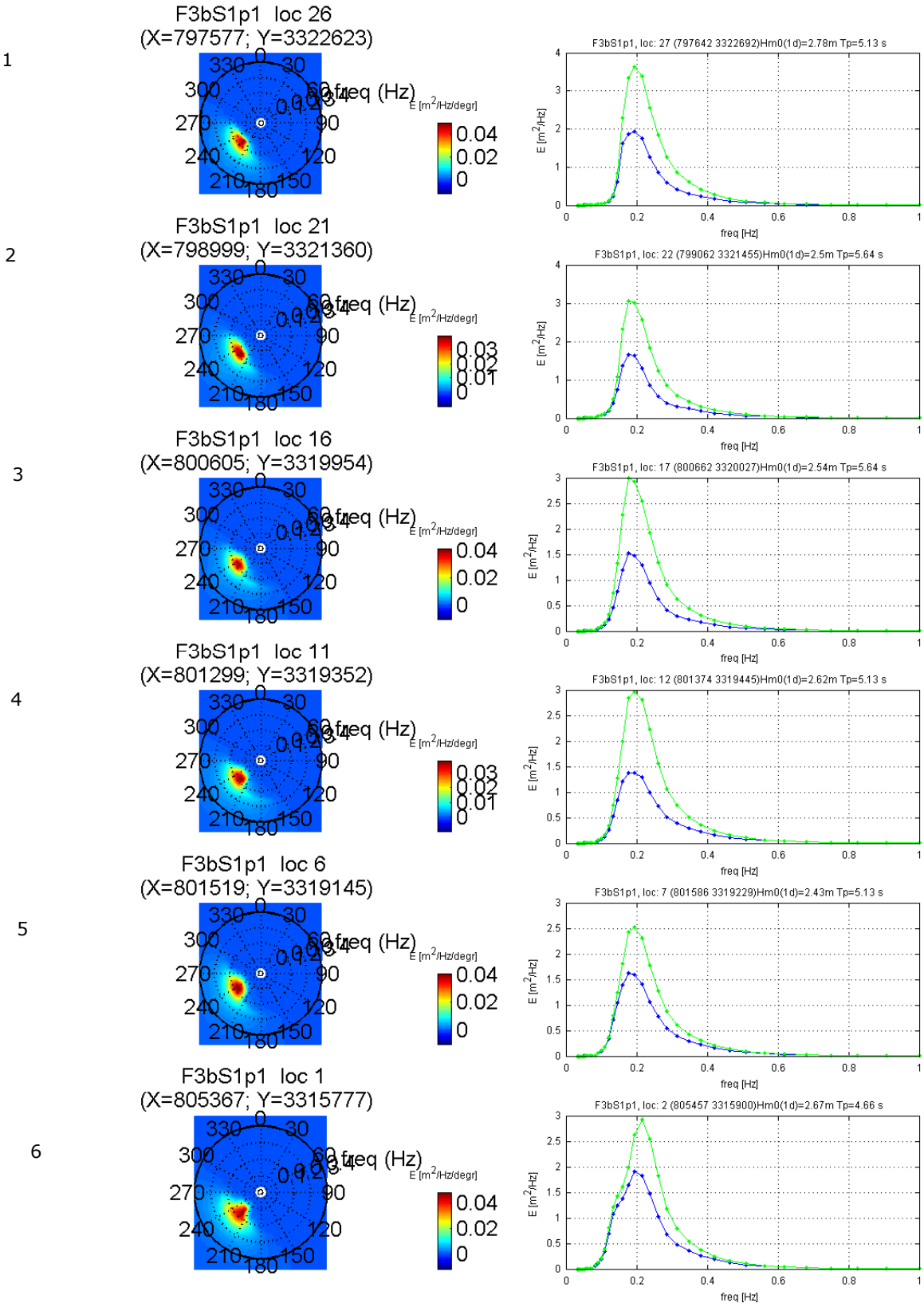


Figure 3.7: SCENARIO 1 Wave energy spectra t3 (8am). 2d spectra and blue lines refer to the pre described output locations on the levees (L) 1, 2, 3, 4, 5, 6. The green lines and parameter values in the title refer to locations near the toe (T).

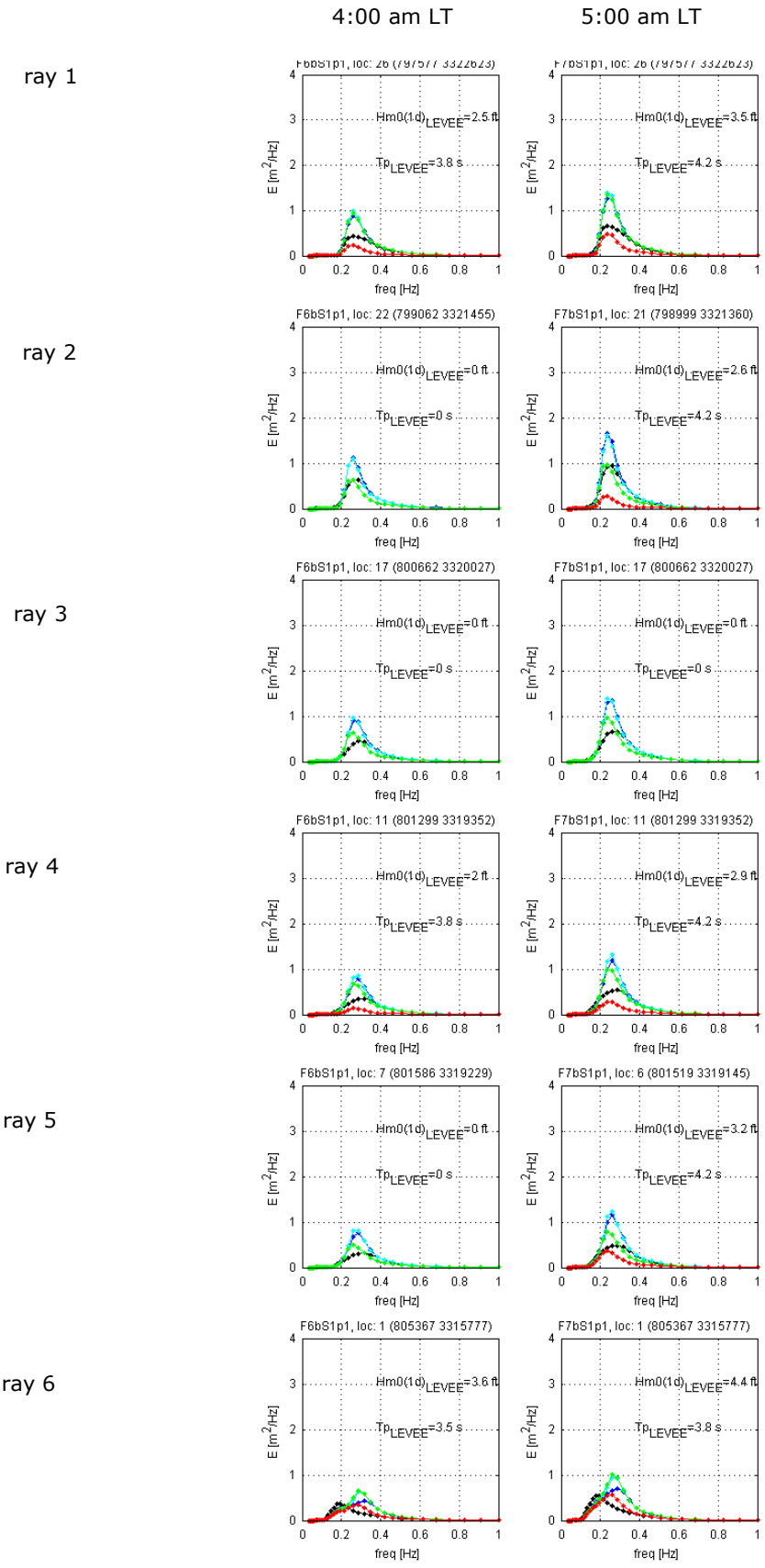


Figure 3.8.a: SWAN computed wave spectra on rays 1-6, 4:00 am (t6) and 5:00 am (t7) black (=just north of MRGO) - blue (=MRGO) - cyan - green (=toe) - red (=levee)

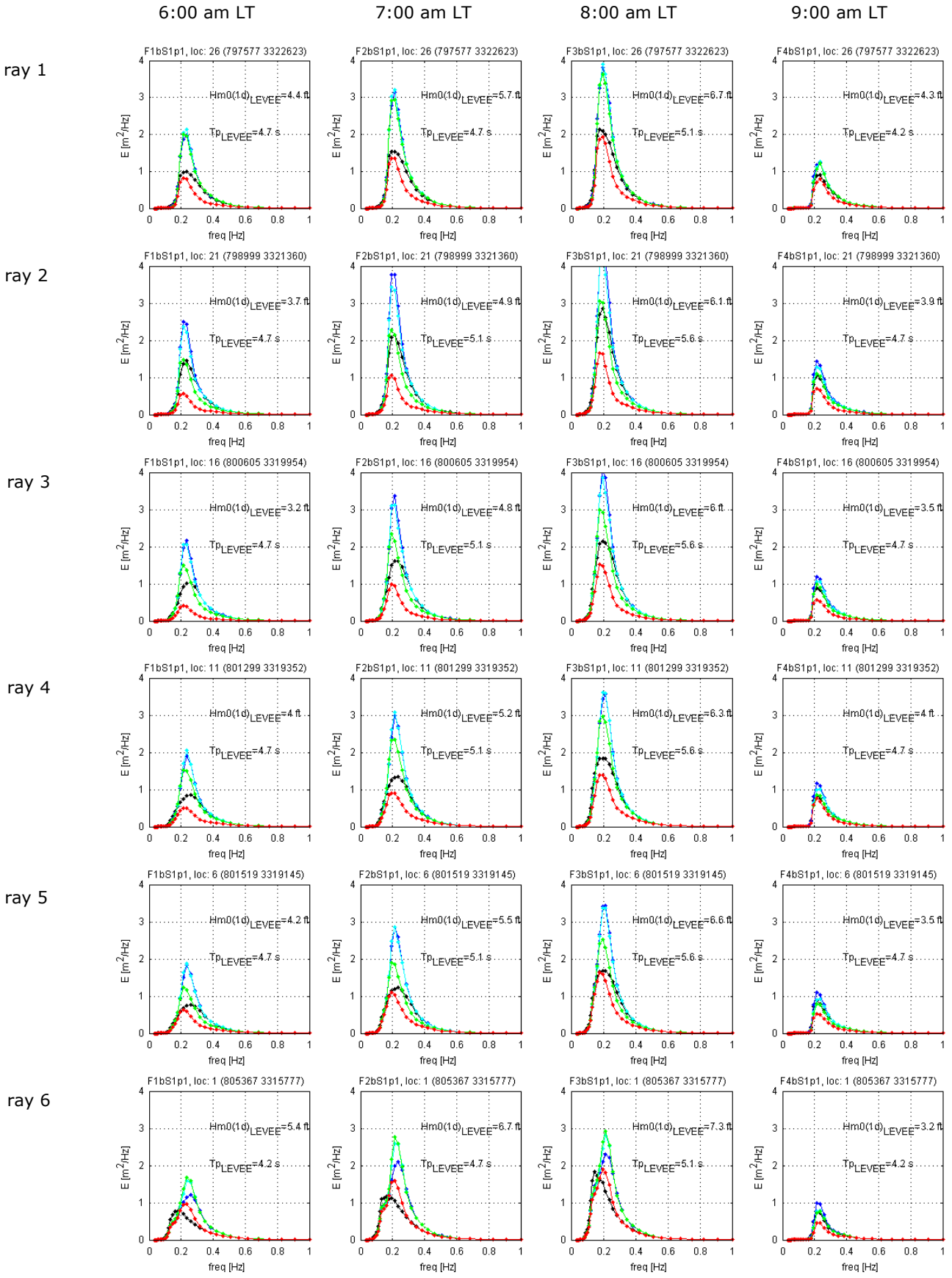


Figure 3.8.b: SWAN wave spectra for rays 1-6, 6am till 9am LT
black (=just north of MRGO) - blue (=MRGO) - cyan - green (=toe) - red (=levee)

