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COMEM

SEDIMENT DYNAMICS OF BEACH CELLS UNDER OBLIQUE SWELL WAVES. A CASE STUDY OF BEACH CELL REPOSNSE AND INTERACTION ON BARBADOS' WEST COAST

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SEDIMENT DYNAMICS OF BEACH CELLS UNDER OBLIQUE SWELL WAVES.

A CASE STUDY OF BEACH CELL RESPONSE AND INTERACTION FOR BARBADOS' WEST COAST

By

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A thesis submitted as partial fulfillment of the Erasmus Mundus Masters of Science Degree in Coastal and Maritime Engineering and Management (CoMEM) at the Delft University of Technology (TUD), Delft, Netherlands in partnership with Norges Teknisk- Naturvitenskapelige Universitet (NTNU) Trondheim, Norway, and Universitat Politècnica de Catalunya (UPC), Barcelona, Spain

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Abstract

Property development along the west coast of Barbados has led to an increasing pressure on the coastline as property owners desire to have their residences close to the sea. The addition of new coastal structures including revetments, breakwaters, and groynes, changes the dynamics of the natural littoral system. The sediment transport mechanism(s) between the beach cells characteristic of the west coast is not fully understood, so accurately predicting the effects of additional structures is difficult. Additionally the potential effects of sea level rise and a healthy reef on the mechanics and stability of the system is un-researched. Recent increases in interest of the design of multi-purpose reefs (MPR) and artificial surfing reefs (ASR) has further led to the desire for insight into the sediment dynamics at headland-reef-bay systems.

This study evaluates the response and interaction mechanism(s) acting at a beach cell system with a focus under swell conditions and oblique waves typical of the west coast of Barbados. Using the Delft3D numerical model and a schematized section of coastline, a sensitivity analysis is conducted on parameters of interest to determine their effects on the sediment transport in the system.

Delft3D was determined to be a valid tool to examine sediment transport in this type of system. Model results indicated that the most important parameters governing the sediment behaviour are the significant wave height, direction, and sediment diameter. Other factors of importance included reef size, reef shape, reef asymmetry, and reef roughness. Perhaps surprisingly, sea level had little effect on overall transport rates but was the most important factor affecting the location and type of transport. These changes to the mode of transport are important as they govern the public perception of what is occurring. The transport associated with elevated sea levels, although not a problem from the system perspective, becomes an issue from the beach user and public opinion perspective as erosion takes place at the beachface where it is highly visible and has significant effects on beach usability.

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1 Introduction

Headlands, reefs, and bays are common coastal features and may be natural, man-made, or a combination of the two. A headland is defined as a point of high land jutting out into the water such as cliffs, while reefs are defined as a chain of rocks or coral at, or near, the surface, and bays are small bodies of water set off from the main body (Merriam-Webster, 2011). In combination these three components may form beach cells. Bypassing is the process of sediment migrating around a headland or headland-reef system. This study examines sediment exchange mechanisms of the beach cell systems typical of the west coast of Barbados.

The west coast of Barbados consists of white sandy beaches separated by sections of fringing coral reef or low limestone cliffs (Bird 1977). A section of sandy beach and its boundaries of either reef or low cliff is referred to as a beach cell with typical cells measuring from 75-800m across (Bird 1977). There are sixteen clearly defined, and three poorly defined, beach cells on the west coast of Barbados (Bird 1979). The sediment dynamics around these reef-bay systems are only partially researched but important similarities may be drawn with research on offshore submerged breakwaters, offshore reefs, surfing reefs, alongshore fringing reefs, and fully embayed beaches

Recent increases in interest of the design of Multi-Purpose Reefs (MPR) and Artificial Surfing Reefs (ASR) has further led to the desire for insight into the sediment dynamics at headland-reef-bay systems. Klein (2004) identifies the need for further research into the sedimentology and morphodynamics at headland-bay coasts while Phillips et al. (2009) identifies the need for research into sediment transport at submerged headland-reef systems.

1.1 Problem Definition

Property development along the west coast of Barbados has led to an increasing pressure on the coastline as property owners desire to have their residences close to the sea. The addition of new coastal structures including revetments, breakwaters, and groynes changes the dynamics of the natural littoral system. The sediment transport mechanism(s) between the beach cells characteristic of the west coast is not fully understood, so accurately predicting the effects of additional structures is difficult. Additionally the potential effects of sea level rise and a healthy reef on the mechanics and stability of the system is un-researched.

1.2 Research Objectives

The main objective of this MSc thesis is to investigate the mechanism(s) of transport between beach cells. Using a schematized section of coastline, a sensitivity analysis is conducted on parameters of interest to determine their effects on the sediment transport in the system. In this way model results are more easily transferred to other sites with similar features or calibrated for a specific location. During the course of the project close reference is made to the west coast of Barbados upon which the model is partially based. Specific objectives are to:

- Investigate the response and interaction mechanism(s) acting at a beach cell system with a focus under swell conditions and oblique waves
- Evaluate the sensitivity of the sediment dynamics to changes in wave characteristics
- Evaluate the sensitivity of the sediment dynamics to changes in sediment characteristics
- Evaluate the sensitivity of the sediment dynamics to changes in beach cell geometry
- Evaluate the sensitivity of the sediment dynamics to predicted levels of sea level rise
- Evaluate the sensitivity of the sediment dynamics to changes in the health of the coral system

2 Background

2.1 Site Introduction

Location & Existing Conditions

Since this report makes continuous reference to Barbados and its west coast beaches a brief description of the location and conditions is included. Barbados is located in the Atlantic Ocean just to the east of the volcanic island arc of the Caribbean. Barbados is a coral island well known for its white sandy beaches and is a popular tourist destination. The dominant wind and waves are generated by the North East Trade winds as they blow across the Atlantic Ocean. These conditions mean that the west coast of the island is usually protected from the direct effects of these winds and waves (Bird 1977) making it very calm and preferred by the majority of tourists and locals for recreational sea bathing. However, seasonal storms such as hurricanes or winter storms in the north Atlantic can generate significant waves on the west coast for short periods of time. In particular, this report focuses on the effects of the waves generated by North Atlantic storms, which arrive to Barbados every winter as long swell waves from the north before refracting and impacting the west coast at oblique angles (Bird 1977). Figure 1 shows the location of Barbados with respect to these conditions.

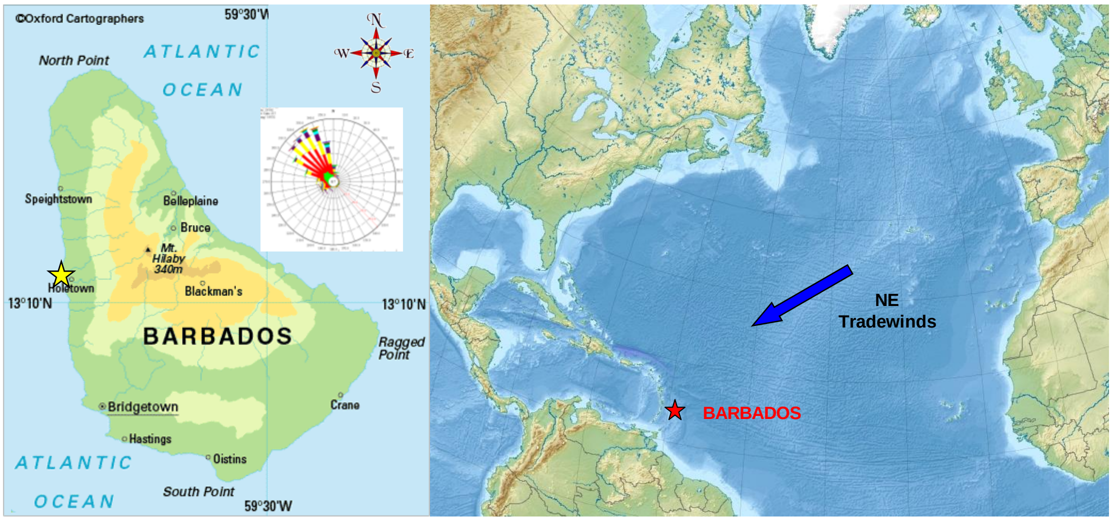

Figure 1 - Location of Barbados and Study Site

On the right side of Figure 1the red star shows the location of Barbados in the Atlantic ocean and the predominant direction of the north-east trade winds. The left side of

Figure 1 shows a more detailed map of Barbados with a wave rose of the waves measured at the location of the yellow star. The wave rose shows that the majority of the waves are indeed incident from the NW-NNW sector as consistent with the refracted swell waves described in Bird 1977.

In the last 30 years, as tourism has grown rapidly in Barbados prompting extensive development of the coastal regions (Nurse 1986). Bird (1979) reports approximately a quarter million tourists arrivals, a number that increased to a million by 2003 according to the Ministry of Tourism. Tourists who visit expect to have access to wide sandy beaches year round. However, the winter is the time of the year when most tourists visit and also when beaches are at their narrowest due to the movement of sediment offshore as they assume their winter storm profiles. This unfortunate coincidence of events over the years has led to the construction of groynes at several locations to enhance a beach for a given hotel or tourist villa. Two problems arise in that firstly the seasonal variation is likely due to cross shore transport which the groyne will do little to mitigate, and secondly a groyne that ensures a wide beach for one hotel due to trapping of longshore transported sediment will cause erosion down drift. In addition recovery of the west coast beaches is dependent on wave action since there is rarely onshore wind on the west coast of the island of the magnitude to promote aeolian transport. Therefore, structures that affect the wave climate will also affect the natural recovery rates. Due to the close proximity of many of the hotels and private residences, this down drift erosion has caused a variety of problems along the coast that compound each other as each property owner seeks their own solution to erosion. Hard structures alter wave action in addition to the sediment dynamics which only leads to further problems along the coast. The Coastal Zone Management Unit of Barbados (CZMU) manages the coastal development and construction of structures on the island to ensure that solutions are no longer implemented on a purely individual basis, but take into account the larger coastal processes involved in these beach cells. Figure 2 shows the zoning of Barbados' coastline according to CZMU with the study site of this report consisting of Sub-Area 6.

Figure 2 - Coastal Sub-Areas of Barbados (CZMU, 2012)

Beach Cell

This report focuses on identifying the general behaviour between the beach cell systems typical of Barbados' west coast and, therefore, a schematized site is used. The typical beach-cell system being examined in this report has already been described by Bird (1977) and Figure 3 shows an adapted version of his schematized beach cell on the left with a satellite image of Sandy Lane (north) and Paynes Bay (south) which show a natural example of these beach cells.

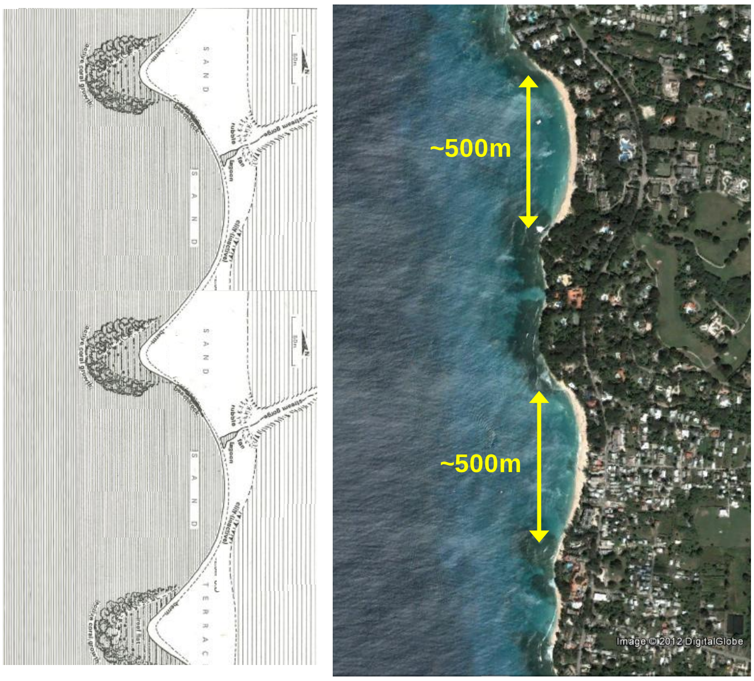

Figure 3 - Schematized and Natural Beach Cells

Figure 3 shows a typical bay bounded by sandy headlands, which terminate in sections of fringing reef. Additional features such as small patch reefs and coral rock located both within, and offshore, of the bay were included in Bird's original sketch but for this report the effects of these patches were assumed to be small and they were omitted in the numerical model. Other features seen in Figure 3 are: the stream gorge which is generally only active during high rainfall events but may have significant effects on sediment supply as discussed further in *Model Setup*; the cliff which is far enough inshore so as to not affect coastal processes; and the sand terraces located on the headlands which often provide preferred locations for property development of hotels and private residences.

Figure 4 shows how the beach cells were schematized in the model. The schematization procedure is discussed further in *Model Setup* but the figure illustrating the situation was included here for reader clarity. The cells are all different sizes, shapes, and orientation among other factors but the model makes use of three symmetric cells to help isolate behaviour of single components.

Barbados West Coast Schematization

Figure 4 - Schematization of the Project Site

Coral Reef

The focus of this report is on sediment transport but the role of coral reefs is acknowledged as being significant in the mechanics of the transport. Figure 5 shows an illustration of the different types of coral reefs. The west coast of Barbados has both fringing and bank reefs with the major focus of this report on the sections of fringing reef located at the headlands of the west coast beach cells. The main characteristics of fringing reefs are that they are shallow and are attached to the shoreline directly.

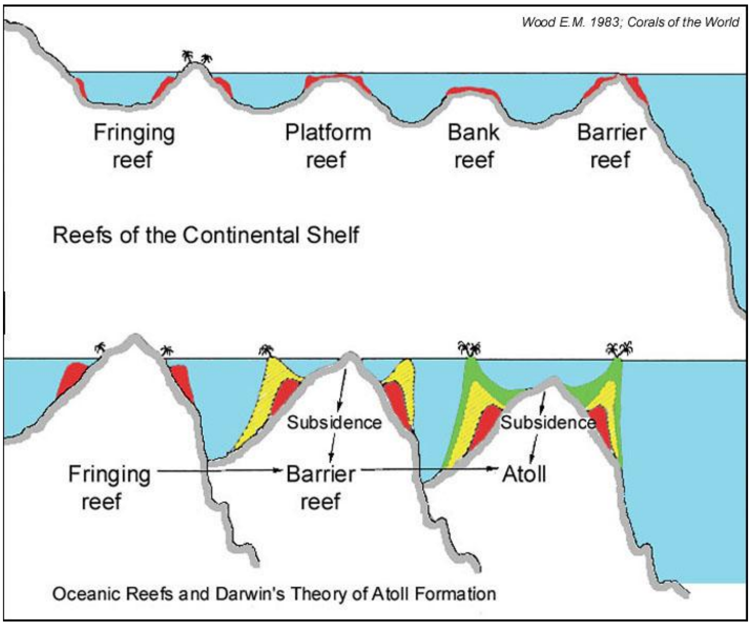

Figure 5 - Types of Coral Reefs (Wood, 1983)

At this project site there are fringing and bank reef but the bank reef is at sufficient depth to not have a significant effect on the processes examined in this report. Figure 6 shows a schematization of the reef situation in Barbados.

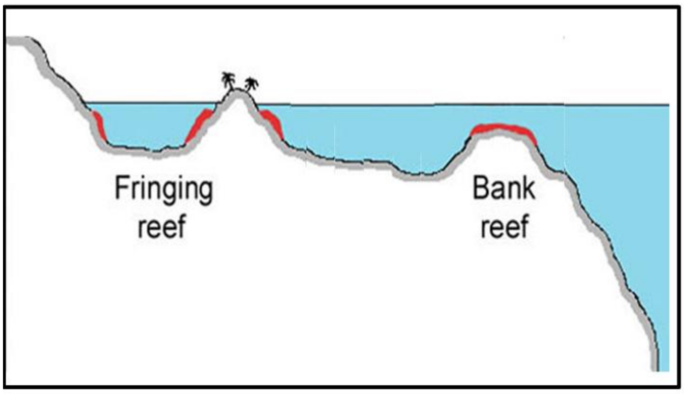

Figure 6 - Coral Reef Types at the Project Site

Paraphrasing from Tosic (2007) the west coast of Barbados consists of a series of fringing reefs (Lewis (1960) which have undergone significant changes over the past 25 years degrading both structurally (Lewis 2002) and biologically (Bell and Tomascik 1993). Significant single events such as Hurricane Allen in 1980 (Mah and Steam 1986) and mass mortality of the black sea urchin (*Diadema antillarum*) (Hunte et al 1986) have caused damage to the reef systems. However, the chronic cause appears to be a result of eutrphoication, suspended particulate matter and sedimentation (Bell and Tomscik 1993) which is associated with higher levels of runoff due to urbanization. This urbanization explanation also helps to explain the observation of the water quality deteriorating towards the south (Tomascik & Sander 1985) as the level of urbanization increases towards Bridgetown in the south-west corner of the island. Tosic (2007) goes on to explain in more detail the biological aspects of the coral reefs but this is beyond the scope of this report which only seeks to evaluate the effects of the physical characteristics of the reefs on the transport.

2.2 Literature Review

As previously mentioned the sediment dynamics around these beach cell systems are largely un-researched but a summary of available research on the topic to date is included. In addition insightful similarities may be drawn with research on alongshore fringing reefs, offshore reefs, offshore submerged breakwaters, surfing reefs, and fully embayed beaches. The similarities and differences from these areas of research are presented in this section.

Previous Research

The research of Bird in the 1970's has proved to be a valuable resource touching on numerous important aspects. Bird 1977 outlines relevant issues including identification of the relatively steady state nature of the coastline which encouraged development too close to the shoreline and the associated problems with implementation of individual solutions to erosion. He makes reference to the seasonality of the storms, the apparent erosion due to migration of sediment offshore during winter and the reorientation of beach cells to incident wave conditions. He identifies storm water runoff as a factor in the sediment balance of the cells and outlines potential transport pathways due to differential setup induced currents.

Bird 1979 provides further insight into aspects of the beach cell behaviour based on measurements taken in Gibbs and Sandy Lane bays in 1970. During this time period Bird conducted research into the dynamics of cells located at Gibbs and Sandy Lane and concluded that during calm conditions, the cells act largely as fully embayed beaches (no inter-bay transfer of sediment) of relatively constant volume with changes in planform to adapt to incoming wave energy. During rough conditions, bypassing of sediment occurs but this bypass mechanism was not fully researched by Bird. Bird 1979 also includes information on the source and composition of sediments, further examination of currents induced by waves around the reefs, and the behaviour of the cell as a closed system.

A further paper by Bird (1987) is less focussed on the sediment dynamics but still reinforces the point that hotels and beachfront structures have had significant effects on the dynamic equilibrium of beaches and beach cells.

From 1991-1995 a Feasibility and Pre-Investment Coastal Conservation Study was commissioned by the Inter-American Development Bank (IDB) and the Government of Barbados. The major components of the study were to research and define strategies for beach creation and stabilization, water quality improvement, and legal and institutional arrangements. In total eight locations were selected for pilot projects of which 6 are located on the west coast of Barbados. These projects identified and proposed solutions for a variety of coastal problems faced at the various locations and provided useful background information for this project.

Baird, a Canadian based Coastal Engineering firm, Smith Warner, a Jamaican based Coastal Engineering firm, and CZMU have collaborated over recent years on several coastal projects located on the west coast of Barbados ranging from shoreline protection such as the Holetown Walkway to marina design such as Port St Charles and Port Ferdinand. Through their past and ongoing projects these companies have completed research into the coastal processes affecting the coast and are valuable sources of information.

Much of the previous research has touched on aspects of sediment exchange at a specific location but as far as the author is aware this is the first attempt to give a general explanation of the mechanisms involved in the overall transport between beach cells under storm conditions.

Fringing Reefs

The reef examined in this study consists of sections of fringing reef as described in *Coral Reef* section of this report. Fringing reefs are attached to the shoreline and extend some distance offshore. In the case of the ones examined in this study the section of reef are located at the headlands of the beach cells.

The presence of a headland-reef system causes an interruption in the sediment transport along the coast. Waves break further offshore and therefore less wave energy reaches the coast. This reduction in incident wave energy leads to a reduction in the transport capacity and can lead to accretion behind the reef. However, headlands also work to focus energy from waves which will, to some degree, counteract the reef's effects on wave energy dissipation. In addition wave setup over the reef can cause local currents to develop which may oppose general sediment transport directions and further complicate sediment dynamics at these headland/reef systems (Elfrink, 2003).

The transmission of wave energy over the reef will govern the sediment dynamics. Lee & Black (1978) and Gerritsen (1980) wrote some of the first papers directly on wave transmission on fringing coral reefs based on field experiments done at Ala Moana Reef in Hawaii. Lee & Black (1978) examined the transfer of wave energy to high and low frequencies through the analysis of wave spectra. Gerritsen (1980) looked at the contributions of friction versus wave breaking to the energy loss of the waves. Young (1989) noted how the shape of reef front determines spectral spreading. Steep reef fronts are associated with plunging breakers, which lead to a much larger redistribution of energy within the spectrum than for less steep reef faces. Lowe et al. (2005) undertook similar research at a fringing reef in Kaneohe Bay, Oahu, Hawaii finally concluding that, on the fore-reef, wave energy losses due to breaking and bottom friction are comparable but that under typical wave conditions the bulk of the wave energy is dissipated through bottom friction, a result that agrees with Fernandez et al. (1998). Hardy (1993) and Fernandez et al. (1998) suggest a bottom friction coefficient for coral reefs of one order magnitude higher than normally used for sandy bottoms while Pequignet et al. (2011) suggest a roughness parametrization may be more appropriate than a constant friction factor and suggests the method identified by Swart (1974). In addition, Lowe et al. (2005) concluded that local measurement of bottom roughness can give good estimates for frictional dissipation without the need for large scale observation of wave transformation. These are important conclusions for the study site in this project as there is no large scale observation of the wave transformation available and roughness of the reef is an important input parameter in the numerical model. The exact parameter choice is discussed in more detail the *Model Setup* and *Results and Discussion* sections of this report.

Sediment transport due to waves and induced currents over shallow reefs has been studied previously. Roberts & Suhayda (1983), Roberts (1983), Sadd (1984), Fernandez et al. (1998), and Roberts (2004) are all studies looking at aspects of sediment transport for reef systems in the Caribbean while Eversole & Fletcher (2003) and Presto et al. (2006) are two studies conducted in Hawaii, all with results potentially applicable to this site. Roberts & Suhayda (1983) looks at the contributions of short versus long waves on transport of coarse versus fine sediments. Eversole & Fletcher (2003) caution on the use of the traditional CERC and Kamphuis formulas to estimate longhsore transport as they were developed for sandy coasts but the presence of reefs significantly changes the sediment dynamics. Delft3D uses the more developed van Rijn 1993 formula.

Roy & Stephens (1980) and Eversole & Fletcher (2003) both caution on the effects of substrate control where the reef structure and sediment supply limit transport rather than the calculated transport gradients. Jet probe data showed coral rubble underlying the mobile sediment layer at a depth less than 1m in certain areas which suggests substrate control may be an important factor. This issue is discussed further in the *Model Setup* and *Results and Discussion* sections of the report.

A survey conducted on August 25, 2011 revealed some characteristics of the underwater formations at the site. The reef is typical of other fringing reefs in the Caribbean in that it consists of shallow coral heads and deeper trenches between them. Sediment transport at similar reef formations has been studied in the Corn Islands, Nicaragua (Roberts & Suhayda, 1983), Cayman Islands (Roberts, 1983), and St Croix

(Sadd, 1984; Fernandez et al., 1998; Roberts, 2004). In the trenches there are patches of sediment along with cobbles and reef rock similar to the formations described in the literature. These pathways between the reef are generally orientated shore normal and therefore facilitate cross-shore transport but impede alongshore transport as reported by Roberts (1983) and Sadd (1984). These findings suggest that separate roughness coefficients should be specified for the reef in the cross-shore and longshore directions.

Offshore Reefs

Offshore reefs, as their name suggests, are located some distance from the shore and separated by a lagoon of significant depth. If they are emerged they form a barrier reef and if they are submerged they form a bank reef as illustrated previously in Figure 5 in the *Coral Reefs* section.

Literature by Young (1989), Symonds et al. (1995), and Hardy & Young (1996) looks into similar issues on wave transmission as mentioned in the *Fringing Reef* section but over offshore and barrier barrier reefs instead of fringing reefs. The authors come to similar conclusions in that wave energy is transferred from spectral peaks to low and high frequencies and that the depth on the reef flat determines the maximum possible wave heights.

The common conclusion that the significant wave height over the reef is largely governed by water depth when in shallow situations means that an accurate estimate of sea surface elevation from wave setup, tides, storm surges and other effects is important when calculating the amount of energy reaching the shoreline. Gerritsen (1980), Young (1989), Symonds et al. (1995), and Pequignet et al. (2011) all make reference to the importance of setup. Gerritsen (1980) proposes a modified Ursell parameter to calculate the setup based on wave height, water depth and period. Generally the setup is considered to be similar to that observed on plane beaches but Symonds (1995) noted that in the case of a barrier reef there is no shoreline boundary and the water level returns to still water level. Symonds suggests that the setup is balance by the high friction associated with flow over shallow reefs.

Offshore Submerged Breakwaters

Offshore submerged breakwaters are another area of recent interest with papers by Ranasinghe (2006a, 2006b, 2010) undertaking research into the shoreline response generated by these structures. The offshore submerged breakwaters may be likened to small bank reefs or detached versions of the coral reef systems located at the headlands of the beach cells in Barbados, and therefore, some of behaviour of the offshore structures may give insight into the behaviour of their attached counterparts. Ranasinghe (2006a) examined a variety of field cases, including some surfing reefs, and identifies that the responses of submerged breakwaters was not always as expected. The subsequent study (Ranasinghe 2006b) used numerical and physical model results to identify circulation patterns between an artificial surfing reef and the shoreline which explained the differing shoreline responses. The work was further continued and Ranasinghe (2010) presents the shoreline response effects for a single shore parallel submerged breakwater based on numerical model results. One of the conclusions from that research was that a wider crest resulted in less erosion as a result of reduced wave transmission. With that conclusion in mind the coral reef cases typical of Barbados are extreme cases of wide crested breakwaters and therefore should exhibit very low erosion in their lee. The changes, if any, to the circulation patterns between the offshore and the attached cases will also be of interest.

Surfing Reefs

The phenomenon of sediment transport over and around a shallow coral reef has recently gained much attention due to its link with surfing. Shallow coral reefs on a headland represent abrupt changes in the orientation of the coast where wave alignment interacts with the shoreline generating peeling plunging breakers suitable for surfing (Phillips et al. 2009). Figure 7 shows a sketch of the features of a typical artificial surfing reef (ASR). These ASR's are just a special case of offshore submerged breakwaters that are designed with the dual intention of protecting the shoreline and enhancing surfing conditions.

In the last 20 years, the sport of surfing has increased extremely rapidly, both in terms of the number of participants and the amount of money generated by the sport (Mead, 2009). In some cases, towns are even paying millions of dollars for engineered surfing reefs in order to attract surfers and the associated revenue. These surfing headland-reef systems have already been planned and/or implemented with varied success in terms of surfing quality and as shore protection measures. Mount Maunganui in New Zealand is one of the first examples of a purpose design reef system to generate surfing waves (Black & Mead, 2009) with others in planning stages all over the world including Australia (Gold Coast), New Zealand (Wellington and Opunake), England (Boscome) and USA (Oil Piers) (Black & Mead, 2009).

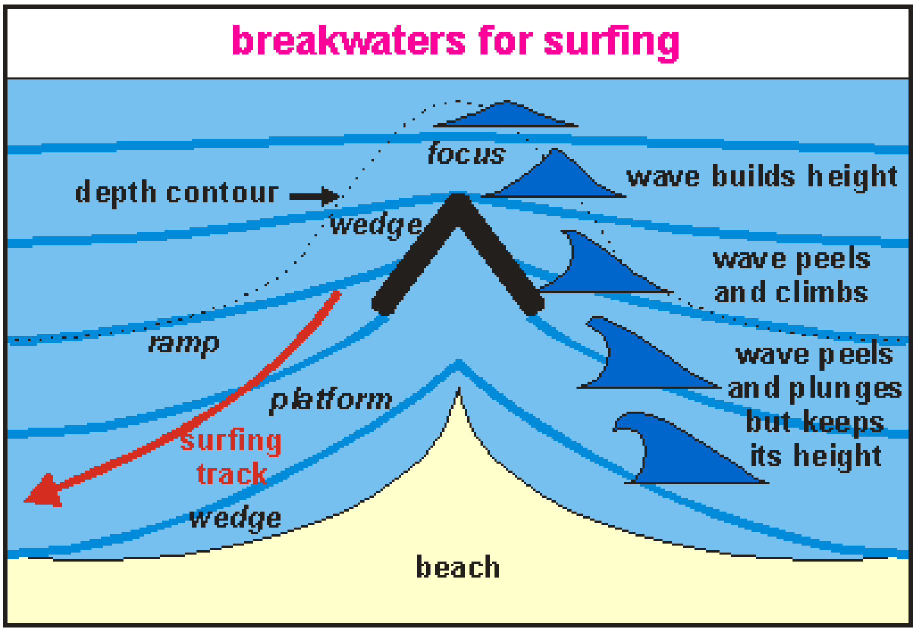

Figure 7 - Sketch of Artificial Surfing Reef Features (Anthoni, 2000)

In another paper by Phillips et al. (2009) the issue of the sediment transport pathways was identified, stating that currently there is no research on the currents and sediment dynamics. The paper examined Ragland headland in New Zealand and identified the importance of the re-circulating current cells in maintaining bed stability at that site.

Since submerged reefs are not only recognized for their ability to produce high quality surf, but also their use as effective measures for coastal protection and marine ecosystem enhancement (Elfrink, 2003; Frihy et al., 2003; Phillips et al., 2009), they may be referred to as multi-purpose reefs. This use as a coastal protection measure is of interest to coastal engineers as the reefs have the potential to provide a long term, unobtrusive solution to erosion (Mead, 2009). Many of the beach protection solutions used currently, including groynes, and breakwaters, are in fact land protection measures as they attempt to mitigate erosion without addressing the cause of the erosion. The use of these multi-purpose reefs as wave rotators aligns the incoming waves with the coast, reducing longshore transport and wave energy thus addressing the cause of the erosion directly (Black & Mead, 2001). An understanding of the hydrodynamic interaction and related sediment transport means it is possible, not only to create new reefs from scratch, but to modify existing reefs to be a more effective shore protection measure while producing high quality surf and enhancing marine habitat.

The west coast of Barbados is already home to several high quality surf reefs, mostly located on the headlands of the beach cells. The use of a multi-purpose reef, or enhancement of an existing headland-reef system, may provide an alternative solution to groynes to solve erosion problems. Black & Mead (2001), Elfrink et al. (2003), Maglio & Harris (2009), and Mead (2009) all express similar ideas on this topic of headland-reef systems for coastal protection. These systems provide a solution that is not only attractive to the coastal property owners but also has the potential to increase the attractiveness of these beaches to the surfing industry thus providing a socio-economic boost to the country. The additional benefit of multi-purpose reefs is the benefit to the marine ecology by providing coastal habitat for fish and marine creatures to live while the headlands may provide extra land for recreational purposes.

Fully Embayed Beaches

Fully embayed beaches are ones where no exchange occurs between adjacent beaches as they are separated by deep headlands or other features that prevent exchange of sediment. It is known that the beach cells on the west coast of Barbados exhibit sediment exchange under some conditions and act as closed cells under other conditions so factors that affect fully embayed beaches may be similar to those that will have the most significant effect in the Barbados cases.

Louiriero et al. (2009) evaluate the response of embayed beaches in southern Portugal and conclude that the geomorphological setting and the orientation of the beach to the incident storm waves appears to be the most significant factor affecting both the transport within the bay and the loss of sediments from the bay either by headland bypassing or cross shore transport. Klein (2004) looks at the morphodynamics of headland-bay beaches in Southern Brazil and also finds that orientation of the beach is an important factor in the observed morphodynamics. Silveira et al. (2010) examined 166 beaches in Southern Brazil with respect to their planform stability. They concluded that no clear relationship was observed between planform stability and other beach characteristics such as morphodynamics, morphodynamic state and shoreline orientation. This conclusion seems to be in contradiction to Louiriero et al. (2009) and Klein (2004). Silveira et al. (2010) gives some explanation of this discrepancy in that their classification of 12 of the 63 beaches common to both studies differed from that of Klein (2004). From these obsevations it would appear the orientation of the beach relative to the incoming waves is important for the morphodynamics of the system.

Klein (2004), Louiriero et al. (2009), and Silveira et al. (2010) all agree that the sediment source is important to understand the dynamics of the beach and may indicate characteristics such as if the beach tends towards a state of dynamic versus static equilibrium (Silveira et al., 2010) or the rate of recovery after erosion (Louiriero et al., 2009). This information can be very important when shoreline development and management takes place in highly urbanized areas (Silveira et al., 2010) where sediment sources may be regulated. Sediment source is very important in a fully embayed as it is the only way to alter the sediment budget and may also prove to be somewhat important in the Barbados case where sediment discharge from storm water runoff will periodically add sediment to the system.

3 Mechanisms and Processes

This chapter continues from the previous one by presenting a brief overview of the overall mechanisms and associated processes that are expected to contribute to sediment transport in this system. Three broad categories were identified as alongshore, cross shore, and rip current induced transport, which are then further broken down in each subsection. Some of the processes are directly related to a single input parameter facilitating simple evaluation of its contribution while others are a result of combinations of inputs and individual contributions are more difficult to separate. The *Results and Discussion* section gives further detail on the mechanisms and processes in relation to the results obtained from the modeling. Table 1 presents a summary of the processes, their effects, and their relative importance to the overall behaviour.

Table 1 - Transport Mechanisms and Processes Summary

Mode		**Effects and Comments**	**Estimated Importance**	**Accuracy of Representation**
Alongshore (A1)	Deep Bypass	Longshore transport is able to occur on the seaward side of the reef	High	Good
Alongshore (A2)	Bypass Over Reef	Longshore transport over the reef itself	Low	Good
Alongshore (A3)	Shallow bypass	Longshore transport along the shorewards edge of the reef.	Medium	Good
Alongshore (B1)	Transport within the Bay	Longshore transport within the bay moves sediment from north to south	High	Good
Cross Shore (X2)	Over Reef	Cross shore loss of sediment over the reef. May be enhanced by shore normal reef channels	Medium	Poor

Cross Shore (X1)	Profile Realignment	The equilibrium profile in the bay will adjust to incoming energy and sediments may migrate offshore temporarily	High	Good
Rip Current (R1)	Rip current	Mass flux and differential setup over the reef induce currents which can move sediment offshore	High	Good

3.1 Alongshore

Figure 8 shows the transport pathways of the four longshore processes described in this section. The labels A1, A2, A3, and B1 type transport are used throughout the remainder of the report to refer to these processes.

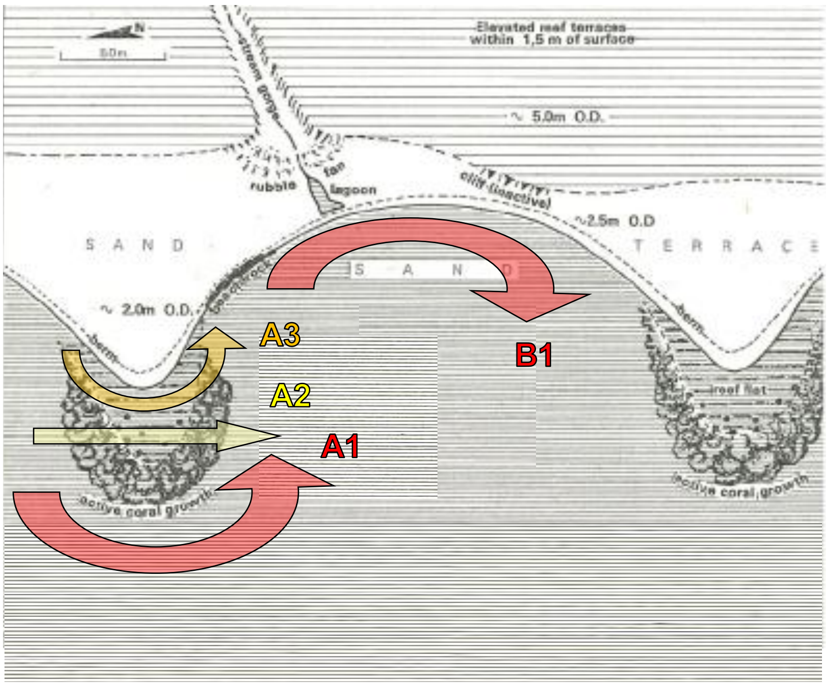

Figure 8 - Longshore Transport Pathways

Uninterrupted Transport (U1)

The uninterrupted transport is the transport which occurs along a section of uniform beach without the effects of structures. This transport develops in the model cases at the north boundary and then starts to be affected by the structures in the different test cases. The U1 transport is uniform and parallel to the shoreline.

Recovery to Uninterrupted Transport (U2)

The recovery of the system to its uninterrupted conditions is important to determine how far downdrift a reef's effects may extend. In some cases the model domain is too small to allow recovery to fully developed uninterrupted transport but the transport values near the south boundary are still useful as an indication of how rapidly the system recovers. The U2 transport is uniform and parallel to the shoreline.

Deep Bypass (A1)

Bypassing of sediments around the outside of the headland reefs in a similar fashion to that seen on beaches that are approaching fully embayed beach conditions is expected. However, due to the depth of several metres on the outer edge of the reef this transport is only likely to occur on the scale of a few days during large swell events though large amounts of sediment may be transported in a short period of time. The headlands have two opposing processes that take place under storm conditions in that the headland geometry promotes focusing of the wave energy while the presence of the reef promotes dissipation of the energy through wave breaking and bottom friction. The dominant process will depend largely on the exact geometry along with the wave and reef characteristics. Important factors in the headland bypassing mechanism are the incoming wave characteristics as there will be some threshold below which no transport takes place.