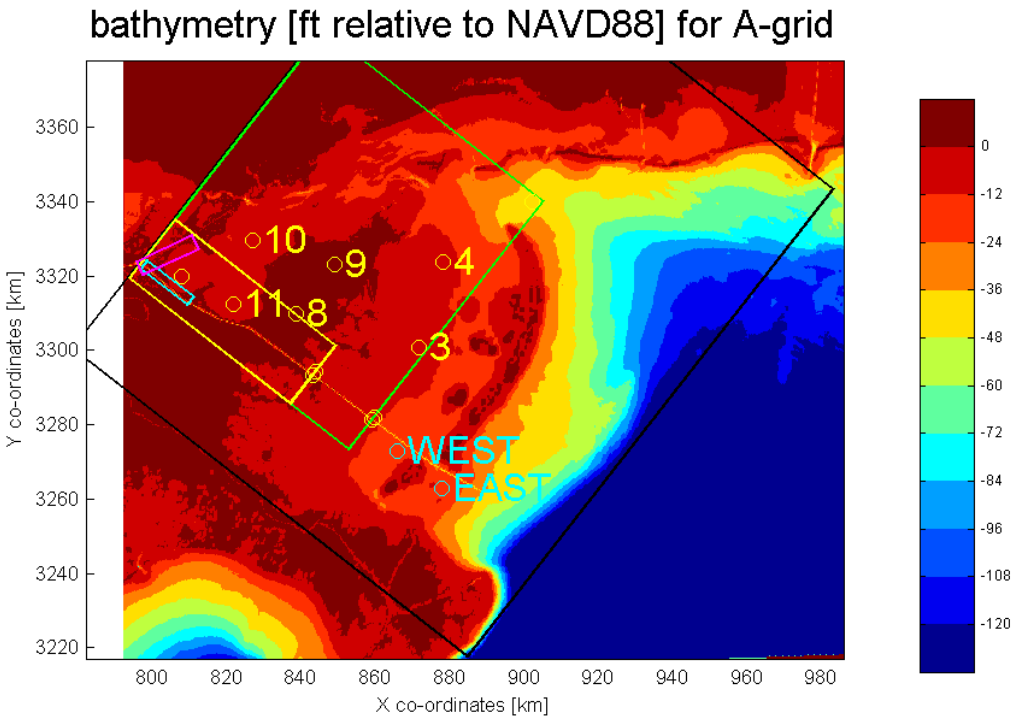


Figure 3.9.a: Output locations for additional spectra, see Figure 3.9.b

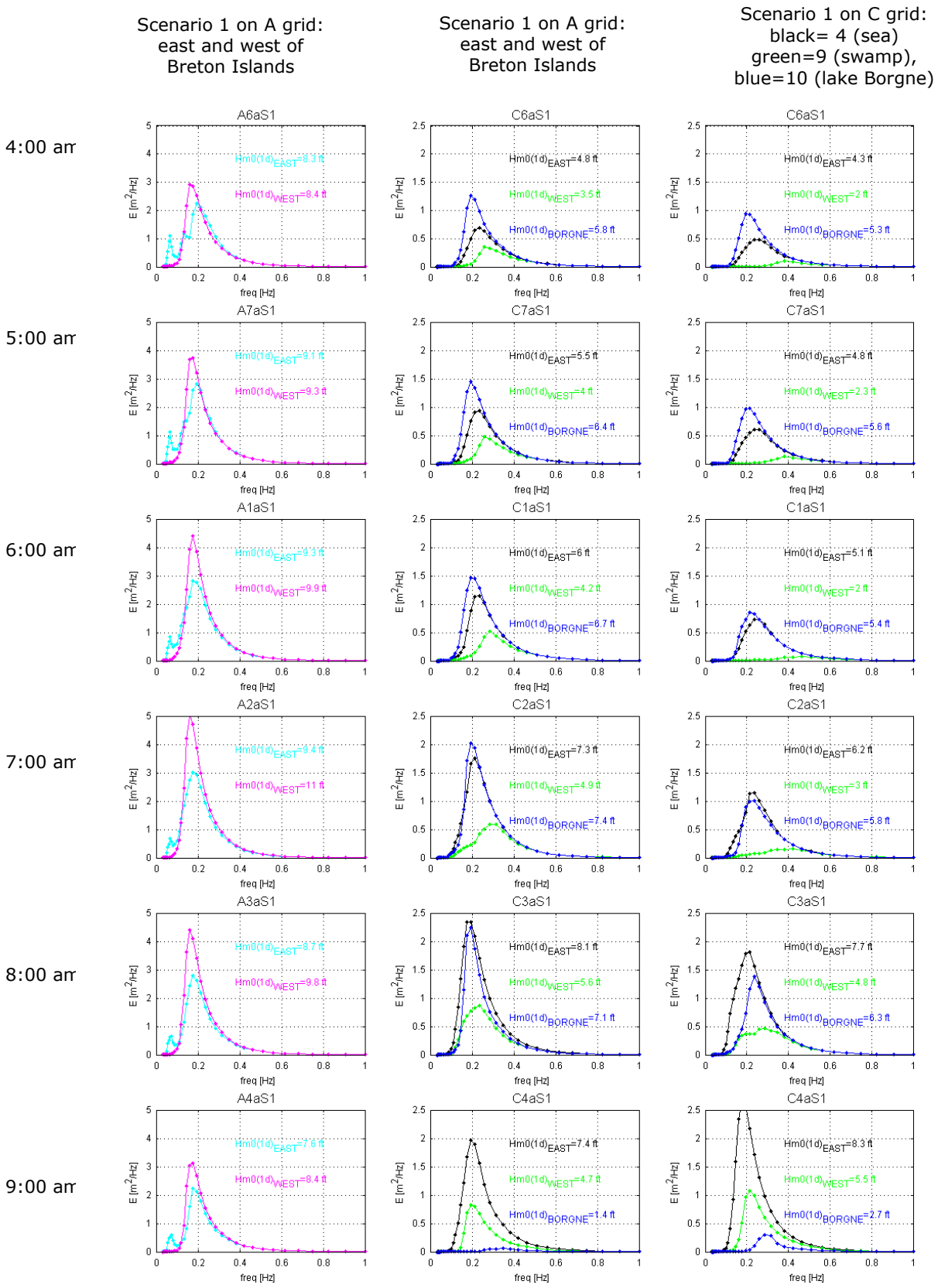


Figure 3.9.b: SCENARIO 1 SWAN wave spectra for 8 locations (see Figure 3.9.a) and 6 time steps

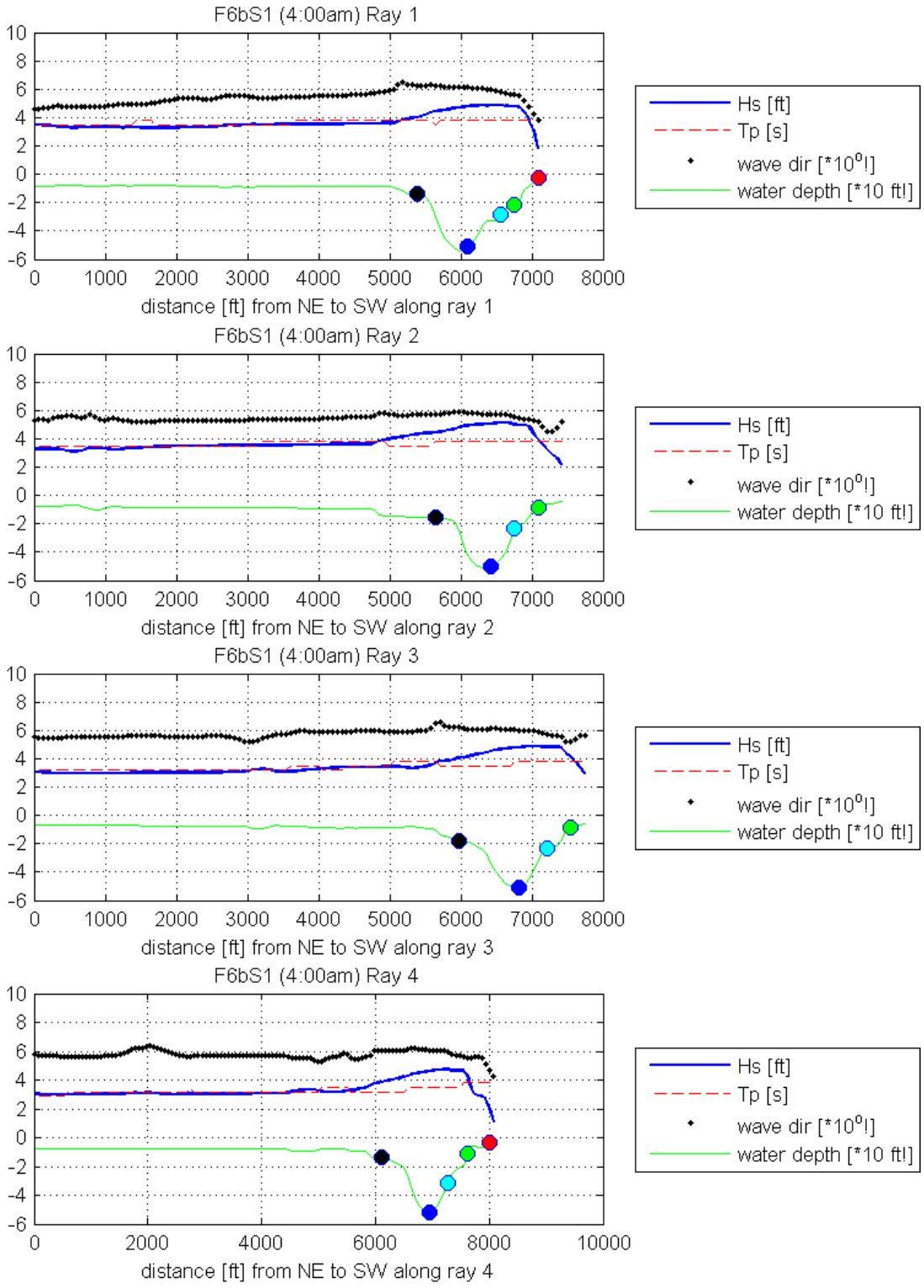


Figure 3.10.a: SCENARIO 1 Wave parameters on rays 1-4 at 4:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

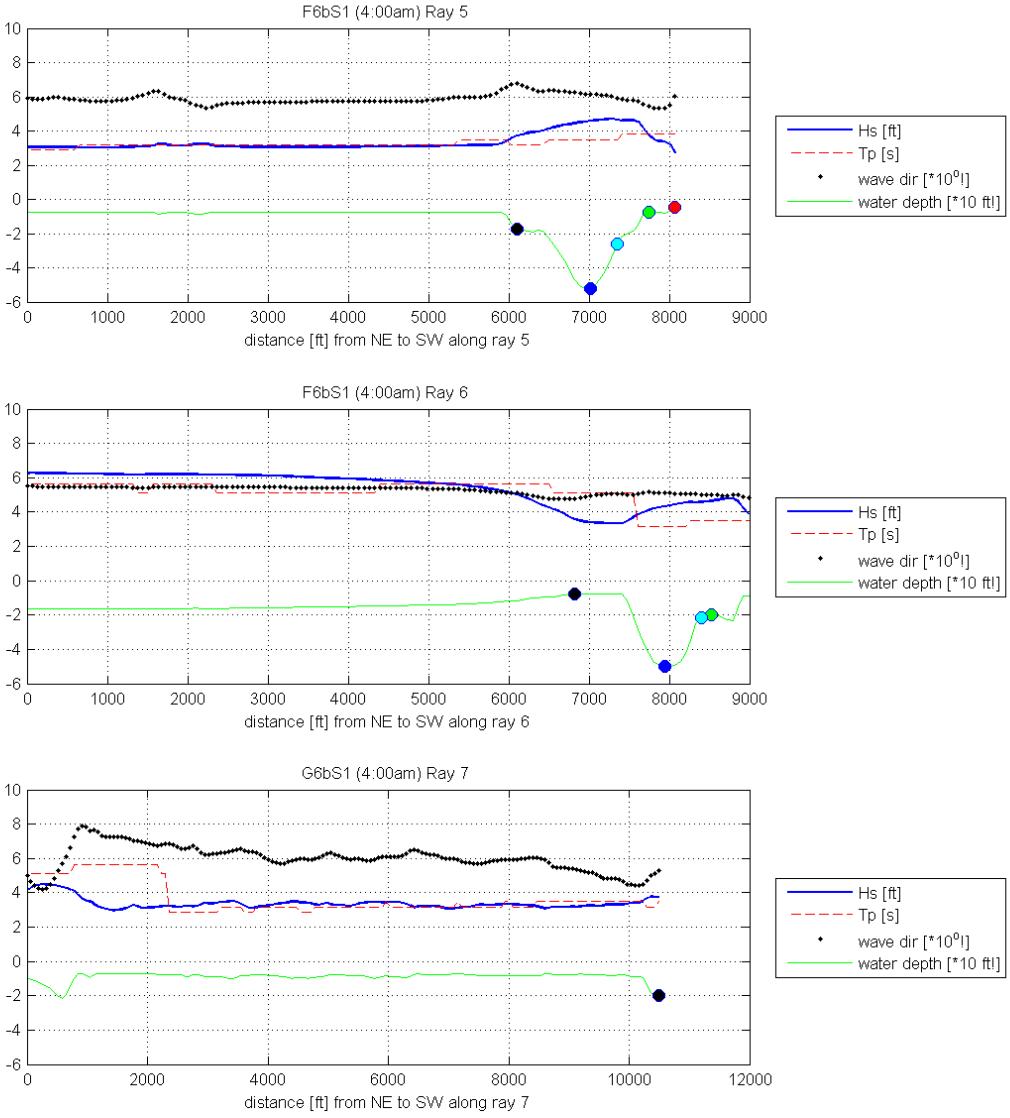


Figure 3.10.b: SCENARIO 1 Wave parameters on rays 5-7at 4:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

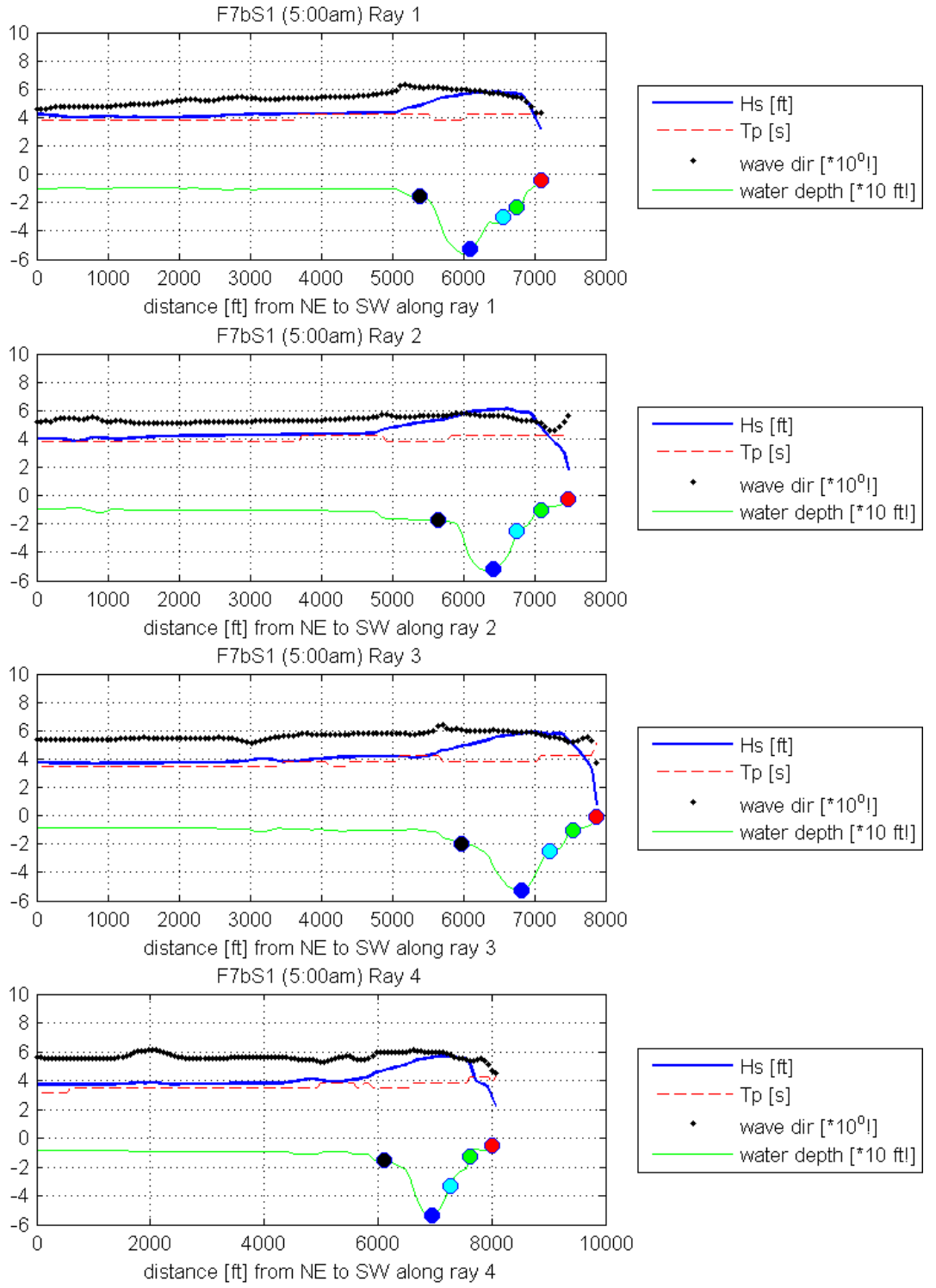


Figure 3.10.c: SCENARIO 1 Wave parameters on rays 1-4 at 5:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

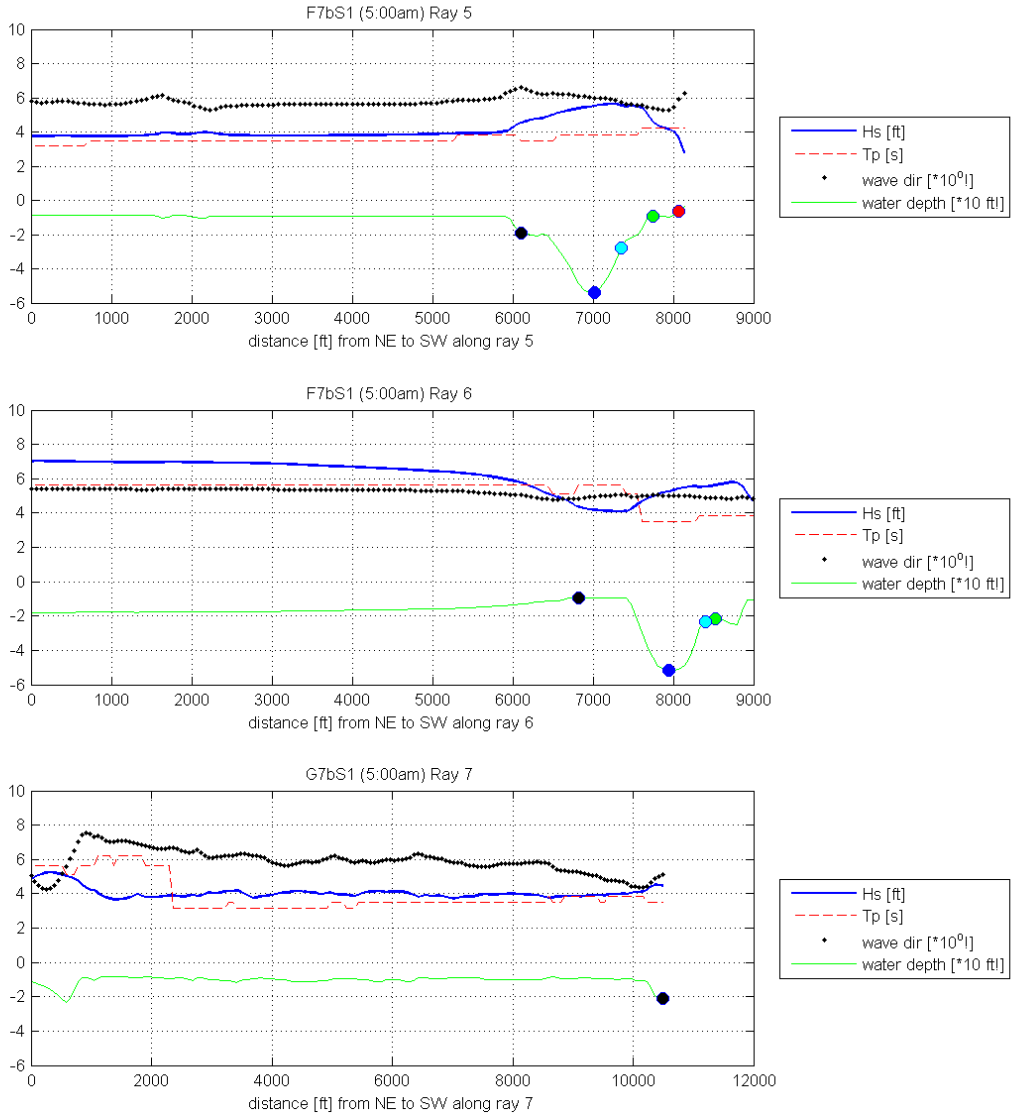


Figure 3.10.d: SCENARIO 1 Wave parameters on rays 5-7 at 5:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

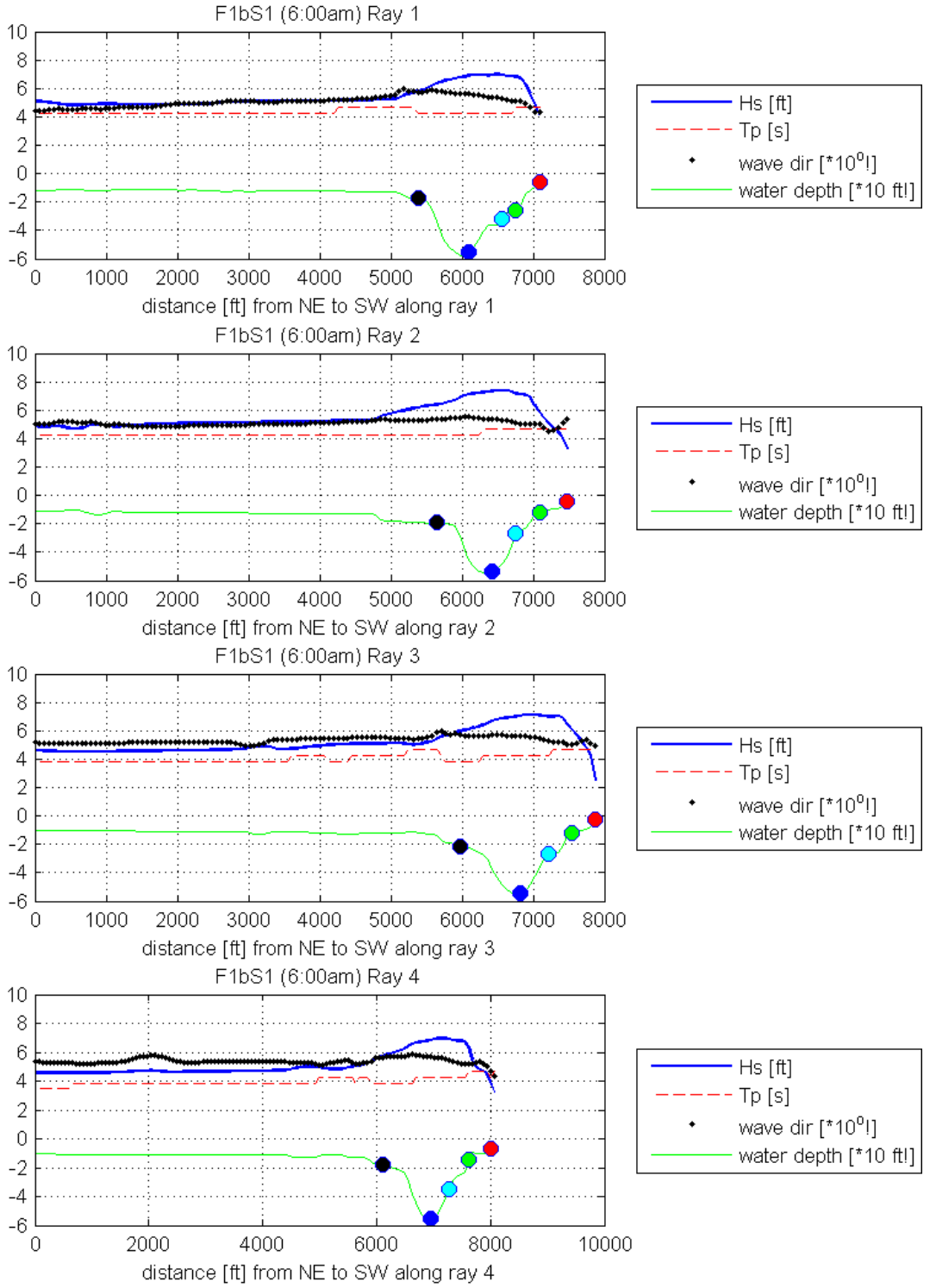


Figure 3.10.e: SCENARIO 1 Wave parameters on rays 1-4 at 6:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

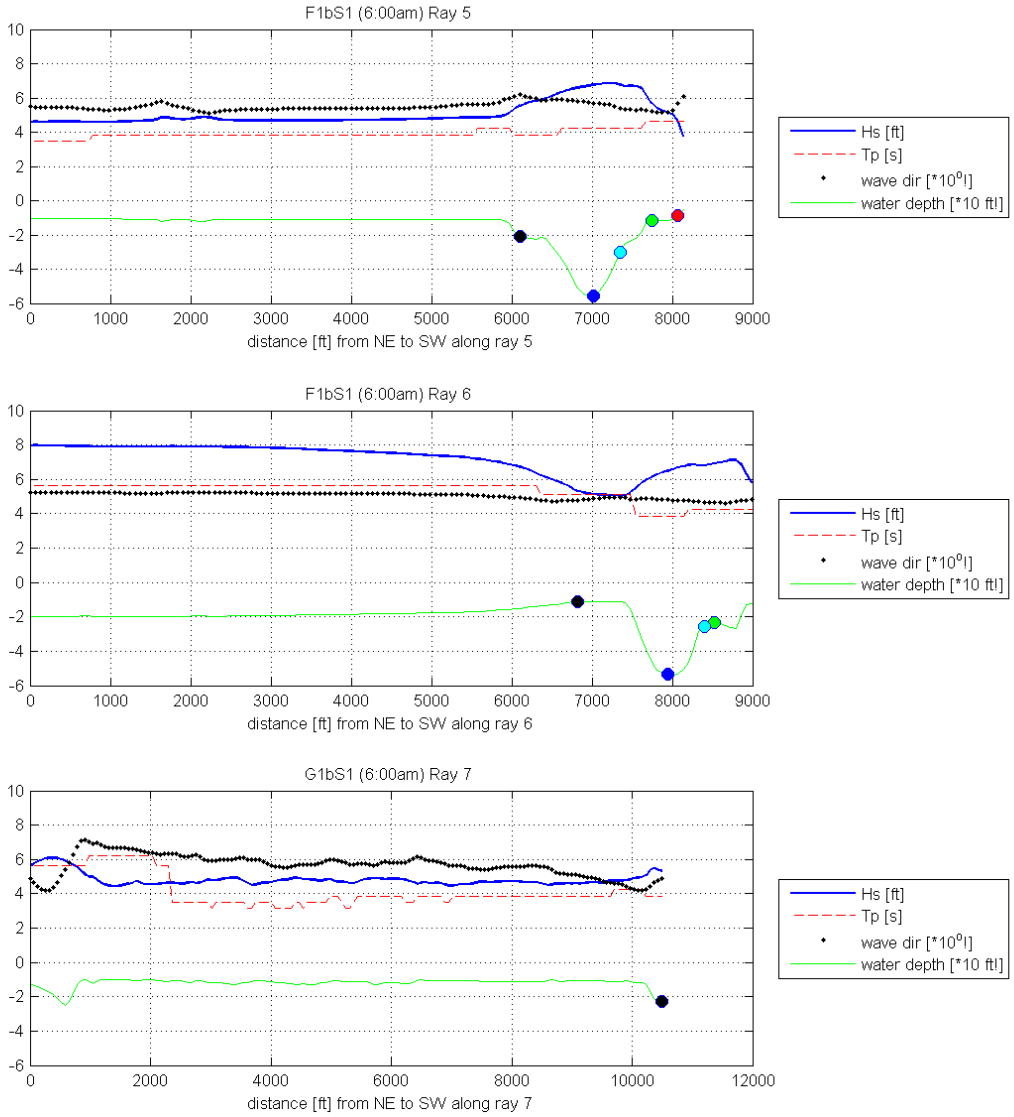


Figure 3.10.f: SCENARIO 1 Wave parameters on rays 5-7 at 6:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

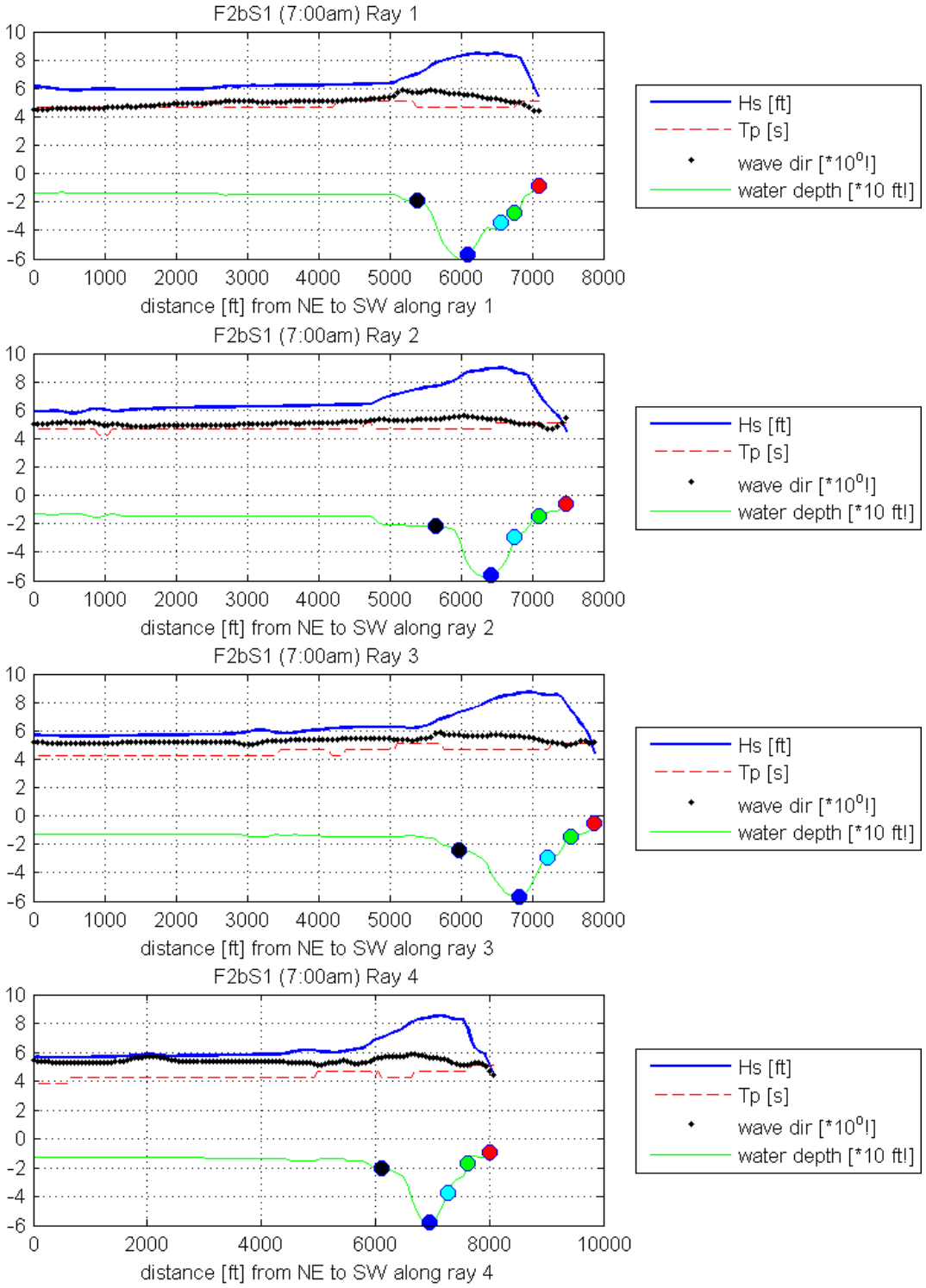


Figure 3.10.g: SCENARIO 1 Wave parameters on rays 1-4 at 7:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

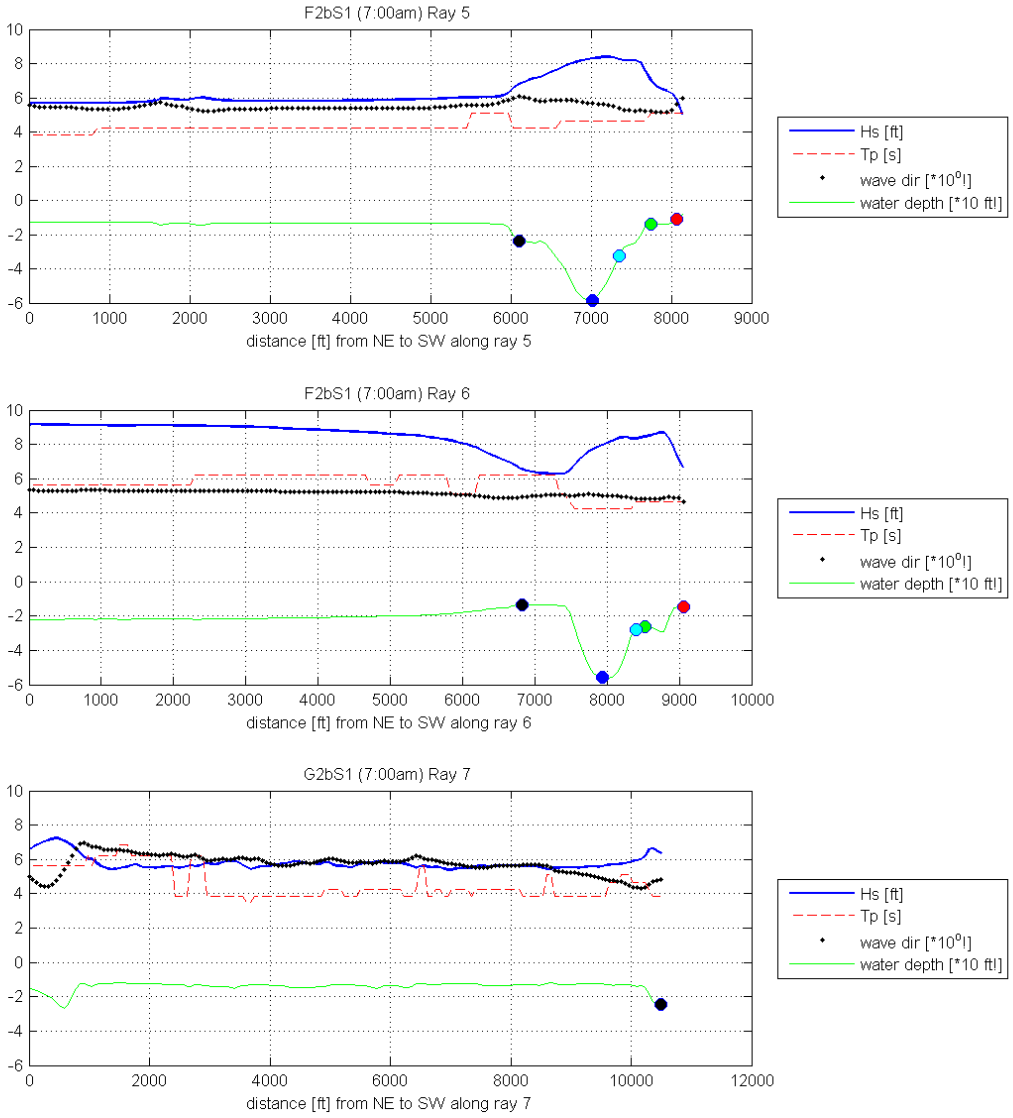


Figure 3.10.h: SCENARIO 1 Wave parameters on rays 5-7 at 7:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