Shallow Bypass (A3)

The coastline often has a strip of uninterrupted sandy beach extending around the headland, especially in the more natural cases still unaffected by property development. At high wave heights and water levels the reef may no longer be able to dissipate all the incoming energy and transport may occur on the inside of the reef. This mechanism of transport will depend highly on the water level over the reef so tides, setup, and sea level are all important factors to evaluate. Differential setup gradients may even cause reversal of the direction in some locations.

Bypass over Reef (A2)

Bypass directly over the reef is expected to have a relatively small contribution. Some transport of fine material is expected due to induced currents over the reef but significant transport is unlikely due to the high levels of bottom friction and turbulence. This mechanism has many significant contributing factors including wave characteristics, water levels, reef roughness, and sediment characteristics and therefore may be difficult to evaluate.

Transport within the Bay (B1)

The transport within the bay is important as it will determine where sediments are deposited. If the transport rates in the bay are smaller than the bypass rates then the sedimentation will be located at the leeward side of the reef while if the transport in the bay is higher than the bypass rates then there will be sedimentation at the on the updrift side of the reef.

3.2 Cross Shore

Figure 9 shows the transport pathways of the three cross shore processes described in this section. The labels X1, and X2 type transport are used throughout the remainder of the report to refer to these processes.

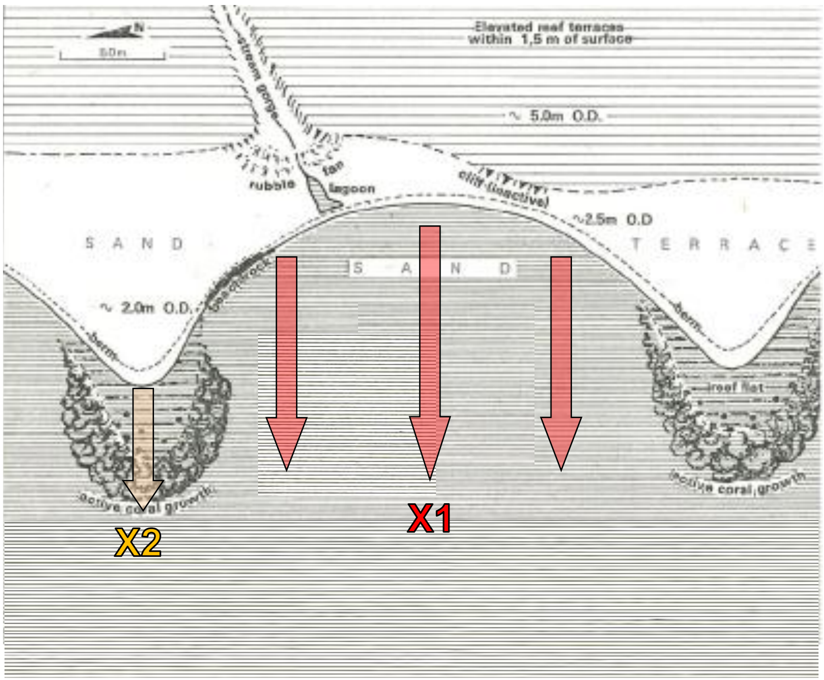

Figure 9 - Cross Shore Transport Pathways

Offshore loss through reef (X2)

Cross-shore loss of sediment through the reef may be facilitated by the shore normal channels characteristic of many fringing reefs. These channels provide preferred pathways for the return flows that balance the onshore mass flux of the breaking waves. Important factors include water levels and wave characteristics. However, the effects of these channels are difficult to reproduce in the model and have only been included as part of the discussion of results later in this report.

Profile Realignment (X1)

The re-alignment of the cross-shore profile from a low to high energy profile accounts for transport of sediment from the foreshore and surf zone to the nearshore area. This process is temporary and after the passage of the storm the sediment will once again be moved shorewards to rebuild the low energy profile. This dynamic equilibrium however can be affected by man-made factors thus causing apparent erosion. Important factors when evaluating this mechanism are the wave and sediment characteristics.

3.3 Rip Currents

Figure 10 shows the transport pathways of the rip current processes described in this section. The label R1 type transport is used throughout the remainder of the report to refer to this process.

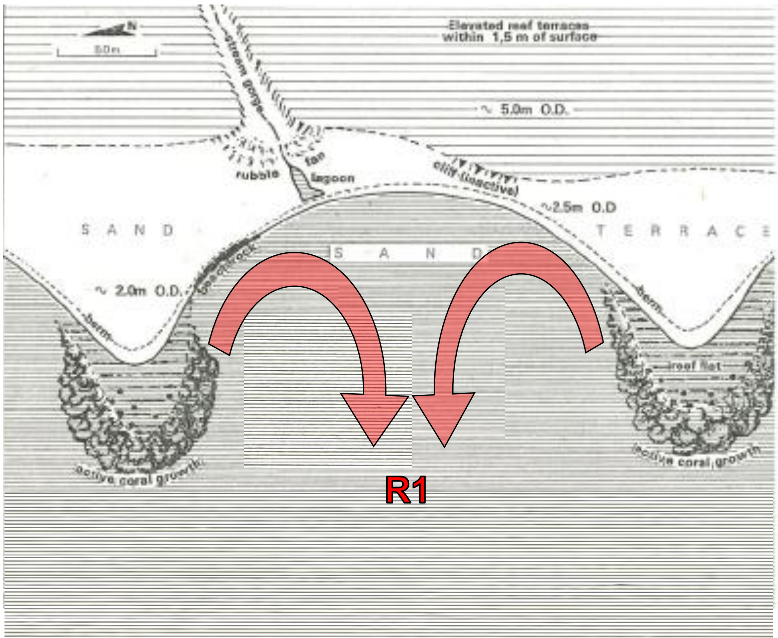

Figure 10 - Rip Current Transport Pathways

Rip Currents (R1)

As a result of differential setup and return flows balancing onshore mass flux, offshore directed currents develop in the beach cells under storm conditions. These rip currents may become quite strong and rapidly transport material offshore. The distance offshore depends on the strength of the current because as the depth increases the flow velocity will decrease and sediments will be deposited. Bird (1970, 1979) mentions these rip currents both in the centres of the bay and at the edges along the reef boundary and reports that they may reach speeds of 0.65m/s.

4 Data Review

The collection of data for this project presented one of the early challenges in terms of quantity, quality, and availability of the necessary datasets. In order to overcome this challenge the decision was made to use a schematized model that resembles the west coast of Barbados but at the same time is not tied directly to a particular location. This method is an attempt to obtain general results into the understanding of the transport mechanisms at work and to facilitate future adaptation of the results to specific situations and locations.

During the model setup field data and observations were used to guide the parameter choices as much as possible. The data was obtained largely from Baird's field investigation for the Holetown walkway project and from general monitoring data from CZMU. Table 2 shows a summary of the data sources and coverage.

Table 2 - Data Review Summary

Project Section	Data Source and Comments
Bathymetry	LIDAR survey (CZMU, 2000 via Baird)
Beach Planform	Bird (1977, 1979) & Aerial photographs
Beach Profile	Holetown monitoring profiles (Baird, 2009-2010), LIDAR (2000)
Grain Size	Holetown sediment samples (CZMU/Baird,2003)
Photos (Aerial)	Historical aerial photos (Baird 2000, GoogleEarth 2004-2011)
Photos (On-Site)	Select dates between March 13, 2009 and October 15, 2011
Sediment Supply	Jet Probe Logs (Baird,2009), Tosic (2007, 2009), Bird (1977)
Settling Velocity	Estimated using Jimenez (2003), Measured by CERMES (2012)
Tides & Sea Level	Parker & Oxenford (1998) , IPCC (2007) Sea Level Rise Estimates
Waves (Nearshore)	Measured nearshore waves (Baird 2003 - 2008), MSW Forecasting
Waves (Offshore)	NOAA buoys 41101 & 41040

Bathymetry

A LIDAR survey was completed in 2000 showing the west coast bathymetry from approximately the shoreline to 50m depth and including important features such as the offshore bank reef in locations such as Dottin's Reef where it becomes shallow enough to influence incoming wave characteristics. The data is of sufficiently high resolution to be adequate as bathymetry input for a numerical model. Due to wave breaking and turbulence however the resolution is lost over the reefs and very close to shore but this missing data can be supplemented with beach profile data to provide a smooth transition from nearshore bathymetry to beach elevations. Table 6 in Appendix A shows a summary of the dimensions of the beach cells of Barbados' West coast.

Beach Planform

Planform data was obtained mostly from aerial photographs and visual surveys of the site. Bird (1977) and Bird (1979) both show schematized beach cell configurations and were used as a further guideline.

Beach Profile

Beach profile data has been collected both by Baird during their design and construction phase of the Holetown Walkway project and for CZMU as part of their beach monitoring programme. The construction monitoring profiles from Baird (2009-2010) were used to supplement those extracted from the LIDAR data and refine the nearshore-to-beach transition of the bathymetry.

Sediment Diameter

Grain size distribution (GSD) information for the area has been collected by Baird for the Holetown walkway project, and by CZMU as part of their beach monitoring programme. Figure 43 in Appendix A shows some sample locations of which the six listed in Table 3 were obtained from Baird for this project.

Table 3 - Sediment Sampling Summary

Point	Site	D_{50} (μm)	D_{75} (μm)	D_{90} (μm)
6	Inn on the Beach (back beach)	378	457	528
7	Inn on the Beach (swash)	434	619	829
8	Inn on the Beach (-0.5-1m)	337	419	468
9	Dive Shop South (back beach)	390	470	595
10	Dive Shop South (swash)	463	694	1494
11	Dive Shop South (-0.5-1m)	348	426	474

The six samples were taken at two main locations (Inn on the Beach and Dive Shop South) with three samples at each location (back beach, swash, and -0.5-1m depth). There was a similar trend at both sites with finest sand located at the -0.5-1m depth with back beach sand slightly coarser and then swash zone sand being the coarsest. An exact estimate for the d_{50} grain size was difficult as the sieve sizes 250µm and then 500µm usually had passing fractions of around 10% and 80% respectively meaning that approximately 70% of the sand sample is between 250-500µm which is quite a wide range in terms of transport characteristics and equilibrium profile. The d_{75} and d_{90} were also obtained from the data to give a better idea of the range of particle diameters present at the site. It can be seen that the swash zone sediment is well graded with a wider range of particle diameters present while the backbeach and nearshore sediment is more uniform.

Photographs (Aerial)

GoogleEarth has a collection of historical satellite imagery. However, these images are all relatively recent (29-Jun-2004, 20-Nov-2004, 08-Nov-2006, 11-Feb-2011) making long term trends difficult to identify with any accuracy. An additional image was available from Baird 2000 making for a total of 5 images over 11 years. Aerial images on the scale of a few days to compare single events are unfortunately not available.

Photographs (On-site)

Personal surveys were conducted on select dates between March 2009 and January 2012 with site photos are available from these surveys. The surveys include photos of the site before and after the construction of the walkway, during calm and storm conditions, and underwater photos showing reef formations and sediment characteristics both in the calm season and under moderate storm conditions. Where possible wave height estimates have been noted at the time of the surveys.

Sediment Supply

The results of jet probe logs completed as part of the site investigation for the Holetown Walkway project were obtained and reviewed. These logs showed that there was a layer of sand approximately 1m thick to supply transport in the nearshore area (0-5m depth). In the logs there is a layer of coral rubble present in some areas at a depth of about 1m below the surface of the sand, which will affect transport characteristics should erosion exceed the sand layer thickness.

Tosic (2007) and Tosic (2009) are two papers from a study that examines the effects of water quality in the Holetown area. As part of the study the discharge and sediment characteristics were measured for the Holetown Lagoon. These papers provide information on the magnitude and concentration of the sediment load being supplied by the waterway during several events which may allow for a more accurate calculation of the sediment budget in Holetown Bay.

Bird (1977) included a section outlining sediment supply noting that the majority of the sand was as a result of attrition of coral reefs and cliffs with a small contribution of fines and silica sand being washed from the land during stormwater discharge.

Settling Velocity

The settling velocity of the sediment is an important factor in determining the equilibrium profile of the beach. Two methods were used to estimate the velocity. The first method was a formula proposed by Jimemez (2003) which estimates the settling velocity of particles based on their grain size. A full explanation is available in his publication but in summary the formula takes into account factors such as particle density, roundness, and fluid viscosity along with the grain size.

However, irregular shaped coral sands make up the majority of the sediment on the west coast of Barbados so a test was carried out to validate the velocity estimates obtained from the Jimenez (2003) formula. A set of direct measurements of the settling velocity were undertaken with the assistance of Dr. Robin Mahon at CERMES in Barbados. Sand samples were collected from the neashore zone and settling times were measured in a glass cylinder filled with seawater. Times were recorded for the first, median, and (approximately) final particles to settle which gives a range of settling velocities for each sample. These settling velocities were then used to reverse-calculate the corresponding particle size using the Jimenez (2003) formula to allow for comparison to the previously measured grain size samples. Table 4 summarizes the measurements and calculated velocities and corresponding particle sizes.

Table 4 - Settling Velocity Test Results

Test#	First Particle			Median Partcile			Last Particle (approx)		
	t (s)	v (m/s)	d_{50} (μm)	t (s)	v (m/s)	d_{50} (μm)	t (s)	v (m/s)	d_{50} (μm)
1	2.9	0.115	1020	--	--	--	11.7	0.028	255
2	3.4	0.098	820	--	--	--	11.2	0.030	265
3	3.5	0.095	795	--	--	--	11.8	0.028	255
4	3.1	0.107	930	--	--	--	11.1	0.030	265
5	3.2	0.104	890	--	--	--	12.4	0.027	245
6	3.1	0.107	930	--	--	--	17.1	0.019	200
7	2.9	0.115	1015	--	--	--	12.0	0.028	250
8	3.2	0.104	890	--	--	--	12.2	0.027	250
9	3.0	0.111	970	--	--	--	15.2	0.022	215
10	3.5	0.095	790	--	--	--	11.6	0.029	260
11	--	--	--	6.3	0.053	420	--	--	--
12	--	--	--	7.9	0.042	345	--	--	--
13	--	--	--	7.3	0.046	370	--	--	--
14	--	--	--	6.5	0.051	410	--	--	--
15	--	--	--	8.4	0.040	330	--	--	--
Mean	**3.2**	**0.105**	**905**	**7.3**	**0.0463**	**375**	**12.6**	**0.027**	**246**

The results show that there is quite a range in the values but the mean velocities obtained from the grain size and Jimenez (2003) formula were very close to those obtained by direct settling measurements.

Tides & Sea Level

Barbados can be considered a microtidal region experiencing a mixed semi-diurnal tide with two low and high tides every 24.8hours and with significant diurnal inequality The maximum tidal range is 1.1m (Parker & Oxenford, 1998) so the effects of a sea level rise as a result of climate change could potentially have significant impacts. The International Panel on Climate Change (IPCC) estimates average sea level rise over the next 100years to be between 0.2 and 0.6m.

Waves (Nearshore)

Baird has a record of waves measured at 6m depth from 09 Oct 2003 to 13 Dec 2008 which was undertaken as part of the data collection process for the Holetown walkway project. Figure 44 in Appendix A shows the location of the gauge while a summary of the data has been included in Appendix B. The summary includes the wave height and period roses, which show that the dominant wave direction at the site is from the north-west, a reduced wave climate, and a storm listing of the wave height, period, direction, and duration of all the storm events that were measured during the recording period. The full time series is also available to analyze the response of the sediment transport to forcing conditions based on a measured time series. Due to the wave gauge location there are likely significant effects from the Dottin's reef and Holetown Hole so the data is suitable as a guideline for parameter choice but not as direct input to the general model. The major effect is the sheltering of the gauge location so that the measured waves are smaller than would be characteristic of the entire coast. There are also some questions into the validity of that dataset as there were some irregularities noted in the directions and some of the wave height-period combinations.

As a further guideline, the wave heights predicted by the surf forecasting website MagicSeaWeed (MSW) were noted at the time of the surveys done from December 18-20, 2011. MSW use the NOAA WaveWatch3 (WW3) model data as input to a SWAN model to provide their surf predictions.

<u>Waves (Offshore)</u>

Offshore wave data is available from two NOAA buoys: 41101 – East of Martinique (400km northeast) and 41040 – West Atlantic (700km east-northeast). However due to the availability of the nearshore wave data and the schematized nature of this model the choice was made to forego the use of a SWAN model to bring these waves into the nearshore area and instead use several wave cases that reflect the climate observed in the field and nearshore data. When the model is applied to a specific case then offshore waves will be an important dataset to collect. Wave direction is also a critical factor as the data available from NOAA is in the form of one dimensional wave spectra.

There are two distinct seasons with respect to the waves at this site which are briefly mentioned by Bird (1977 & 1979). The summer season occurs approximately between June and September when the waves are very small with many days when there are effectively no waves. These seasons are still to be confirmed from the measured wave data. This lack of wave action in the calm summer season is due to the fact that the predominant wave direction is from the east to north east as waves are generated by the trade winds blowing across the Atlantic Ocean. The waves lose much of their energy as they are refracted and diffracted 180 degrees around the island to impact the west coast and hence have little to no energy remaining when they arrive. The winter season is approximately October to April when large storms in the North Atlantic send swell waves southwards to Barbados where they are able to reach the normally protected west coast. One major exception to this rule is the effect of hurricanes. The hurricane season is the same as the summer season (approximately June-September) and can account for very high winds and waves experienced on the west coast during this time. However direct hurricane impacts in Barbados are rare occurring about once every 20 years (NOAA, 2011) as most hurricanes turn north before they reach the island. With this information the swell/storm wave angle from the north-west is a result of the winter swells that are experienced at the site.

5 Model Description and Setup

5.1 Model Description

Numerical modeling in general has the potential to provide relatively quick and cheap insight into the behaviour of a system. Advantages over physical models and field studies include the ability to rapidly test different scenarios, to isolate single parameters to study their sensitivity, and to introduce idealized conditions in an attempt to remove natural irregularities that may reduce the quality of results. Numerical models are also much cheaper than a corresponding physical model or field study. These four reasons in particular made a numerical model the optimal choice for this investigation. However, disadvantages including the fact that a numerical model may fail to capture all the relevant processes occurring in a system and to overcome this limitation, a detailed physical model or field study is needed to calibrate and validate the numerical results.

Delft3D

Delft3D (v 4.00.01) is a package of integrated numerical models developed by Deltares. Delft3D is capable of simulating a variety of hydrodynamic and morphologic processes accurately in a limited computational time (Deltares 2010a). Delft 3D has proved to be a robust model in a variety of coastal problems (Lesser et al 2004). The full 3D version is very computational intense and therefore the majority of the project scenarios are completed in depth averaged mode (2DH) to reduce computational time. Figure 11 shows how the components of the model integrate with each other.

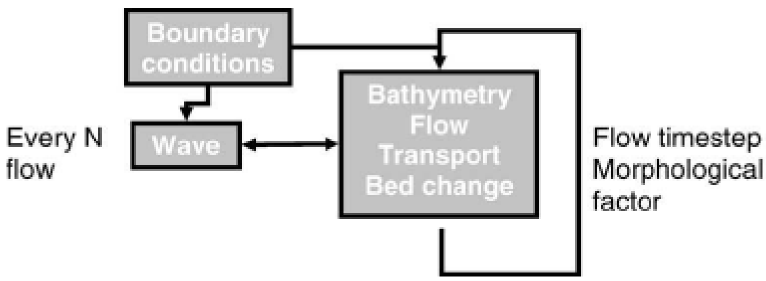

Figure 11 - Delft3D Modelling Scheme (Roelvink, 2006)

A wave module and a flow module work in combination so that bathymetry changes as calculated in the flow modules are used to update the boundary conditions in the wave module for wave propagation calculations. This feedback loop is repeated at a user specified interval depending on the level of detail needed in the calculations. This combination of hydrodynamics with mophodynamics makes the model very powerful. Vlijm (2011) provides a concise summary of the functions of the operation of the flow and wave modules.

Delft3D Flow

Delft3D Flow is a non-stationary process based numerical model which solves the Navier-Stokes equations for an incompressible fluid under the shallow water and Bousinesq assumptions. In the vertical, the Navier-Stokes equations reduce to hydrostatic pressure assumption so vertical accelerations are neglected. For the computation of the suspended sediment transport an advection-diffusion equation is used. For more on the governing equations refer to Lesser et. Al. (2004) and Deltares (2010a).

Delft3D Wave (SWAN)

Delft3D Wave, better known as SWAN (Booij et al., 1999; Deltares, 2010b), is a third generation spectral wave model using a Eulerian approach. In SWAN the evolution of the wind generated waves is based on a two dimensional wave action-density spectrum and is calculated simultaneously for each point in space. SWAN is capable of simulating wave propagation, wave generation by wind, non linear wave-wave interactions and wave energy dissipation for given conditions like bathymetry, wind, flow, and water level. By online coupling of SWAN to Delft3D Flow, wave-induced processes such as wave induced (shear) stresses and additional turbulence are accounted for in flow computations.

5.2 Model Setup

This section identifies how the important model input parameters were selected. Table 7 and Table 8 in Appendix A show a summary of the major model input parameters that are discussed in this section and their associated runID#.

Grids

Two grids are used for the setup of this model, one for the SWAN module and one for the Flow module. Figure 12 shows the two grids as they are setup in the model with grey being the flow grid and red being the wave grid. The SWAN grid consists of 89x289 (cross shore x longshore) cells which vary from 40x10m on the offshore boundary to 5x10m on the shoreline boundary. The Flow grid consists of 174x199 cells which are all 5x10m. There is significant overlap in the two grids to allow for accurate coupling of the processes.

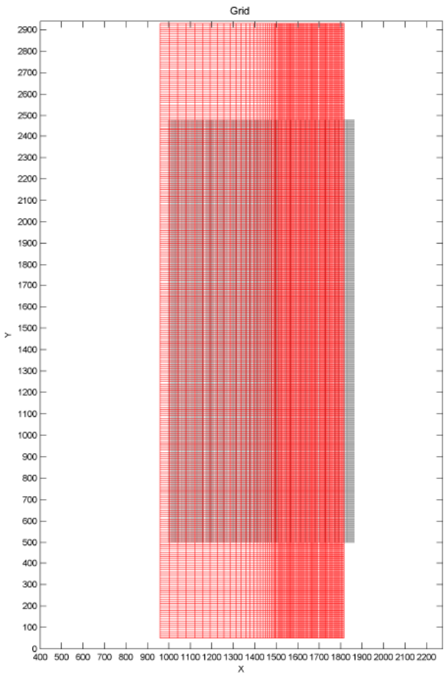

Figure 12 - Delft3D Wave and Flow Grids

Bathymetry

The choice was made to use a schematized bathymetry whereby the reefs and bays are symmetric and regular shaped. This decision was made as the transport is complex and so understanding what mechanisms are at work becomes extremely difficult if a detailed irregular bathymetry is used. The use of a schematized bathymetry should allow individual effects to be isolated more easily. The initial profile was a uniform sandy coast with a Dean profile from MSL to a depth of 12m on the offshore boundary and a linear sloping beachface to a berm at +2.5m above MSL. The Dean profile was based on a settling velocity of 0.046m/s (sediment diameter 375µm) with the estimation of this value described in the *Settling Velocity* section of this chapter. This cross-shore profile seemed appropriate based on a study of the LIDAR data and profile monitoring data from Baird 2009. The schematized beach cell presented in

Bird 1977 and Bird 1979 show a steeper sloping nearshore region so that depths in the bay and outer edge of the reef are greater than used in this model. The final bathymetry then built upon this initial profile with the addition of small sandy headlands and then coral reefs immediately offshore of the headlands. Figure 13 shows a sketch of the Dean, reef, and shoreface profiles that were used.

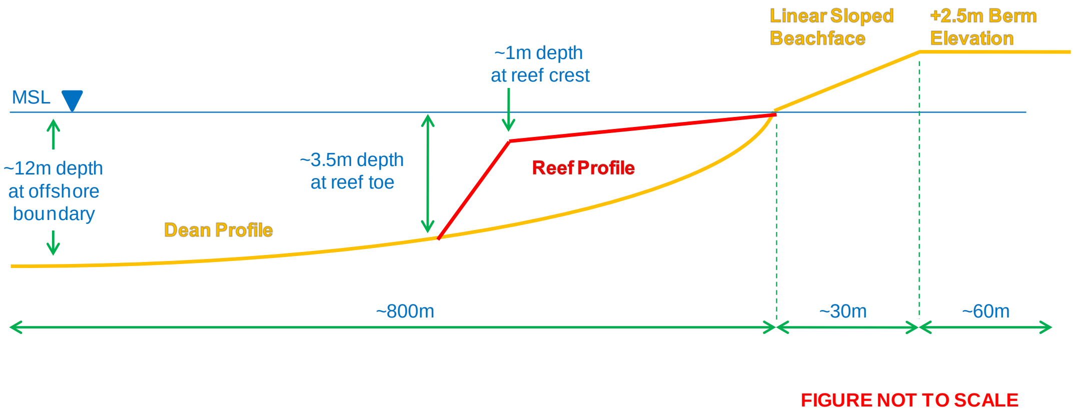

Figure 13 - Sketch of Typical Profile

Bay size was varied from a minimum bay size of 300m longshore by 40m cross shore to 600m longshore and 80m cross shore. The ratio of longshore to cross shore was also varied with constant longshore dimensions of 450m and cross shore dimensions from 40 to 115m. These ranges of bay size and ratio fall within the ranges observed in the field. Figure 14 shows how the bay sizes were defined with the north to south (longshore) dimension and the east to west (cross shore) dimension.

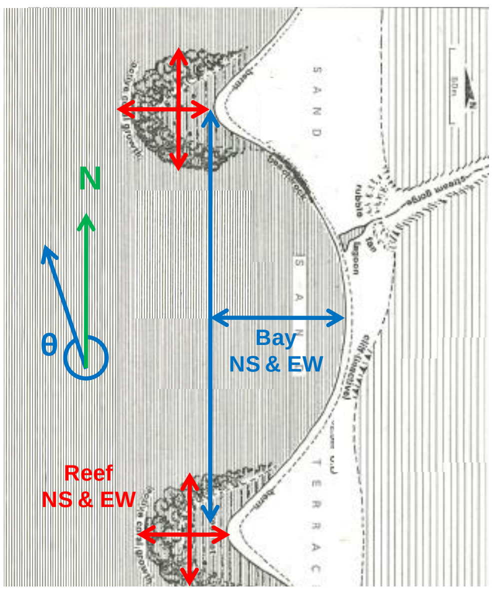

Figure 14 - Characteristic Bay and Reef Dimensions

The planform of the beach was based on aerial images, data from Bird (1979), and site observations. The images suggested a trend of wider summer beaches and narrower winter beaches. This observation follows logically from the dominant wave climates during these two seasons, low energy in summer and high energy storms in the winter. A final beach width of 30m, measured from MSL to berm crest, was chosen. This width corresponds to the measured data from Bird (1979).

In the field there is often a gravel step present at the shoreline but it was not included in the model as one of the simplifications to the bathymetry. Further justification is that the step is dispersed under the high energy conditions which are the focus of this report (Bird, 1979). Another simplification was the omission of all patch reefs that are present in many of the bays. These were indicated in the schematization by Bird (1977) but their effects were assumed to be small in the general behaviour of the system.

Reef

The reef is a significant factor so a series of schematized geometries based on field observations were used. The geometries were varied based on the size and ratio of the reef from 100x50m to 400x200m (longshore x cross shore dimensions respectively) which were consistent with the reef sizes and ratios observed in the field. Figure 14 shows how the reef sizes were defined with the north to south (longshore) dimension and the east to west (cross shore) dimension.

Model Regime

The model was run in a depth averaged mode for the initial runs to ensure that previous results and circulation patterns were satisfactorily duplicated and to save time. Ranasinghe (2005) describes offshore submerged breakwaters as highly 3D structures, a description that can be logically extended to the reef situation as studied in this report. However based on the results of some preliminary test runs, it was decided that running a full 3D model would gain little insight into the processes identified as being the most significant, while coming at a high computational and time cost so only 2DH runs were used.

Significant Wave Height (H_s)

This report aims to focus on the effects of large swell waves and consequently for the base case a significant wave height of 1m was chosen. A Weibull analysis of the nearshore measured wave data shows that a return period of one year for a 24 hour storm with wave heights of 1m is appropriate. However, due to sheltering effects as mentioned previously it may be expected that the return period be somewhat lower (more frequent).

Bird (1979) and Bagnold (1940) suggested that, based on observations of the berm elevation, the maximum wave height that can be expected in the bay is 2.9m which corresponds to a significant wave height of 1.45m. During Hurricane Ivan in 2004 waves of 1.77m were measured at the Holetown gauge location. Based on this information a significant wave height of 1.5m was selected as appropriate. However, as a test of an extreme case, and as a measure to account for sheltering effects that may have been experienced at the Holetown gauge, a significant wave height of 2m was also considered in the model runs.

Sensitivity analysis of the system response was conducted with wave heights of 0.25, 0.5, 0.75, 1.0, 1.5, and 2.0m. In these cases, the focus is on the effects of different wave heights but the period must also be changed in order to achieve the same wave steepness. For the model a wave steepness of 0.0064 (corresponding to a wave height of 1m and period of 10s) was chosen and wave periods for the other wave heights were calculated accordingly. This steepness is based on the offshore wave characteristics which is a slight simplification as discussed later in the *Results and Discussion* section.

Swell decay was not considered in this model. The wave height (along with period and direction) were held constant for the duration of the model run.

Peak Period (T_p)

Since the focus of the study is on swell conditions longer wave periods are of more interest. A period of 10s corresponding to the significant wave height of 1m was selected for the base case. The nearshore data shows that for a 1m wave there was a measured period range of 5-15 seconds so 10s fits well within this range. A sensitivity analysis of the system response to changes in wave period, and corresponding wave steepness, was conducted. With 1m waves and wave period varied on a 2 second interval from 6-14s.

Wave Direction (θ)

Direction was proposed as one of the most important driving factors. Wave directions of 270degrees (shore normal), 275, 285, and 305 were tested. The wave rose from the Holetown gauge shows that higher wave angles were present at the gauge location but due to further refraction and shoaling as the wave propagates to shore the angle of incidence it is unlikely to reach more extreme values than the 305 degree test case.

Sea Level

Sea level was held constant for the majority of the runs (representing MSL). Since Barbados is a microtidal environment the tides were assumed not to have much effect on the transport but to confirm a series of sensitivity runs were completed to model extreme low and high tides, and an extreme high tide in combination with the effects of different sea level rise (SLR) estimates. The IPCC (2007) estimates SLR in the next 100years to be 0.2-0.6m on average but an extreme case of 1.0m SLR on top of high tide was also considered for two reasons. Primarily because SLR is a major concern for small island states and low lying coastal areas such as Barbados; a position echoed by Iniss (2011), and secondly Dr Inniss continues on in the interview to say that measured effects of SLR are already higher than estimates predicted. Final sea levels that were used in the model were +1.55, +1.15, +0.75, +0.55, -0.55m.

Sediment Diameter

The large ranges in measured particle size are difficult to incorporate into the model. A value d_{50} value of 375µm was used as the final value in the model, which corresponds most closely to the sediment in the -0.5-1m and backbeach zones. It was assumed that the coarser sediment observed in the swash zone is part of a thin band of coarse sediment that forms a gravel step but which will be dispersed during the high energy conditions (Bird, 1979), which are the focus of this report.

The choice of grain size affects other parameters such as the roughness and the settling velocity, which in turn affects the equilibrium profile. The effects of an increase to d_{50}=475μm and a decrease to d_{50}=275μm were evaluated in the model to determine the sensitivity of the system. The analysis will also provide some understanding on what may happen should nourishment options be more commonly considered in the future.

Settling Velocity

The settling velocity was based on two estimates. The first estimate based on the formula proposed by Jimenez (2003) which relates the fall velocity to the sediment shape and diameter. The second estimate is based on a rough field test involving measuring the time taken for the sediment to sink in a measuring cylinder resulting in a direct settling velocity measurement (Mahon, 2012). The estimates from both methods agreed well with each other and a value of 0.046m/s was used.

Bottom Roughness

One of the points of interest of the author, among others, was the effect that regeneration of the natural coral reefs would have on the transport in the system. It was proposed that the regeneration would have two main impacts on the system, a decrease in the effective water level above the reef due to the coral growth and an increase in the roughness of the reef due to the same coral growth. Water level considerations are covered in the *Sea Level* section while the choice of reef roughness is described in this section.

Usually the roughness parameter is used to calibrate a model but in this case the roughness was varied as an input parameter and not as a calibration parameter. This process represents a deviation from the common procedure.

Initially the validity of the roughness coefficients used in a previous report (Vlijm, 2011) was evaluated. With a d_{50} of 375μm a Manning's roughness was estimated following the procedure outlined by Julien (2002), which was converted to a Chézy coefficient of $67m^{1/2}/s$ for the sand. Following the suggestions of Hardy (1993) and Fernandez et al. (1998) the friction factor associated with the sand was increased an order of magnitude to obtain the value for the reef and corresponded to a Chézy coefficient of $21m^{1/2}/s$. These values correspond well to values in literature (Julien,

2002) and to the values used by Vlijm (2011) of 65 for sandy areas and 20 for rubble mound areas.

In order to evaluate the roughness sensitivity the friction factor was doubled which corresponded to a decrease in Chézy coefficient from 20 to 15. In terms of river mechanics Chézy coefficients in this range correspond to heavy vegetation (Julien, 2002) so further reduction would likely approach the validity boundaries of the equation and not give meaningful results. Instead the roughness was decreased by 50% resulting in a Chézy coefficient of 45 which is a smoothing of the reef that could be as a result of coral death and destruction. A Chézy coefficient of 45 corresponds roughly to a boulder-cobbled bed (Julien 2002) and may represent coral rubble characteristic of a dead reef.

In the model there is an option to introduce different cross shore and longshore roughness coefficients. It has already been noted that the cross shore and longshore characteristics of the reefs are different due to the presence of the shore normal channels so this parameter choice presented the opportunity to evaluate the effects of different directional roughness. Chézy coefficients of 45 in the cross shore and 15 in the longshore were used to exaggerate the effects for easier analysis.

Duration

The duration of a typical storm event is around 4 days. For the model runs a storm duration of 40 days was used to simulate 10 consecutive storms. This duration was chosen to allow the full development of transport and sedimentation patterns and to evaluate the morphological changes occurring over time.

The hydrodynamic spin up time is 12 hours before morphological changes start to occur. The morphology acceleration factor was set to eight for all the test cases.

Sediment Supply

Sediment supply is important for the development of sedimentation/erosion patterns. The sediment thickness parameter was held constant over all the test cases with a sediment thickness of 5m everywhere except directly on the reef which was set to zero thickness. The sand layer thickness revealed by the jet probe logs was as thin as

1m in some areas but the decision was made to use 5m thickness in order to allow the transport patterns to develop unhindered and then effects of the reduced layer thickness are addressed in Chapter 6.

Another decision was made to omit the effects of the storm drains that empty into the bays. They are a source of sediment but detailed study of their effects on the system is beyond the scope of this report therefore only a qualitative discussion has been included in the *Stormwater Discharge* section in Chapter 8.

A discussion on the effects of the reduced sediment layer thickness and sediment discharge from storm events are included in the *Results and Discussion* section.

Transport Rates

The longshore and cross shore transport rates are critical in analyzing the behaviour of this system. Figure 15 shows the typical transects that were used to measure the transports within and between the cells. On the left the longshore transports were measured in terms of the three bypass modes (A1, A2, A3) and the transport within the bay (B1) while the cross shore was not possible to separate the modes (X1, X2, R1) but transects spaced every 25m (cross shore distance) are used to obtain the relevant cross shore transports for the north and south sides of a given cell.

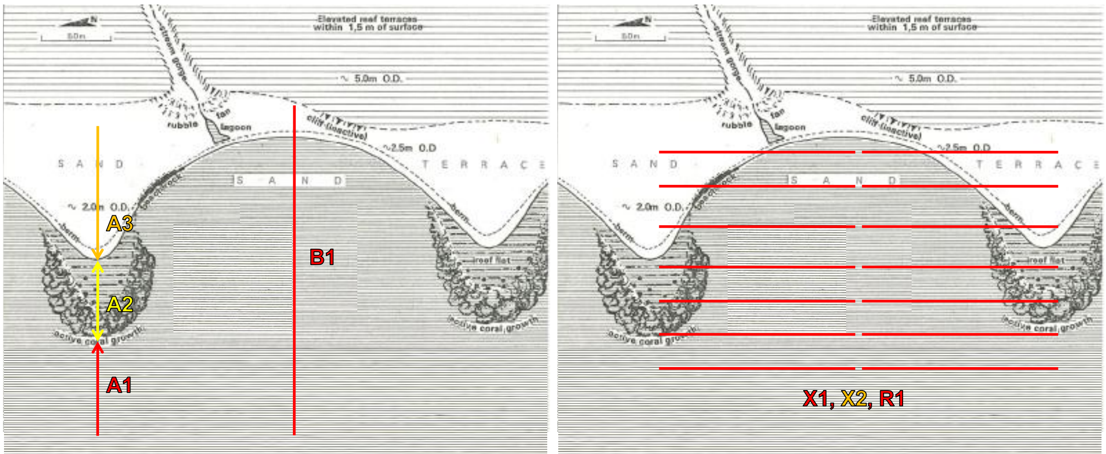

Figure 15 - Transects used to Measure Transport Rates

Wind

The west coast is sheltered by the land and therefore experiences a very different wind climate to the east coast of the island where the wind characteristics are usually measured. Usually there is little to no wind due to the sheltering effects of the land and therefore running the model without accounting for wind effects should not cause significant errors. The exception to this rule would be the case of a hurricane where very strong winds and seas from the west could be experienced but that case it beyond the scope of this report.

6 Results and Discussion

The results and a discussion of the significant findings of this thesis are included in this section. The results are presented in four broad categories for ease of analysis; the reference cases, the forcing scenarios, the geometry scenarios, and the miscellaneous scenarios. Each section is then further broken down and the individual results and trends are presented for each parameter under consideration. In keeping with the scope of this report the results are presented as the response within the beach cell and the interaction between the cells. A single page report on each model run showing the initial bathymetry, final sedimentation/erosion patterns, longshore transport, cross shore transport, depth averaged velocity, and nearshore significant wave height has been included in Appendix C with the runID numbers listed in the title of each section for ease of reference.