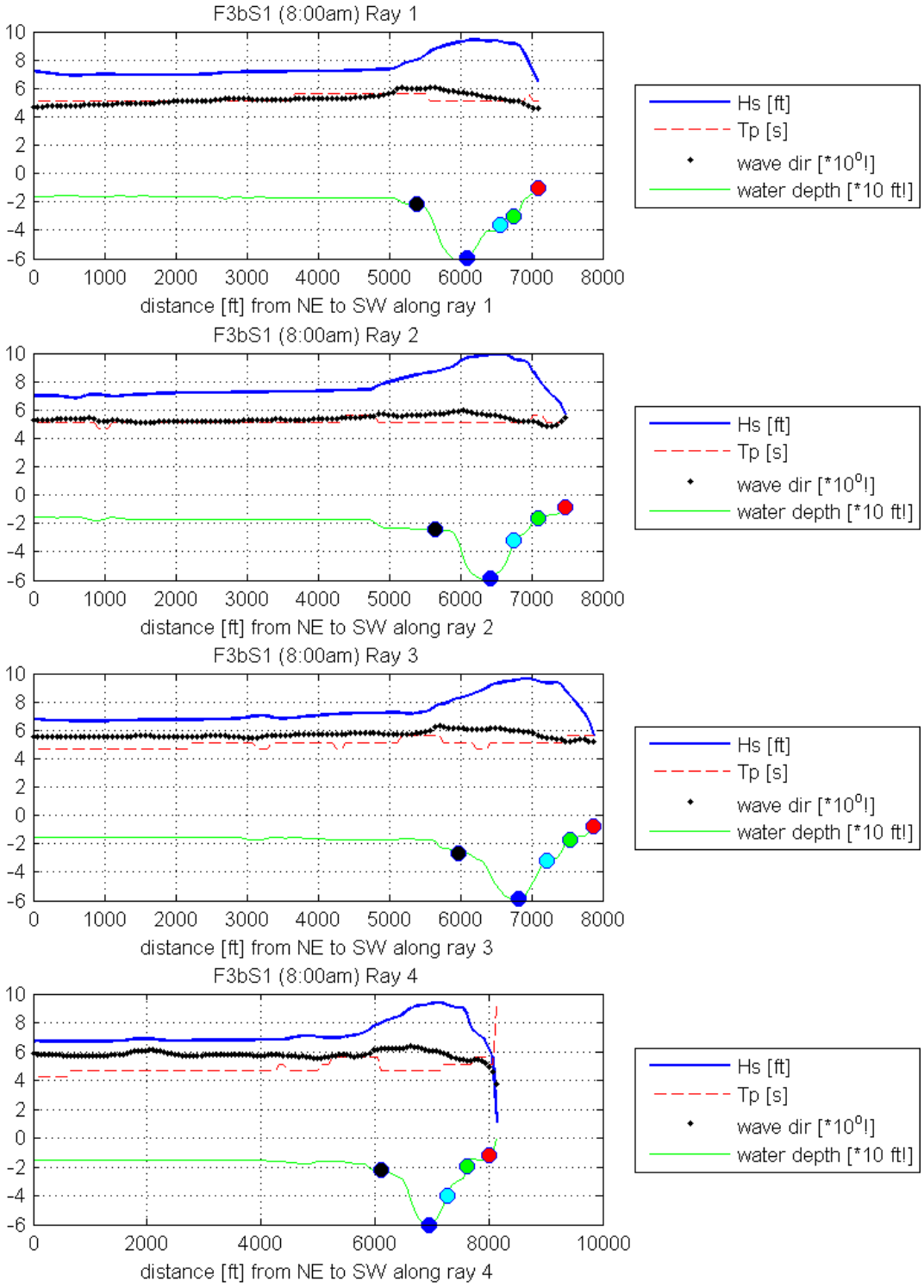


Figure 3.10.i: SCENARIO 1 Wave parameters on rays 1-4 at 8:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

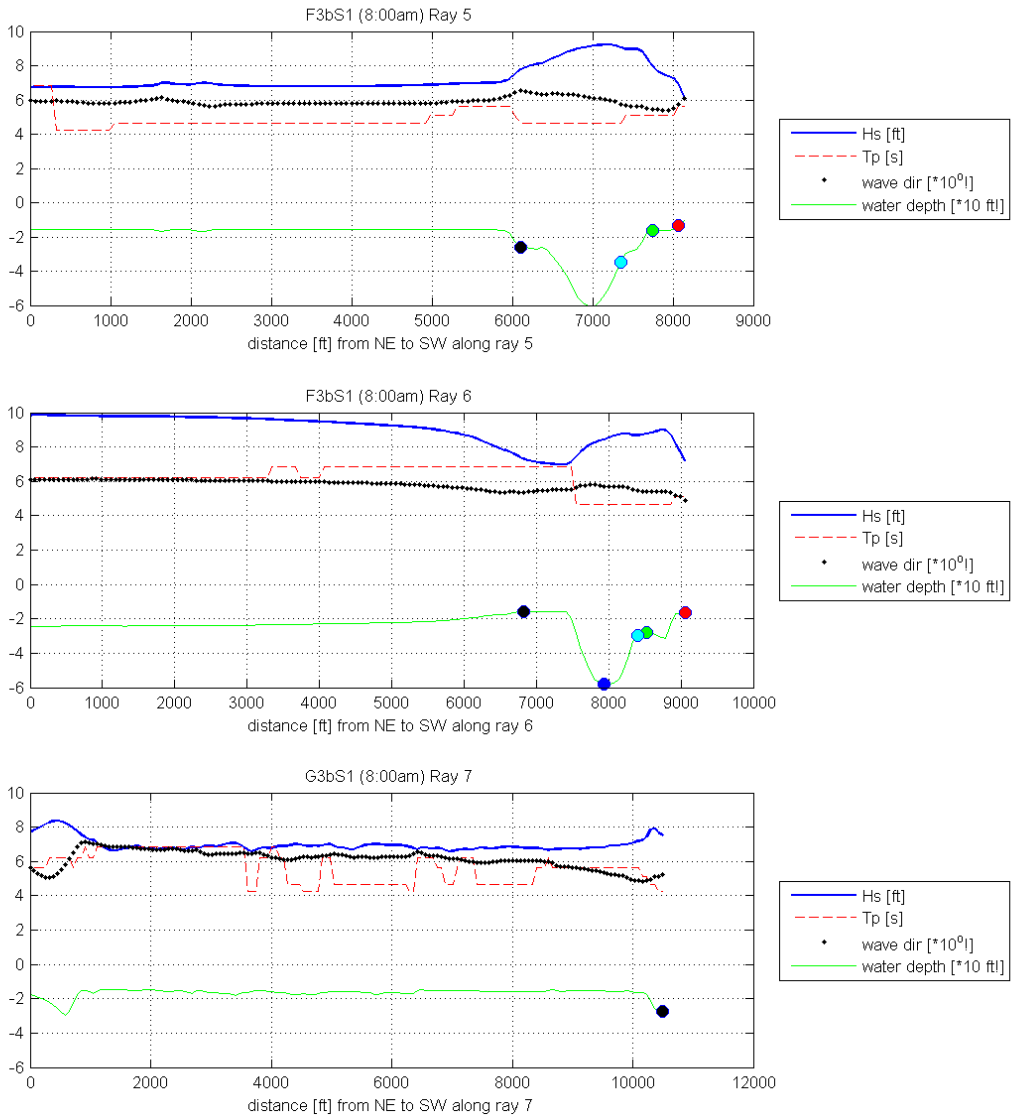


Figure 3.10.j: SCENARIO 1 Wave parameters on rays 5-7 at 8:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

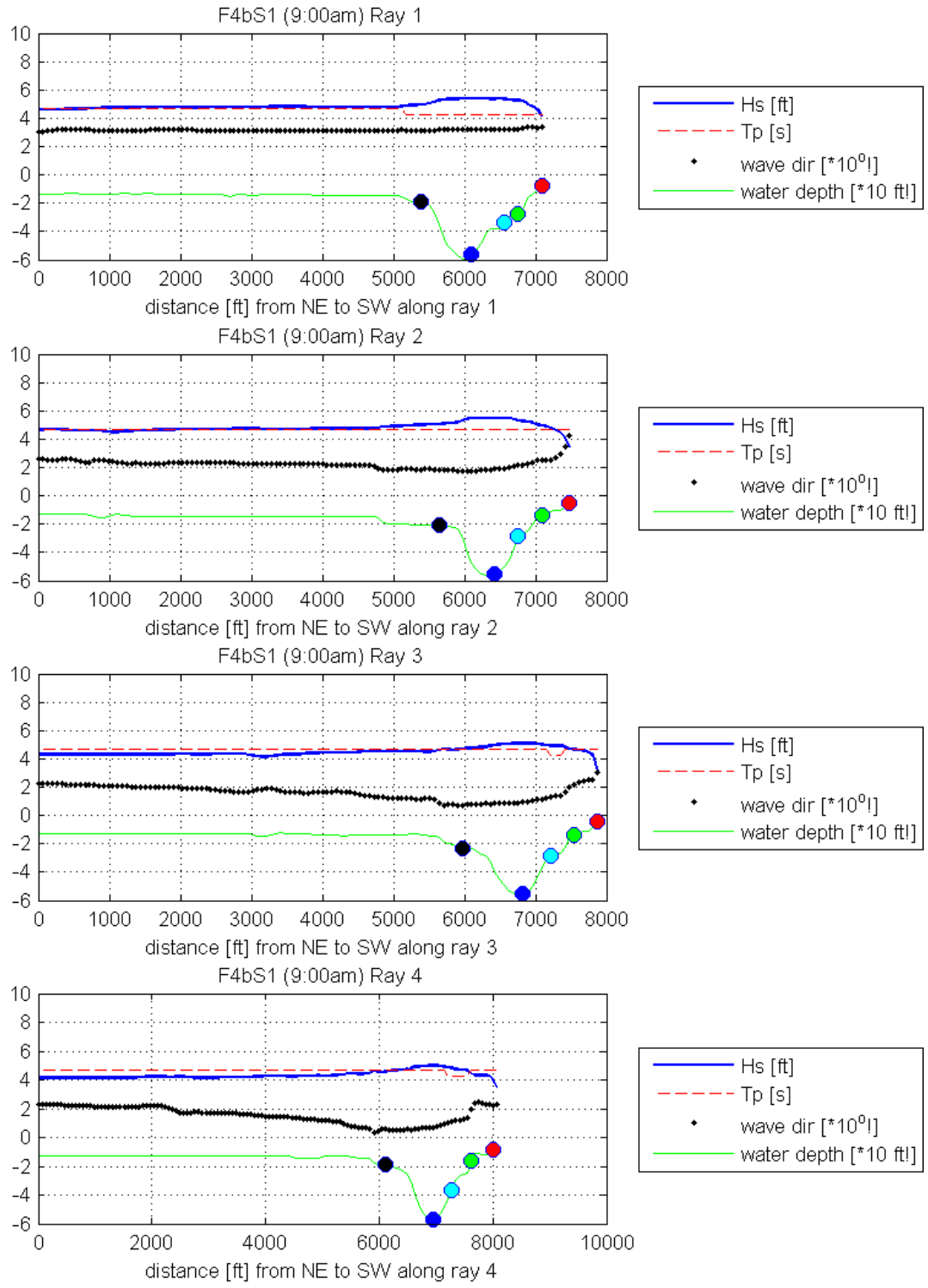


Figure 3.10.k: SCENARIO 1 Wave parameters on rays 1-4 at 9:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

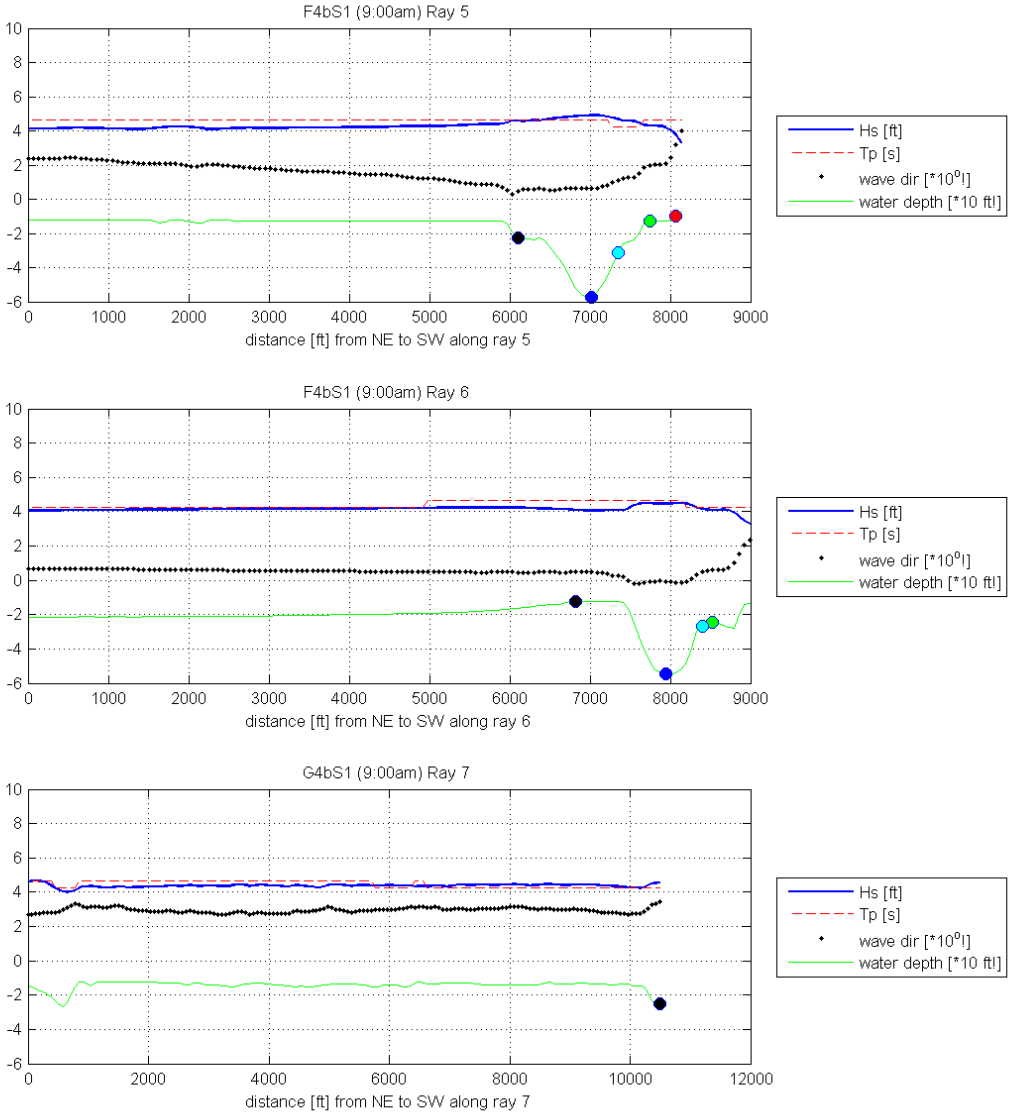


Figure 3.10.l: SCENARIO 1 Wave parameters on rays 5-7 at 9:00 am LT
(colored circles indicate output locations and refer to colors in Figure 3.8)