An error was noted in the initial results where the transports in the longshore uniform cases showed a decreasing transport (sedimentation) when it is expected that transport would be uniform under longshore uniform conditions. The error appears to be as a result of the diffraction calculations occurring in the model as the irregular behaviour did not appear once the diffraction calculation parameter was switched off. Only the reference cases were re-run to assess the validity of the remaining results as time did not permit for the re-running of all the test scenarios. It was found that the changes to the model increased the transport magnitudes by 0-100% but that the trends were similar in shape for the *Base Case* so that the results and discussion of the following forcing scenarios, geometry scenarios, and miscellaneous scenarios should be valid subject to increased magnitudes. However, it is recommended that the scenarios be re-run to confirm should this study be continued.

6.1 Reference Cases

The reference cases were used to set control factors to allow more meaningful comparisons of the forcing and geometry scenarios. Four reference cases were used in this report; one of an alongshore uniform beach, one of a coastline with bays but no reefs, one of a longshore uniform fringing reef, and finally the one which is used as the official base case for this report which consists of the “typical” beach cell. In practice neither the *Longshore Uniform* nor the *No Reef* cases were observed at the project site but situations similar to the *Longshore Uniform Fringing Reef* and *Base Case* were observed in the field. These four cases were all run under the *Base Case* forcing conditions of H_s 1.0m, T_p, 10s, and direction 285degrees.

6.1.1 Longshore Uniform *(runID# G17r)*

The *Longshore Uniform* case was used to determine the uninterrupted longshore transport (U1) that would develop under the *Base Case* forcing conditions. Since the shoreline is longshore uniform, no separation of bay response and cell interaction is possible for this case. The longshore transport (U1) was steady between 172-174 m^3/day under the rerun scenario (G17r). The results also show that there is movement of the sediment offshore to a distance not exceeding 150m. This movement is expected as the profile adjusts to a shallower slope consistent with a storm profile.
Bed level changes are small and associated with the profile realignment. Maximum depth averaged velocities observed are on the order of 0.5m/s in the surfzone and directed parallel to shore.

6.1.2 No Reef *(runID# G16r)*

The second reference case, *No Reef*, is one where there are bays and headlands but no reefs. This case of an incomplete beach cell was used to help isolate the effects of the bay (shoreline shape) without the effects of the reef, on the transport. Longshore transport is 164m^3/day in the first transect which is consistent with the uninterrupted transport (U1) estimate of 172-174m^3/day. The transport then decreases by about 30%, to about 115m^3/day, due to the effects of the headlands. Recovery to uninterrupted transport (U2) conditions takes place a few hundred metres after the final headland. There is a slight increasing trend in transport over the three reefs in the re-run results *(G16r)* which is contradictory to the initial results *(G16)* and indicates the results may differ by more than just a simple shift in magnitude.

Beach Cell Response

Within the beach cell the longshore transport (B1) is on the order of 150m^3/day which is a slight reduction from the uninterrupted longshore transport (U1).

Significant differences from the *Longshore Uniform* case start to arise when the cross shore transport is observed. Onshore sediment flux observed at the northern sides of the bays and offshore flux at the southern sides which, coupled with the gradients in longshore transport, lead to erosion and sedimentation patterns as shown in the run report in Appendix C.

The sedimentation patterns show erosion on the order of 50cm and accretion on the order of 35cm with erosion focused on the headlands where wave energy is highest due to focusing effects. There are also what appear to be scour channels directly to the south side of the headlands which could be due to channeling of water due to onshore mass flux. Accretion occurs at the south side of the cell where the transport gradients are decreasing. Accretion also takes place at the south side of the headlands which appears to be a case of the headland migrating down drift, similar to the behaviour sometimes observed with migrating sandbars.
Maximum depth averaged velocities are on the order of 0.5m/s in the bayhead and at the headland. The currents follow the shoreline and dissipate rapidly seaward of the surfzone.

Beach Cell Interaction

In this case it is again difficult to clearly separate the effects into response and interaction and much of the significant behaviour has been described previously in the *Beach Cell Response* section. One characteristic of interaction that was omitted however is that of the proportion of the bypass. There is quite a significant amount of sediment exchange between the bays with about 115m^3/day bypassing the headlands (A1+A3) and entering the downdrift bay. The model report shows that the majority (65-70%) of the transport however takes place through the transect where the reef will be located which means the existence of a reef will have significant effects on transport magnitudes.

6.1.3 Longshore Uniform Fringing Reef *(runID# G18r & G18ar)*

The *(G18)* scenario builds upon the first two reference scenarios in that it was developed to isolate the transport occurring past the reef in a longshore uniform situation. Similar to the *Longshore Uniform* case no separation of bay response and cell interaction is possible for this case. Longshore transport (A1) was constant at 2m^3/day while cross shore transport was negligible on the observed cross sections with the exception of the outer edge of the reef where there was movement offshore on the order of 10m^3/day. This movement is likely as a result of the abrupt changes to slope and roughness at the sand/reef boundary which coincides with the surfzone and high levels of turbulence would be expected at that location.

Subsequent to these results a further case *(G18a)* was run with the same geometry but larger waves (H_s=1.5m T_p=12s). This was done as a result of the observation that 1m waves appeared to be near the threshold value for bypass to occur at the reef and therefore the bypass, and associated behaviour, would be better developed under the 1.5m waves.

Under the larger wave forcing the transport rates increased to between 49 and 50m^3/day. Other behavior changes included the cross shore flux at the offshore reef/sand boundary decreasing from from 10m^3/day to 3m^3/day and moving in an offshore direction.

In both cases the bed level changes and depth averaged velocity are small. In the case with 1.0m waves bed level changes are effectively zero while under 1.5m waves they increase slightly to the order of 5-10cm of erosion right at the sand/reef interface. Depth averaged velocities increase from about 0.2m/s under 1.0m waves to about 0.35m/s under the 1.5m waves and are strongest along the outer edge of the reef.

6.1.4 Base Case *(runID# F03, F03r)*

The final reference case, referred to as the *Base Case*, consists of the "typical" beach cell in terms of geometry and forcing conditions as determined for the project site. Initial longshore transport (U1) is 167m^3/day which is consistent with the other reference cases however further transport reduces significantly due to the effects of the headlands and reefs. The difference between the initial *(F03)* and the re-run *(F03r)* test cases was a shift in magnitude while the trends remained similar. While this section considers the numbers from the re-run case *(F03r)* the references throughout the remainder of the report to the *Base Case* is in reference to the initial results *(F03)*.

Beach Cell Response

Within the beach cell the longshore transport (B1) is on the order of $45m^3$/day which is almost a 75% reduction from the uninterrupted longshore transport showing the reef has a significant effect. Cross shore patterns are similar to the *No Reef* case with onshore flux at the northern side of the cell and offshore at the southern side. At the northern side of the cell there is a convergence of transport around 50m offshore where a small offshore flux meets the dominant onshore flux thus leading to some accretion in this area.

Sedimentation and erosion patterns perhaps explain the behaviour within the cell more clearly. Scour channels can be observed on either side of the reef which are present as a result of the offshore directed currents that balance the onshore mass flux from the waves. These currents at the reef/sand interface were described by Bird (1977 & 1979) and were present on the same order of magnitude as described. (0.5-0.65m/s). These currents carry sediment offshore at the south side of cells and then deposit it as they slow upon reaching deeper water which forms an area of accretion on the north-west corners of the reef. In general there is also a movement of sediment from the north to the south side of the cell as it re-orients itself to the incoming wave energy. Currents in the bay are directed parallel to the shore and are slightly lower on the order of 0.3m/s.

Beach Cell Interaction

The proportion of bypass (A1+A2) is on the order of 12-$14m^3$/day passing a transect through the reef and surf zone which is a significant decrease from the *No Reef* case. There are two modes of transport present with $3m^3$/day transported over the reef itself (A2) while 9-$11m^3$/day is transported around the outside boundary of the reef (A1). These differing modes of transport are discussed in more detail in subsequent sections of this report. The transport within the cell is higher than the bypass at the headland/reef which results in the sedimentation at the south side of the cell and the north side of the reef.

6.1.5 Reference Case Summary

In summary the four reference cases have already given quite some insight into the behaviour expected in this system. Figure 16 shows a comparison of the longshore transport rates of the four cases.

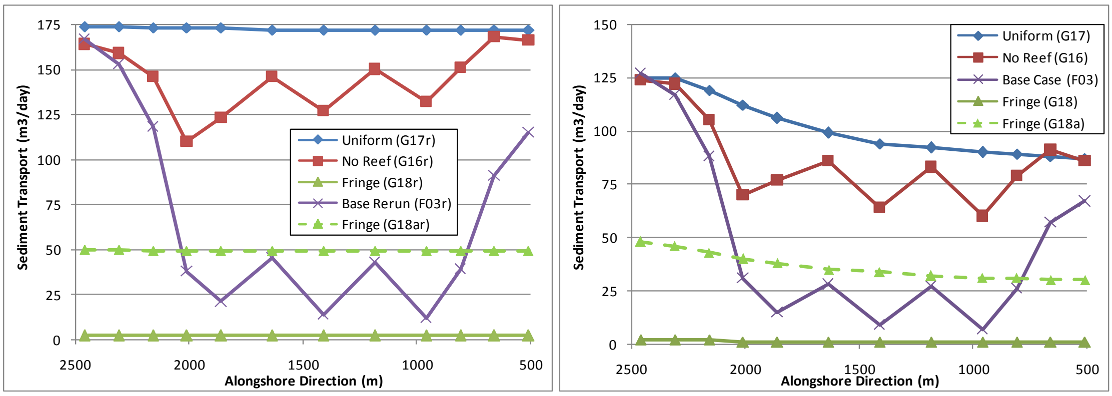

Figure 16 - Longshore Transport Rates of the Reference Cases

The graph on the left shows the results of the re-run test scenarios after diffraction calculations were switched off while the graph on the right shows the initial results with the gradients in transport. The most important results to note between the two sets of results is the similar shape of the *Base Case* result curves which implies that further behaviour of the system may differ in magnitude but overall patterns should be valid from the discussion and results presented in the following three chapters. The *No Reef* case however switches from a decreasing trend in transport under the initial test runs to an increase in transport under the re-run cases. This result presents evidence that maybe trends will change thus reinforcing the recommendation that all results be re-run should this study be continued.

The effects of the headlands and reefs are clearly seen with the sawtooth shape in the *No Reef* and *Base Case* transports. The *Longshore Uniform* and *Longshore Uniform Fringing Reef* *(G18r)* & *(G18ar)* all show the characteristic uniform transport rates that would be expected.

In terms of transport modes the *Longshore Uniform* is uninterrupted transport (U1); *No Reef* is difficult to define but could be considered either A1 or A3 at the headlands since there is no reef present and B1 transport within the bay; the *Longshore Uniform*

Fringing Reef cases are entirely deep bypass (A1). The *Base Case* transport at the headlands is split between deep bypass (A1) and over the reef (A2) at approximately 4:1 ratio with B1 transport in the bays. There was no A3 transport recorded in the *Base Case*.

6.2 Forcing Scenarios

The forcing scenarios examine the effects to changes in the incoming wave characteristics. Specific parameters tested were wave direction, significant wave height, and peak wave period.

6.2.1 Wave Direction *(runID# F01, F02, F03, F04)*

Four wave directions were tested; 270 (shore normal; *F01*), 275 *(F02)*, 285 *(F03)*, and 305 *(F04)* degrees. Results were consistent with expectations in that transport increased with angle of incidence. Figure 17 shows the daily transport calculated for the four cases. The undisturbed transport (U1) increased from 0 in the shore normal case to almost 750m^3/day in the case of 305 degrees showing that the transport rates are sensitive to the angle of wave incidence.

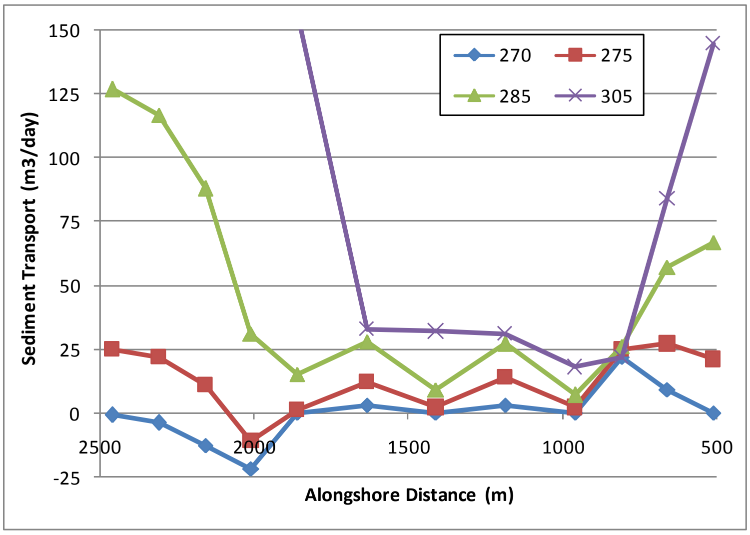

Figure 17 – Longshore Transport Rates of the Direction Scenarios

Beach Cell Response

The observed longshore response in the cells showed an increasing trend of transport to the south side of the cell which is expected as the sediment realigns to the incoming wave energy. For the shore normal case *(F01)* there is a significant reversal in transport at the north side of the first cell which is a result of the mass flux from the incoming waves forming a diverging current at the headland/reef. This trend of a current reversal at the north side of the headland/reef is present in all the cases but the magnitude decreases rapidly with increasing angle of wave incidence and is no longer significant in the large scale transport from the 285degree case. However, the current reversal remains as a small eddy present on the north side of the reef in all the cases as is clearly seen in the plot of depth averaged velocity. This eddy can be confirmed from personal experience as it is used to assist with paddling out to the surf breaks on the north west corners of the reef. The overall rate of increase of transport in the bay (B1) decreases as the wave angle increases which can be explained by the increasing shadow zone on the leeward side of the reef.

The observed cross shore response was limited to within the beach cell and showed the development of rip currents similar to those described in the *Mechanisms and Processes* section. These rip currents (R1) were best developed and symmetrical for the shore normal case as would be expected and then broke down as the angle of wave incidence increased. In terms of transport these currents moved sediment offshore which is then deposited in deeper water as the transport capacity decreases. In the shore normal case the sediment deposits were in the centre of the bay and then as the angle of wave incidence increased the deposits slowly migrated to the south. Sediment transport at the southern side of the bay is directed offshore in all cases while the cross shore transport at the north side of the bay is offshore for the shore normal case and then slowly switches to onshore by the extreme 305deg case. It is difficult to quantify exactly the contribution from rip current induced transport (R1) versus the natural profile realignment to storm waves (X1) or any loss over the reef (X2) as they all merge with each other.

Maximum depth averaged velocities ranged from 0.4m/s for the shore normal case to 0.55m/s in the 305 degree case. The maximum velocities are always located at the reef/sand interface where the wave induced currents are located. In the 305degree case there is a shift of the maximum velocity to the outer edge of the reef.

Beach Cell Interaction

In the shore normal case the system response is almost perfectly symmetric as would be expected and therefore there is no interaction between adjacent cells (A1, A2=0). As the angle of wave incidence increases there is an increasing amount of bypass between the cells. For the 285deg and 305deg cases there is a significant longshore transport that is blocked by the first reef. With increasing wave angle the differences in transport between the cells (A1, A2) versus within the cells (B1) reduces. In the case of 305deg almost constant transport rates are observed over the reef and bay (A1+A2~=B1) (constant transport in Figure 17) while the 285deg case still has clearly defined differenced in transport within the bay (B1) greater than bypass at the headlands (A1, A2) (sawtooth shape in Figure 17). Bypass will level out at some point as it cannot increase indefinitely but at a greater angle than tested.

Figure 18 shows the trends of transport within the cell and bypass between the cells. The graph shows that while both transports are increasing, the transport within the bay (B1) appears to be approaching a plateau while the transport at the headlands (A1, A2, A3) shows and increasing rate over the range tested. As mentioned previously this behavior is due to the increased shadow zone on the leeward side of the reef with large angles of incidence which allows headlands to be exposed to full wave energy while the bays are partially sheltered.

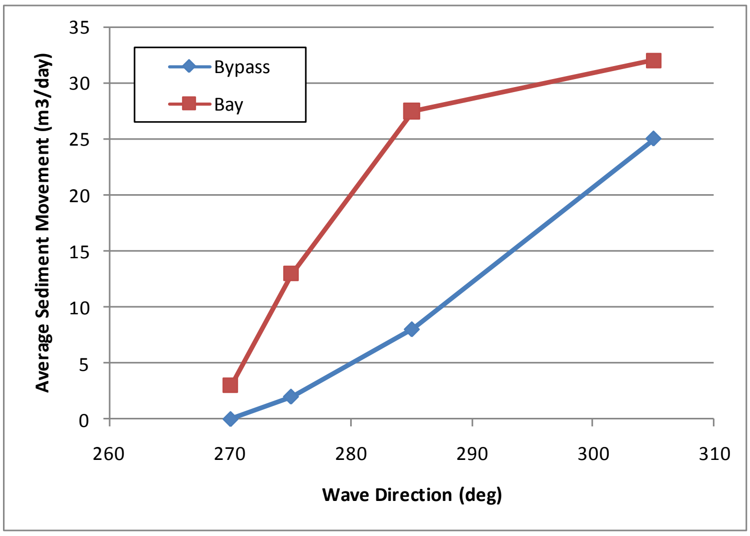

Figure 18 - Longshore Transport Trends of the Direction Scenarios

In the untested scenario where there are waves from the south the sand will move in the opposite direction, realigning the beach to the north side of the cell. This process would help to act as a buffer to bypass as realignment will need to occur before the bypass is initiated and therefore will have implications on the equilibrium profile of the cell.

U2 transport recovered to 25-100% of U1 transport over the test cases at a distance of 450m downdrift of the centre line of the southern reef. Recovery takes place slower (a longer distance downdrift) under the larger wave angles as would be expected from the increased shadow zone behind the reef.

6.2.2 Significant Wave Height *(runID# F03, F05, F06, F07, F07b, F08)*

The significant wave height is perhaps the most obvious factor affecting the magnitude of the transport. Six significant wave heights were tested: 0.25m *(F05)*, 0.5m *(F06)*, 0.75m *(F07b)*, 1.0m *(F03)*, 1.5m *(F07)*, and 2.0m *(F08)*. Figure 19 shows two graphs with the one on the left showing daily transport and the one on the right showing the normalized transport of the 1.0, 1.5, and 2.0m waves. The undisturbed transport (U1) increased from effectively 0 in the 0.25m case to just over 750m^3/day in the case with 2.0m waves.

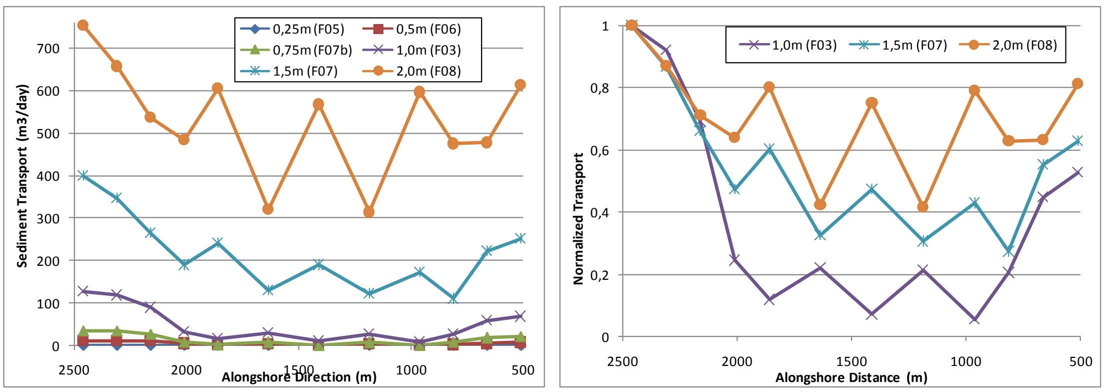

Figure 19 - Longshore Transport (Gross and Normalized) of the Significant Wave Height Scenarios

<u>Beach Cell Response</u>

The response within the cell is consistent with expectations with effectively no movement under 0.25m wave and maximum movement under 2.0m waves. The patterns are similar to those observed before with longshore transport from the north to the south side of the bay (B1) and with cross shore movement onshore at the northern side of the bay and offshore at the southern side of the bay (X1, X2, R1). Cross shore movement extends a significant distance offshore under the larger wave conditions with sediment moving out of the cells.

Not only does the magnitude of transport increase rapidly with wave height but the proportion of transport within the bay relative to undisturbed transport increases significantly. The graph of normalized transport only includes the three cases where bypass occurred and shows that in the case of 1.0m waves, the transport in the bay is around 20% of the undisturbed transport. In the case of the 2.0m waves however, the transport past the reefs is almost 40% of the undisturbed transport showing that the reefs are becoming less effective at sheltering the bay from the incoming wave energy with larger waves.

The direction of the sawtooth in the graph changes between the 1.0m and the 1.5m wave cases. This change means that under the 1.0m waves there is a higher proportion of transport in the bay than at the headland (B1>A1+A2+A3) while in the 1.5m and larger cases the converse is true with transport at the headlands higher than that observed in the bays(A1+A2+A3>B1). This has important consequences for the sediment balance and sedimentation patterns of the bays. While the B1 transport is greater than the A1+A2+A3 the bay is rotating clockwise around the centre of the bay (greater beach width in the south and narrower in the north) while when the B1 transport is less than the A1+A2+A3 the opposite rotation is occurring. Effectively under large waves the system is rotating against the direction that would be expected under conventional sediment dynamic theory. However, the most significant bed level changes associated with this rotation appear to occur in the nearshore zone so the rotation may not be clearly visible to a beach user or in historic photos.

As a result of these changed transport rates the sedimentation and erosion patterns change. In the cases with the smaller waves the sediment deposits are generally seen on the north side of the reef where the transport within the bay is decreasing as it makes its way around the headland/reef. However, in the case with the larger waves where transport around the reef is higher than in the bay the deposits shift and are seen on the south side of the reef.

These two different areas of deposition under different wave conditions are a significant result as they show that under smaller waves the sediments in the bays are moved to the south side and then relatively rapidly during storm events these deposits are moved around the headland/reef into the next bay and deposited in the shadow of the reef. These deposits may then work their way back onshore due to the cross shore processes which are almost always onshore directed in that location.

Depth averaged velocities range from zero under the smallest wave forcing to 0.7m/s under the 2m wave scenario. The patterns are consistent with the base case but increase in magnitude and the distance they extend offshore as the wave heights are increased.

Beach Cell Interaction

The threshold for transport between these cells occurs somewhere between 0.75m and 1.0m. Under this threshold the bay acts as an enclosed system as described by Bird (1977, 1979) while above this threshold there is interaction and exchange of sediment between adjacent cells. Similar to the response observed in the bay, the proportion of transport past the reef increases with increasing wave height. At the near threshold case of 1.0m wave the bypass is about 10% of the undisturbed transport which increases to 80% in the case of 2.0m waves. Figure 20 shows the trends observed in the transport rates within the bay and the amount bypassing the reefs.

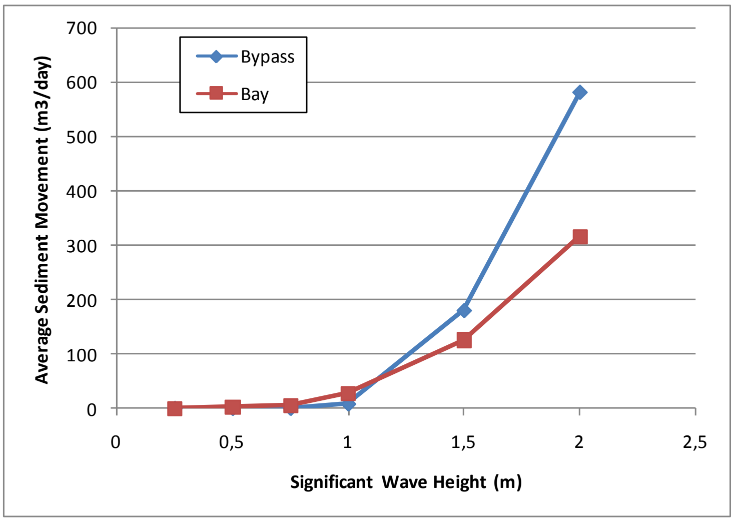

Figure 20 - Longshore Transport Trends of the Significant Wave Height Scenarios

Both the transport in the bay and the bypass past the reef show increasing trends and these results are consistent with expectations. The transport in the bay (B1) is initiated at a lower wave height than the transport at the headland (A1, A2) but the rate of transport at the headland increases faster with the transition from B1 dominant to A1+A2 dominant transport occurring between wave heights of 1.0m and 1.5m. Sand in the bay will be mobile under smaller waves as it is available for transport at shallower water depths than at the reef. At the reef there is a threshold depth before the sediment transport initiates which explains why the transport is initially higher in the bays (under smaller waves). As the waves increase the intensity of breaking at the reef increases significantly while the intensity breaking inside the bay also increase but at a slower rate due to sheltering and diffraction effects. The increased wave heights are visible on the north west corners of the reef in the significant wave height plots of the model reports for these cases. These processes explain why the transport at the headlands increases (A1+A2) at a faster rate than the transport in the bays (B1) as seen in the graph in Figure 20.

The point where the lines in the graph in Figure 20 cross is the point where the rotation of the bay switches; clockwise under the smaller waves and anticlockwise under larger waves.

U2 transport had recovered 55-80% over the test cases at a distance of 450m downdrift of the centre line of the southern reef. Recovery took place faster (shorter distance downdrift) under the higher wave conditions.

6.2.3 Peak Period *(runID# F03, F09, F10, F11, F12)*

The period of the wave was varied with constant wave height to change the steepness of the incident waves. Shorter periods result in each individual wave having less energy but waves arrive more frequently while longer period waves have higher energy per wave but arrive less frequently. These differences in the incident energy profile have impacts on the transport. The five cases tested were 6s *(F09)*, 8s *(F10)*, 10s *(F03)*, 12s *(F11)*, and 14s *(F12)*. Figure 21 shows the daily transport and the normalized transport associated with these test cases. It is interesting to note that the undisturbed transport (U1) actually decreases with increasing wave period from about

170m^3/day with the short periods to 80m^3/day with the long periods. This may be explained by the longer settling period between waves thus allowing particles to settle before the next wave impact rather than be advected with the currents.

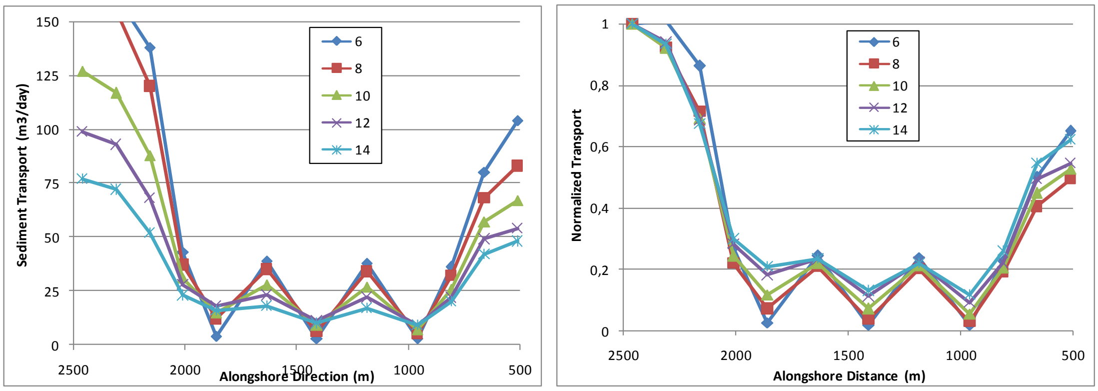

Figure 21 - Longshore Transport (Gross and Normalized) of the Peak Period Scenarios

<u>Beach Cell Response</u>

The response in the cell is similar to the response of the undisturbed transport with a reduction in transport with longer period waves. Normalized transport shows that there is more transport at the headlands (A1, A2) with the longer period waves. Transport proportions range from close to 0 in the 6s case to around 15% in the 14s case while the normalized transport in the bay (B1) remains constant around 20% The differences observed here are not as pronounced as with some of the other forcing parameters.

Cross shore processes (X1, X2, R1) are similar to those seen before with onshore flux at the north side of the bay and offshore at the south side. In this case the cross shore processes occur within 225m of the bayhead shoreline.

Bed level changes are most significant under the small period waves and follow the patterns of the *<u>Base Case</u>*. Changes range from +/-0.2m under the long (14s) period waves to +/-0.5m under the short (6s) period waves. Scour holes on the south sides of the reefs and deposits on the northern outer corner are observed in each case.

Current velocities peak around 0.4m/s in all cases and the patterns are consistent with the *<u>Base Case</u>*.

Beach Cell Interaction

The bypass magnitudes fall into quite a small range with longer period waves showing a slight increase in the transport from 3m^3/day with 6s period to 9m^3/day with 14s period.. Figure 22 shows the trends in transport.

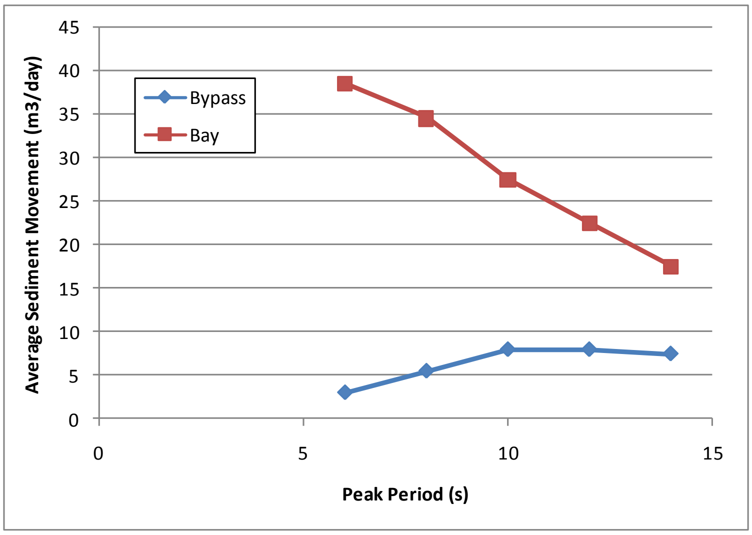

Figure 22 - Longshore Transport Trends of the Peak Period Scenarios

An interesting result is the apparent opposite trends between the beach cell response and the beach cell interaction in that longer period waves move less sand in the bays (B1) but more at the headlands (A1+A2). It is thought that this results is due to the changing breaker type at the reef face as described by Young (1989). Larger waves will also have a higher instantaneous mass flux when the wave breaks and therefore is capable of moving a greater amount of sediment.

U2 transport had recovered 55-60% over the test cases at a distance of 450m downdrift of the centre line of the southern reef. Recovery took place slightly faster (shorter distance downdrift) under the longer period wave conditions.

6.3 Geometry Scenarios

The geometry of the beach cells was of high interest to the author for two main reasons. The first reason was that the rough geometry is quite easy to obtain even from a GoogleEarth image and yet it is important to the magnitudes of transport. Secondly is that due to the significant effect the geometry has on the system it provides a potential method to address erosion and other coastal problems without the use of classical breakwaters and revetments which are often undesirable to recreational beach users.

6.3.1 Bay Size *(runID# F03, G01, G03)*

The size of the bay will affect how much the system is able to revert to uninterrupted conditions before being affected by the next headland. Larger bays will allow for more return to uninterrupted behavior in the bay while small closely spaced bays will have significant effects on each other. Three cases were tested with bays spaced at 300m *(G01)*, 450m *(F03)*, and 600m *(G03)*. Uninterrupted transports (U1) were all on the order of 125m^3/day as observed from the *Base Case*. Figure 23 shows the daily transport under these three bay size scenarios. Note that the bays are difference sizes so the peaks and low points in the characteristic sawtooh shape occur at different distances alongshore.

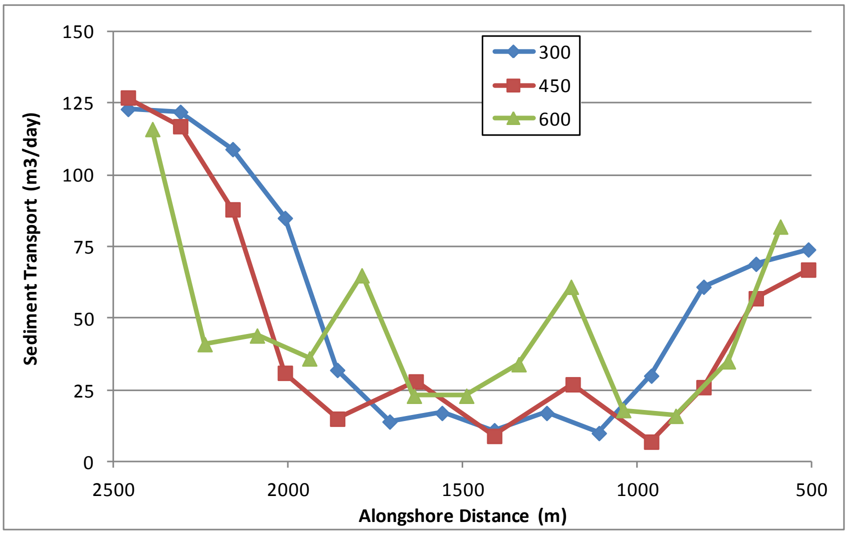

Figure 23 - Longshore Transport Rates of the Bay Size Scenarios

Beach Cell Response

The three scenarios all show the same characteristic behavior with the amount of transport within the bay (B1) increasing with bay size. This result is expected as the sheltering effect of the reefs decreases in the larger bays and the transport is able to increase towards the uninterrupted rates. The *Longshore Uniform* case can be considered a case of an infinite bay while the case of the *Longshore Uniform Fringing*

Reef may be considered a case of zero bay size which provide information to help develop a transport rate curve.

Cross shore transport is consistent with previous results with onshore flux at the north side of the bay and offshore at the centre and south side. The magnitude of the transport show an increase with the size of the bay.

Sedimentation and erosion patterns show some changes between the three test scenarios. In the case of the 300m bays *(G01)* there is dominant erosion in the bay with sedimentation taking place on the north west corner of the reef. As the bay size increases to 450m *(F03)* there are section of erosion due to scour channels on the north side of the bay and to a lesser degree the sound side of the bay but with a distinct sediment deposit in the centre of the bay and again on the north west corner of the headland and reef. In the case of the 600m bays *(G03)* the patterns are similar to the 450m bays *(F03)* just of greater magnitude.

Depth averaged velocities peak around 0.4m/s with the patterns of all three cases following those of the *Base Case*.

Beach Cell Interaction

The transport data indicated that as the size of the bay increases so does the rate of bypass (A1+A2). This may be explained by the longshore currents having more time to develop and then having extra momentum which upon meeting a reef will result in offshore currents which will help to move sediment around the reef to the next bay. This effect is seen on almost all of the model runs where the first (northern) of the three reefs always exhibits a higher bypass than the following two reefs due to its role in interrupting the undisturbed longshore transport that has developed. Figure 24 shows the trends in transport in the bays and bypass at the reefs for these cases. The values from the *Longshore Uniform Fringing Reef* case were added as a bay size of zero to get intercept points for the curves.

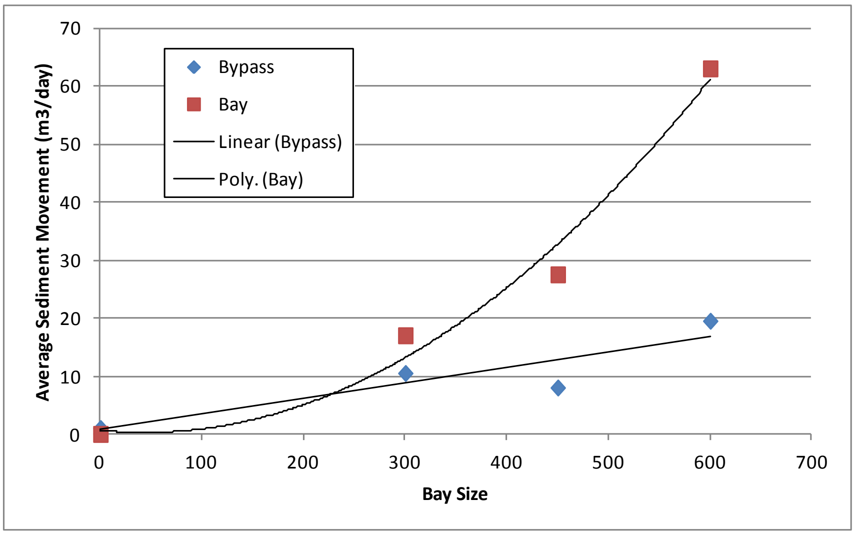

Figure 24 - Longshore Transport Trends of the Bay Size Scenarios

The transport in the bay showed a non linear increase and a second order polynomial trend line was fitted. The gradient of this line however will decrease at some point and the transport will reach a constant value as represented by the *Longshore Uniform* case. The point at which this constant transport will occur was not determined and therefore the data points were not included in the graph. The bypass at the headland/reef appeared to follow a linear increasing trend which will also reach a constant value at a given bay size. Similarly the exact point at which the transport reaches steady state was not determined and therefore the data points were not included in the graph.

U2 transport had recovered 50-70% over the test cases but downdrift distances where the measurements were taken varied but recovery rates appear to be somewhat similar over the bay sizes with a slight increase seen in the larger bays.

6.3.2 Bay Ratio *(runID# F03, G05, G06, G07)*

The bay ratio looks at the effects of the planform of the bay. In a bay that extends further inland it is expected that there will be less transport than in a bay that is more exposed. Four cases were tested with cross shore bay dimensions of 40m *(G05)* 60m *(F03)*, 90m *(G06)*, and 115m *(G07)*. Uninterrupted transport (U1) for all four cases was on the order of 125m^3/day, consistent with the *Base Case*. Figure 25 shows a graph of the daily transport over the four cases.