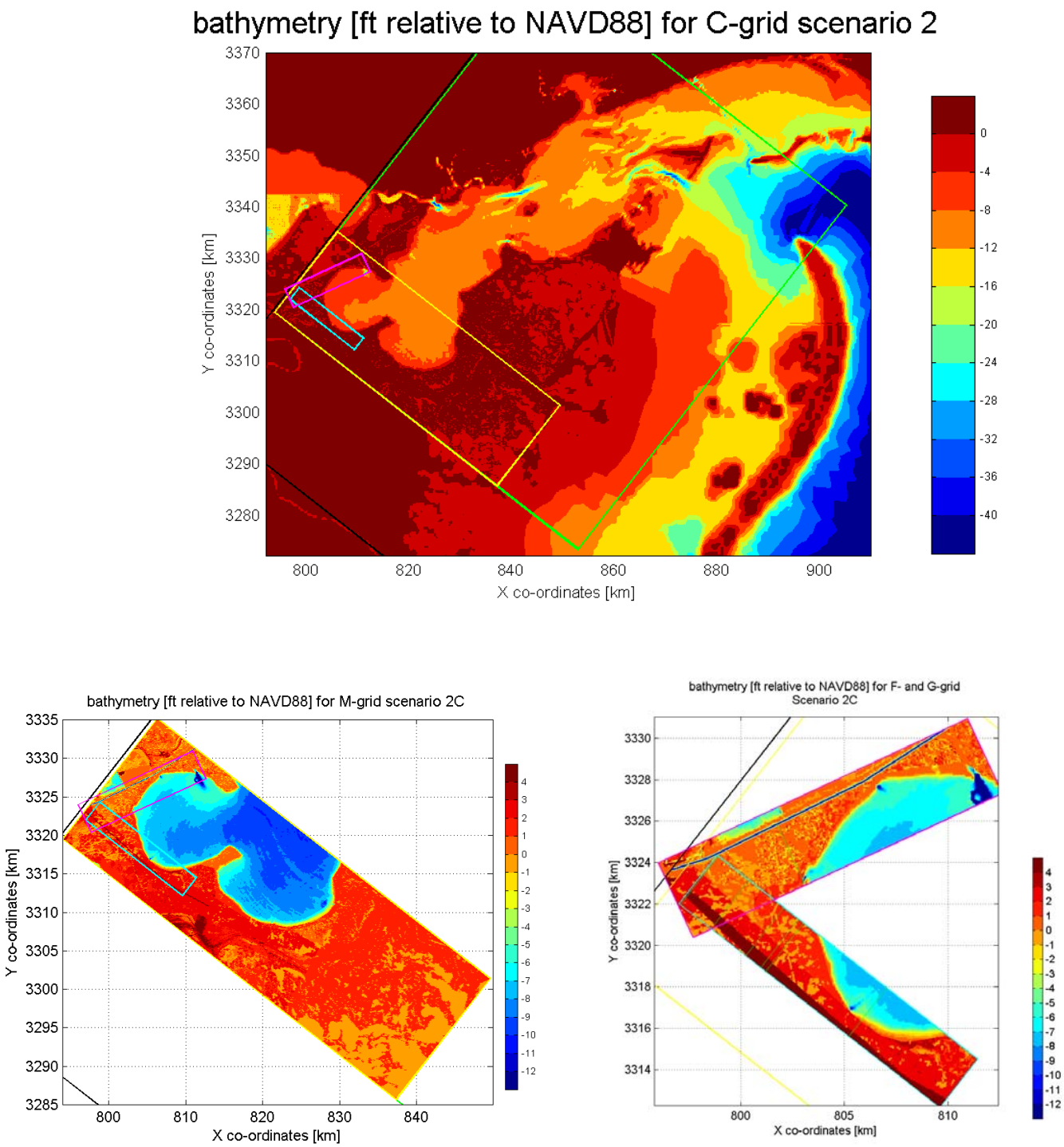


Figure 4.4: Scenario 2C: Bathymetry for C, M, F and G grids [feet relative to NAVD88]

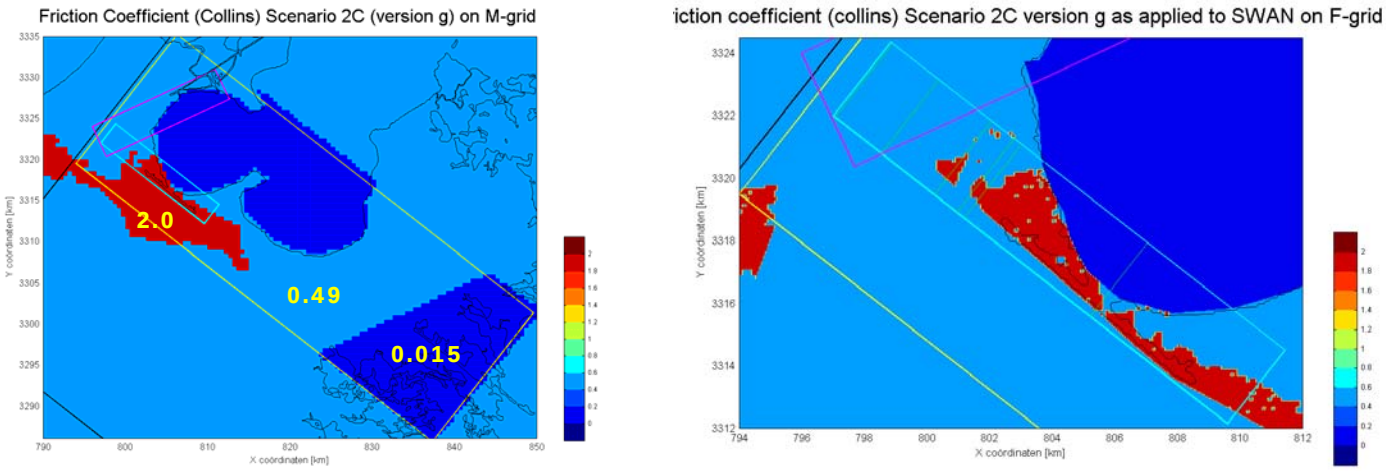


Figure 4.6.a: Scenario 2C version g; Applied friction coefficient for SWAN computations on M-grid and F-grid

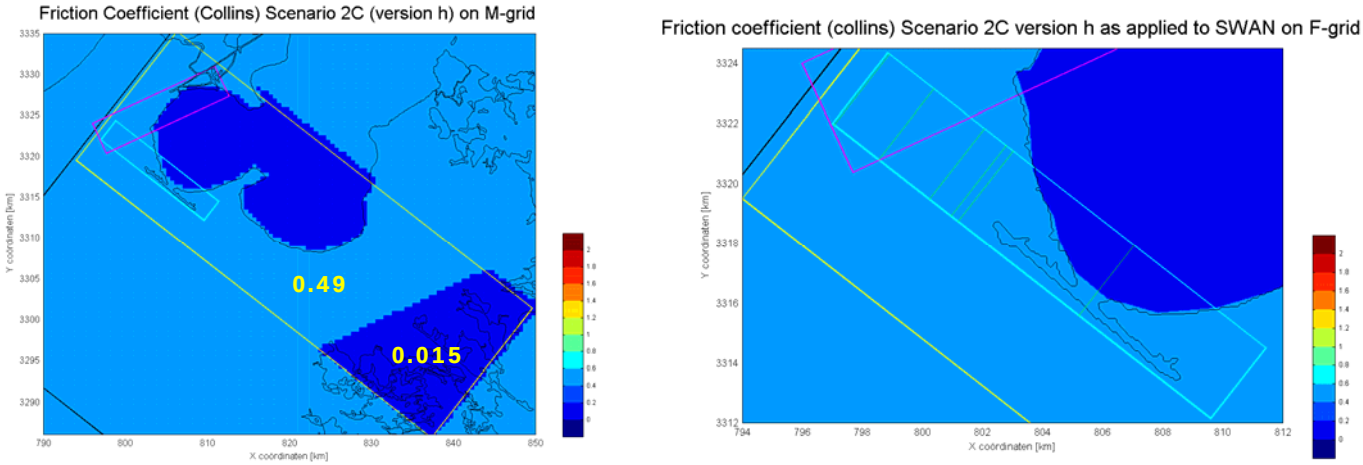


Figure 4.6.b: Scenario 2C version h; Applied friction coefficient for SWAN computations on M-grid and F-grid

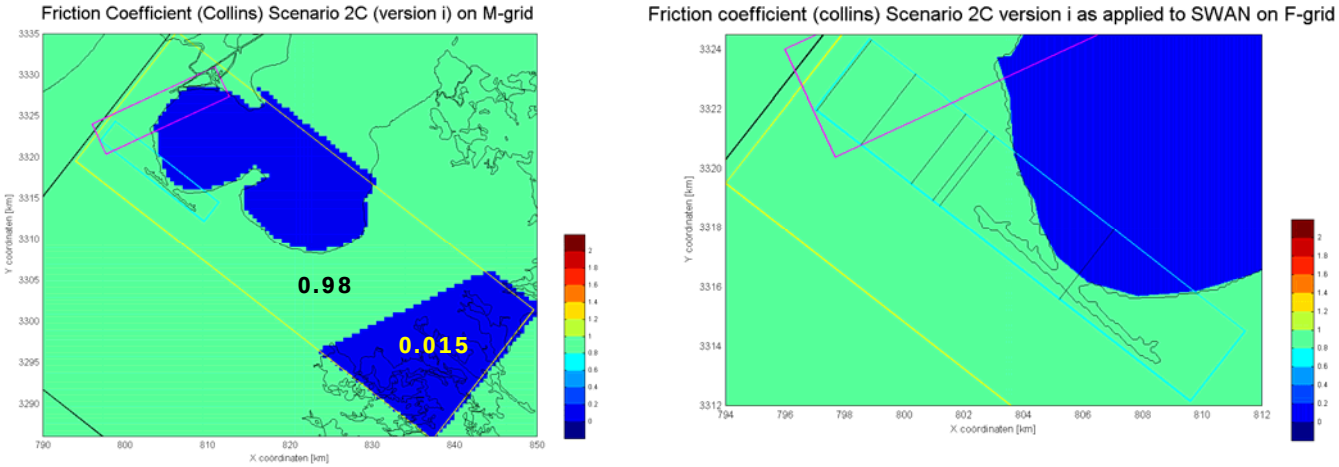


Figure 4.6.c: Scenario 2C version i; Applied friction coefficient for SWAN computations on M-grid and F-grid

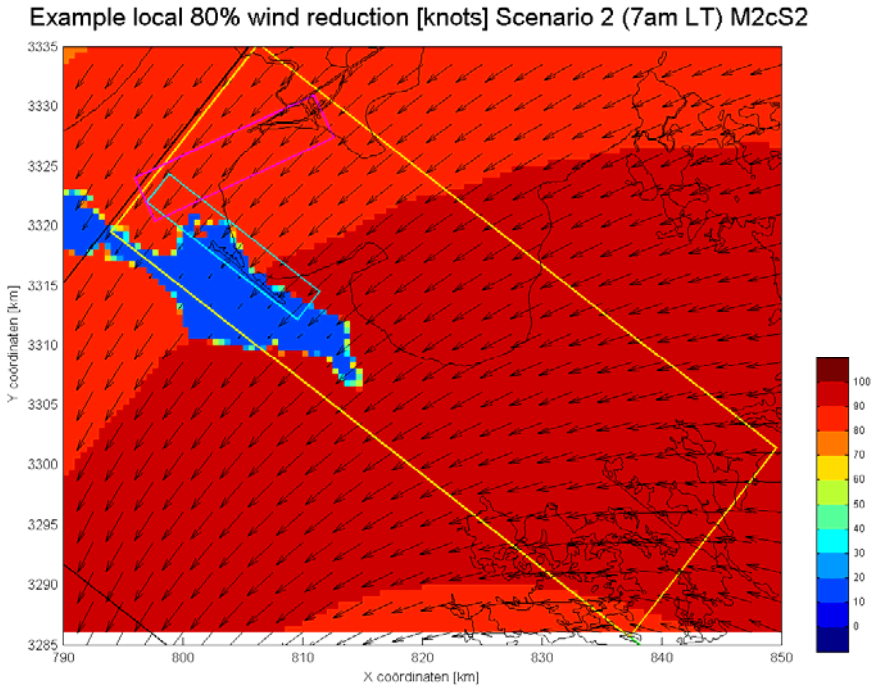


Figure 4.7: Scenario 2C version g; Example wind field [knots] 7am

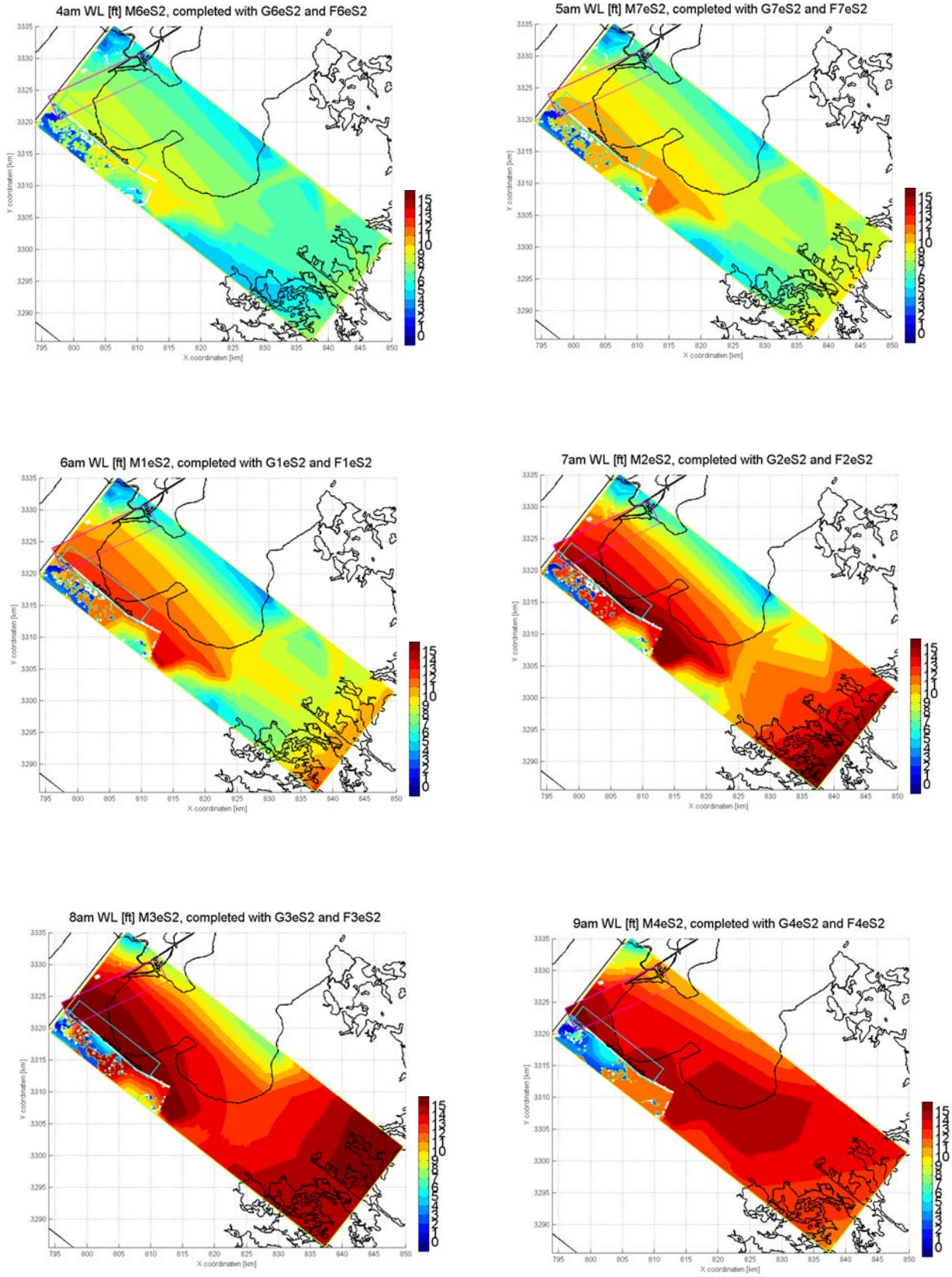


Figure 4.8: Scenario 2C: Surge water level fields [ft relative to NAVD88] 4am, 5am, 6am, 7am, 8am, 9am LT based on data from FINEL and ADCIRC