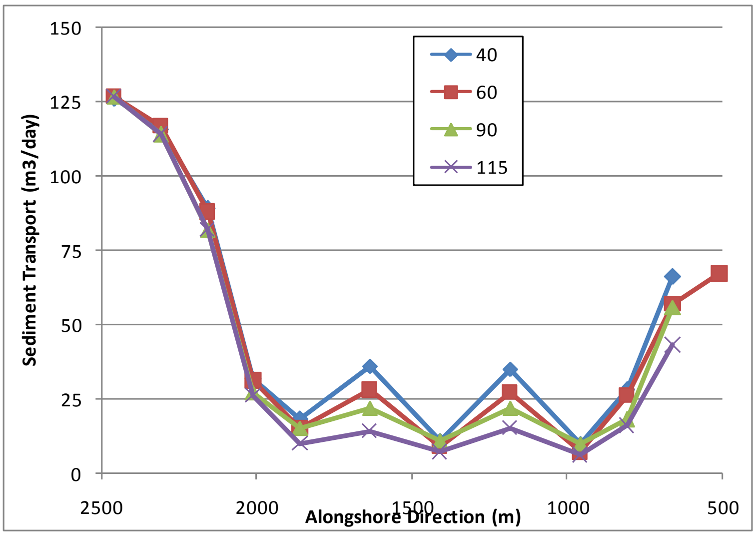

Figure 25 - Longshore Transport Rates of the Bay Ratio Scenarios

<u>Beach Cell Response</u>

Longshore transport within the cells (B1) showed a decreasing trend as was expected due to the higher sheltering effects associated with more inland bays.

Cross shore trends are similar to those seem consistently throughout the project with onshore flux at the north side of the bay and offshore at the south side.

Sedimentation and erosion patterns are similar over the four cases with sand movement from the north to the south sides of the bay and scour channels developing where mass flux induced currents exit the reef.

Depth averaged velocities peaked around 0.4m/s consistent with the *<u>Base Case</u>*.

<u>Beach Cell Interaction</u>

The trend for bypassing at the reef (A1+A2) was not well defined but appeared to have a slightly decreasing trend which is what would be expected as the reefs extend into deeper water and thus transport capacity around the reef is reduced.

Figure 26 shows the trends in transport measured over these four cases both within the bay and the bypass at the reef.

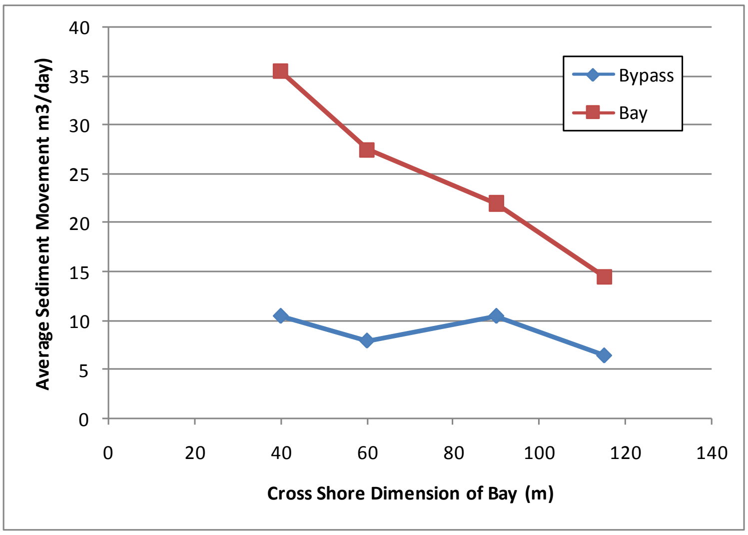

Figure 26 - Longshore Transport Trends of the Bay Ratio Scenarios

U2 transport had recovered 35-55% over the test cases at a distance of 450m downdrift of the centre line of the southern reef. Recovery took place faster (shorter distance downdrift) under the smaller bay ratios (more exposed shoreline) which would be expected.

6.3.3 Reef Size *(runID# F03, F07, G08, G09, G10, G08a, G09a, G10a)*

In some places the reefs are quite extensive between the bays while in other places the reefs are quite small. Larger reefs will have large effects on disrupting the transport while smaller reefs will have less of an effect. Eight cases were tested for under the *Reef Size* scenarios. The reef sizes have been referred to by their longshore dimension while the ratio (longshore:cross shore) is held constant. The four initial cases are 100m *(G10)*, 200m *(F03)*, 300m *(G09)*, and 400m *(G08)*. However to gain further insight the same geometries were run with larger waves (H_s 1.5m, T_p 12s) resulting in four extra cases of *G10a*, *F07*, *G09a*, and *G08a* corresponding to the respective previous cases with 1.0m waves. Uninterrupted transport (U1) rates ranged from 125-132m^3/day under 1.0m waves and from 387-516m^3/day under 1.5m waves. Figure 27 shows a graph of the normalized transport rates for these 8 cases.

Beach Cell Response

The longshore transport in the bay (B1) decreases as the reef size increases which is consistent with expectations as a larger reef will have a greater sheltering effect on the bays than a smaller reef.

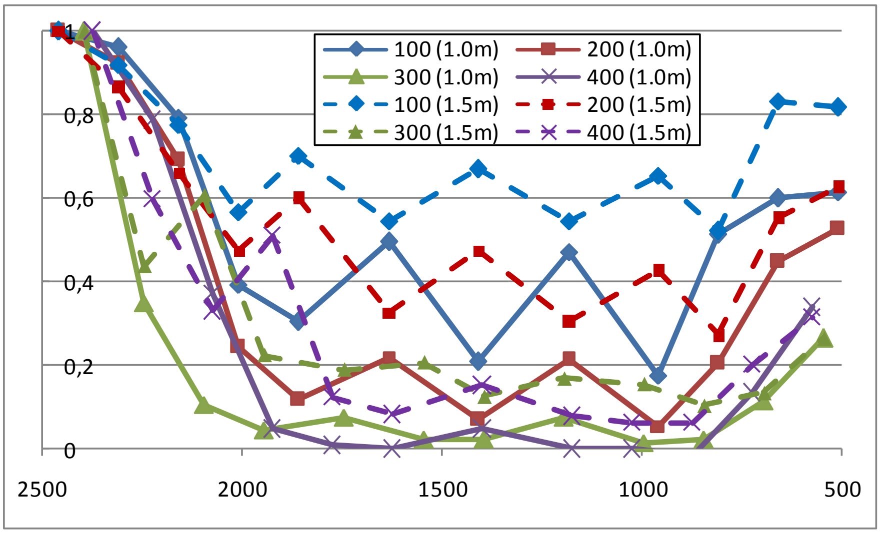

Figure 27 - Longshore Transport Rates of the Reef Size Scenarios

The *Reef Size* was one of the few test cases that altered the cross shore transport patterns. The smaller reef sizes (100m, 200m) were consistent with the general pattern of onshore flux at the north side of the bay and offshore at the south side of the bay while the larger bays (300m, 400m) tended towards offshore flux at both the north and south side of the bay, similar to a pure rip current (R1) situation.

In the case of the smallest (100m) reef there was significant erosion on the shoreward side of the reef (A3) as the reef is below the threshold to dissipate the wave energy before it reaches the shore. The other three cases with larger reefs were all of sufficient width to dissipate all energy before it reaches the shore and therefore there is no erosion of the headland behind the reef (A3=0). In general erosion decreased in magnitude as the size of the reef, and its associated sheltering effects, increase. Patterns of sedimentation and erosion generally followed those observed in the *Base Case* with the addition of a sediment deposit on the outer edge of the two larger reefs (300m, 400m) as the transport capacity (A1) decreased along the length of the reef. Some of this sediment is brought back onshore over the reef by cross shore flux (-X2).

Depth averaged velocities increased slightly as the reef size decreased, peaking around 0.5m/s. The patterns of the currents also changed with the two smaller reefs showing similar characteristics to the *Base Case* while the larger two reefs tended towards the rip currents seen in the shore normal and 275degree *Wave Direction* cases; very low velocities at the centre of the bay near the shoreline but with offshore directed currents from the middle of the bay and skewed to the south. Under the larger wave forcing (1.5m) the velocities peaked around 0.7m/s.

Beach Cell Interaction

Larger reef size leads to reduced bypass (A1+A2+A3). The mode of transport changes over these test cases. For the 100m reef the transport is entirely outside the reef (A1), for the 200m reef it is split between outside (A1) and over the reef (A2), for the 300m case it is dominant outside the reef (A1) and then there is divergent transport on the reef itself (+/- A2) while in the 400m case there is no bypass either outside or over the reef (A1=A2=0)

The result from the previous section is important to explain the interaction behavior of these cells; identifying that the smaller waves/larger reefs build up deposits on the downdrift side of bays and then during storm events these deposits are transported around the headland/reef sections to adjoining bays.

In the cases with the larger reefs a decreasing transport outside the reefs (A1) was observed which leads to sedimentation outside the reef. However examination of the cross shore transport shows that much of the sediment is transported onshore over the reef (X2) and then a divergent transport gradient from the centre of the reef either transports the sediment north (-A2) to the previous bay or south (+A2) to the next bay. However, the shore normal channels in the reef which were omitted from the model may have an effect on this behaviour and their effects should be confirmed to validate this transport pathway. Figure 28 shows the trends in transport over the 8 test cases both within the bay and at the headland/reef.

In all the test cases the transport appears to be non-linearly correlated with the reef size; an increase in the reef size leading to a reduction in the transport. Under the smaller (1.0m) waves the transport in the bay is higher than at the headland/reef while under the larger (1.5m) waves this trend inverts for the two smaller reef cases (100m, 200m). These results show that the size of the reef has a greater effect on the transport at the headland/reef than in the bay but also shows once again that the waves play a significant role in the mode and magnitudes of transport. The shape of the reef also has significant effects on the cross shore transports observed in the system.

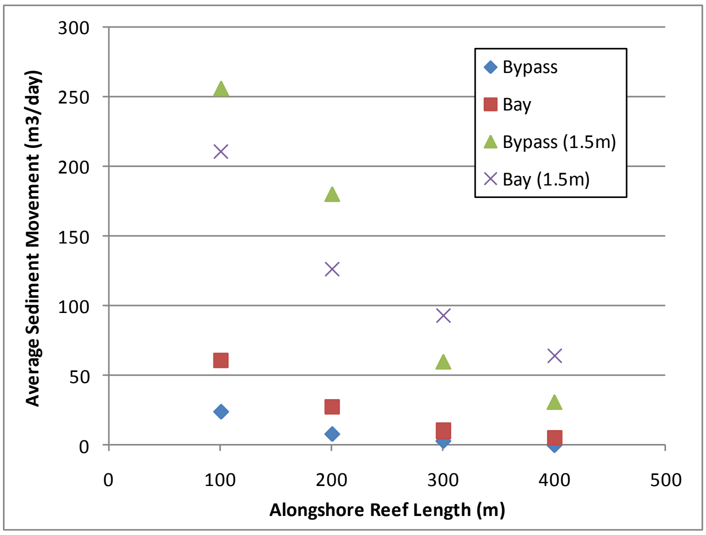

Figure 28 - Longshore Transport Trends of the Reef Size Scenarios

U2 transport had recovered 25-80% over the test cases but downdrift distances where the measurements were taken varied. Recovery took place faster (shorter distance downdrift) with the smaller reef cases which would be expected as the shadow zone is smaller.

6.3.4 Reef Ratio *(runID# F03, G11, G12, G13)*

The reef ratio looks at the effects of the planform of the reef. With a reef that extends further offshore it is expected that there will be less transport than in a bay that is more exposed. Four cases were tested with cross shore reef dimensions of 65m *(G13)* 100m *(F03)*, 200m *(G12)*, and 300m *(G11)*. Uninterrupted transport for all four cases was on the order of 125m^3/day, consistent with the *Base Case*. Figure 29 shows a graph of the daily transport over the four cases.

Beach Cell Response

The longshore transport in the bay (B1) increases with the smaller reef sizes. This result is expected as a longer reef in the cross shore direction will have a greater sheltering effect on the bay. A very long reef acts as a large groyne with much the same effects.

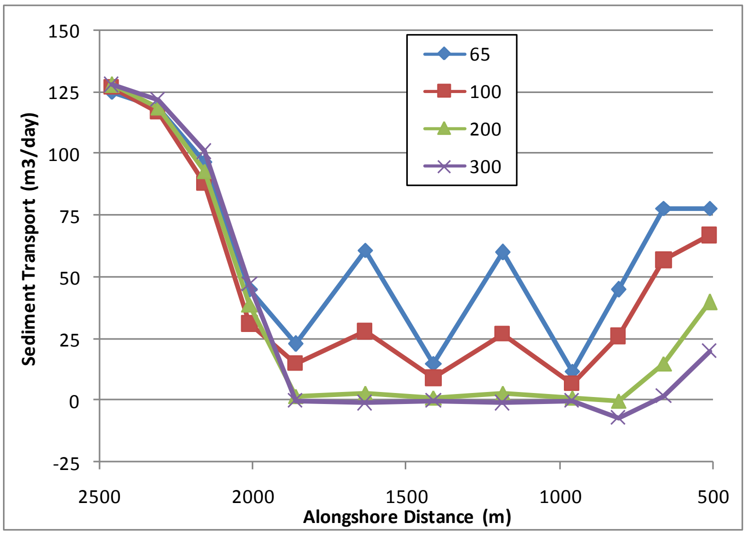

Figure 29 - Longshore Transport Rates of the Reef Ratio Scenarios

Cross shore response for the two smaller cases (65m, 100m) are similar to previous results with onshore flux at the north and offshore at the south side of the cell. In the two cases with larger reefs (200m, 300m) the crosshore transport is less well defined with converging transports at the north side of the cell; offshore near the shoreline (X1) and onshore at the offshore side of the reef (R1). On the south side of the cell the transports are again similar to previous results and consistently offshore directed.

In terms of sedimentation and erosion very little bed level change is observed in the two cases with larger reefs (200m, 300m) which is likely due to the offshore edge of the reef being beyond the depth of closure and the sediment in the bay being strongly sheltered by the reefs. In the two cases with smaller reefs (65m, 100m) the typical small wave sedimentation patterns are observed with deposits on the north side of the reefs and a movement of sediment in the bay from the north to the south.

Depth averaged velocities decrease with the larger reefs. In the case of the 300m reef the current velocities do not exceed 0.25m/s while with the 65m reef case the velocities peak at 0.5m/s. Patterns are similar to those described in *Reef Size* with the smaller cases(65m, 100m) resembling the *Base Case* while the larger cases (200m, 300m) tend towards a south skewed rip current type pattern. This result is as a result of the reef acting as barriers to the flow so the currents in the bay must be directed offshore to balance the onshore flux from the waves over the reef.

Beach Cell Interaction

The bypass at the reef follows a strong trend with increasing bypass (A1+A2) associated with decreasing cross shore reef dimensions. In the 300m case there is no transport around the reef while in the 200m case the transport is starting to develop and then for the two smaller reef cases there is a well developed transport around the outside of the reef. As the cross shore size of the reef reduced so does the magnitude of the A2 transport as the cross section width gets narrower.

In the case of the smallest reef (65m) there is a reversal of transport over the reef itself (-A2) and to a very small degree on the shoreward edge of the reef (-A3). It is proposed that the reason for this reversal is that a small proportion of the sediment that is bypassing the reef (A1) is brought back onshore over the reef (-X2) and caught in the eddy at the north side which transports the sediment northwards (-B1) against the general direction of transport. Upon re-entering the bay this sediment then enters the main transport pathway again (+B1) and the loop restarts. This result means that although there is a measured reversal in transport it is part of a loop and therefore there is no net transport from the south cell to the north cell (A1+A2+A3>0). Figure 30 shows the trends in transport at the reef and within the bays for the different cross shore reef dimensions.

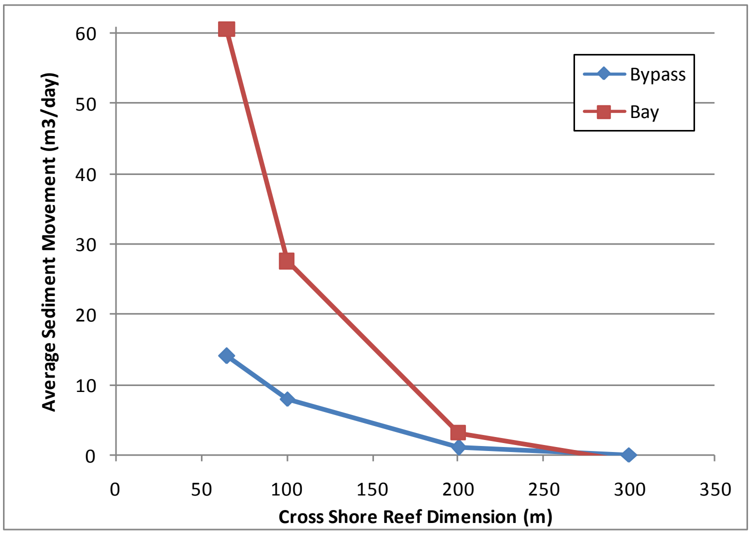

Figure 30 - Longshore Transport Trends of the Reef Ratios Scenarios

The graph shows the strong trend in the bypass (A1+A2+A3) but even stronger in this case is the trend in the bay (B1). As the bays become more exposed the transport rates increase significantly. Since transport in the bay is higher than transport around the reef there will be sedimentation in the south side of the bay.

U2 transport had recovered 15-60% over the test cases at a distance of 450m downdrift of the centre line of the southern reef. Recovery took place faster (shorter distance downdrift) under the smaller reef ratios (more exposed shoreline) which would be expected.

6.3.5 Asymmetry *(runID# G14, G15)*

In practice it is unlikely to find three similar beach cells in a row and therefore two asymmetric systems were tested. In some cases the behaviour of a cell may be affected by adjacent or farther cells. There are also significant implications for sedimentation and erosion patterns and changes in transport rates between the bays that may lead to some bays gaining sediment while others lose sediment. *G14* is a case of a large reef followed by progressively smaller ones while *G15* is a small reef followed by progressively larger ones. Uninterrupted transport (U1) rates were consistent with the base case of 125m^3/day. Figure 31 shows the daily transport for the two cases.

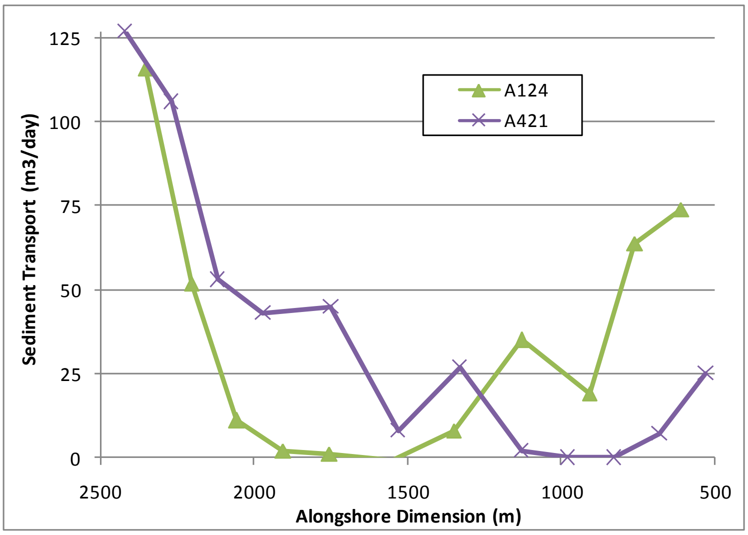

Figure 31 - Longshore Transport Rates of the Asymmetry Scenarios

Beach Cell Response

The results of these test runs did not show any unexpected behaviour. When a larger reef is updrift it will have a sheltering effect on the downdrift bay and the transports in the bay (B1) are reduced. Conversely a smaller reef updrift will mean that the larger reef downdrift is more exposed and transport may increase.

In the test case *G14* there was actually a reversal of transport in the bay (-B1) between the 400m and 200m reefs. This was the only case of all the test scenarios where there was a net reversal of transport in the bay.

In the test case *G15* it can be seen that a larger downdrift reef can also reduce the gross transport in the bay (B1) which appears to be a results of the reduced bypass (A1+A2) around the larger reef. In case *G15* in the first cell the B1 transport is $45m^3$/day with $8m^3$/day bypassing (A1+A2) the 200m reef to the next cell. In the case with only 100m reefs *(G10)* the B1 transport in the first cell is $62m^3$/day but with $26m^3$/day bypassing (A1+A2) the downdrift reef into the next cell. In both cases the net transport within the cell is almost the same at 37 & $36m^3$/day respectively. This is an important result showing that due to asymmetry the gross transports may change but that net transports may be on the same order of magnitude. This result is not necessarily applicable to all asymmetry cases and would need to be further investigated.

Sedimentation magnitudes are significantly reduced in the *G14* case as the first large reef shelters the smaller downdrift ones while the locations remain similar. In *G15* the sedimentation magnitudes are similar to those observed in the respective cases for each of the reef sizes showing that smaller updrift reefs have a lesser effect than a larger updrift reef.

Currents are low in the *G14* case due to sheltering while they peak on the order of 0.4m/s in the *G15* case which is consistent with previous results.

Beach Cell Interaction

The bypass rates of downdrift reefs were also affected as seen in case *G14* where the 200m reef affects the 100m reef. An A1+A2 bypass rate of $17m^3$/day was observed outside 100m reef which is a clear reduction from the 22-$26m^3$/day observed in test case *G10*.

One result that may be extended across all the cases is that when there is a larger reef updrift a bay will likely suffer a net loss of sediment, as seen in case *G14*, while conversely if the larger reef is on the downdrift side of the bay then there will be a net gain of sediment in the bay, as seen in case *G15*.

U2 transport recovered 20% in the case with increasing reef size *(G15)* while 65% recover was seen in the case of decreasing reef size *(G14)*. These large differences are largely due to the size of the last reef and its individual sheltering effects on the downdrift coastline; smaller reefs having less sheltering effect than larger ones and therefore allowing faster recovery towards uninterrupted longshore transport rates.

6.4 Miscellaneous Scenarios

6.4.1 Sediment Diameter *(runID# F03, F07, F07c, F07d, F18, F19)*

Analysis of the sensitivity of the system response to sediment diameter was determined to be important for two reasons. The first reason was that there was a very wide range of grain sizes measured in the field. The second reason is that beach nourishment is an increasingly popular option used for beach rehabilitation but it can often be difficult to find sources of nourishment sand with the exact properties as the in situ sand. Larger sediment will be more stable but will reduce exchange between bays while smaller sediment will become mobile more easily feeding other bays but may also be eroded faster than is desired. In addition to the runs with 1.0m waves a second set of model runs with 1.5m waves were tested to see how the response changed. Six runs are compared with wave height/d_{50} combinations of 1.0m/275µm *(F18)*, 1.0m/375µm *(F03)*, 1.0m/475µm *(F19)*, 1.5m/275µm *(F07c)*, 1.5m/375µm *(F07)*, 1.5m/475µm *(F07d)*.Figure 32 shows the graphs of the daily transport on the left and the normalized transport on the right. The solid lines represent the 1.0 wave heights while the dashed lines correspond to the 1.5m wave heights.

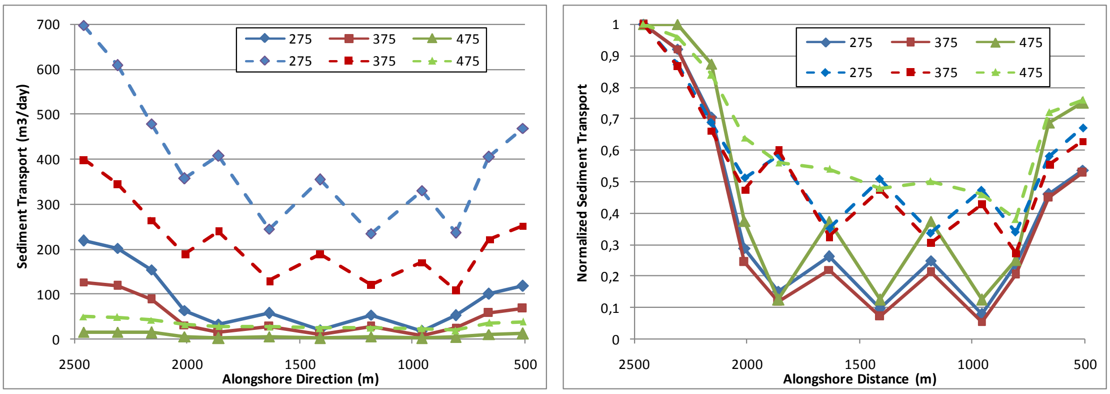

Figure 32 - Longshore Transport (Gross and Normalized) of the Sediment Diameter Scenarios

The uninterrupted transport (U1) has a wide range of values over these tests from 16m^3/day under 1.0m waves and 475μm sand to 697m^3/day under 1.5m and 275μm sand. These results illustrate that this is a sensitive parameter and care should be taken with its selection in any validation cases.

<u>Beach Cell Response</u>

As expected larger waves and smaller sediment diameter both lead to higher transports. Within the bay the longshore transports (B1) ranged from 6m^3/day under 1m/475μm to over 200m^3/day under the 1.5m/275μm case. The sediment transport in the bay increased almost 500% with a 50% increase in wave size (10x factor) while even more pronounced was the 1000% increase in transport with the 60% decrease in d_{50} (15x factor). This factor was observed over both wave heights tested.

Normalized transports showed similar proportions of transport for the 275μm and 375μm sediment but a deviation for the 457μm case where transport in the bay increased proportional to the transport over the rest of the domain. This results was the same for both wave heights tested.

It would appear upon initial inspection that the behaviour of the 475μm sediment under 1.5 waves is not following the sawtooth trend exhibited by the other test cases. However, it is believed that this case is just in the transition range where the transport at the headland (A1+A2) is overtaking the transport in the bay (B1) while the other cases are already distinctly in either the (B1>A1+A2) or (B1<A1+A2) regimes.

Cross shore patterns within the bay were consistent with other results with onshore flux at the north side of the bay and offshore at the south side. Magnitudes of transport followed the trend of the longshore transport with larger waves and smaller sediment diameters resulting in higher transport rates. In the cases of *F07* and *F07c* there was significant cross shore transport outside the cell but the onshore and offshore are on the same order of magnitude so the net loss from the cell is not expected to be significant.

Sedimentation and erosion patterns were similar to those observed in the *Base Case* with the magnitude varying depending on the sediment diameter; smaller diameter resulted in more extreme bed changes. Bed level changes ranged from +/-0.1m with the 475µm sand under both wave conditions to +/-0.5m with 275µm sand under both wave conditions. Similar to the results of the *Significant Wave Height* section the location of the sediment deposits switches from updrift of the reef under 1.0m wave to downdrift of the reef under the 1.5m waves. The sediment diameter is therefore important in the magnitude of the deposits but less so for the location.

The sediment diameter appears to have little effect on the depth averaged velocity. The current magnitudes and patterns from test cases with 1.0m waves closely resemble those from the *Base Case* while the test cases with 1.5m waves show the same patterns with higher magnitudes (similar to case *F07*).

Beach Cell Interaction

Similar to the transport within the bay (B1) higher waves and smaller sediments result in higher bypass rates (A1+A2). The graph of normalized transport shows that the normalized transport at the headland is effectively constant over the different sediment diameters. The dominant mode of transport at the headlands is bypass around the reef (A1) though transport over the reef itself (A2) becomes significant especially under large waves and fine sediments; at almost $60m^3$/day in the case of 1.5m/275µm the transport is significant The proportions however are approximately constant at 5 (A1) to 1 (A2) the reef. Transport inside of the reef (A3) was not observed.

It is also interesting to note that while the sediment diameter is responsible for a 1000% increase in transport over the range tested that the bypass with 1m/275μm is still less than with 1.5m/475μm. This outlines the importance of the depth at the outer edge of the reef as, even with fine sediments, bypass will be greatly reduced if the reef extends past the depth of closure of the system. The depth of closure will move onshore with an increase in sediment diameter and offshore with a decrease. Figure 33 shows the trends of transport in the bay and at the reef for these test runs.

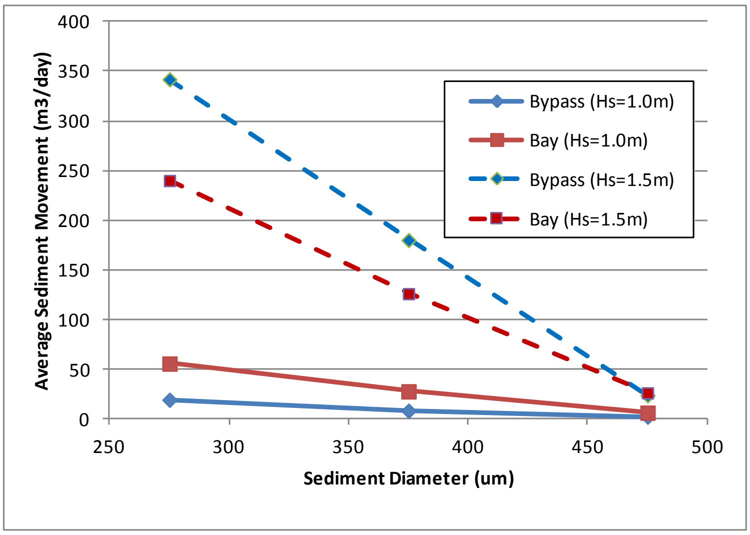

Figure 33 - Longshore Tranpsort Trends of the Sediment Diameter Scenarios

The slope of the lines increase with the increase in wave heights showing that the relative effects of the changes to sediment diameter become more pronounced at higher wave heights.

U2 transport recovered 50-75% over the test cases at a distance of 450m downdrift of the centre line of the southern reef. Recovery took place slightly faster (shorter distance downdrift) under the larger sediment diameters.

There was a concern as to the sediment supply due to the presence of coral rubble layer at a depth as shallow as 1.0m below the bed level. Based on the sedimentation and erosion patterns which did not exceed 1m bed level change the sediment supply is not a problem for the scenarios tested.

6.4.2 Sea Level *(runID# F03, F13, F14, F15, F16, F17)*

Sea level rise is a popular topic among scientists and engineers. The effects of sea level rise are in particular important for small islands as the affected areas may represent a large proportion of the total land area. The results from the sea level scenarios show that this interest is well placed as there is a significant effect on the transport observed in the system. Six test cases were examined with varying water levels of: +1.55m *(F13)*, +1.15m *(F14)*, +0.75m *(F15)*, +0.55 *(F16)*, 0.00m *(F03)*, -0.55 *(F17)*. Uninterrupted transport rates (U1) were consistent with the base case of 125m^3/day except for the case of -0.55m *(F17)* which showed a slight reduction to 111m^3/day as a consequence of the altered slope at the water/beach interface. Figure 34 shows the daily transports measured for these test cases.

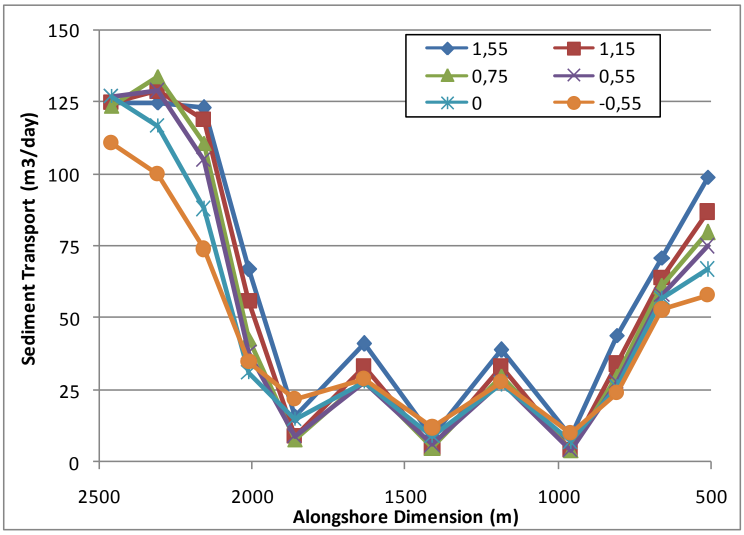

Figure 34 - Longshore Transport Rates of the Sea Level Scenarios

Beach Cell Response

The transport in the bays (B1) showed an interesting trend in that at low and high sea levels the rate was higher but there was an apparent decrease in transport around the mean sea level to high tide (+0.55m) level. This implies that there is an optimal sea level for minimum transport within the bay.

Cross shore transport patterns were similar to previous results with onshore flux at the north side of the bay and offshore at the south.

Sedimentation and erosion patterns show some significant changes over the test cases. With the highest sea levels the bed level changes tend to be focused along the shoreline and appear to be primarily profile realignment with the sediment being deposited within 50m of the shoreline. As the sea level rises the patterns tend towards the typical behaviour observed in previous results with sediment movement from the north to south of the bay and a deposit on the north west corner of the reef.

Depth averaged velocities increase with sea level rise likely as a result of higher wave transmission over the reefs which results in higher mass flux and the associated currents. Maximum current velocities ranged from 0.3-0.5m/s over the test cases.

Beach Cell Interaction

The beach cell interaction under these test cases showed the most interesting behaviour in terms of transport modes. Figure 35 shows a graph of the trends in transport in the bay and at the headlands. The graph shows that the bypass transport (A1+A2+A3) follows a trend similar to the B1 transport with a minimum transport occurring around high sea levels (+0.75 - +1.15m) and increased transport both below and above this range.

These results have some important implications. Further testing is necessary to confirm but it would appear that some amounts of sea level rise will actually result in reduction in transport between bays and therefore a more stable system. The problem with this situation is that even if the transport is reduced the location of the erosion shifts to the shoreface (A3 becomes significant).

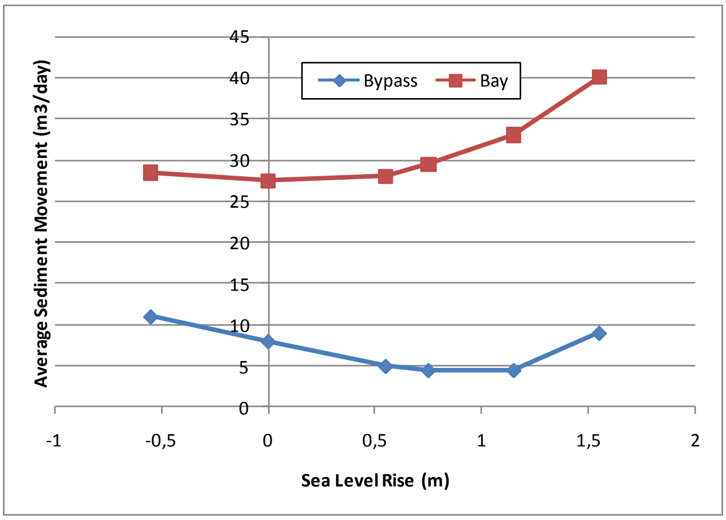

Figure 35 - Longshore Transport Trends of the Sea Level Scenarios

Despite the fact that the eroded sediment is deposited only a few metres offshore the public will only see the apparent "beach loss". This introduces the issue that, even though sea level rise may result in a more stable system overall, from a beach user perspective it is undesirable and there will be pressure on the authorities to combat the "beach loss". Figure 36 shows a graph of the total transport past the headlands and its three components (A1, A2, A3).

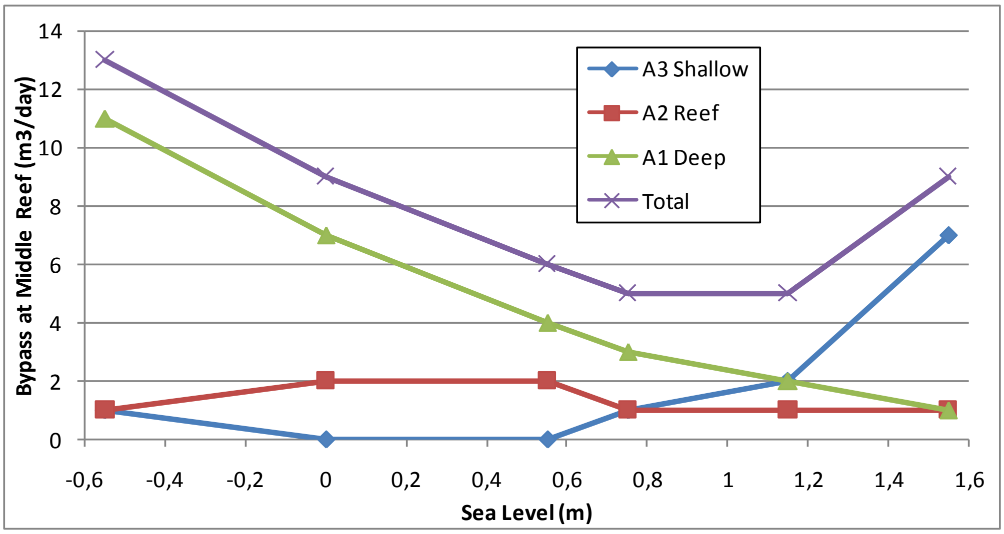

Figure 36 - Longshore Transport Trends (by mode) of the Sea Level Scenarios

An examination of the transport constituents shows that the mode of transport changes with the sea level. At very high sea levels the majority of the transport is taking place on the shoreward side of the reef (A3) while at low sea levels the bypassing around the outside of the reef is dominant (A1). These changes in mode are appropriate as at high sea levels more wave energy may propagate over the reef and impact the shoreline and therefore profile realignment (X1) will take place. At very low sea levels the depth of the sediment on the outside of the reef is reduced and there is increased transport via that pathway (A1).

The *F13* case with highest A3 transport bears some resemblance to the case of a submerged breakwater near to the shoreline as described by Ranasinghe (2010). Similar "two cell" current patterns develop with diverging transport at the headland resulting in erosion of the shoreline behind the breakwater. This result introduces the idea that the case of the reef moving relatively farther offshore (change in geometry or further increase in sea level) could result in different sedimentation patterns at the shoreline behind the reef such as 4-cell accretion though the changes would need to be quite extreme. Figure 37 shows a photo of the Holetown Walkway as the shoreline was before construction (left side) and post construction (right side).