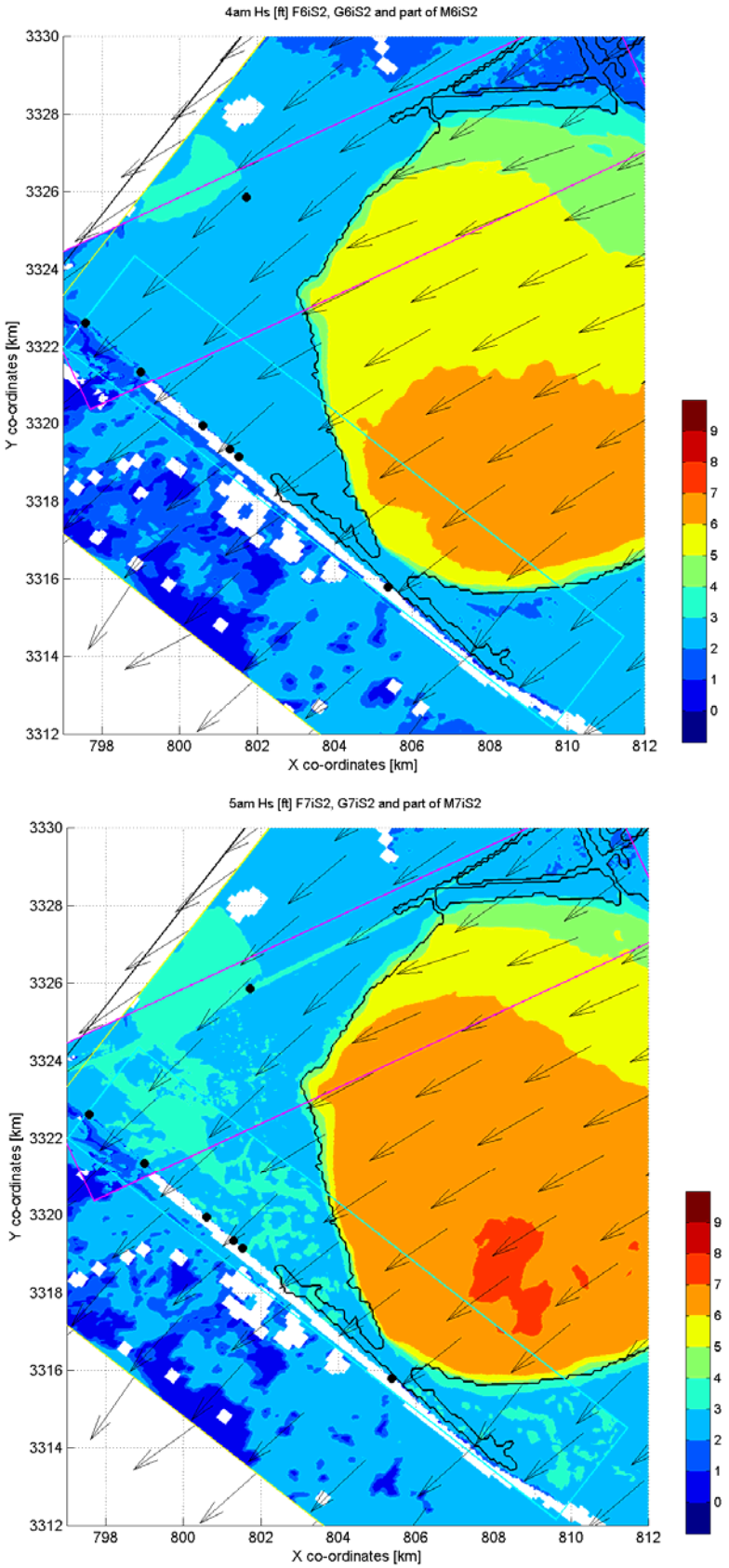


Figure 4.9.a: Scenario 2C version i: SWAN results Hs [ft] and direction 4am, 5am

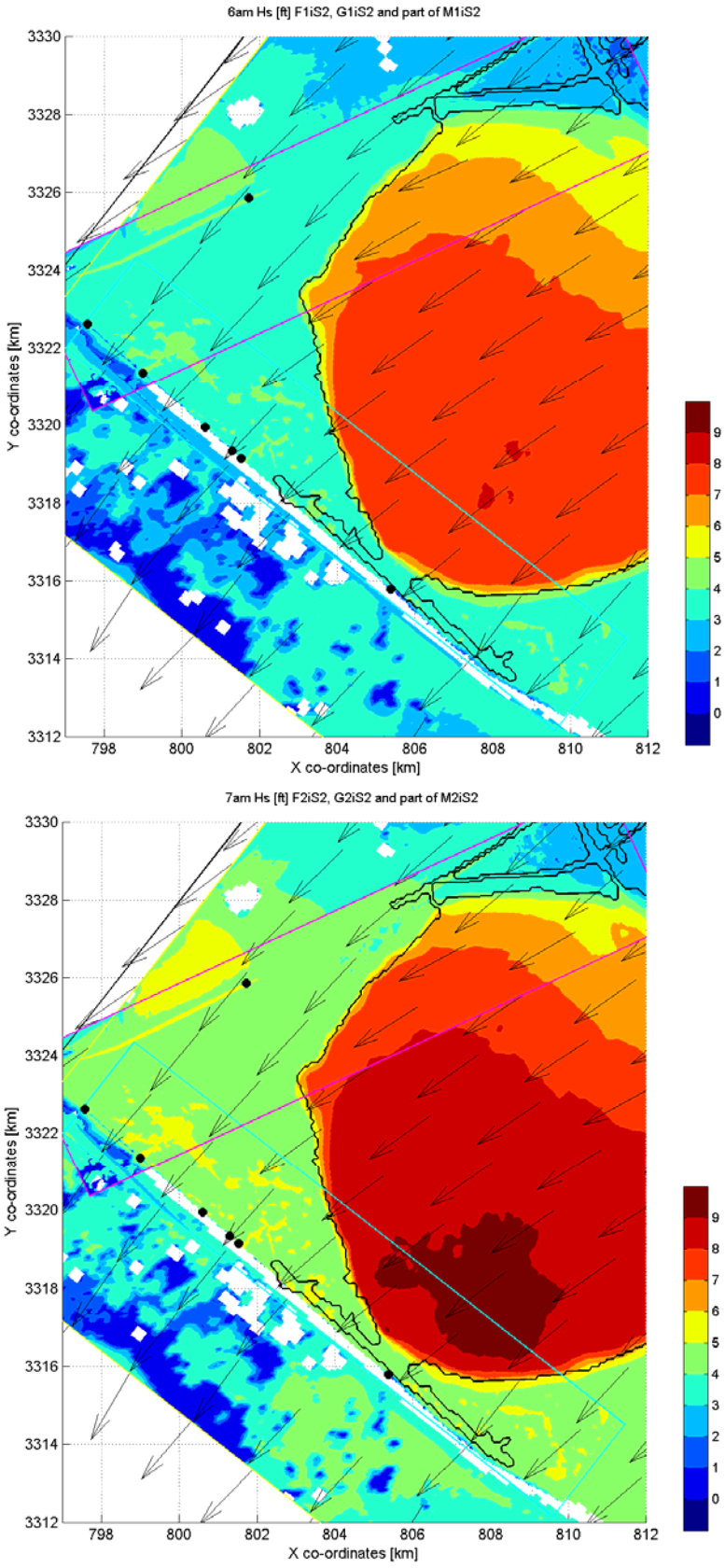


Figure 4.9.b: Scenario 2C version i: SWAN results Hs [ft] and direction 6am, 7am

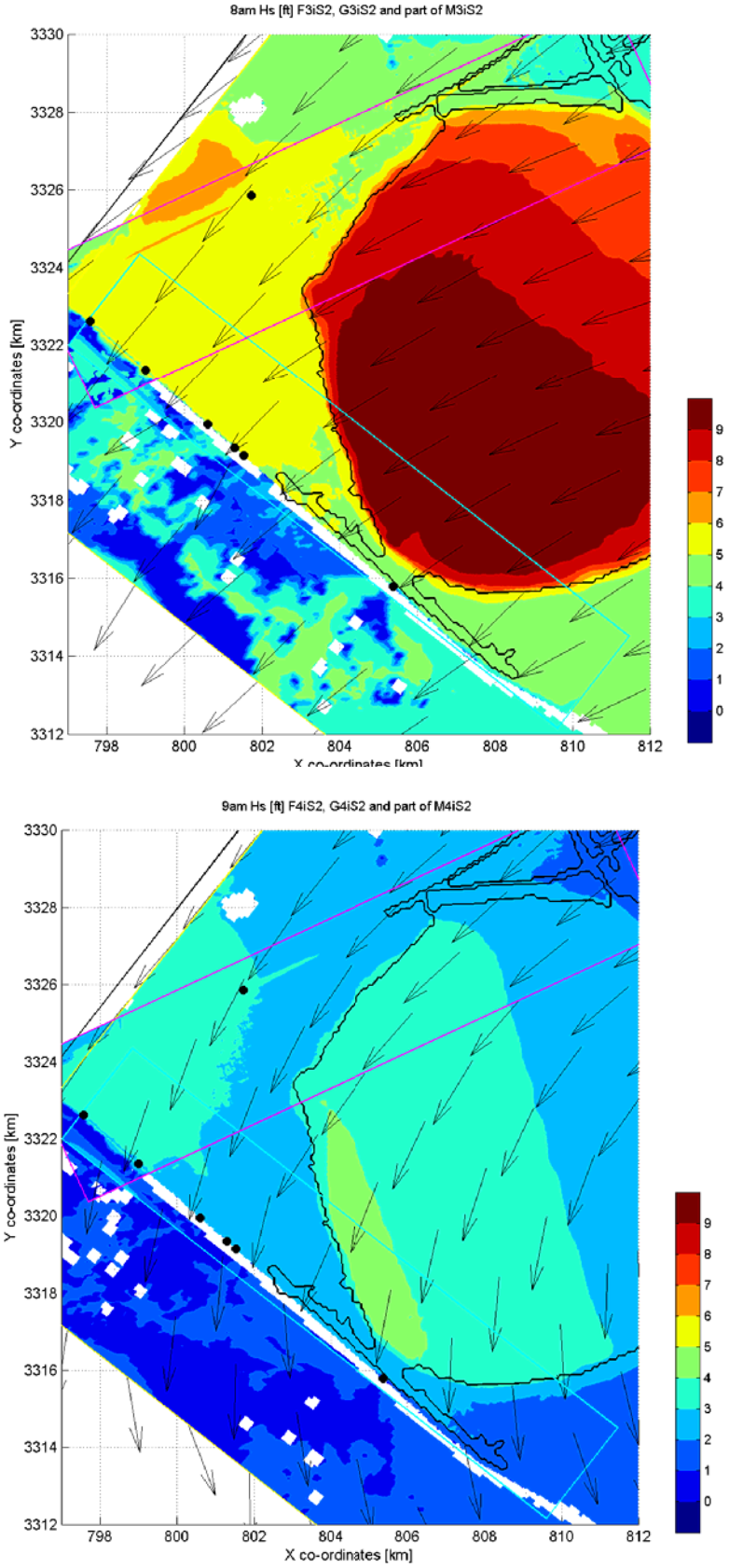


Figure 4.9.c: Scenario 2C version i: SWAN results Hs [ft] and direction 8am, 9am

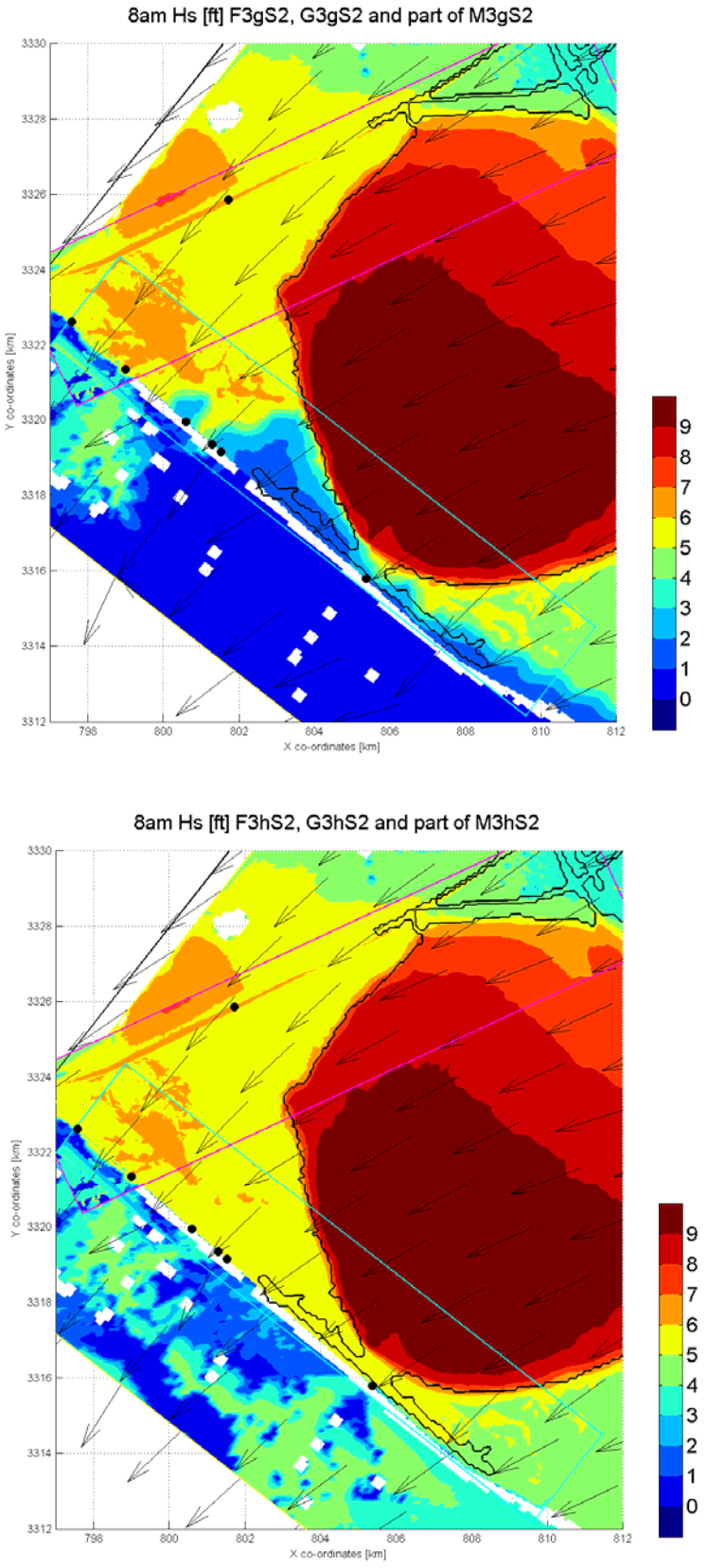


Figure 4.10: Scenario 2C version g and h; SWAN results Hs [m] and direction 8am

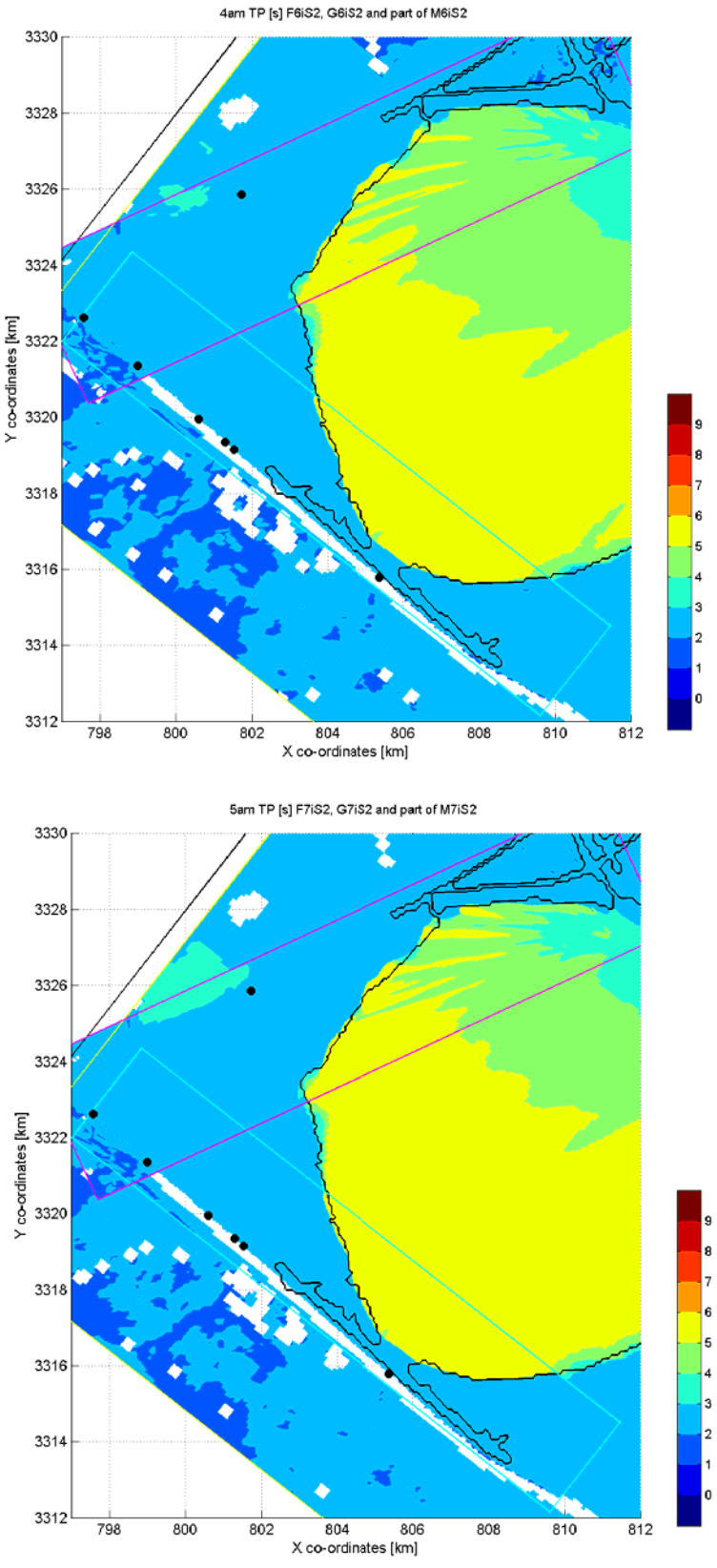