Figure 37 - Holetown Walkway Pre and Post Construction

The Holetown Walkway is a project where a walkway was constructed shoreward of the reef as a result of reduced beach width behind the reef which prevented beach users from walking around the headland. It is not clear if this situation is an exact result of sea level rise and changes to the transport modes but results are expected to be similar.

U2 transport had recovered 50-80% over the test cases at a distance of 450m downdrift of the centre line of the southern reef. Recovery took place faster (shorter distance downdrift) under the higher water levels which would be expected as reefs will have a reduced sheltering effect on downdrift coastlines under higher water levels.

6.4.3 Reef Roughness *(runID# F03, F20, F21, F22)*

Reef roughness is often only used as a calibration parameter in models but in this modeling series it was used to simulate reef health with a rougher reef being a healthier one with more coral growth. It was also used to simulate the shore normal channels that are present in the reefs. Uninterrupted transports (U1) were all consistent with the base case and Figure 38 shows the transport rates over the remainder of the model domain.

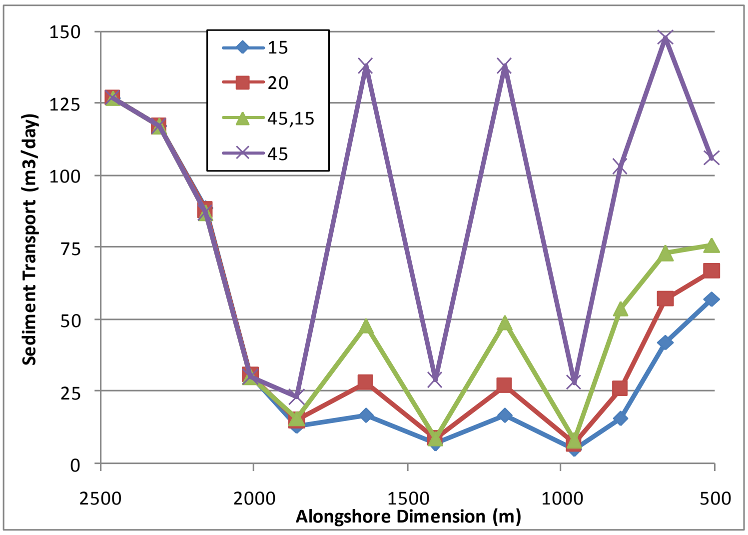

Figure 38 - Longshore Transport Rates of the Reef Roughness Scenarios

Beach Cell Response

The beach cell response is quite dependant on the reef roughness. The transport in the bay (B1) is very sensitive to changes in roughness with transport actually exceeding the uninterrupted transport in the case with Chézy coefficient of 45 *(F20)*. It should be noted however that the case with directional roughness {45,15} *(F22)* showed 65% reduction from the case of 45 only showing that the longshore roughness is extremely important for the amount of wave energy that is transmitted over the reef and incident in the down drift bay. This result confirms that the shore normal channels in the reef are significant and need to be accounted for in a full model of the system.

Cross shore transport patterns are largely unchanged from previous results.

Sedimentation and transport patterns are similar to previous results with movement to the south side of the bay and a sedimentation patch on the north west of the reef. The decrease in roughness (increase in Chezy Coefficient) results in larger deposits and erosion holes but in largely the same locations over the different test cases.

Depth averaged velocities have quite a large range over these cases with maximums on the order of 0.2m/s for the highest reef roughness (15) and 0.7m/s for the lowest reef roughness (45). This trend was expected but the magnitude of the change was higher than expected and shows that increases and decreases in the coral growth can have significant changes on the hydrodynamics of the system. The patterns of the currents however is unaffected and follows those established in the *Base Case*.

Beach Cell Interaction

The transport between the cells (A1+A2) also shows an increasing trend with increasing Chézy coefficient though less strong than the trend seen in the bay. As the Chézy coefficient increases (smoother reef) there is a higher proportion of transport over the reef itself. The change in mode shows that the roughness and by extension the health of the reef is important in determining the transport rates. Figure 39 shows the transport rates associated with the different reef roughness scenarios.

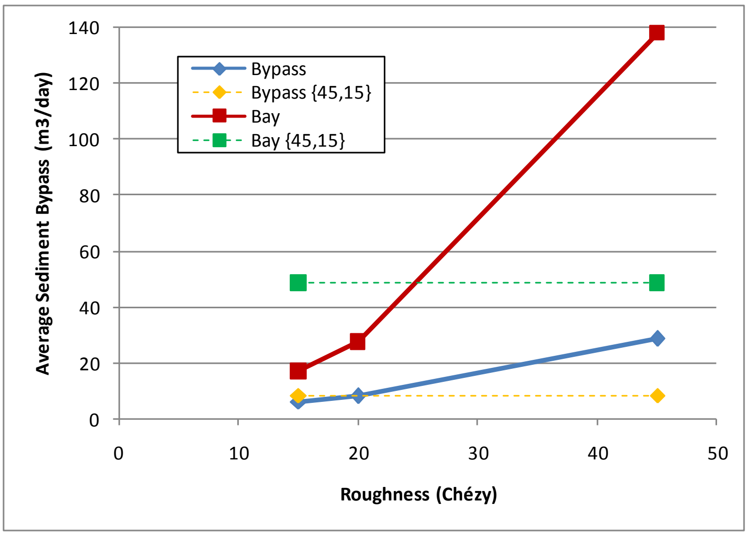

Figure 39 - Longshore Transport Trends of the Reef Roughness Scenarios

The graph shows that the transport in the case with differential reef roughness {45,15} lies between that of either 45 only or 15 only which is expected. The graph also shows that the slope of the transport trend in the bay is higher meaning that the reef roughess has a larger effect on the transport in the bay (B1) than it does at the reef itself (A2). This can be explained by the higher longshore currents which are allowed to develop under the less rough conditions and are seen clearly in the depth averaged velocity plots.

U2 transport had recovered 45-80% over the test cases at a distance of 450m downdrift of the centre line of the southern reef. Recovery took place faster (shorter distance downdrift) under the lower reef roughness levels (higher Chézy coefficient) which would be expected as reefs will have a reduced sheltering effect on downdrift coastlines under higher water levels.

7 Conclusions

The conclusions in this section are based upon the results from the initial test runs however the validity of these results was brought into question due to a modeling error. It is though that the overall trends will remain similar while magnitudes of transport increase but it has been recommended that the results be checked should this study be continued. Table 5 presents a brief summary of the relative effects of each parameter tested on the transport rates and the assigned sensitivity value of the parameters. A summary of the conclusions from the *Results and Discussion* section on each parameter is included after the table.

Wave Direction

The response of the system has a high sensitivity to wave direction. As the angle of incidence increases so does the transport at exposed sections of the coast. A counter process is the increasing shadow zone on the downdrift side of the reef which reduces wave energy reaching the shoreline in that region. These two effects result in a faster increase in rate of transport at the headlands than in the bays although for the range tested the transport in the bay was always higher.

Table 5 - Summary of Relative Effects of Test Parameters on the Different Transport Modes

Parameter		Relative Effect on Transport						Sensitivity
		U_1	A_1	A_2	A_3	B_1	U_2	
θ	↑	↑↑	↑	↑	Ø	↓	↓	High
H_s	↑	↑↑	↑↑	↑↑	Ø	↑	↑	High
T_p	↑	↓	↑	↑	Ø	↓	↑	Low
d_{50}	↑	↓↓	↓↓	↓↓	Ø	↓↓	↑	High
Bay Size	↑	Ø	↑	↑	Ø	↑	↑	Low
Bay Ratio	↑	Ø	↓	↓	Ø	↓	↓	Low
Reef Size	↑	Ø	↓	↓	↓	↓	↓	Med
Reef Ratio	↑	Ø	↓	↓	↓	↓	↓	Med
Asymmetry	↑	--	--	--	--	--	--	Med
Sea Level	↑	↑	↓	↑↓	↓↑	↓↑	↑	High
Reef Rgh	↑	Ø	↓	↓	Ø	↓	↓	Med

Ø no change, ↑ weak trend, ↑distinct trend, ↑↑ strong trend

Experiencing wave angles greater than those tested (305deg) is unlikely due to the effects of refraction and shoaling. An exception may be an extreme case such as a hurricane impact. Another possibility is waves from south which could act as buffer in the system moving sediment back to north side of the bay and changing equilibrium conditions.

The direction of cross shore transport at the north side of the bay changes with the angle of wave incidence, offshore under small angles and onshore under larger angles.

The eddy formed at the north side of the reef near the shoreline has been confirmed with personal experience of the author.

Significant Wave Height

The response of the system has a high sensitivity to wave direction. Larger waves lead to higher total and higher normalized transport with the threshold for sediment bypassing and interaction of the beach cells occurring around a significant wave height of 1m. This threshold for transport between the cells means that interactions take place during relative short discrete storm events where large transports may occur for a few days and then during the remainder of the time there is no interaction between the sediments of adjacent cells. The calm periods (H_s<1.0m) still affect the sediment within a bay and move them from the north to the south side of the bay.

Cross shore transports are of relatively high magnitude compared to other test scenarios but onshore and offshore rates balance each other so there is little net change in the sediment balance.

Peak Period

The response of the system has a low sensitivity to peak wave period. Trends were weak but longer period waves result in less transport in bay but higher transport at the headlands which is thought to be as a result of changes to the breaker type at the reef face. In general large long period swell waves are better than large short period hurricane waves for the system stability.

Sediment Diameter

The response of the system has a high sensitivity to sediment diameter. Sediment diameter is the most sensitive of the parameters tested illustrating that accurate sediment size definition is important in modeling. Over an order of magnitude difference in transport rates was observed between different sediment diameter scenarios.

The sensitivity to sediment diameter increases with increased wave height which can lead to very high changes in transport rates with relatively small changes to the two parameters.

Any plans for nourishment should be carefully considered as changes to sediment diameter will change transport rates and can move the depth of closure of the system which can have significant effects on transport patterns depending on the boundaries of the cell (reef and bay geometry).

Bay Size

The response of the system has a low sensitivity to bay size. The transports are higher with larger bays. There was a greater effect on the transport in the bay due to increased distances for longshore currents to develop towards the uninterrupted levels before being affected by the next reef.

Bay Ratio

The response of the system has a low sensitivity to bay ratio. Trends were weak but a decrease in transport rates with more sheltered bays was visible and is consistent with the behaviour that would be expected under those conditions. The effect on the bay response is more that at the headland/reef which is expected from the sheltering effects of longer headlands.

Reef Size

The response of the system has a medium sensitivity to reef size. Large reefs lead to less transport and higher sheltering effect at the bays while the converse is true for small reefs. Cross shore transport patterns change with larger reefs and tend towards the rip current style of transport. Higher current velocities are associated with smaller reefs as longshore currents are less disrupted. There are some small changes to mode of transport with some transport occurring shoreward of the smallest reef case. Transport shoreward of the reef becomes a significant issue as it governs public perception of the system and reduces the usable beach area.

Reef Ratio

The response of the system has a medium sensitivity to reef ratio. The reef ratio appears to have similar effects as reef size in terms of trends and patterns. Effects on transport are most pronounced in the bay due to sheltering effects of the reefs. These sheltering effects have implications for the equilibrium shapes of these bays.

The reversal of transport over the reef in the smallest case is likely from a closed loop and not actually a net transport from south cells to more northern cells.

Asymmetry

The response of the system has a medium sensitivity to asymmetry. A large reef may have an effect on the adjacent or farther reefs downdrift while smaller reefs tend to have reduced effects on their downdrift counterparts.

Changes in transport associated with different reef sizes leads to different sedimentation and erosion patterns and will have effects on the sediment balance in a bay. A bay will almost certainly have a higher amount of sediment under equilibrium conditions if the downdrift bay is larger than the updrift bay as sediment will be trapped much the same as it would updrift of a groyne. The converse will also be true.

Although based on limited results there was an interesting result with gross versus net transport where the gross transports varied depending on updrift conditions while the net transport remained constant. These results would need to be tested further before a definitive statement on that aspect of the behaviour can be made.

Sea Level

The response of the system has low sensitivity to sea level however, the mode of transport changes and therefore a sensitivity value of high was assigned overall. This change is to do with the public perception of what is occurring in the system. As transport and erosion shift to the shoreface with higher sea levels the effects become more visible to the public and the usable beach area may be reduced. Even though the overall changes to transport rates from a system perspective may be small the large effects to the visible beach area warrant a high importance/importance score for this parameter.

Sea level rise results in more transport on the inner edge if the reef while a lowering of sea level causes higher transport on the outer edge. The minimum total transport actually occurs in between the high and low test cases, at slightly higher levels than used for the base case (+0.75-+1.15m) implying an optimum sea level for minimum transport characteristic of each cell.

At the highest sea levels tested the system shows a response somewhat similar to the two-cell current patterns described by Ranasinghe for offshore submerged breakwaters with erosion of the shoreline behind the reef. This has implications in that if the behaviour resembles offshore submerged breakwaters in the range tested then maybe the similarities can be extended to further cases.

The Holetown walkway is not an exact case of response to impacts of sea level rise impacts but illustrates the type of behaviour and a common response that could be expected.

Reef Roughness

The response of the system has medium sensitivity to reef roughness which was used to gauge the effects of a healthy living reef versus a dead and eroding reef. Lower roughness results in higher transport which is partly due to higher wave transmission over the reef.

The overall bypass rates were relatively constant but a higher proportion takes place over the reef so the mode is changing. The case with different cross shore and longshore roughness was an attempt to test for the effects of the shore normal channels in reef but resulting effects were seen more prominently in the bay rather than the bypass at the reef illustrating that the channels may be important but not necessarily for the reasons initially considered.

General Conclusions

The general conclusions of this report are:

- The use of Delft3D is a valid approach to evaluate the sediment dynamics in this type of system.
- Significant wave height and incident wave direction are sensitive parameters while peak period is of lesser importance.
- Significant wave height plays a role in the direction of rotation of the bay with the rotation under large waves against the expected direction.
- Sediment size is the most sensitive parameter which has significant implications for nourishment projects.
- Cell geometry has a wide range of effects with reef characteristics more important that bay characteristics on the overall transports.
- Cell geometry is an area that may be modified to help provide solutions to erosion problems in the future.
- Sea level rise has a small effect on overall transport rates but due to the changing modes of transport and their associated public perceptions this parameter increases in perceived, and therefore assigned, sensitivity.
- There appears to be an optimum sea level associated with minimum transport which will be a unique characteristic of each individual reef.
- Coral reef health was simulated using reef roughness and was deemed to be of medium sensitivity.
- There may be optimum groups of conditions for the most desirable dynamic equilibrium of these systems.

8 Recommendations for Future Work

This topic was of high interest to the author but the scope was necessarily limited due to time constraints. This section provides some areas for future work and consideration should this research be continued.

Re-run Model Scenarios

Due to time constraints it was not possible to re-run all the test scenarios with diffraction switched off so the completion of these modeling scenarios would be necessary to confirm the results presented in this report are valid.

Model Validation

Most important would be an attempt to validate the model with field data. This was deemed to be difficult due to lack of historic data for comparison of model results to real cases.

Further Parameter Scenarios

For this report a selection of what were considered the most important parameters were tested but there are still many parameters that may have effects and can be tested. One case in particular is to extend the model to the types of beach cells seen on the south-east coast which are more classic vertical cliff face and pocket beach scenarios and to look at the system response in those cases.

Within these scenarios some combinations of extreme scenarios should be added to see what the compounded effects may be as simple addition of separate responses may not be valid.

Storm Sequence

The sequence of storm versus calm periods very likely plays an important role in the development of the equilibrium shapes of these beach cells and therefore will have effects on the transport rates. The model cases in this report were run for one constant wave condition but decay of swell both in terms of height and direction will have effects on where sediment deposits, scour channels and bathymetry features develop.

System recovery

Recovery of the system, in terms of profile realignment, was briefly tested with a run of storms (1.5m waves) and calm periods (0.25m waves) but the small waves have little effect on sediments that were deposited offshore. Perhaps some more attention to reproducing the recovery behaviour of the beach is necessary to further validate the results. Erosion at the shoreline was reproduced but the subsequent recovery was not. Figure 40 shows erosion after large swell event with profile realignment obvious in the shallower sloped foreshore while the backbeach is at the pre-storm elevation.

Figure 40 - Erosion due to Profile Realignment after a Storm event

Cementing of Particles

Often the sediment, cobbles, and reef rock in the shore normal channels were covered by what appeared to be a growth of algae as shown in the photo on the left of Figure 41. It is important to note that the algal growth was observed during the relatively calm season during the August survey but not in December when the average wave energy is higher. The clean and mobile sediment as seen in the December survey is shown in the photo on the right of Figure 41.

Figure 41 - Apparent Algal Growth on Intra-Reef Sediment (25-Aug-2011) versus Mobile Sediment (18-Dec-2011)

The roughness of the reef reduces water circulation at the seafloor and may even approach stagnation conditions in calm periods in deep and narrow trenches. This low circulation allows deposits of debris and organic matter from stormwater runoff to form which allows the growth of the algae/mucous layer. Eutrophication and lower salinity levels in the bay due to periodic storm water runoff may also be a contributing factor at this site. This algae growth may affect the sediment dynamics at this site as it loosely binds the sediment and consequently reducing the transport capacity through the reef. This phenomenon was also observed by Sadd (1984) and Roberts (2004) at their study sites in St Criox. This observed algae growth was limited to the trenches between the coral heads and did not extend past the limits of the reef. Regular unbound sand was observed on the outer edge of the reef (approximately 3-4m water depth), on the north and south boundaries, and in the active region of sediment between the inner edge of the reef and the sea defense.

Stormwater Discharge

Another sediment supply issue that was not considered in the model is that of the load from stormwater runoff. The storm drains are generally not permanent outlets as there are inner basins that retain discharge from small to moderate rainfall events. The outlets are blocked by naturally placed sediment most of the time. However, during periods of high rainfall, the beach barrier breaches and the sediment from the runoff and the inner lagoons is discharged into the bay. Although not confirmed, this discharge would appear to be an important source of both fine and coarse sediment for this project site. Presto et al. (2006) mentions similar events occurring at his site in Hawaii where storm discharge deposited fines onto the reef. Figure 42 shows a stormwater outlet a few days after a breach. The channel has been filled but the effects of the scour are still apparent.

Figure 42 - Stormwater Discharge Outlet in Holetown showing the inner basin, the scour channel, and subsequent natural closure of the outlet by wave action

Total Sediment Balance

Sediment production at the reef and discharge from land based sources will have an effect on the sediment size and quantity in the bay and will vary from bay to bay. There is an offshore canyon, known as the Holetown Hole, which may be a sediment sink in the area. It was postulated that certain bay geometries may even exhibit a preferred sediment size with natural sorting occurring. Since sediment diameter was identified as the most important factor governing the system response a thorough understanding of the situation is desirable.

Swimmer safety

The focus of this report was the movement of sediment but using the velocities obtained in the model results one could conduct a study of swimmer safety along the coast.

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Appendix A – Additional Figures and Tables

Table 6 - Beach Cell Dimensions of Barbados' West Coast

	Name	Type	Bay			North Reef			South Reef			Dir		Structures
			N-S	E-W	Ratio	N-S	E-W	Ratio	N-S	E-W	Ratio			
1	Six Men's	Partial	260	20	13,00	150	80	1,88	100	160	0,63	335	-25	Yes?
2	Speighstown	Full	600	120	5,00	200	70	2,86	390	120	3,25	0	0	Yes
3	Godings Bay	Full	600	100	6,00	390	120	3,25	250	160	1,56	0	0	No
4	Road View	Full	340	30	11,33	250	160	1,56	110	100	1,10	345	-15	Yes
5	Mullins	Partial	480	100	4,80	170	70	2,43	100	300	0,33	350	-10	No
6	Gibbs	Full	480	80	6,00	120	75	1,60	250	110	2,27	5	5	No
7	Lower Carlton	Full	800	140	5,71	250	110	2,27	250	200	1,25	350	-10	No
8	Read's Bay	Full	400	30	13,33	250	200	1,25	170	100	1,70	350	-10	Yes
9	St Albans	Full	250	40	6,25	170	100	1,70	120	140	0,86	350	-10	No
10	Alleynes	Full	1440	170	8,47	120	140	0,86	460	120	3,83	5	5	No
11	Heron Bay	Full	540	70	7,71	230	100	2,30	280	220	1,27	340	-20	No
12	Holetown	Partial	1500	260	5,77	280	220	1,27	450	150	3,00	355	-5	No
13	Sandy Lane	Full	590	120	4,92	450	150	3,00	240	110	2,18	355	-5	No
14	South Sandy Bay	Full	250	30	8,33	240	110	2,18	260	90	2,89	0	0	No
15	North Paynes Bay	Full	600	90	6,67	260	90	2,89	180	120	1,50	355	-5	No
16	Tamarind Cove	Full	260	20	13,00	180	120	1,50	180	90	2,00	5	5	No
17	South Paynes Bay	Full	780	110	7,09	180	90	2,00	260	90	2,89	0	0	Yes
18	Risk Road	N/A	380	40	9,50	260	90	2,89	300	70	4,29	5	5	No
19	Batt's Rock	Full	460	110	4,18	130	110	1,18	140	240	0,58	350	-10	No
20	Freshwater Bay	Full	490	90	5,44	140	240	0,58	350	580	0,60	340	-20	No

Point	Site_Holet
1	Discovery Bay (-0.5-1m depth)
2	Discovery Bay (swash)
3	Carew House (back beach)
4	Carew House (swash)
5	Carew House (-0.5-1m depth)
6	Inn on the Beach (back beach)
7	Inn on the Beach (swash)
8	Inn on the Beach (-0.5-1m depth)
9	Dive Shop south (back beach)
10	Dive Shop south (swash)
11	Dive Shop south (-0.5-1m depth)
12	Beachlands (back beach)
13	Beachlands (swash)
14	Beachlands (-0.5-1m depth)

Figure 43 - Sand Sample Locations (Baird, 2000)

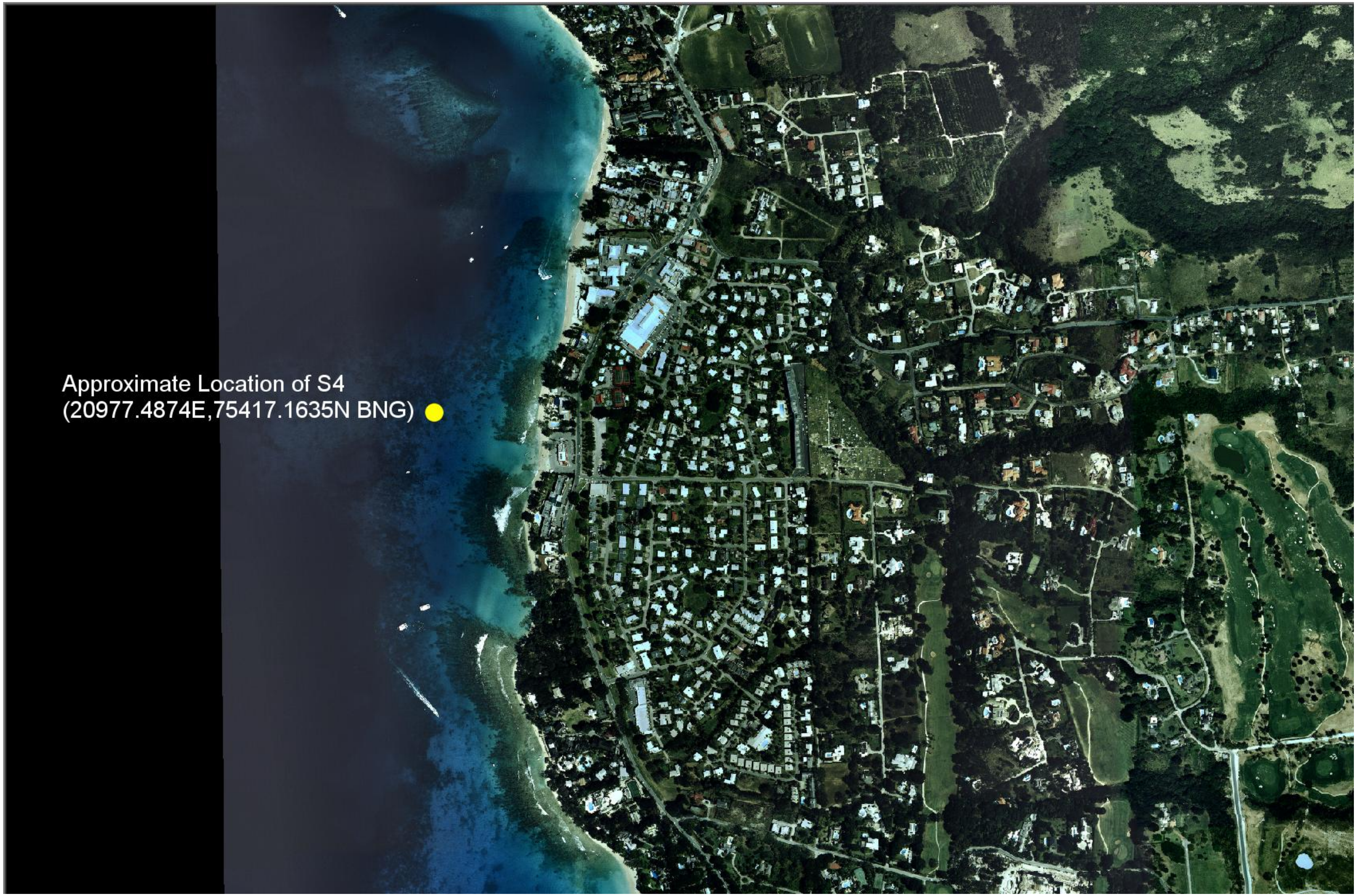


Figure 44 - Nearhsore Wave Gauge Location (Baird, 2000)

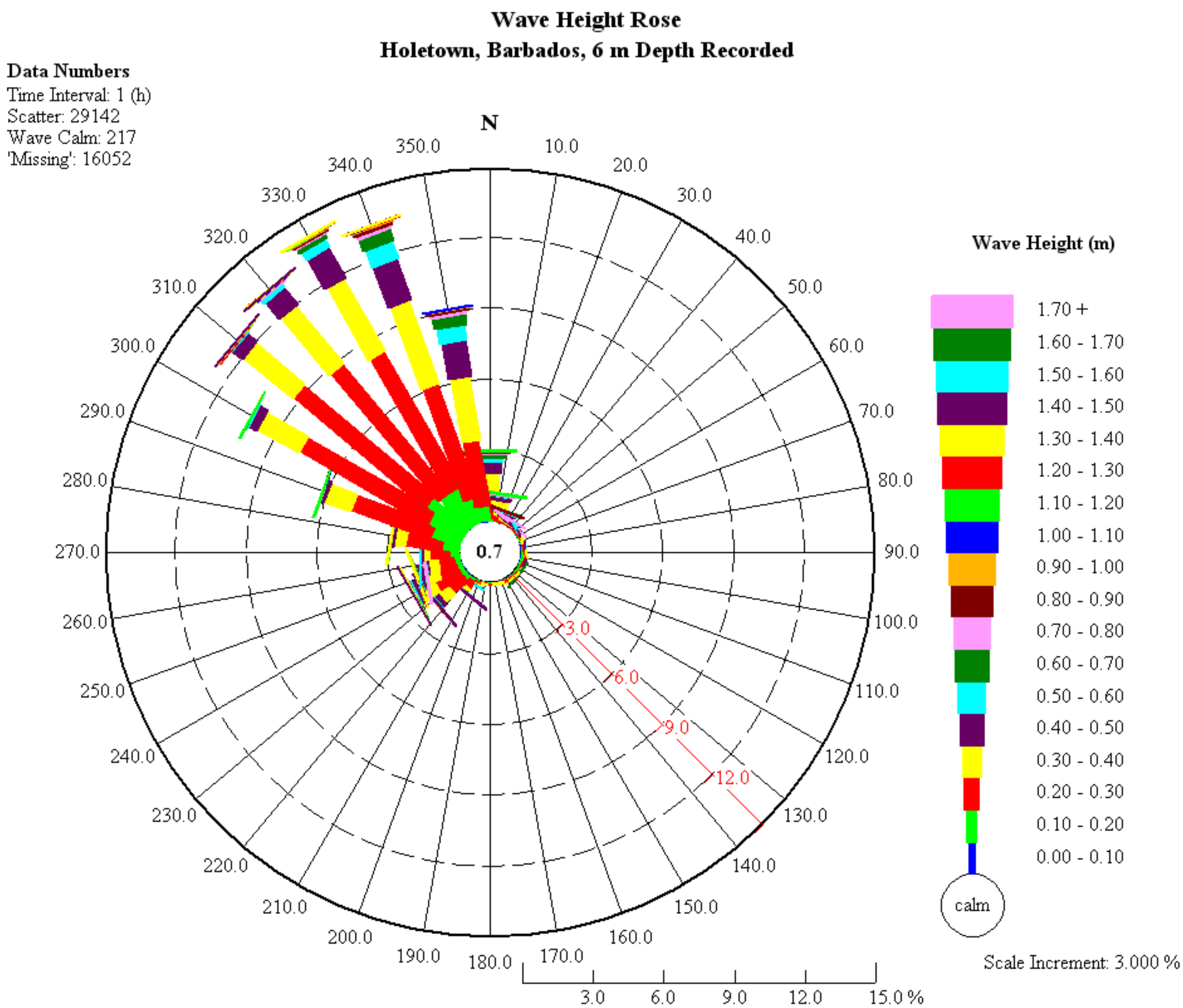
Table 7 - RunID and Parameter Input Summary for Forcing Scenarios

RunID	Bathy	H_s (m)	T_p (s)	H_s/λ_{deep}	Dir	SL	d_{50} (μm)	reef.rgh	Dur (days)	Focus	Notes
F01	450.60	1	10	0,00641	270	MSL	375	20	40	Dir	
F02	450.60	1	10	0,00641	275	MSL	375	20	40	Dir	
F03	450.60	1	10	0,00641	285	MSL	375	20	40	Dir	***Base Case***
F04	450.60	1	10	0,00641	305	MSL	375	20	40	Dir	
F05	450.60	0,25	5	0,00641	285	MSL	375	20	40	H_s	Vary H_s but with constant steepness so T_p follows
F06	450.60	0,5	7	0,00654	285	MSL	375	20	40	H_s	
F07	450.60	1,5	12	0,00668	285	MSL	375	20	40	H_s	
F07b	450.60	0,75	12	0,00334	285	MSL	375	20	40	H_s	try to find initiation wave height
F07c	450.60	1,5	12	0,00668	285	MSL	275	20	40	H_s	look at d50 effects with bigger waves
F07d	450.60	1,5	12	0,00668	285	MSL	475	20	40	H_s	look at d50 effects with bigger waves
F08	450.60	2	14	0,00654	285	MSL	375	20	40	H_s	
F09	450.60	1	6	0,01781	285	MSL	375	20	40	T_p, Steep.	Vary steepness/period
F10	450.60	1	8	0,01002	285	MSL	375	20	40	T_p, Steep.	
F11	450.60	1	12	0,00445	285	MSL	375	20	40	T_p, Steep.	
F12	450.60	1	14	0,00327	285	MSL	375	20	40	T_p, Steep.	
F13	450.60	1	10	0,00641	285	1,55	375	20	40	SLR	Ekstrem value in case cuz of underestimation
F14	450.60	1	10	0,00641	285	1,15	375	20	40	SLR	100yr (h) SLR w/ MHWS (IPCC 2007)
F15	450.60	1	10	0,00641	285	0,75	375	20	40	SLR	100yr (l) SLR w/ MHWS (IPCC 2007)
F16	450.60	1	10	0,00641	285	+0.55	375	20	40	SLR	MHWS
F17	450.60	1	10	0,00641	285	-0.55	375	20	40	SLRe	MLWS/reef growth
F18	450.60	1	10	0,00641	285	MSL	275	20	40	d_{50}	Changes slopes, ws, etc etc. Not incl here
F19	450.60	1	10	0,00641	285	MSL	475	20	40	d_{50}	eg nouishments
F20	450.60	1	10	0,00641	285	MSL	375	30	40	rgh	Check w/ Robin/Hazel for reasonable values
F21	450.60	1	10	0,00641	285	MSL	375	15	40	rgh	
F22	450.60	1	10	0,00641	285	MSL	375	30,15	40	rgh	u,v difference

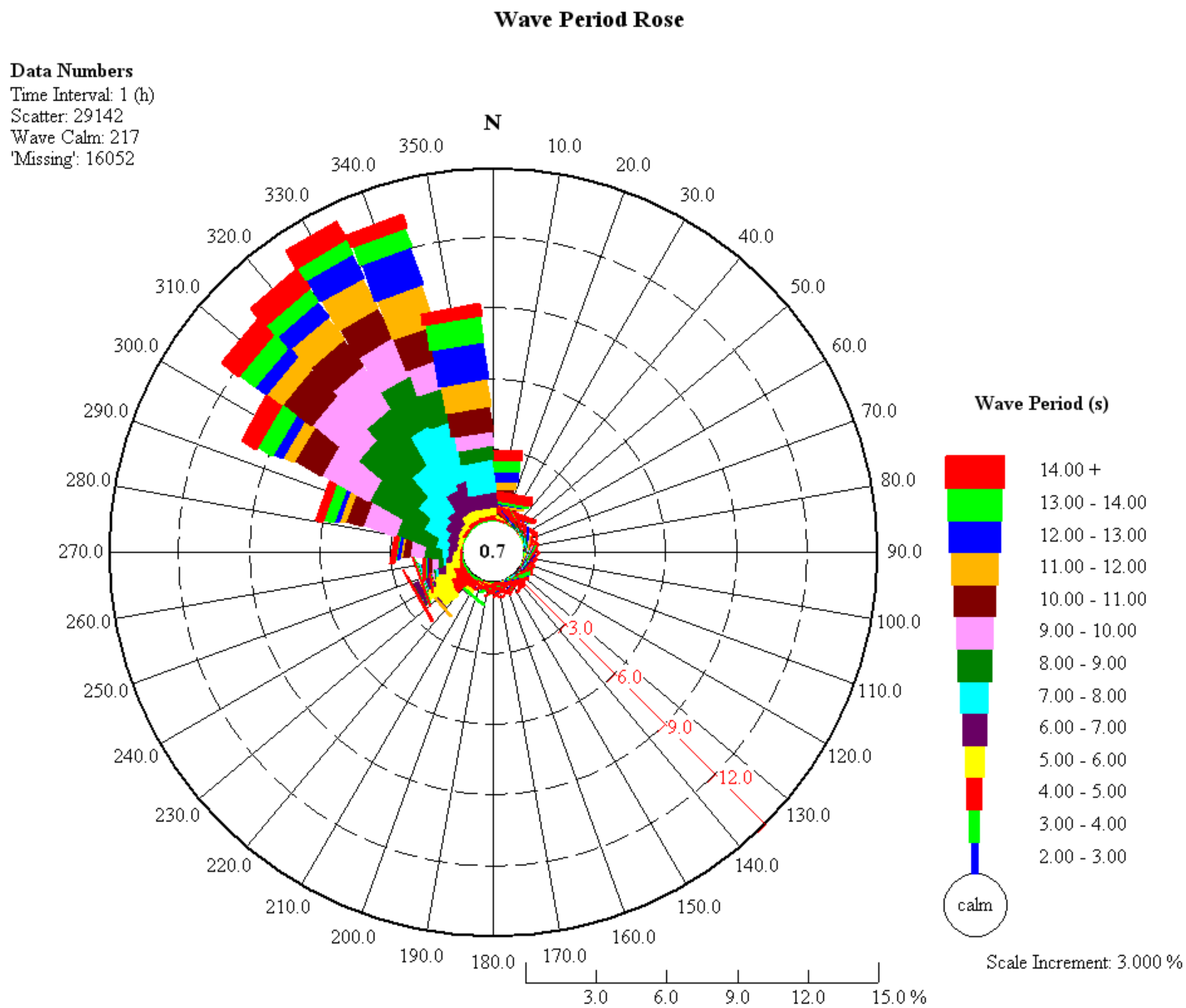
Table 8 - RunID and Parameter Input Summary for Geometry Scenarios

runID#	Name	Bay			North Reef			South Reef			Dir	Profile
		N-S	E-W	Ratio	N-S	E-W	Ratio	N-S	E-W	Ratio		
G01	Bay Size	300	40	7,50	200	100	2,00	200	100	2,00	0	Dean
G02	*Base Case*	450	60	7,50	200	100	2,00	200	100	2,00	0	Dean
G03		600	80	7,50	200	100	2,00	200	100	2,00	0	Dean
G05	Bay Ratio	450	115	3,91	200	100	2,00	200	100	2,00	0	Dean
G06		450	90	5,00	200	100	2,00	200	100	2,00	0	Dean
G07		450	40	11,25	200	100	2,00	200	100	2,00	0	Dean
G08	Reef Size	450	60	7,50	400	200	2,00	400	200	2,00	0	Dean
G09		450	60	7,50	300	150	2,00	300	150	2,00	0	Dean
G10		450	60	7,50	100	50	2,00	100	50	2,00	0	Dean
G08a	Reef Size	450	60	7,50	400	200	2,00	400	200	2,00	0	Dean
G09a	H_s=1.5m	450	60	7,50	300	150	2,00	300	150	2,00	0	Dean
G10a		450	60	7,50	100	50	2,00	100	50	2,00	0	Dean
G11	Reef Ratio	450	60	7,50	200	300	0,67	200	300	0,67	0	Dean
G12		450	60	7,50	200	200	1,00	200	200	1,00	0	Dean
G13		450	60	7,50	200	65	3,08	200	65	3,08	0	Dean
G14	Reef Asymmetry	450	60	7,50	1	2	4				0	Dean
G15		450	60	7,50	4	2	1				0	Dean
G16	No Reef	450	0	0	0	0	0	0	0	0	0	Dean
G17	Plane	0	0	0	0	0	0	0	0	0	0	Dean
G18	Fringe	450	60	7,50	210	140	1,50	210	140	1,50	0	Dean
G18a	Fringe (H_s=1.5m)	450	60	7,50	210	140	1,50	210	140	1,50	0	Dean

Appendix B – Nearshore Wave Data Summary



Wave Height Rose
Holetown, Barbados, 6 m Depth Recorded
Data Numbers
Time Interval: 1 (h)
Scatter: 29142
Wave Calm: 217
'Missing': 16052
N
0.7
3.0
6.0
9.0
12.0
Wave Height (m)
1.70 +
1.60 - 1.70
1.50 - 1.60
1.40 - 1.50
1.30 - 1.40
1.20 - 1.30
1.10 - 1.20
1.00 - 1.10
0.90 - 1.00
0.80 - 0.90
0.70 - 0.80
0.60 - 0.70
0.50 - 0.60
0.40 - 0.50
0.30 - 0.40
0.20 - 0.30
0.10 - 0.20
0.00 - 0.10
calm
Scale Increment: 3.000 %
3.0
6.0
9.0
12.0
15.0 %


Wave Period Rose
Data Numbers
Time Interval: 1 (h)
Scatter: 29142
Wave Calm: 217
'Missing': 16052
N
350.0
340.0
330.0
320.0
310.0
300.0
290.0
280.0
270.0
260.0
250.0
240.0
230.0
220.0
210.0
200.0
190.0
180.0
170.0
160.0
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.7
3.0
6.0
9.0
12.0
3.0
6.0
9.0
12.0
15.0 %
Wave Period (s)
14.00 +
13.00 - 14.00
12.00 - 13.00
11.00 - 12.00
10.00 - 11.00
9.00 - 10.00
8.00 - 9.00
7.00 - 8.00
6.00 - 7.00
5.00 - 6.00
4.00 - 5.00
3.00 - 4.00
2.00 - 3.00
calm
Scale Increment: 3.000 %

Wave Distribution By Height And Period (All Directions)

Date Range: 09 Oct 2003 08PM to 13 Dec 2008 08PM

Season: All

	Wave Period (s)																			
Wave Height (m)	2.00-3.00	3.00-4.00	4.00-5.00	5.00-6.00	6.00-7.00	7.00-8.00	8.00-9.00	9.00-10.00	10.00-11.00	11.00-12.00	12.00-13.00	13.00-14.00	14.00-15.00	15.00-16.00	16.00-17.00	17.00-18.00	18.00+	Total	A (%)	C (%)
0.00-0.10		61	19	14	2	4	5	3	2	2	1	1	1	2	1	2	14	134	0.32	99.26
0.10-0.20		62	187	196	330	846	986	550	280	143	105	81	29	25	14	1	3	3838	9.10	98.94
0.20-0.30		158	614	960	874	1869	2920	2177	1350	753	611	717	315	204	210	72	39	13843	32.83	89.84
0.30-0.40		119	354	535	475	683	697	926	962	740	602	523	153	91	133	54	19	7066	16.76	57.01
0.40-0.50		43	97	162	210	280	139	191	260	357	371	250	75	52	44	16	12	2559	6.07	40.25
0.50-0.60		8	19	37	50	80	30	32	43	126	143	86	51	22	15	5	8	755	1.79	34.18
0.60-0.70		3	5	21	28	33	11	12	23	62	127	68	42	10	15	7	7	474	1.12	32.39
0.70-0.80		1	5	6	16	13	9	4	4	26	42	30	20	2	7	6	1	192	0.46	31.26
0.80-0.90			3	2	11	16	6	5	4	13	20	30	15	6	9	4		144	0.34	30.81
0.90-1.00		1	1	5	8	4	3	1		5	5	10	5	3				51	0.12	30.47
1.00-1.10				1	3	2	3	1		3		2	3	2	1	3		24	0.06	30.35
1.10-1.20			1	1	2	2		3		1			2		2	6	2	22	0.05	30.29
1.20-1.30				2	1		1		2			3			2	3	2	16	0.04	30.24
1.30-1.40				2	1	4		1				1	1		1	2	1	14	0.03	30.20
1.40-1.50				3			1	1									3	8	0.02	30.17
1.50-1.60								1										1	0.00	30.15
1.60-1.70																				30.14
1.70+		1																1	0.00	30.14
Totals		457	1305	1947	2011	3836	4811	3908	2930	2231	2027	1802	712	419	454	181	111	29142		
A(%)		1.08	3.10	4.62	4.77	9.10	11.41	9.27	6.95	5.29	4.81	4.27	1.69	0.99	1.08	0.43	0.26		69.12	
C(%)	99.26	99.26	98.18	95.08	90.46	85.69	76.60	65.19	55.92	48.97	43.68	38.87	34.59	32.90	31.91	30.83	30.41			

Meta Data

0.74% Calm Conditions (Wave Height<0.00 m and Wave Period<2.00 s)

Number of records this selection: 29142

Total records used in selected interval (including calms): 29359

Missing data (not included in calculation): 16052

Wave height (all data): Max: 1.70 Min: 0.00 Mean: 0.30

Wave height (scatter only): Max: 1.70 Min: 0.01 Mean: 0.30

Wave period (all data): Max: 28.80 Min: 3.00 Mean: 9.39

Wave period (scatter only): Max: 28.80 Min: 3.00 Mean: 9.36

Legend

Row and column percentages have the following meanings:

A -- based on records in this selection

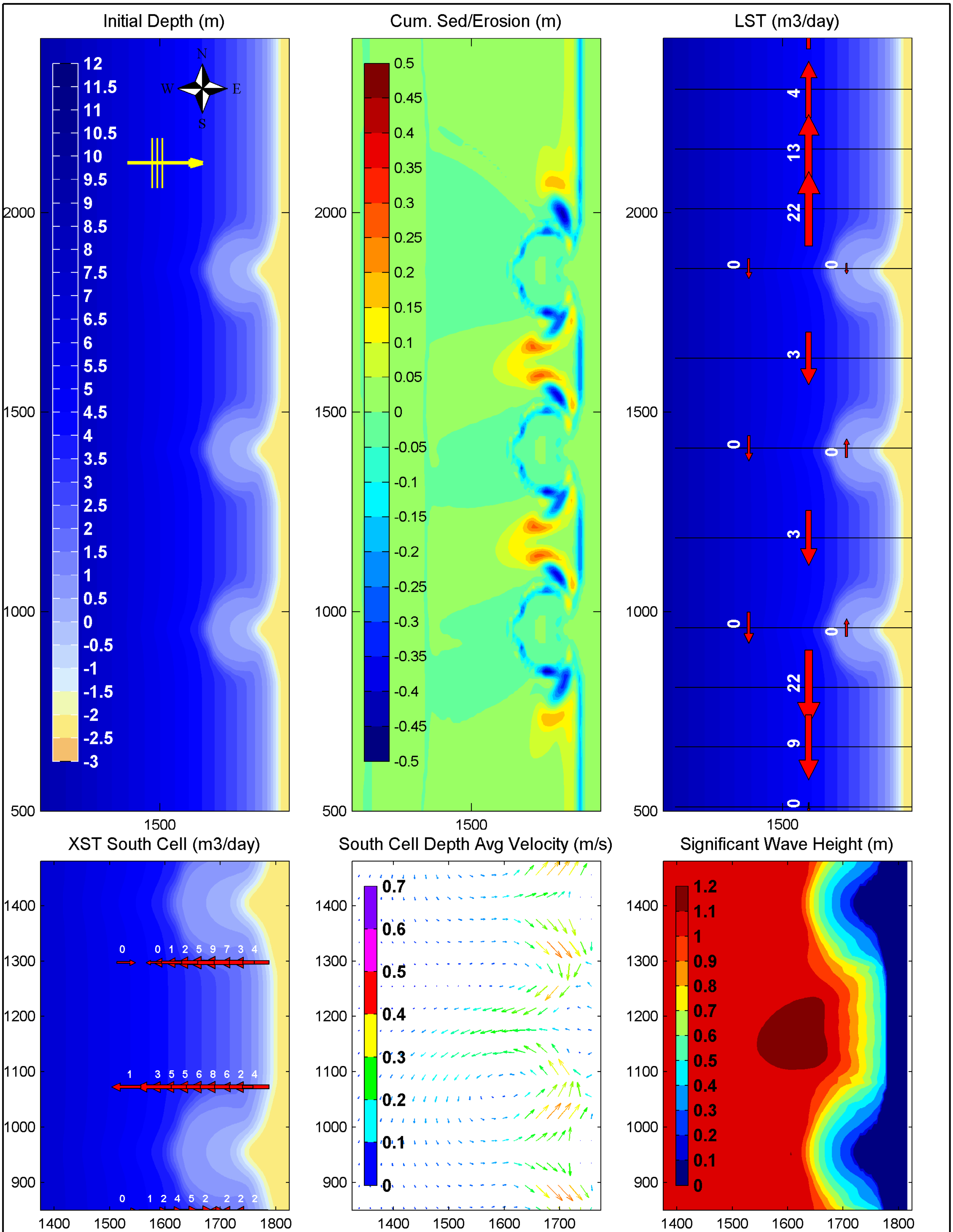
C -- percent exceedance

Frequencies of occurrence are reported in 'counts'

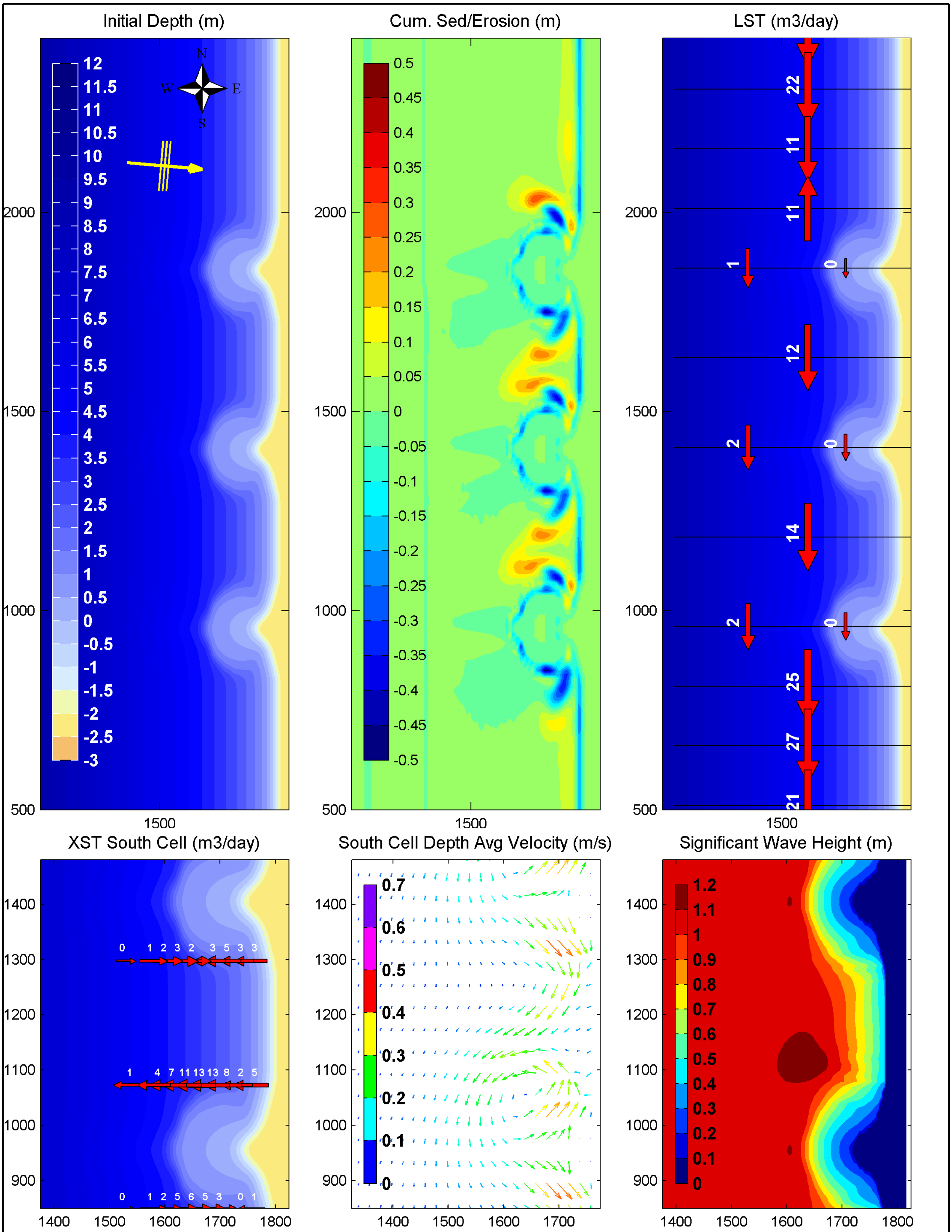
Source Data File: P:\11493.000 Barbados Coast Guard\E - Analysis and Design\Recorded Waves\Measured_Holetown_UTC-03-08.bts
Date Range: 09 Oct 2003 08PM to 13 Dec 2008 08PM
Wave Height Threshold: 0.70 Number of storm events: 34
Min. Time Between Storms: 72 hours Min. Storm Duration: 1 hours

Row	**Storm Time**			**Dur.**	**Height**	**Period**	**Dir.**
No.	**Start**	**End**	**Peak Height**	**(h)**	**(m)**	**(sec)**	**(deg)**
1	14 Apr 2008 07PM	14 Apr 2008 07PM	14 Apr 2008 07PM	1	1.70	3.10	256
2	16 Oct 2008 10AM	17 Oct 2008 09AM	17 Oct 2008 03AM	24	1.51	9.20	273
3	20 Mar 2008 01AM	21 Mar 2008 08PM	20 Mar 2008 04PM	44	1.49	18.50	320
4	17 Aug 2007 06AM	18 Aug 2007 04AM	17 Aug 2007 09AM	23	1.47	5.00	221
5	07 Sep 2004 04PM	08 Sep 2004 01PM	08 Sep 2004 01AM	22	1.44	8.57	244
6	23 Jan 2007 05AM	24 Jan 2007 05AM	23 Jan 2007 05PM	25	1.37	14.50	334
7	30 Dec 2003 05AM	31 Dec 2003 11PM	30 Dec 2003 09AM	43	1.22	5.64	326
8	07 Sep 2008 07PM	07 Sep 2008 11PM	07 Sep 2008 09PM	5	1.12	5.00	11
9	27 Mar 2004 02AM	28 Mar 2004 03PM	27 Mar 2004 09AM	38	1.09	11.70	341
10	21 Feb 2007 11PM	27 Feb 2007 05PM	22 Feb 2007 05AM	139	1.08	15.20	351
11	13 Jul 2005 11PM	14 Jul 2005 10AM	14 Jul 2005 03AM	12	1.04	7.00	252
12	29 Jan 2006 07AM	30 Jan 2006 04PM	30 Jan 2006 10AM	34	1.04	13.00	348
13	20 Feb 2005 08AM	24 Feb 2005 11AM	20 Feb 2005 11AM	100	1.03	6.10	337
14	18 Jan 2004 08PM	19 Jan 2004 03PM	19 Jan 2004 03AM	20	0.98	15.17	345
15	31 Jan 2004 12PM	01 Feb 2004 05PM	01 Feb 2004 04AM	30	0.98	13.21	343
16	21 Feb 2004 10PM	22 Feb 2004 08PM	22 Feb 2004 11AM	23	0.98	15.63	335
17	27 Feb 2006 09AM	27 Feb 2006 09PM	27 Feb 2006 10AM	13	0.93	14.50	357
18	31 Jan 2005 05PM	05 Feb 2005 08AM	04 Feb 2005 05PM	112	0.86	13.90	355
19	24 Aug 2006 01PM	24 Aug 2006 05PM	24 Aug 2006 01PM	5	0.84	5.50	240
20	09 Feb 2005 01AM	10 Feb 2005 11AM	09 Feb 2005 12PM	35	0.83	10.10	344
21	05 Jul 2005 11AM	05 Jul 2005 11AM	05 Jul 2005 11AM	1	0.83	4.00	277
22	22 Nov 2008 12PM	22 Nov 2008 02PM	22 Nov 2008 12PM	3	0.83	14.30	9
23	27 Sep 2005 08PM	28 Sep 2005 01AM	27 Sep 2005 09PM	6	0.78	13.00	350
24	18 Jul 2008 06AM	18 Jul 2008 07AM	18 Jul 2008 06AM	2	0.77	4.90	224
25	23 Dec 2004 07AM	23 Dec 2004 07AM	23 Dec 2004 07AM	1	0.76	14.30	359
26	11 Mar 2006 06AM	11 Mar 2006 07AM	11 Mar 2006 07AM	2	0.76	11.80	349
27	01 Sep 2007 10AM	01 Sep 2007 02PM	01 Sep 2007 11AM	5	0.75	6.20	223
28	21 Jan 2005 05PM	21 Jan 2005 10PM	21 Jan 2005 05PM	6	0.74	11.70	322
29	25 Nov 2008 04PM	26 Nov 2008 11PM	26 Nov 2008 10PM	32	0.73	7.80	347
30	16 Oct 2005 09PM	16 Oct 2005 09PM	16 Oct 2005 09PM	1	0.72	18.80	324
31	30 Dec 2005 05AM	30 Dec 2005 05AM	30 Dec 2005 05AM	1	0.72	6.00	347
32	24 Nov 2007 03AM	24 Nov 2007 08AM	24 Nov 2007 08AM	6	0.72	14.70	8
33	30 Dec 2004 10PM	30 Dec 2004 10PM	30 Dec 2004 10PM	1	0.71	12.60	346
34	06 Jan 2008 12PM	06 Jan 2008 02PM	06 Jan 2008 12PM	3	0.70	13.60	345

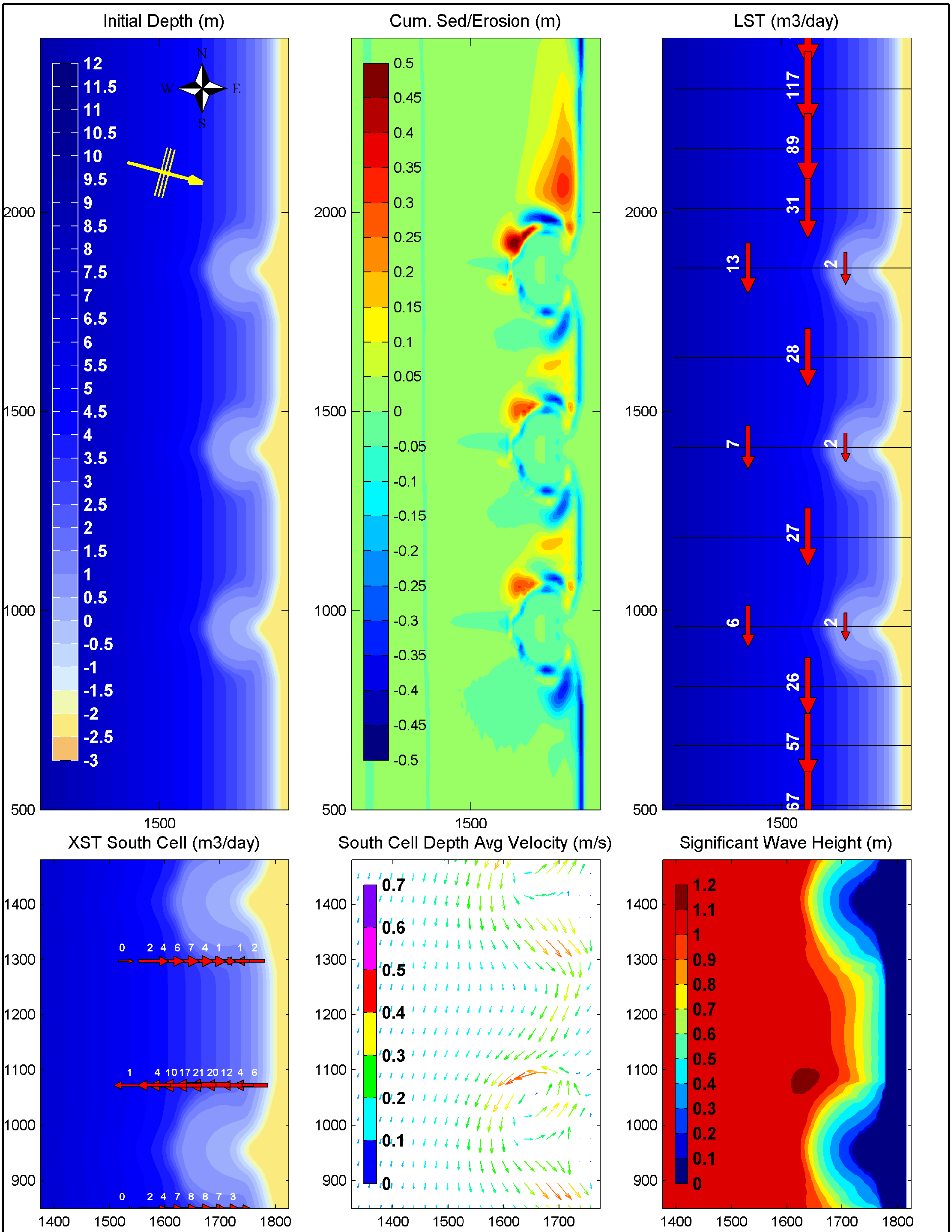
Appendix C – Modeling Reports



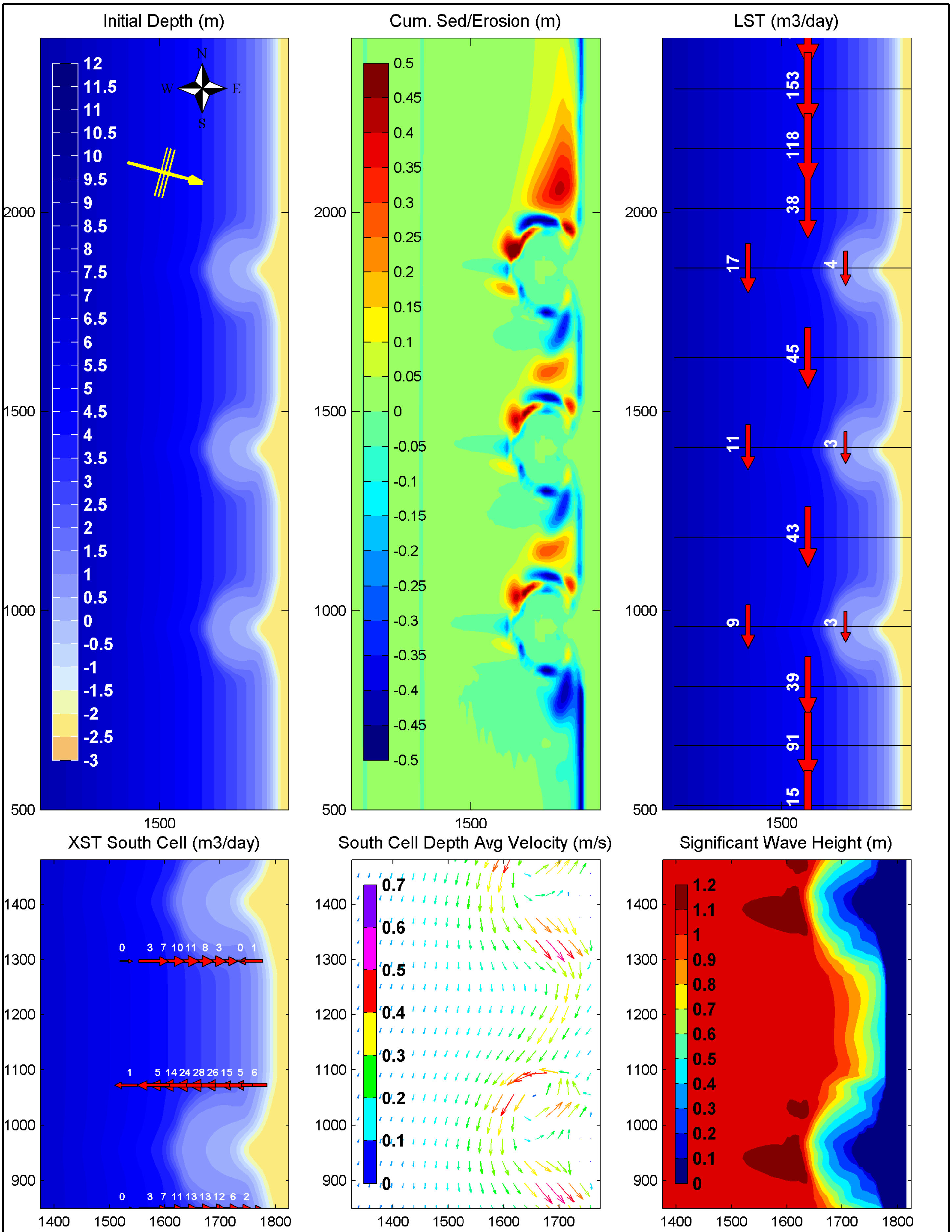
FORCING: Hs 1.0m, Tp 10s, Dir 270deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F01
	DIRECTION	
Deltares Delft Hydraulics	DATE	25/05/2012



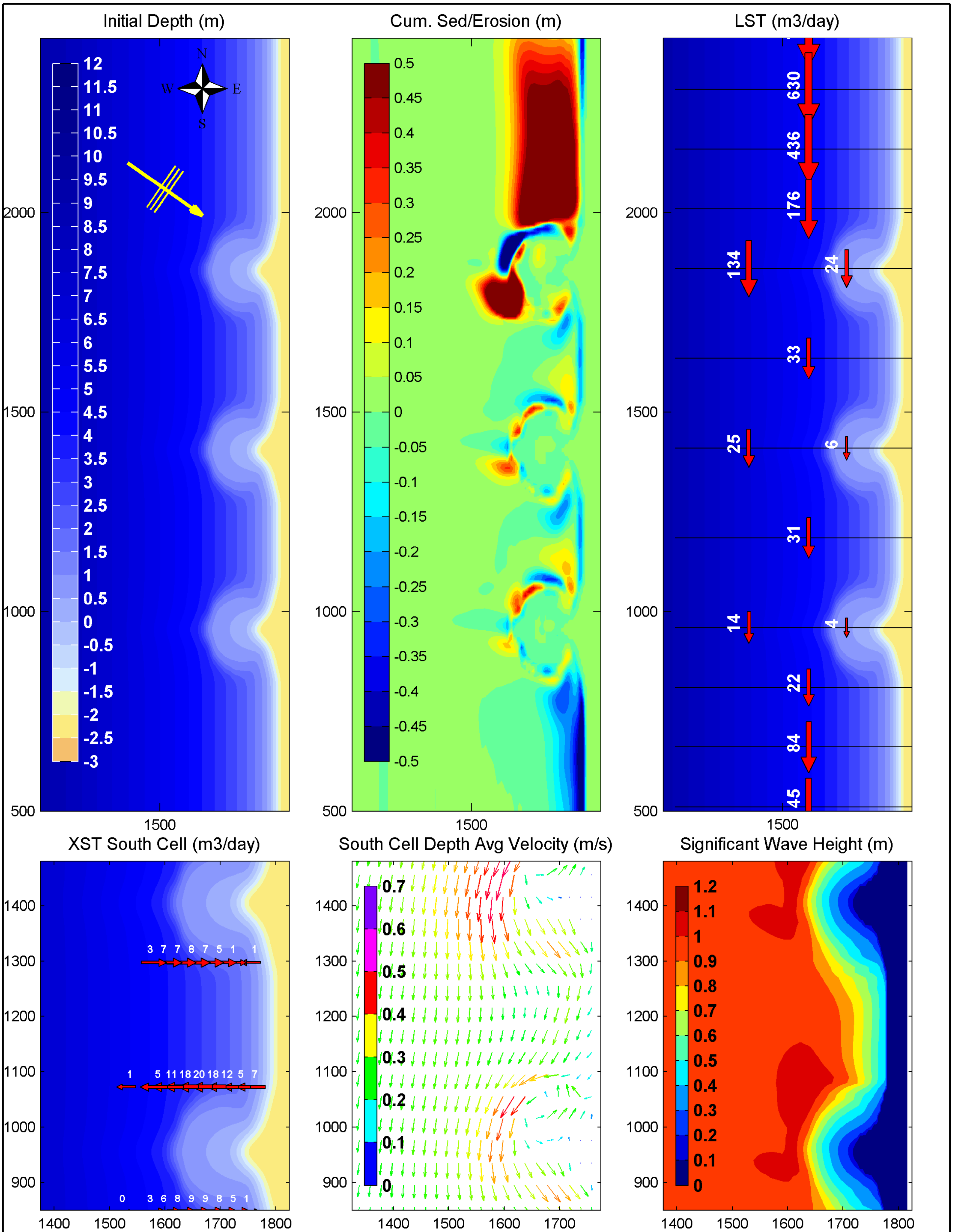
FORCING: Hs 1.0m, Tp 10s, Dir 275deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F02
	DIRECTION	
Deltares Delft Hydraulics	DATE	25/05/2012



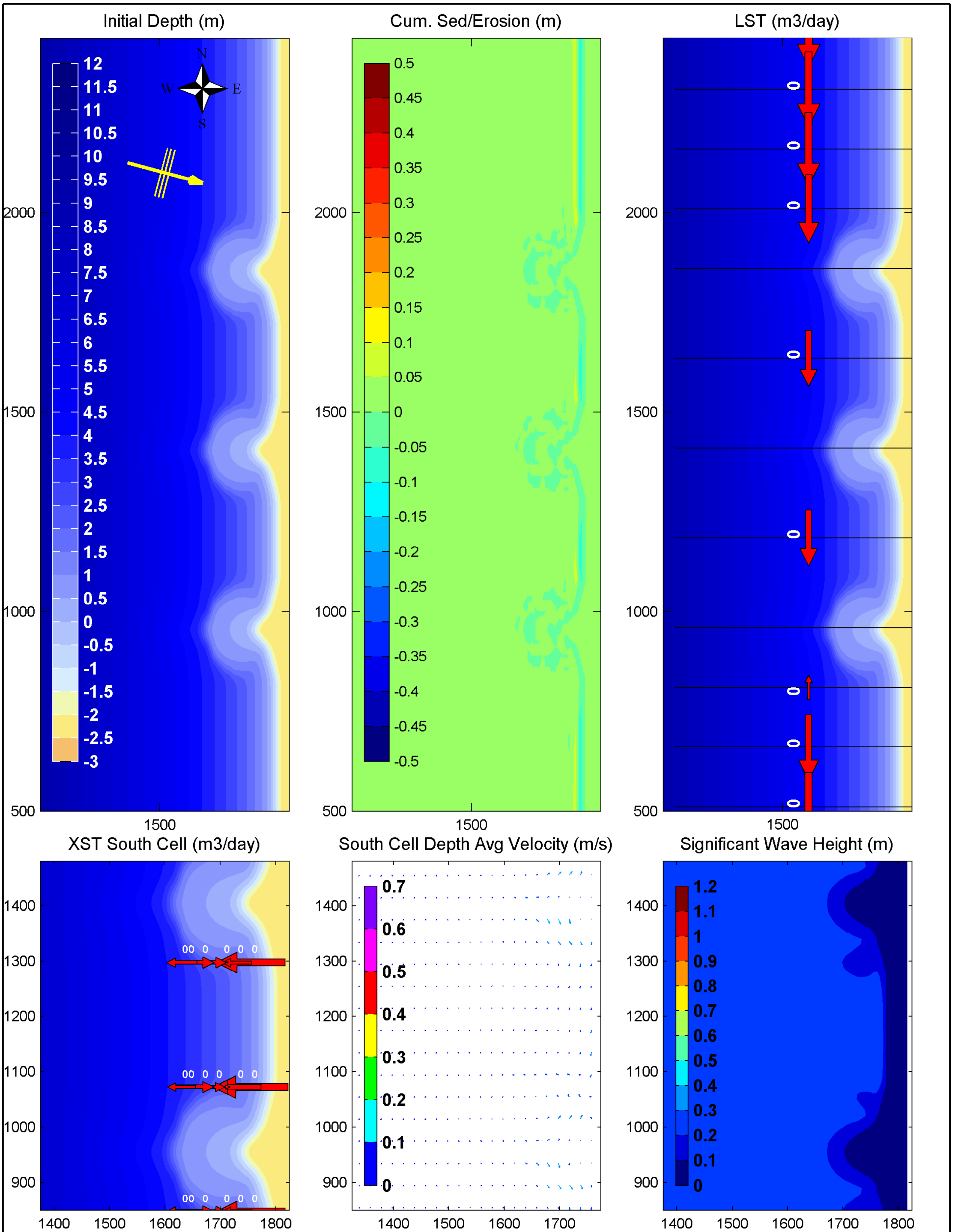
FORCING: Hs 1m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F03
	BASE CASE	
	DATE	23/05/2012



FORCING: Hs 1m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F03r	
	BASE CASE (rerun)		
Deltares Delft Hydraulics	DATE	23/05/2012	

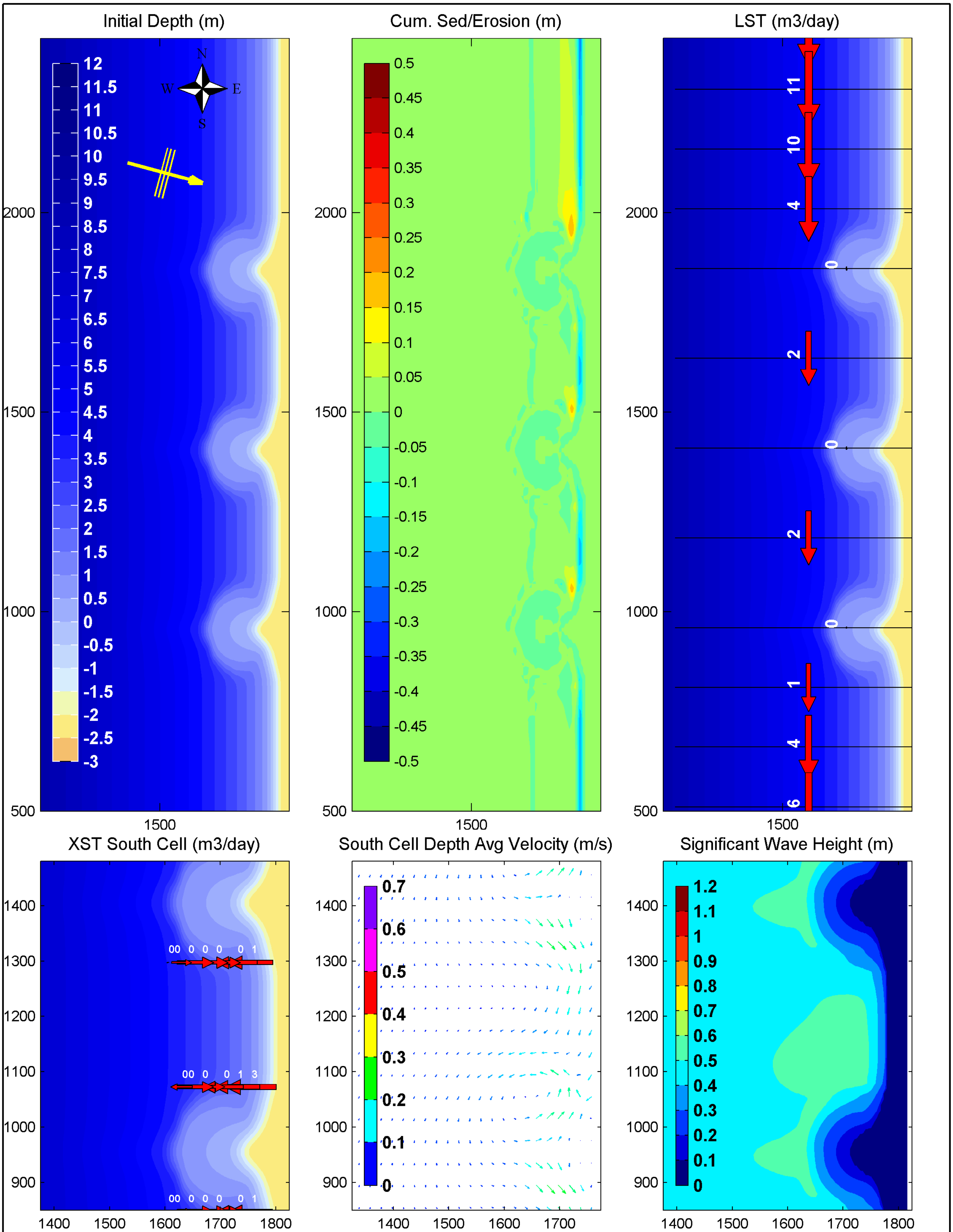


FORCING: Hs 1.0m, Tp 10s, Dir 305deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F04
	DIRECTION	
	DATE	25/05/2012