Figure 4.11.a: Scenario 2C version i: SWAN results peak period Tp [s] at 4am and 5 am

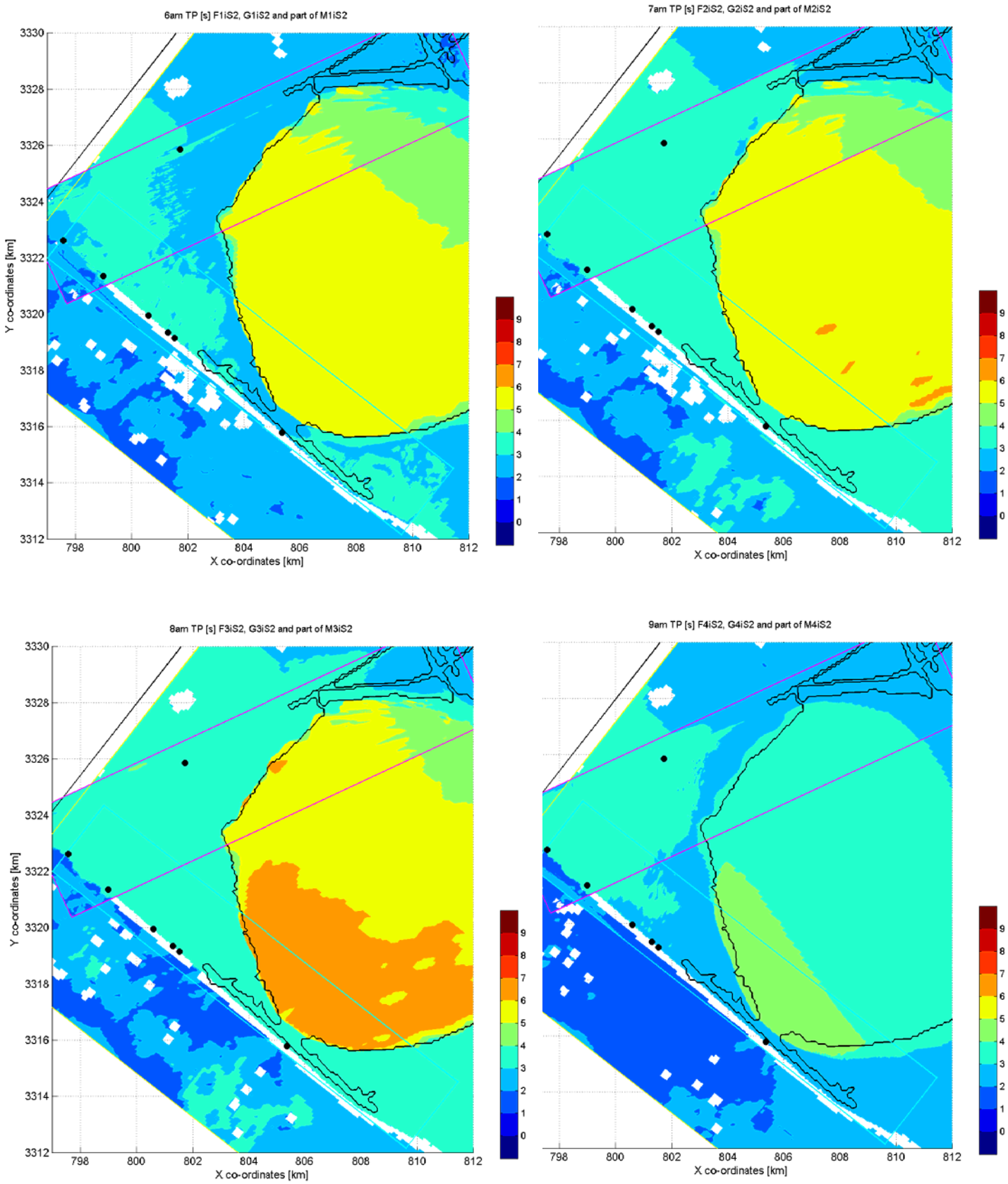


Figure 4.11.b: Scenario 2C version i: SWAN results peak period Tp [s] at 6, 7, 8, 9 am

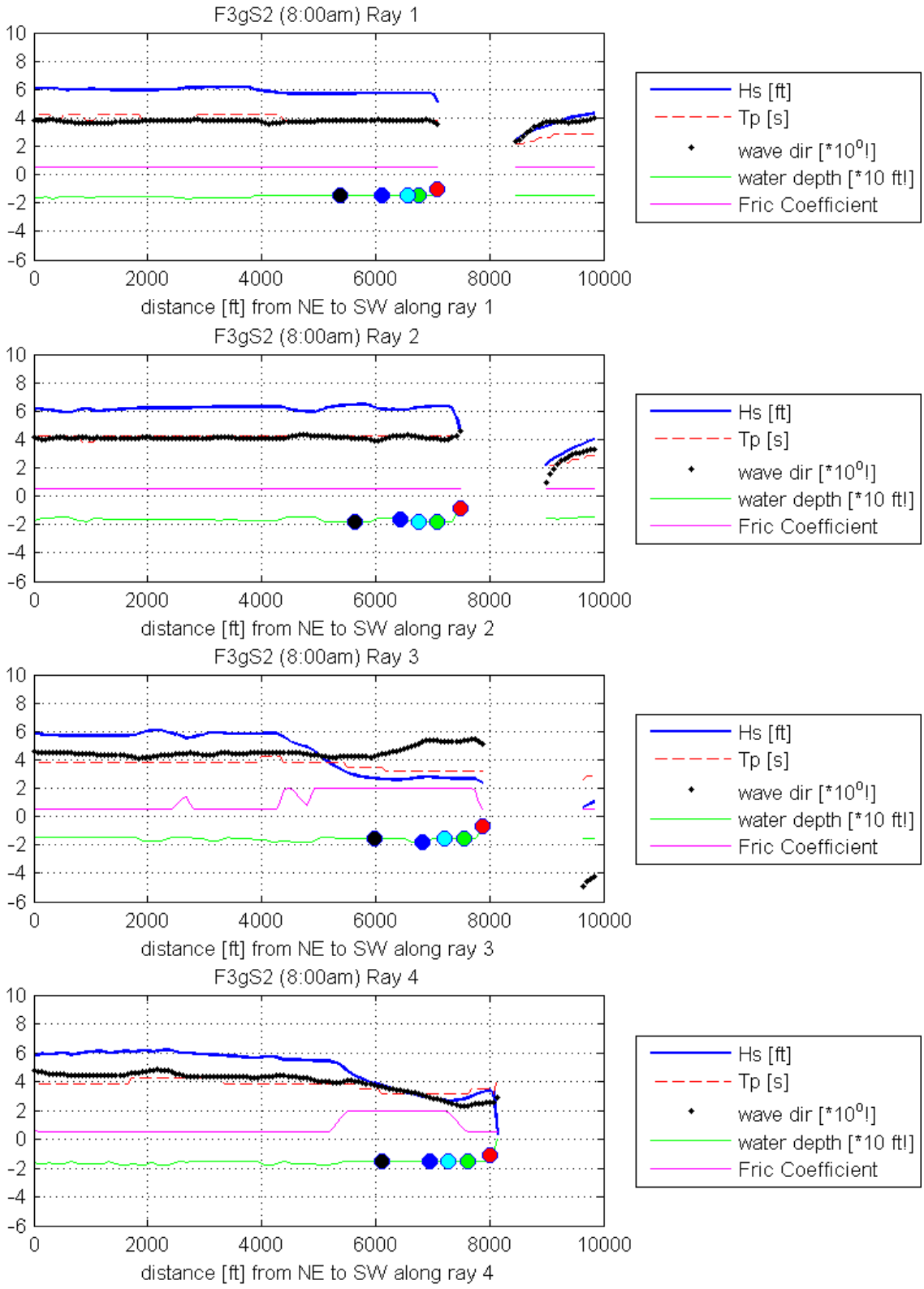


Figure 4.12.a: Scenario 2C-version g; Wave parameters on rays 1-4 at 8 am LT (colored circles indicate output locations)

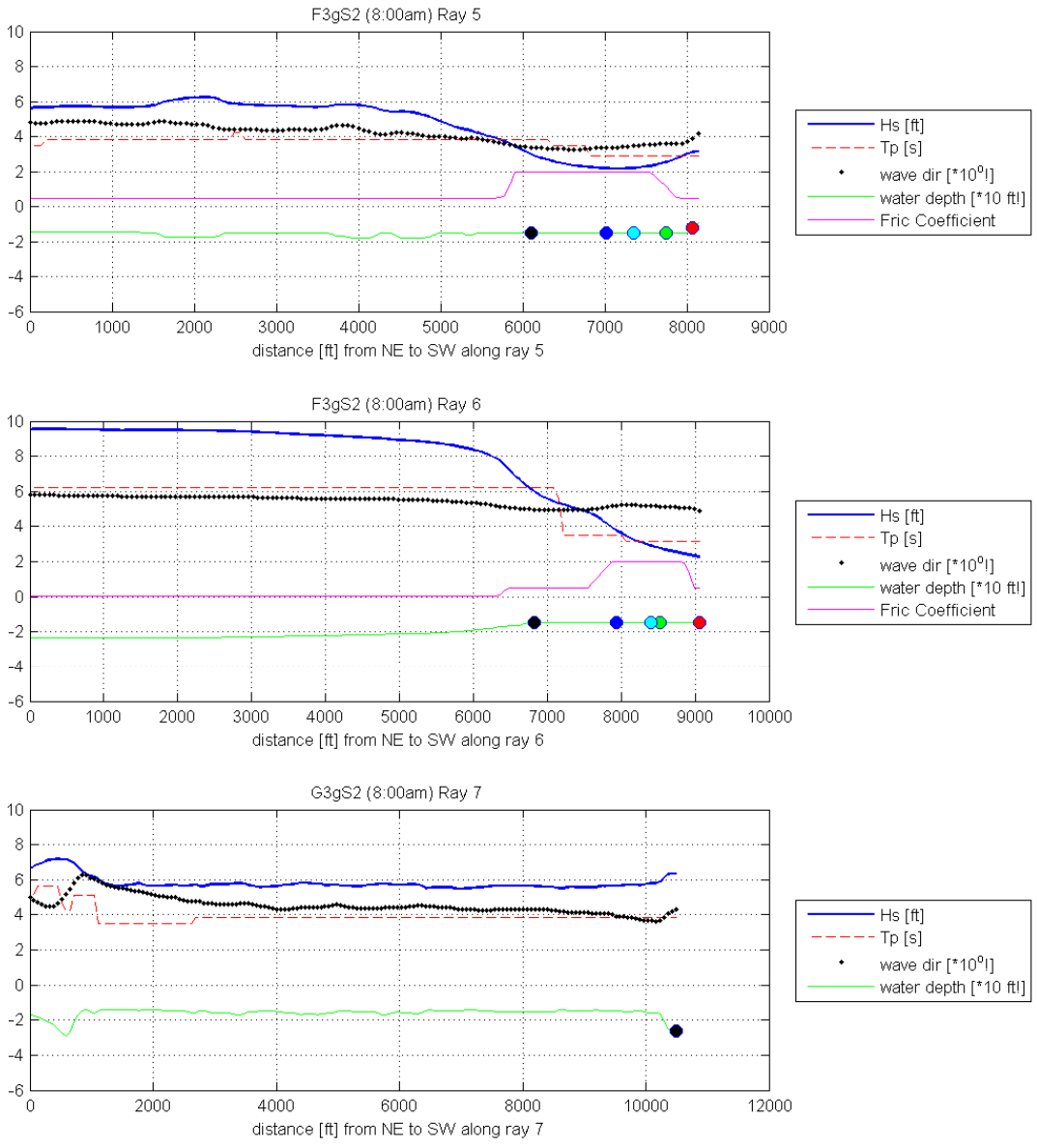


Figure 4.12.b: Scenario 2C-version g; Wave parameters on rays 5-7 at 8 am LT (colored circles indicate output locations)