FORCING: Hs 0.25m, Tp 5s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

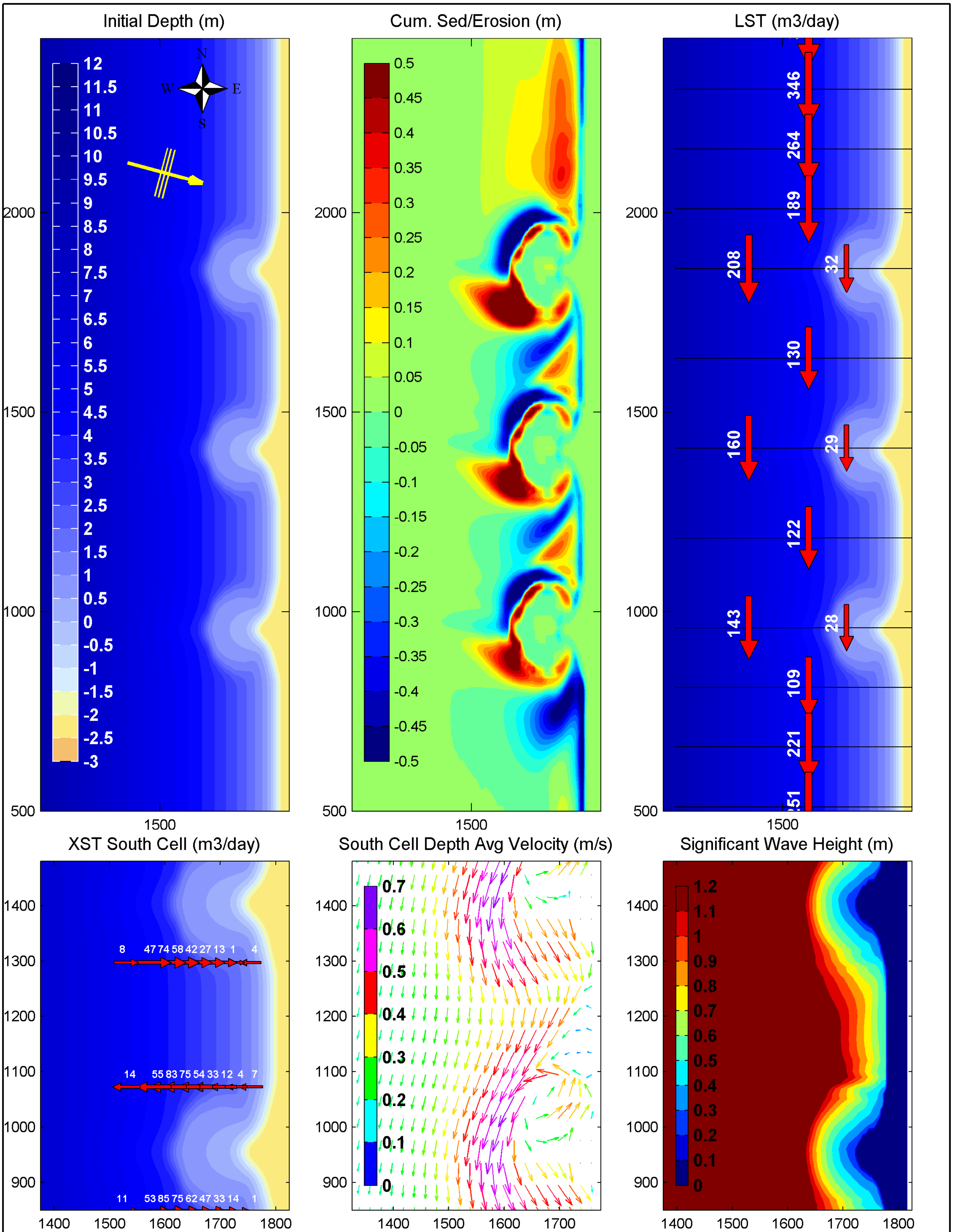
RUN ID#	F05
SIG. WAVE HEIGHT	
DATE	23/05/2012



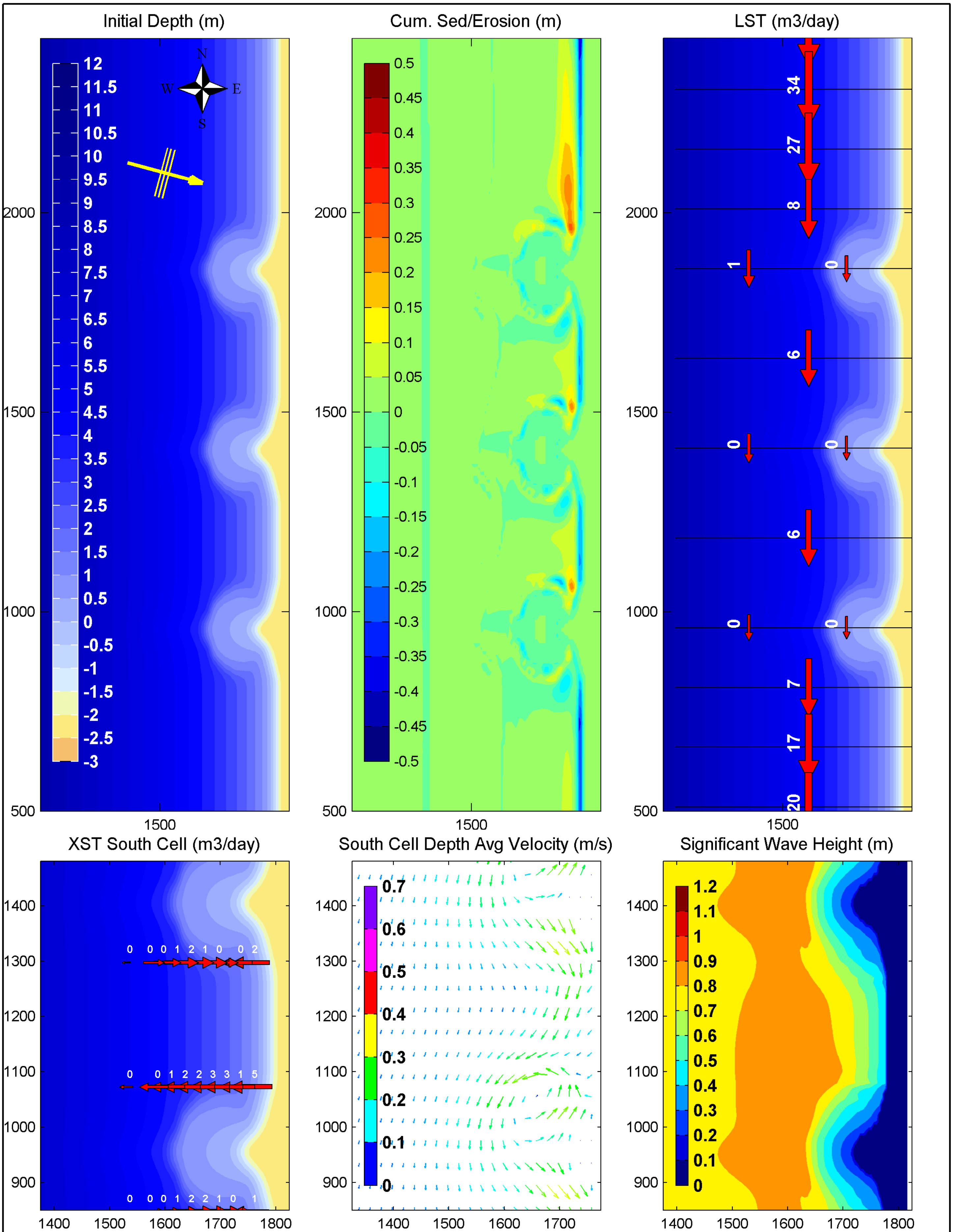
FORCING: Hs 0.50m, Tp 7s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

RUN ID#	F06
SIG. WAVE HEIGHT	
DATE	23/05/2012

Deltares
Delft Hydraulics



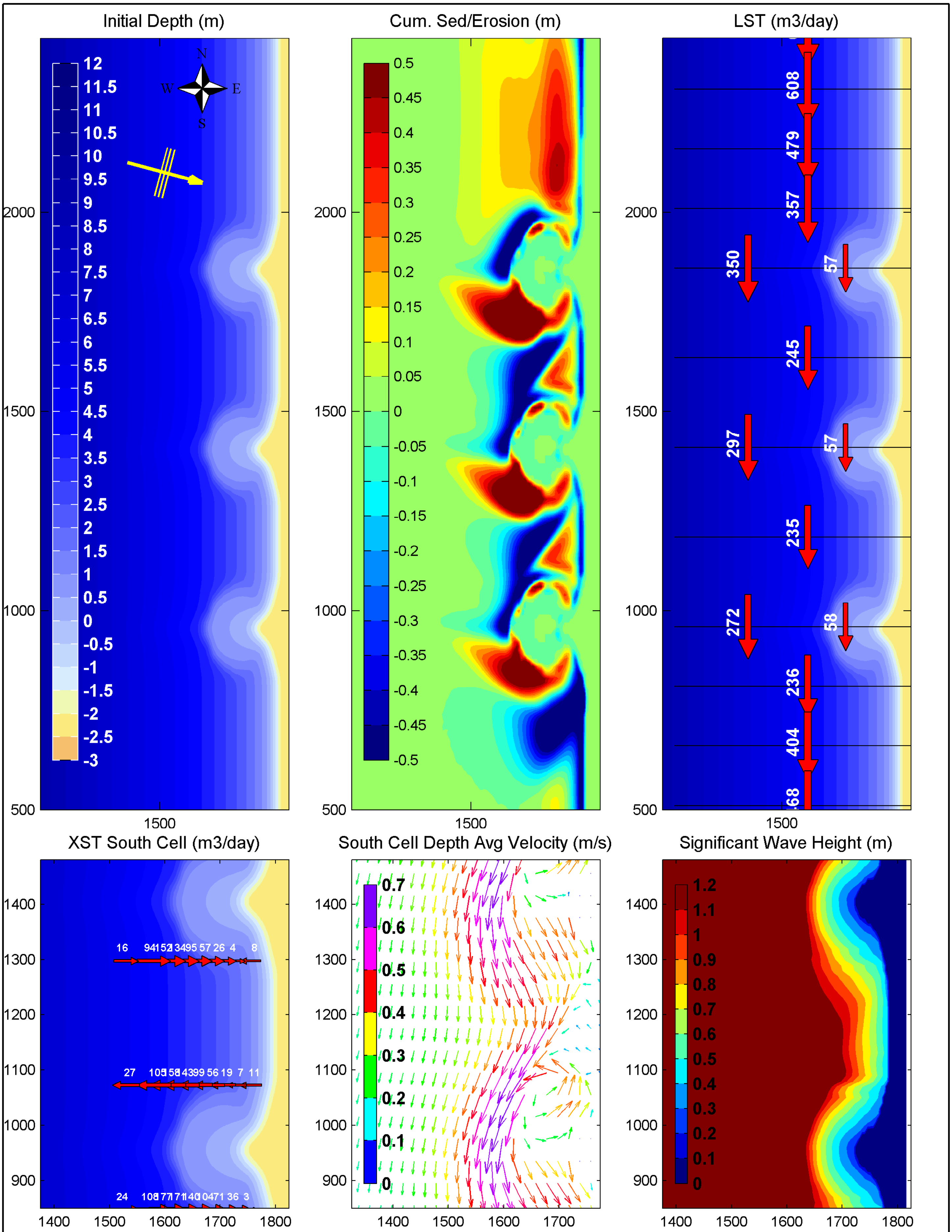
FORCING: Hs 1.50m, Tp 12s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F07
	SIG. WAVE HEIGHT	
Deltares Delft Hydraulics	DATE	23/05/2012



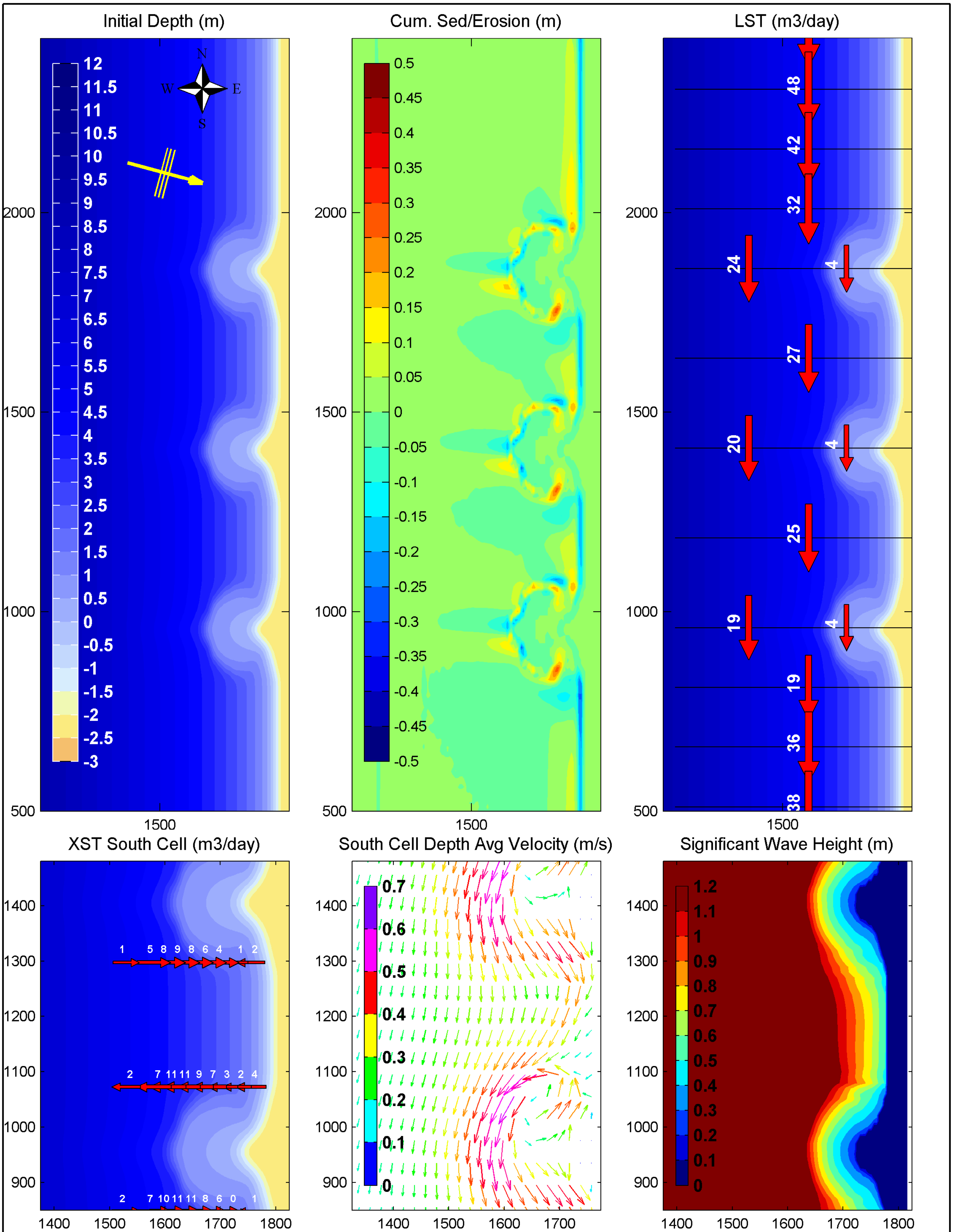
FORCING: Hs 0.75m, Tp 8.25s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

RUN ID#	F07b
SIG. WAVE HEIGHT	
DATE	23/05/2012

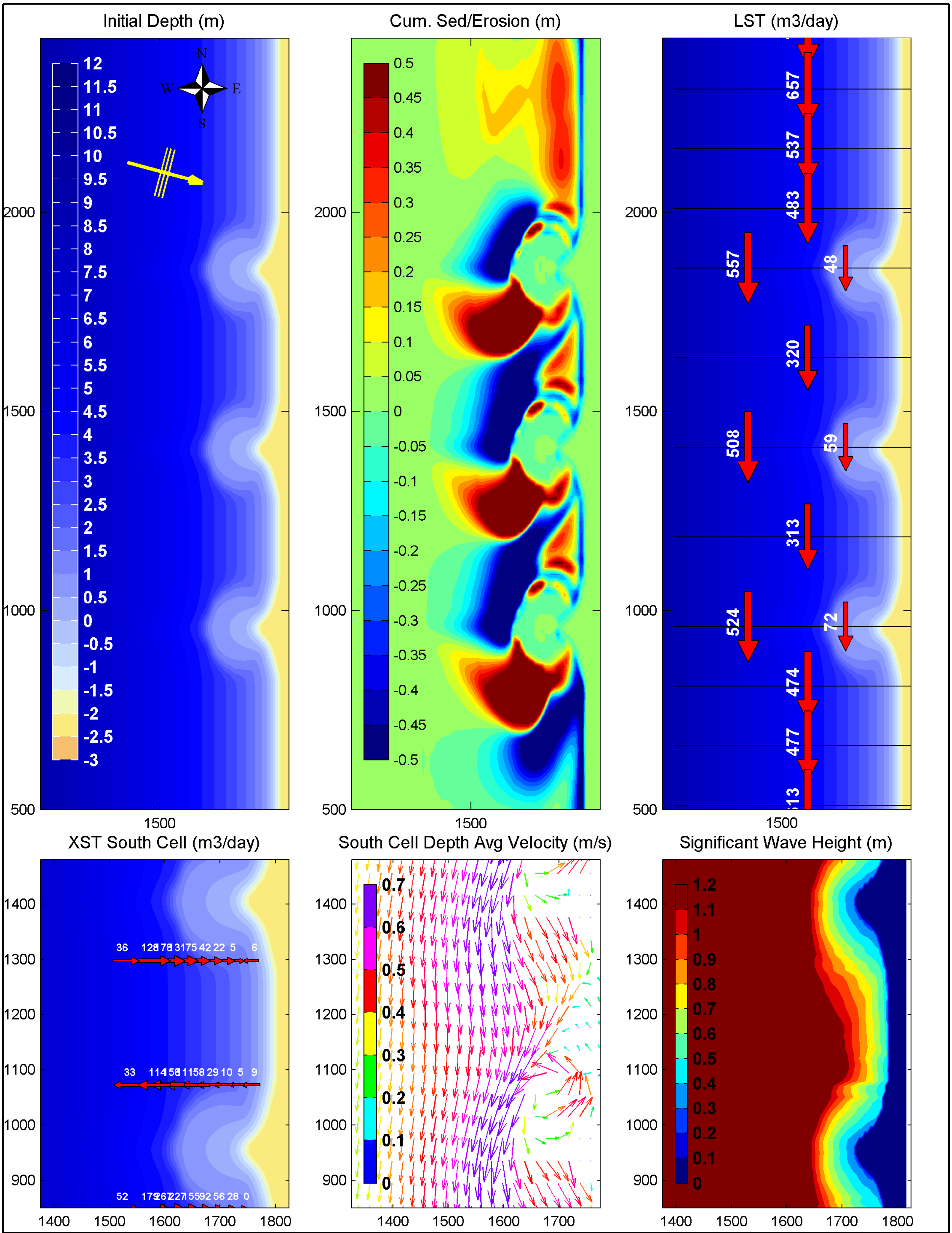
Deltares
Delft Hydraulics



FORCING: Hs 1.5m, Tp 12s, Dir 285deg, D50 275um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F07c
	SEDIMENT DIAMETER	
Deltares Delft Hydraulics	DATE	23/05/2012

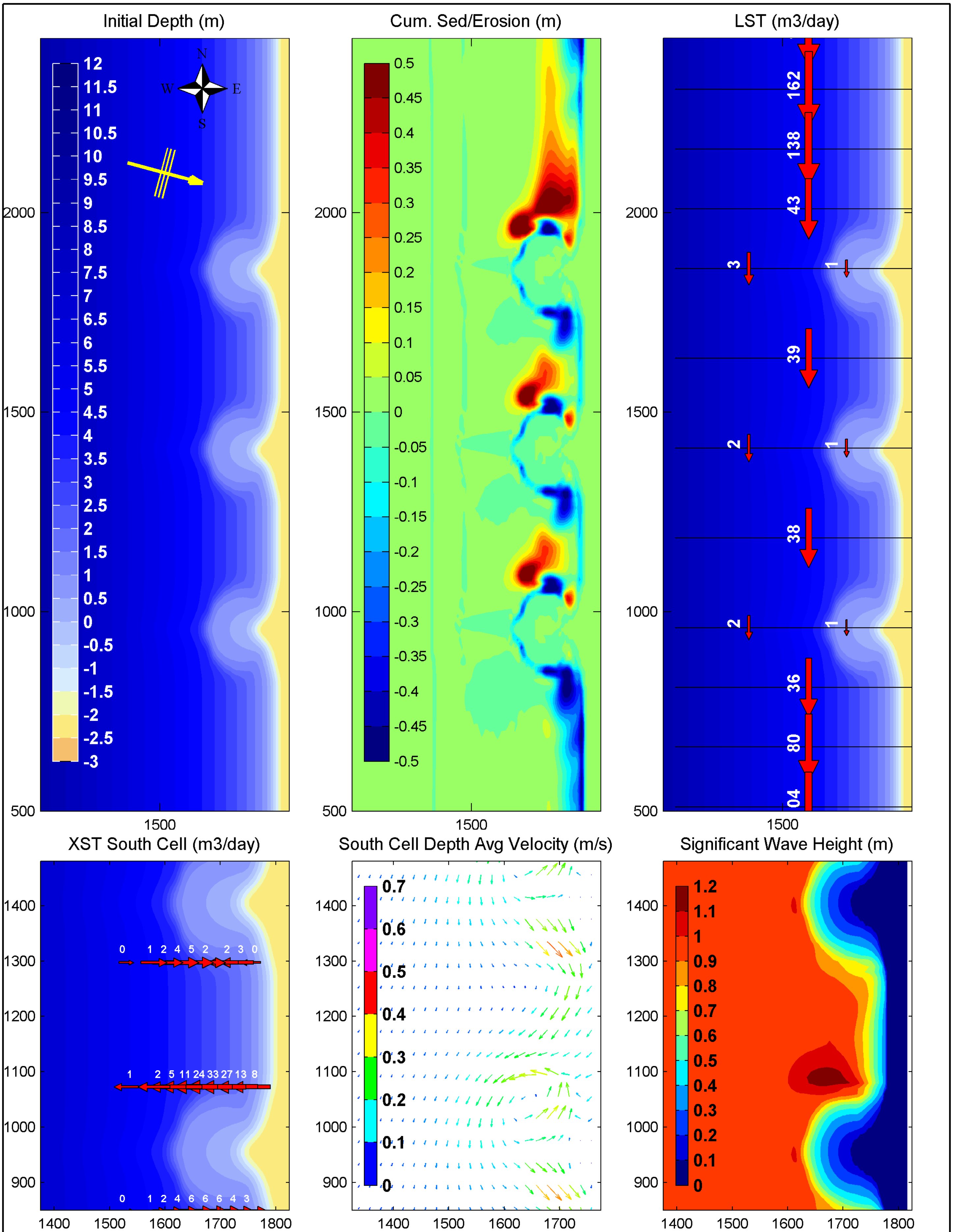


FORCING: Hs 1.5m, Tp 12s, Dir 285deg, D50 475um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F07d
	SEDIMENT DIAMETER	
Deltares Delft Hydraulics	DATE	23/05/2012



FORCING: Hs 2.0m, Tp 14s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

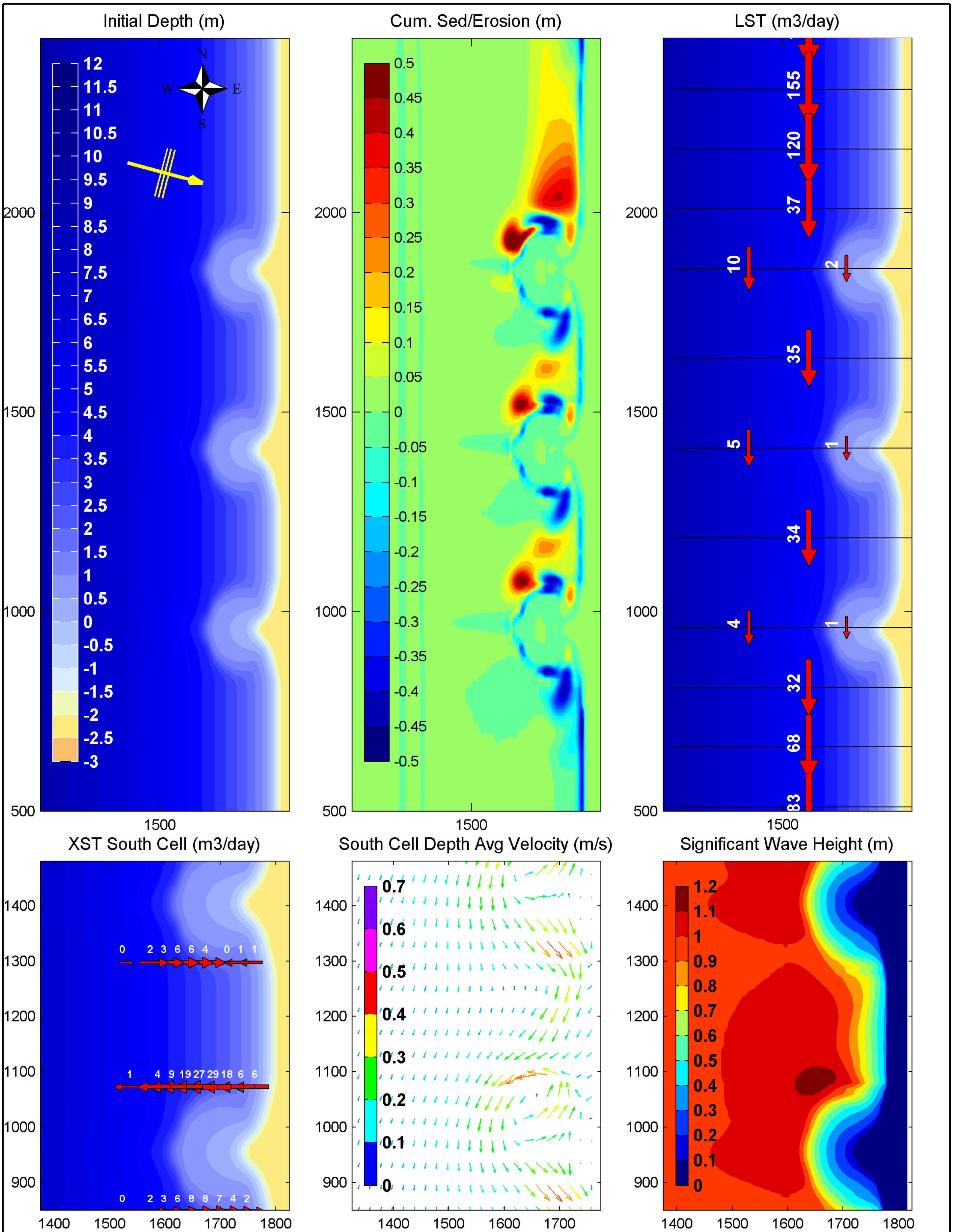
RUN ID#	F08
SIG. WAVE HEIGHT	
DATE	23/05/2012



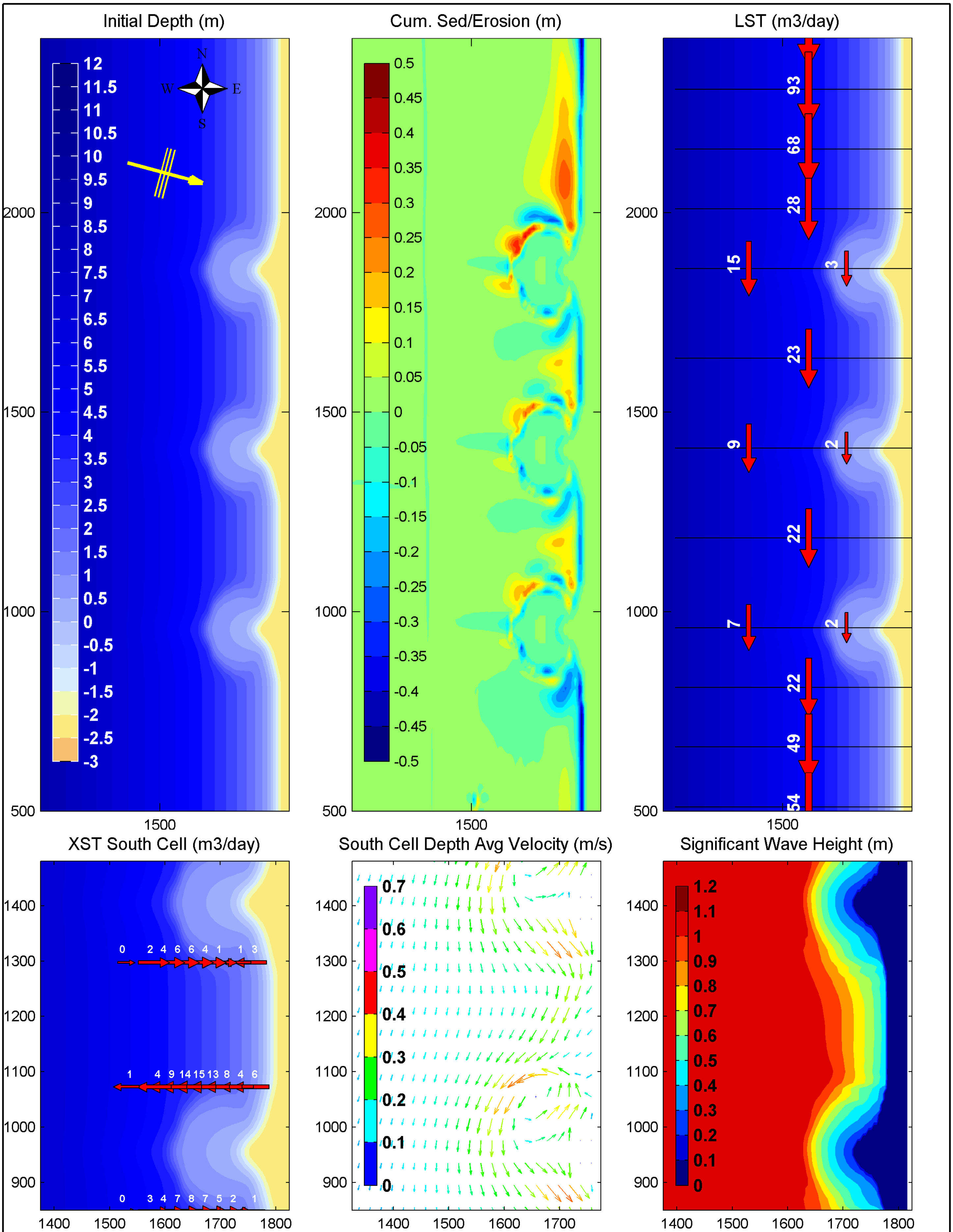
FORCING: Hs 1.0m, Tp 6s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

RUN ID#	F09
PEAK PERIOD	
DATE	23/05/2012

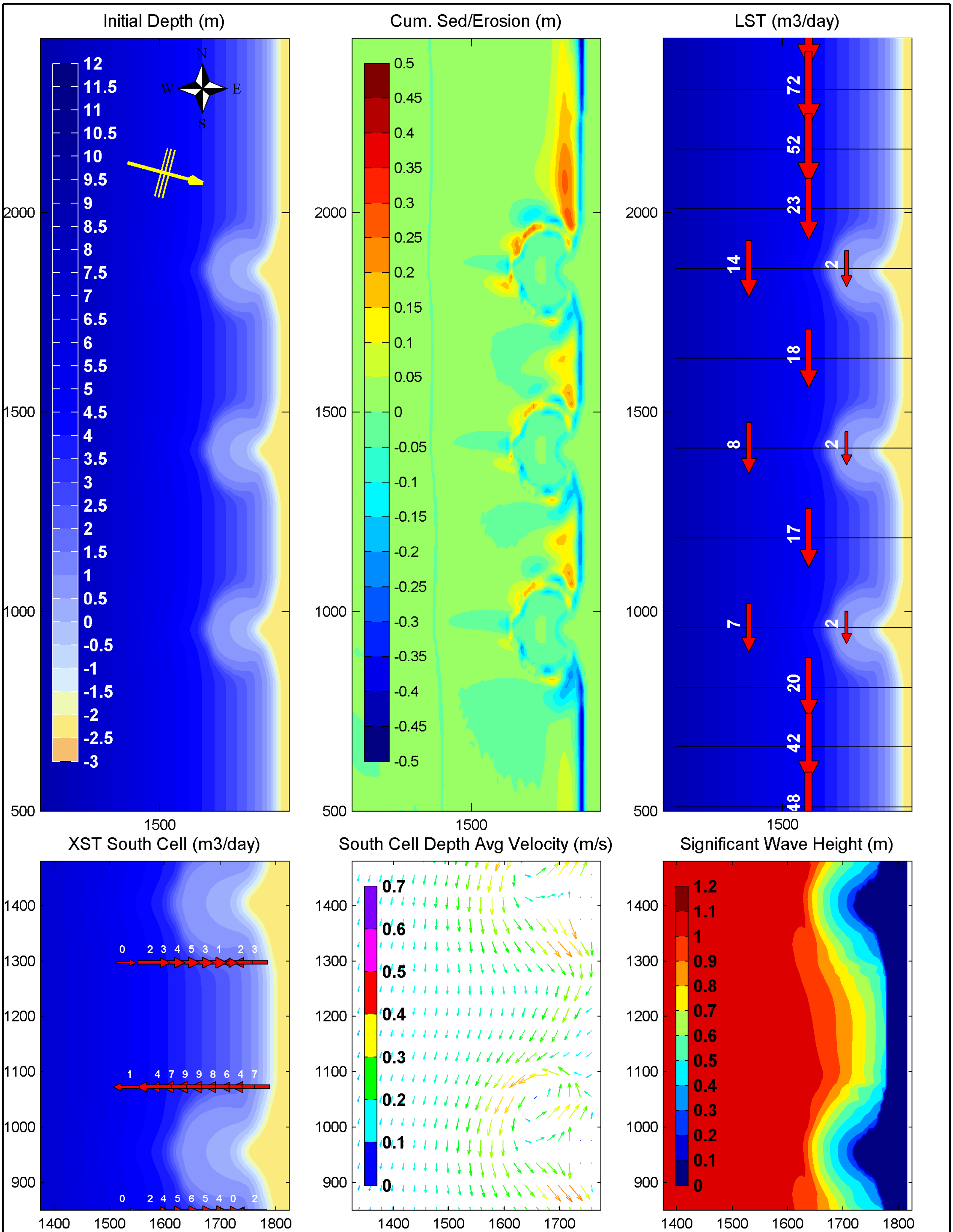
Deltares
Delft Hydraulics



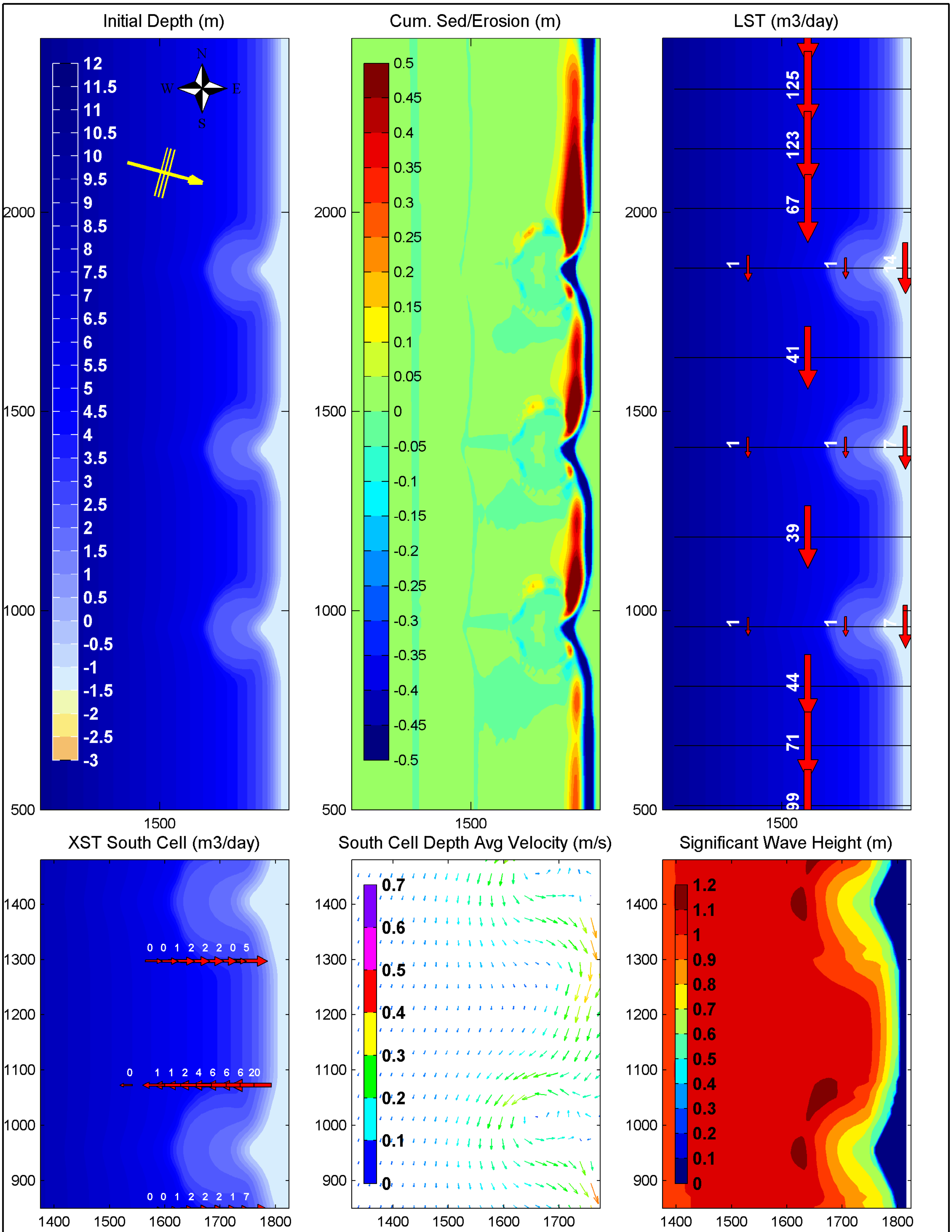
FORCING: Hs 1.0m, Tp 8s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F10
	PEAK PERIOD	
Deltares Delft Hydraulics	DATE	23/05/2012