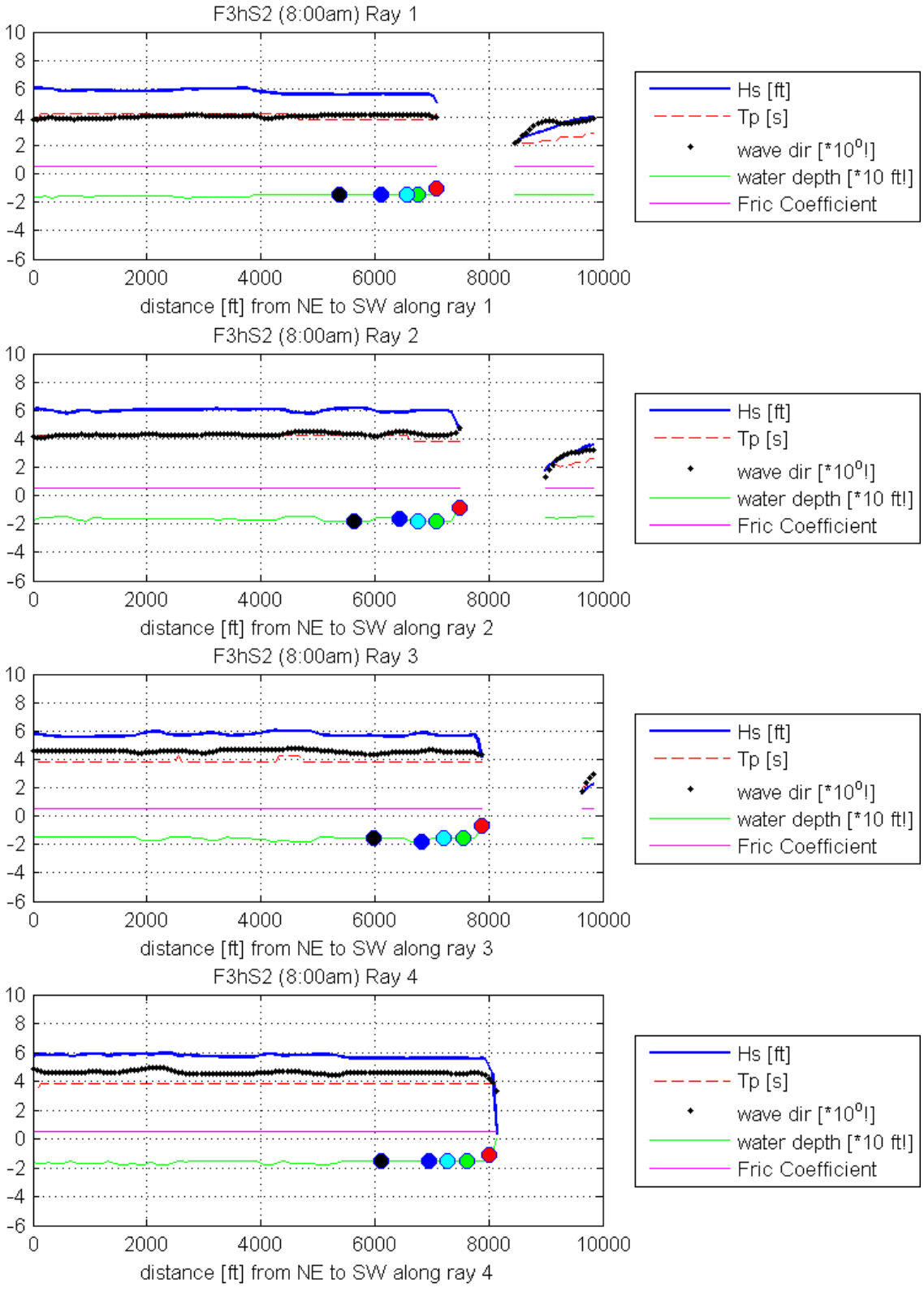


Figure 4.12.c: Scenario 2C-version h; Wave parameters on rays 1-4 at 8 am LT (colored circles indicate output locations)

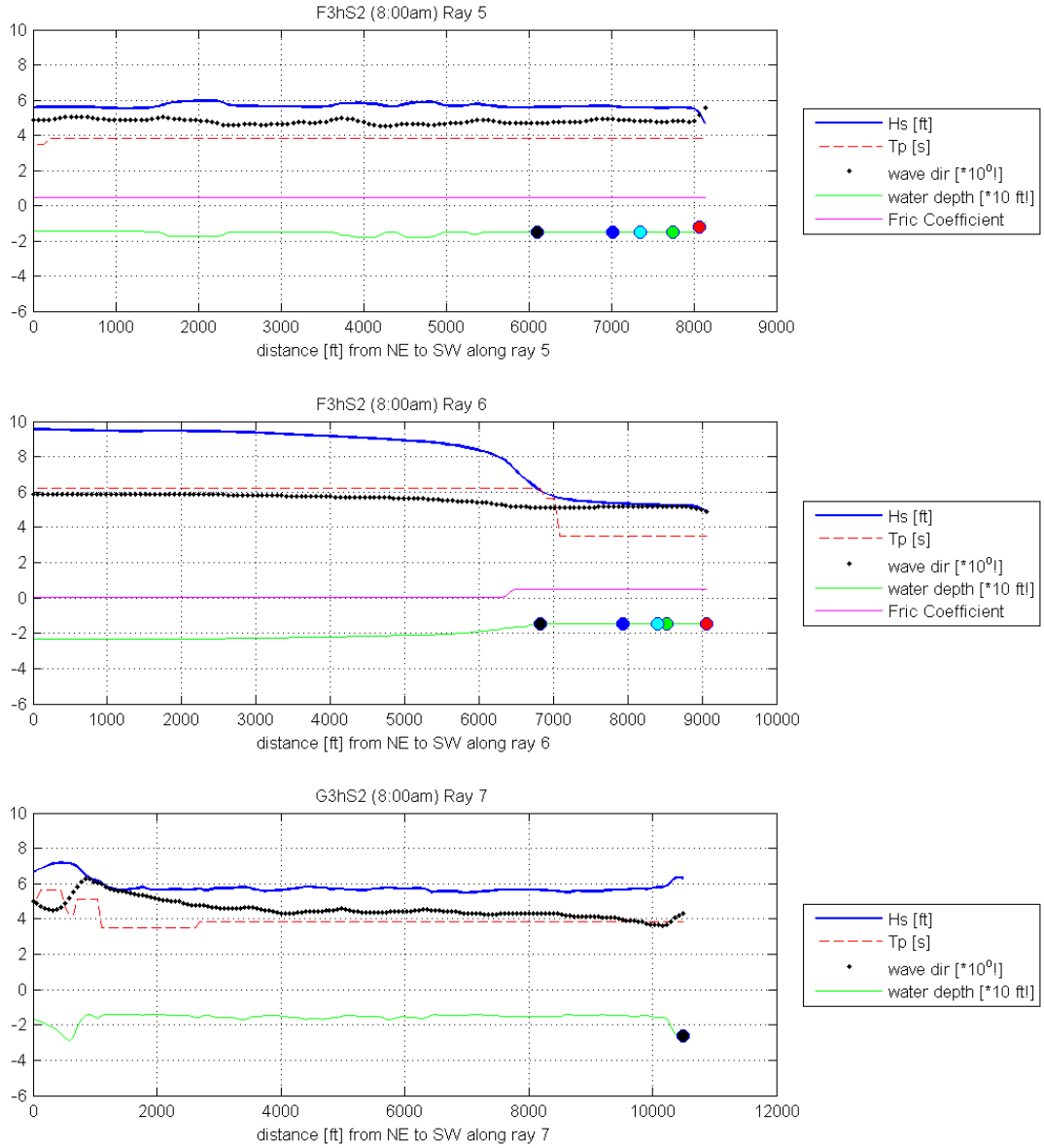


Figure 4.12.d: Scenario 2C-version h; Wave parameters on rays 5-7 at 8 am LT (colored circles indicate output locations)

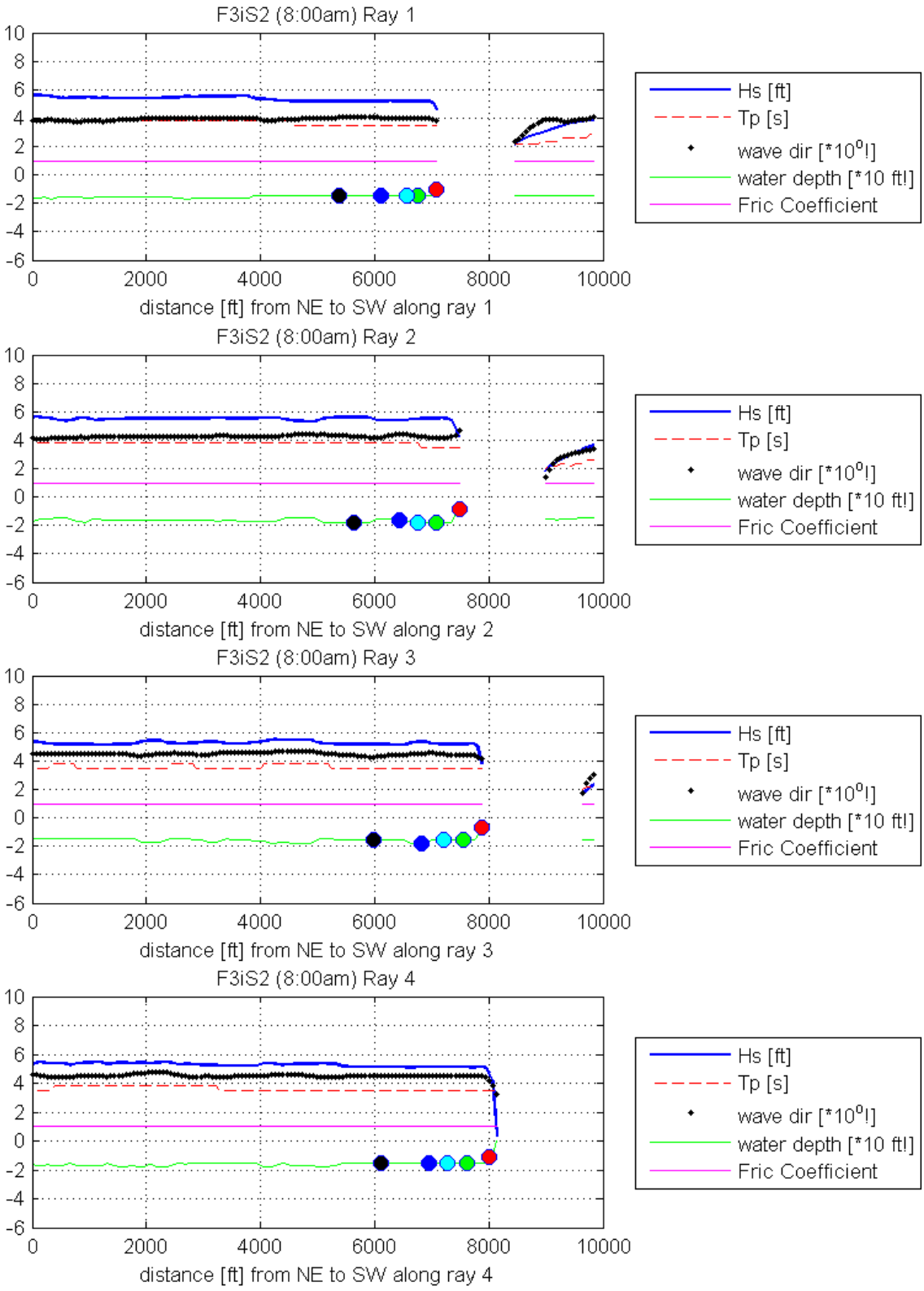


Figure 4.12.e: Scenario 2C-version i; Wave parameters on rays 1-4 at 8 am LT (colored circles indicate output locations)

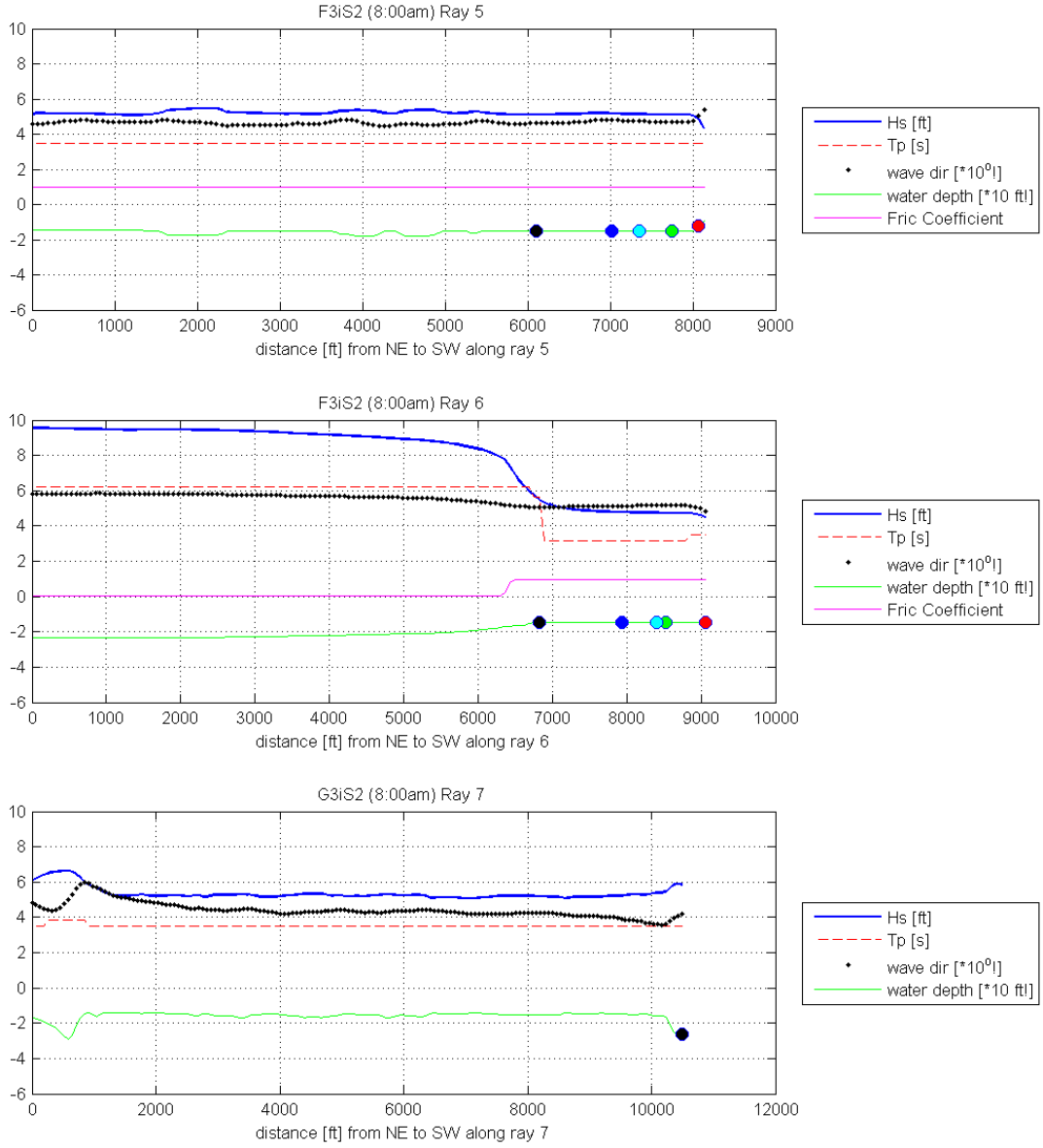


Figure 4.12.f: Scenario 2C-version i; Wave parameters on rays 5-7 at 8 am LT (colored circles indicate output locations)