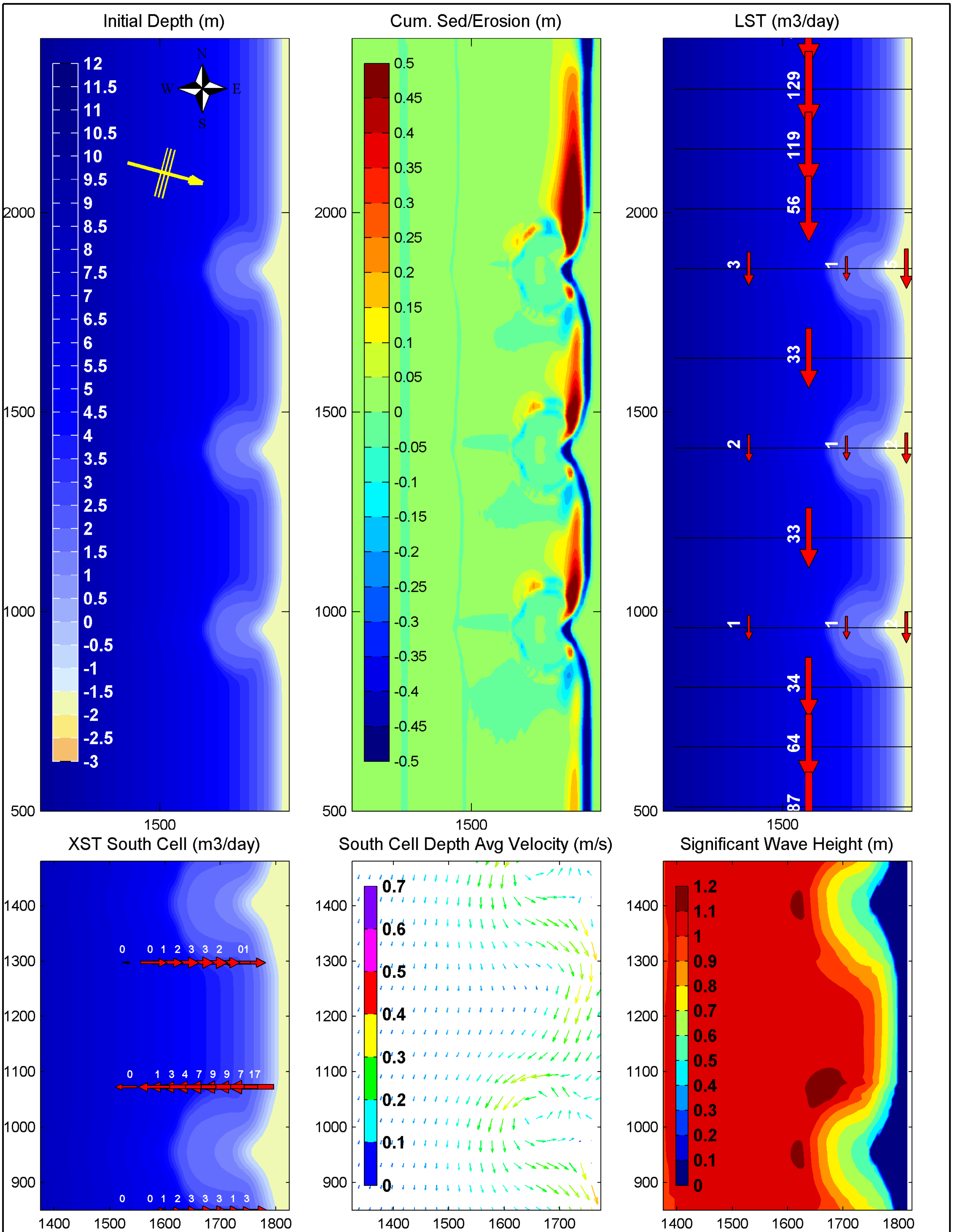
FORCING: Hs 1.0m, Tp 12s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F11
	PEAK PERIOD	
Deltares Delft Hydraulics	DATE	23/05/2012



FORCING: Hs 1.0m, Tp 14s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F12
	PEAK PERIOD	
	DATE	23/05/2012



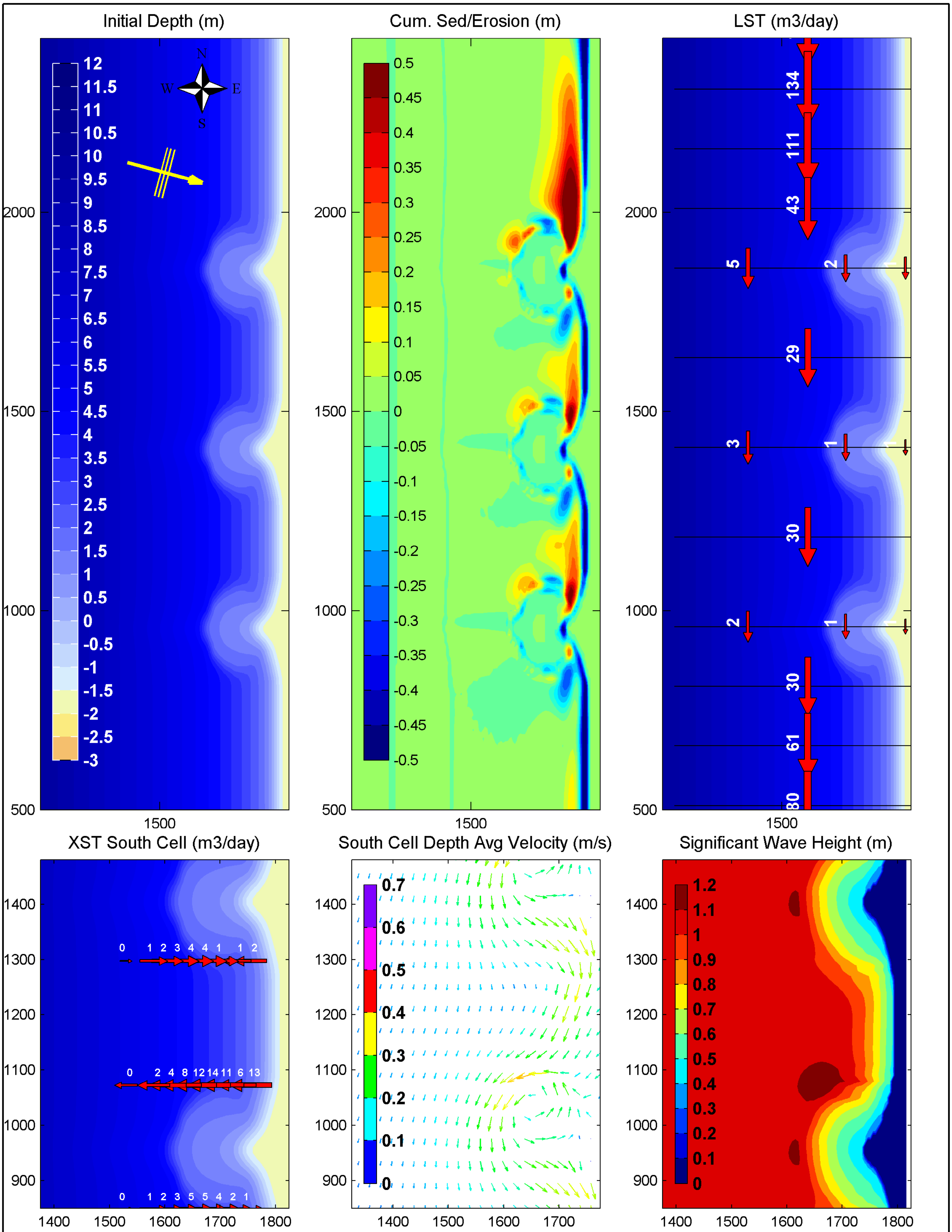
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR +1.55m, Reef rgh 20 (Chézy)	RUN ID#	F13
	SEA LEVEL	
Deltares Delft Hydraulics	DATE	23/05/2012



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR +1.15m, Reef rgh 20 (Chézy)

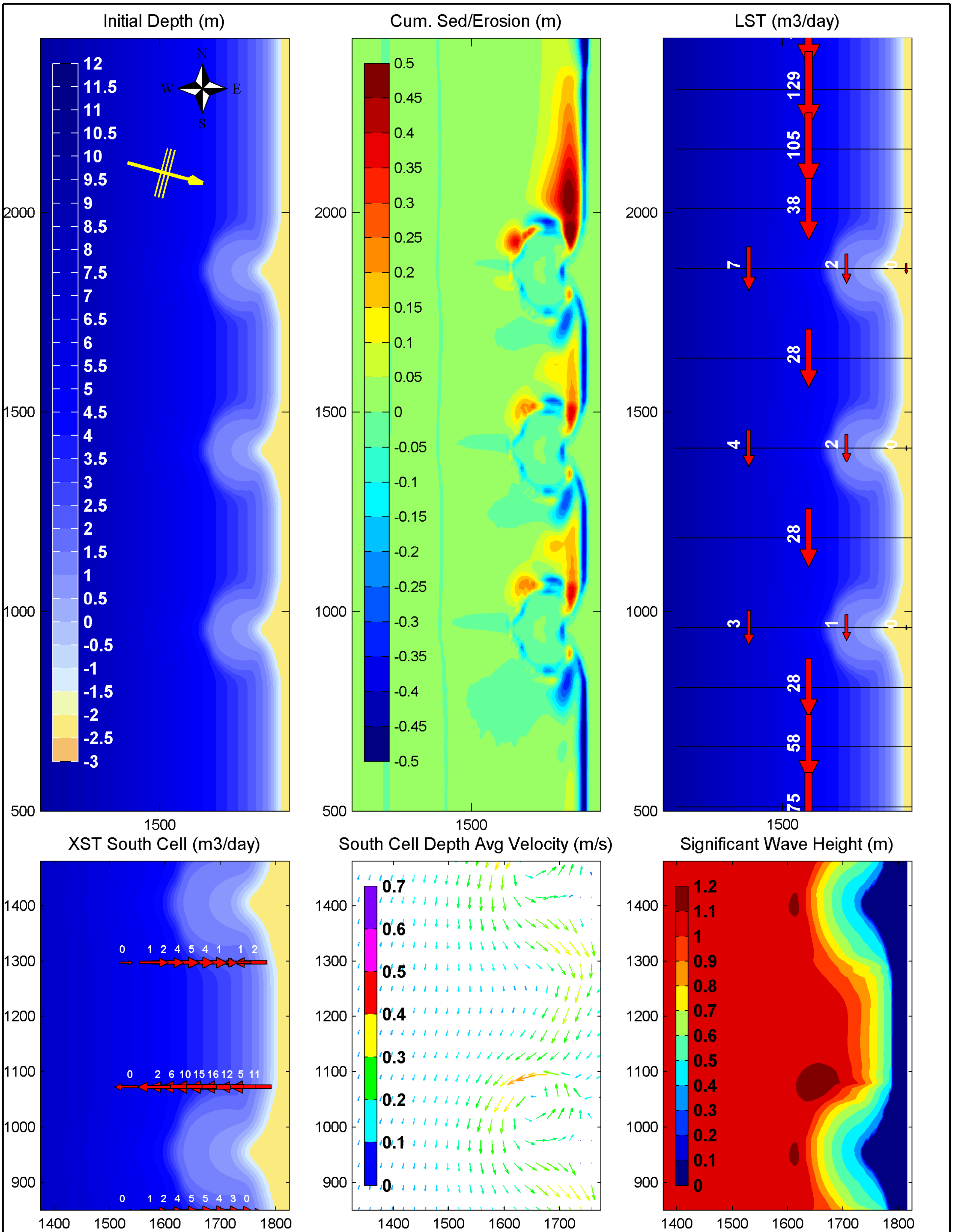
RUN ID#	F14
SEA LEVEL	
DATE	23/05/2012

Deltares
Delft Hydraulics

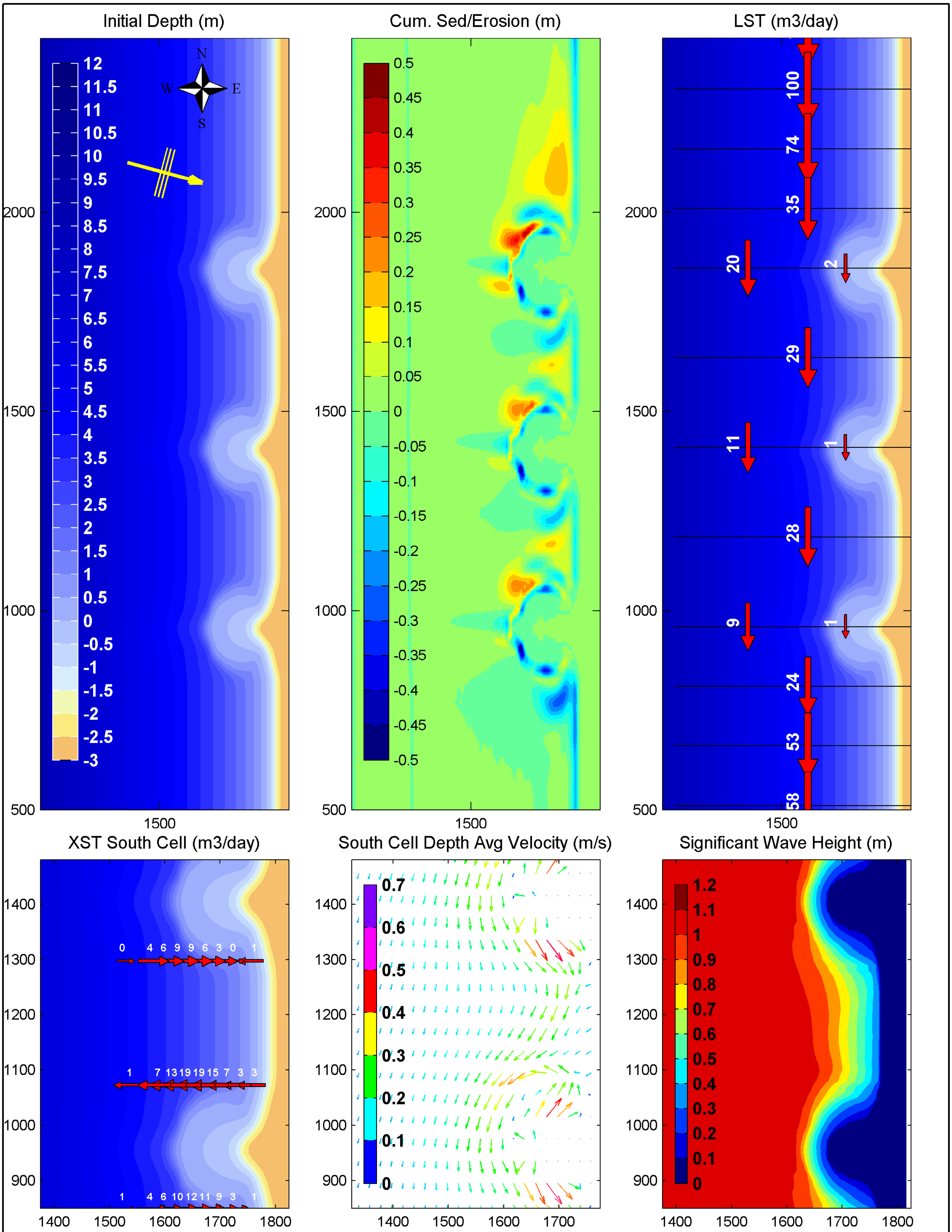


FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR +0.75m, Reef rgh 20 (Chézy)

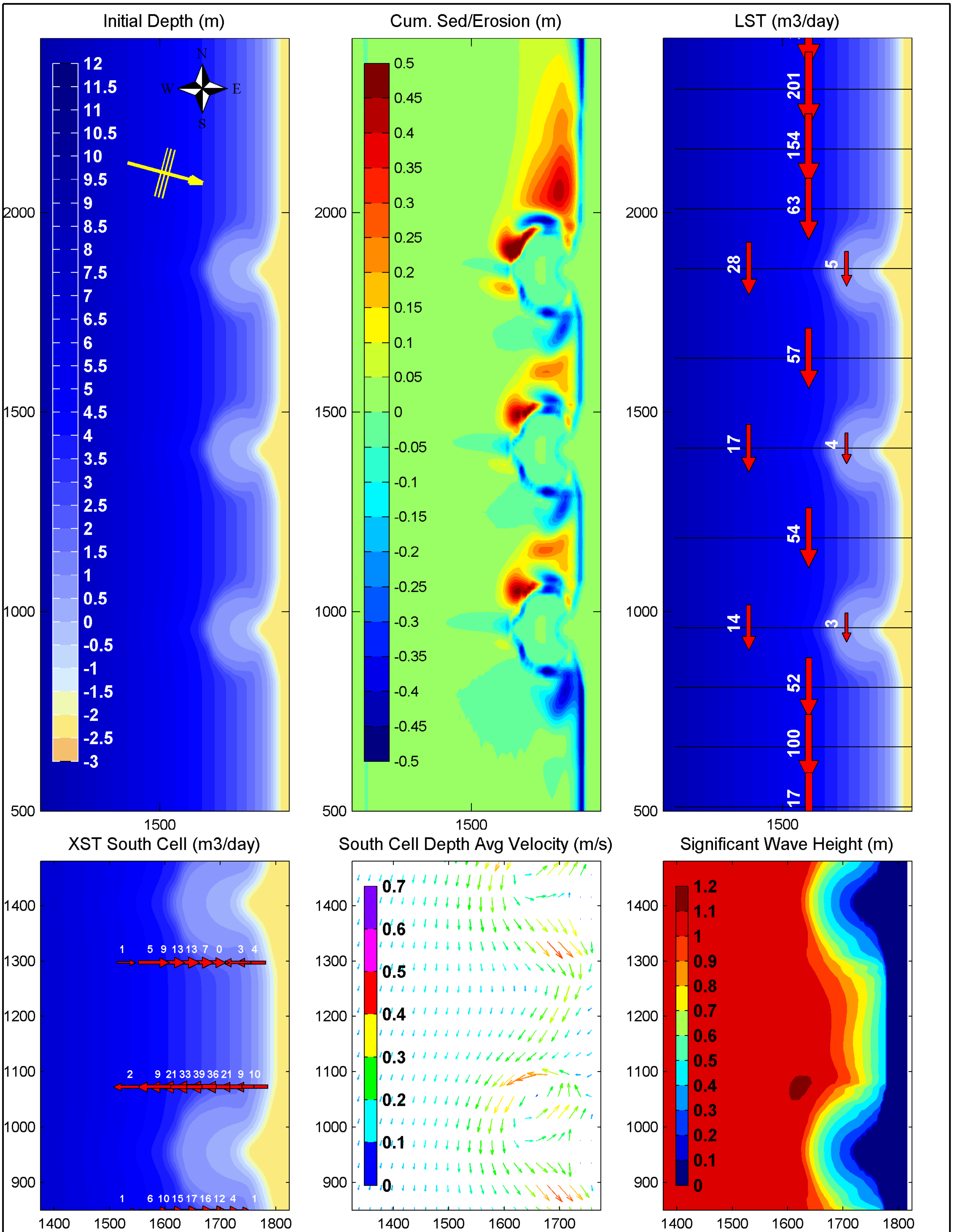
RUN ID#	F15
SEA LEVEL	
DATE	23/05/2012



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR +0.55m, Reef rgh 20 (Chézy)	RUN ID#	F16
	SEA LEVEL	
Deltares Delft Hydraulics	DATE	23/05/2012

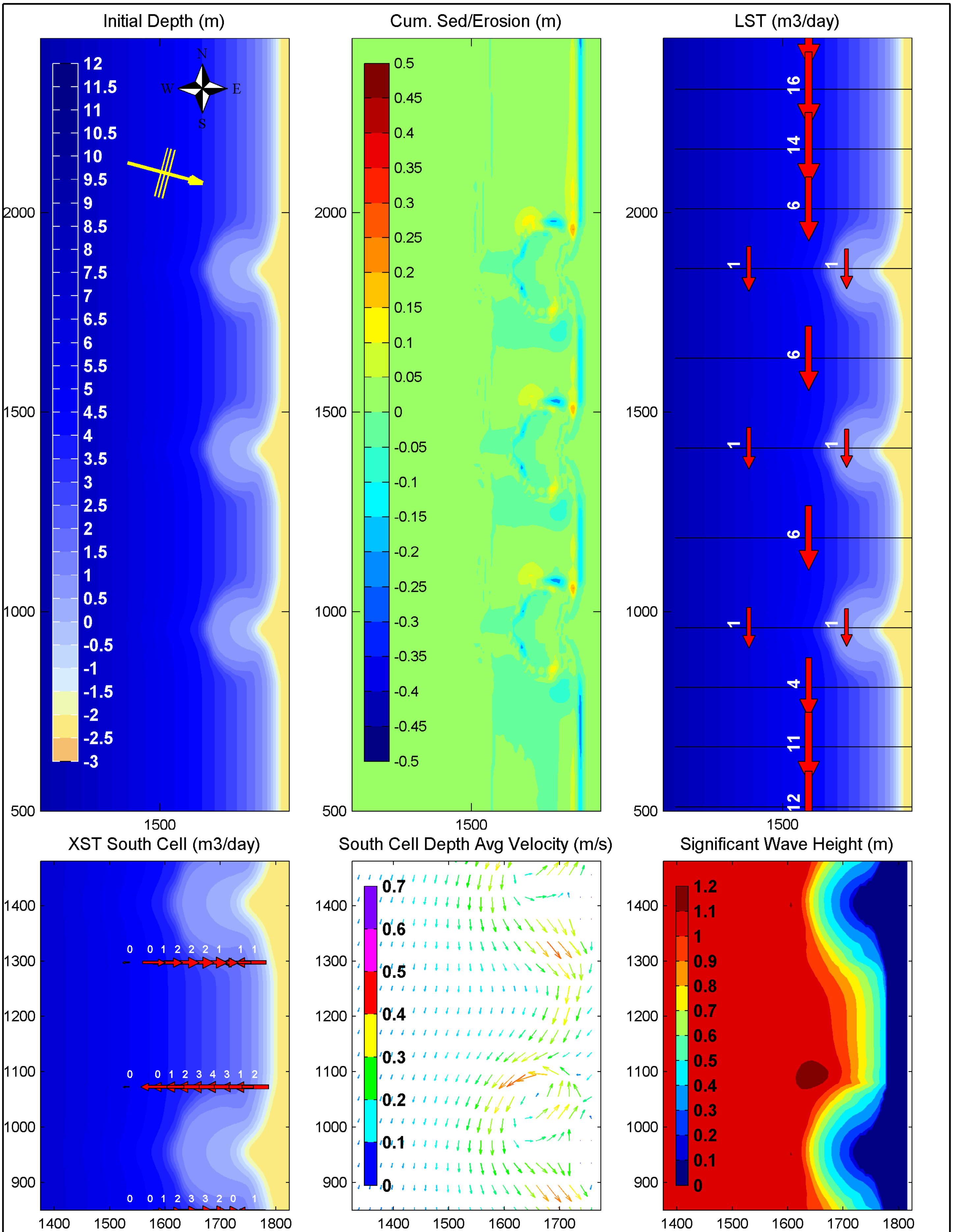


FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR -0.55m, Reef rgh 20 (Chézy)	RUN ID#	F17
	SEA LEVEL	
Deltares Delft Hydraulics	DATE	23/05/2012

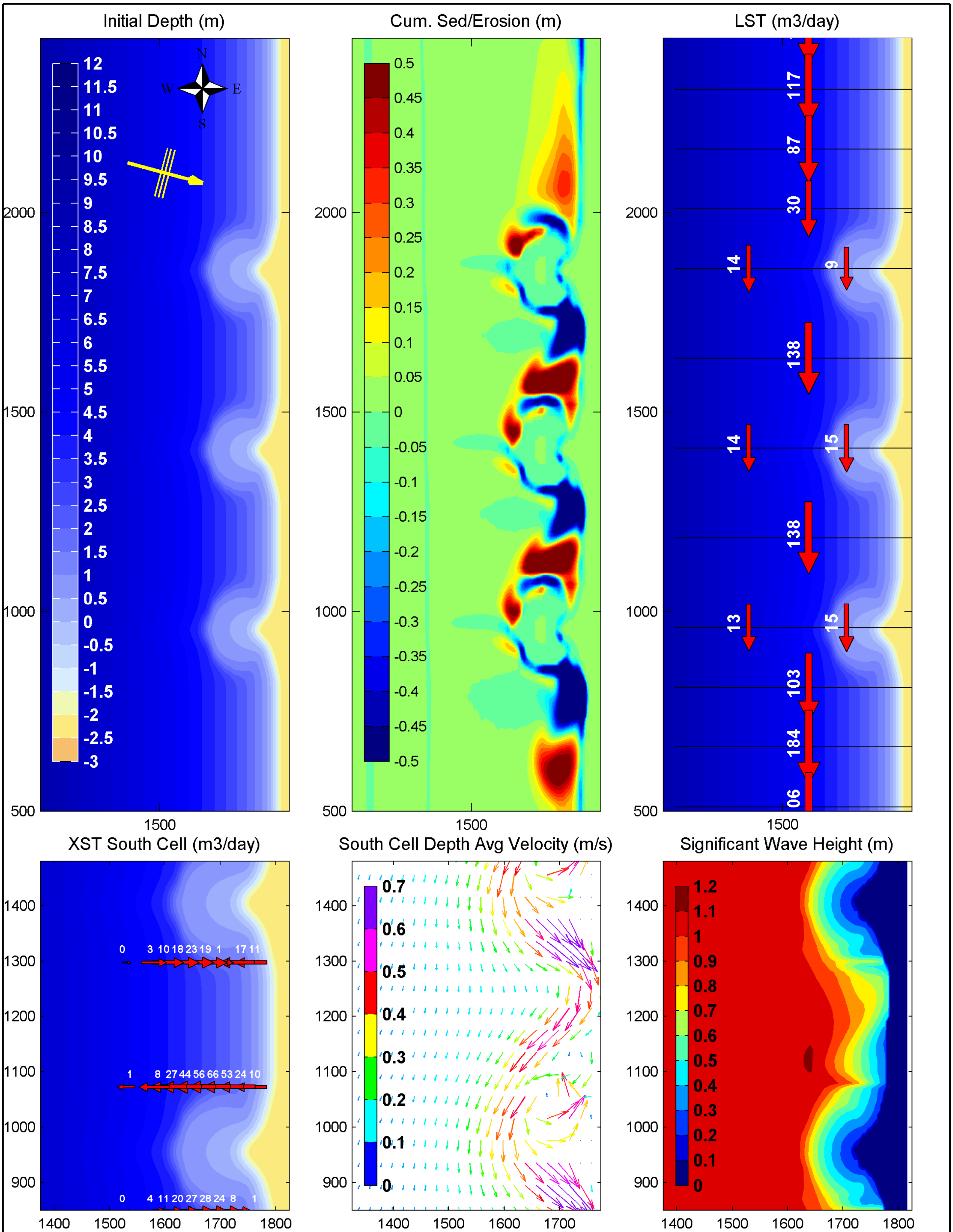


FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 275um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

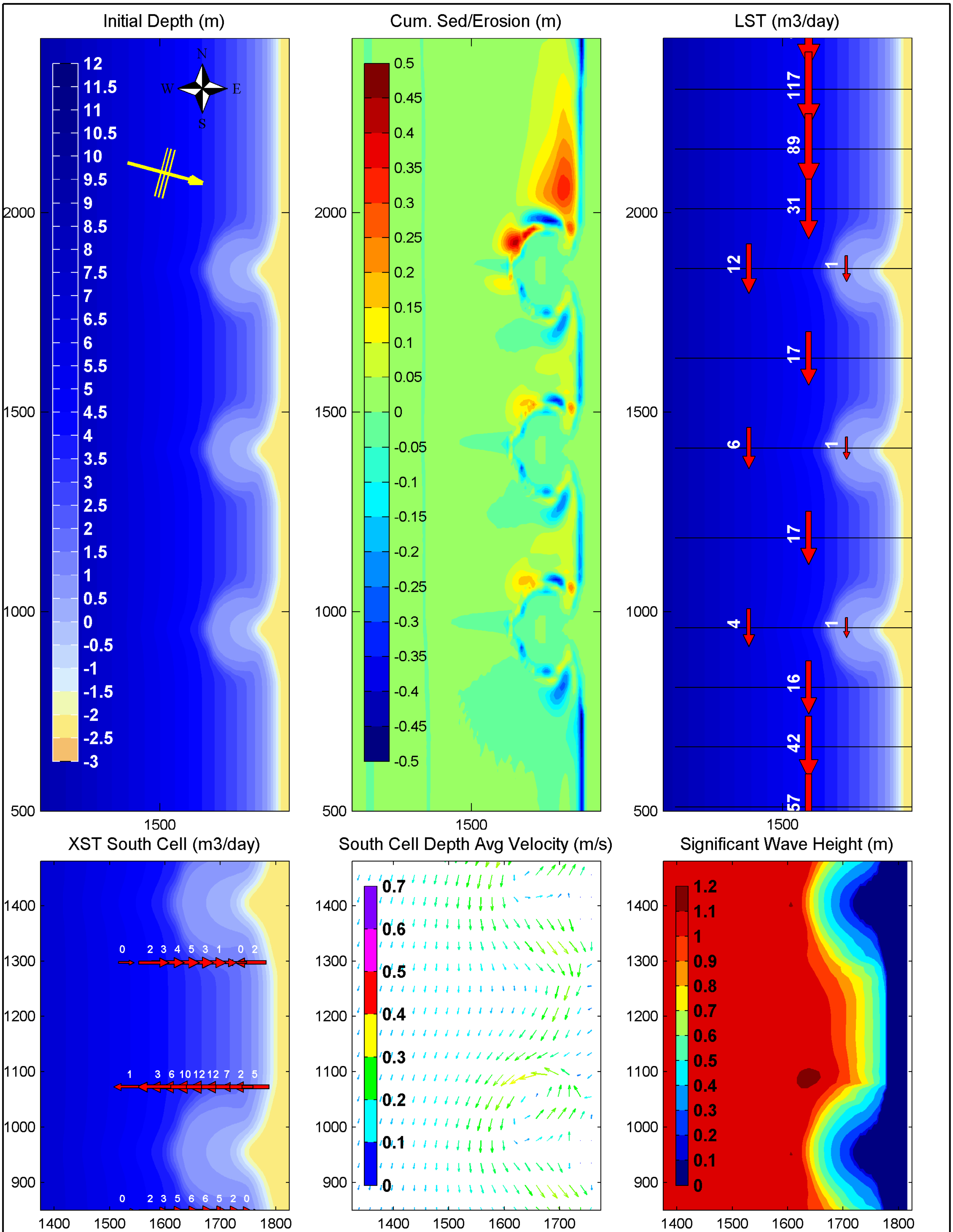
RUN ID#	F18
SEDIMENT DIAMETER	
DATE	23/05/2012



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 475um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	F19
	SEDIMENT DIAMETER	
Deltares Delft Hydraulics	DATE	23/05/2012



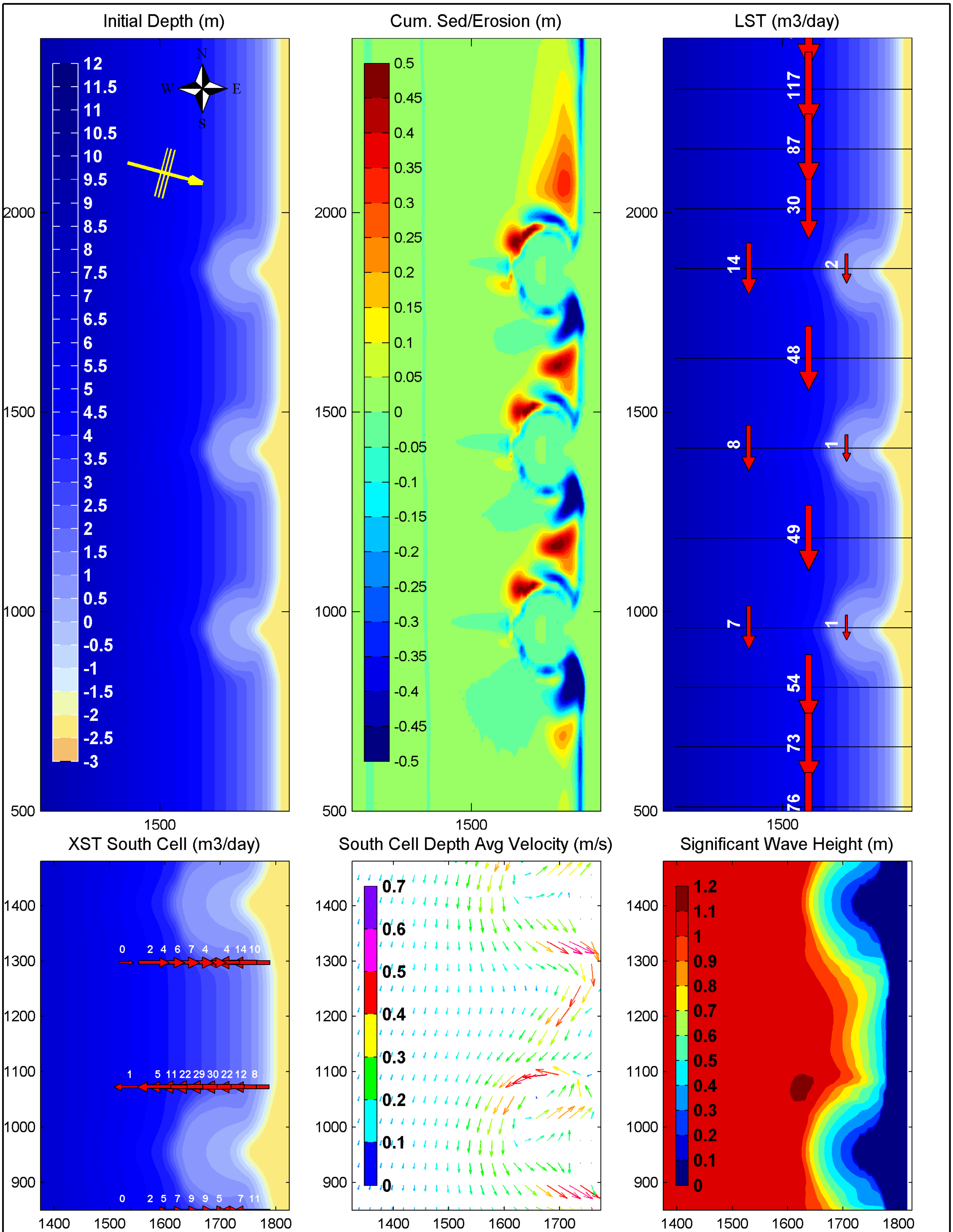
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.100 MISC: SLR 0.0m, Reef rgh 45 (Chézy)	RUN ID# F20
	REEF ROUGHNESS
Deltares Delft Hydraulics	DATE 25/05/2012



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR 0.0m, Reef rgh 15 (Chézy)

RUN ID#	F21
REEF ROUGHNESS	
DATE	23/05/2012

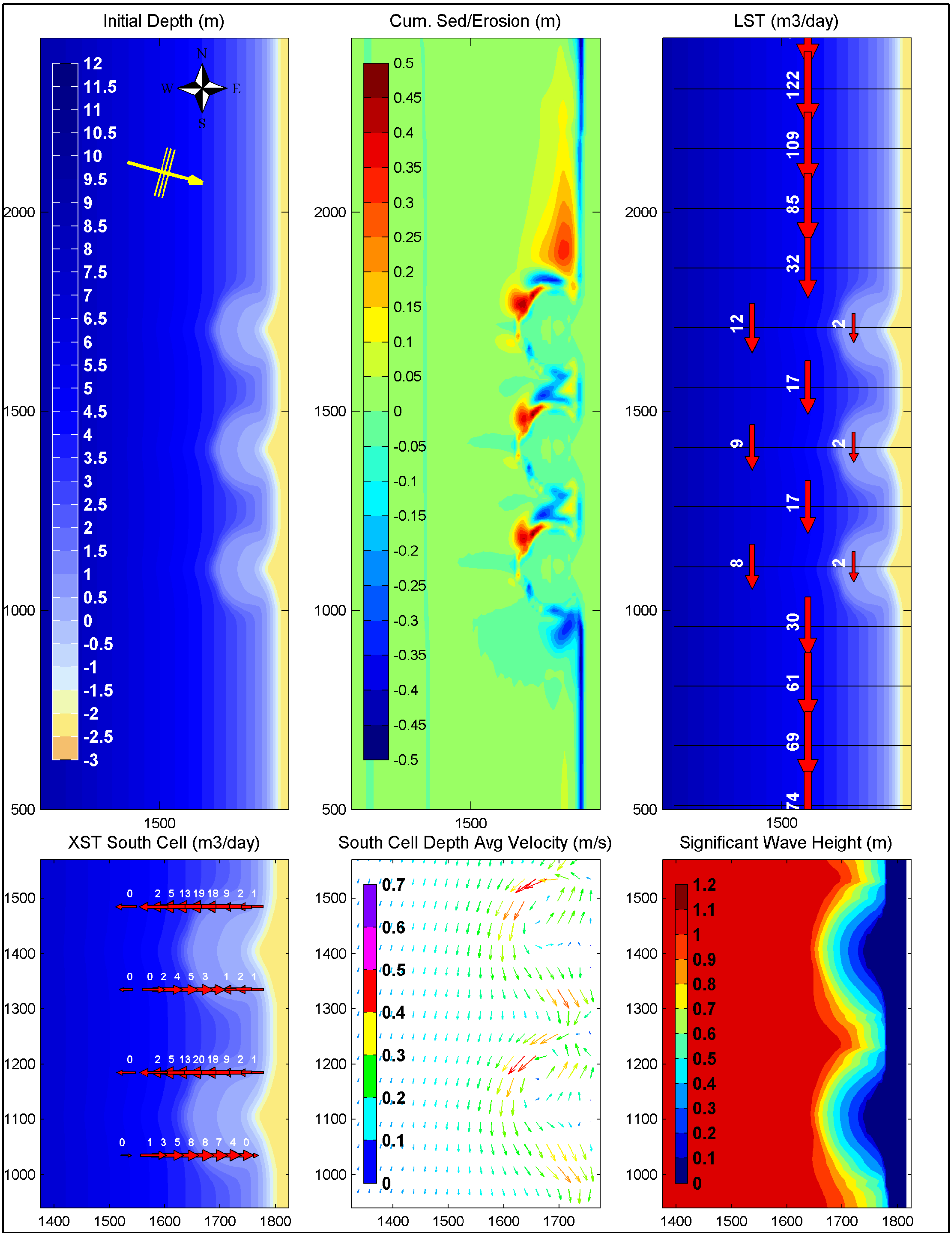
Deltares
Delft Hydraulics



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 200.100
MISC: SLR 0.0m, Reef rgh 45,15 (Chézy)

RUN ID#	F22
REEF ROUGHNESS	
DATE	23/05/2012

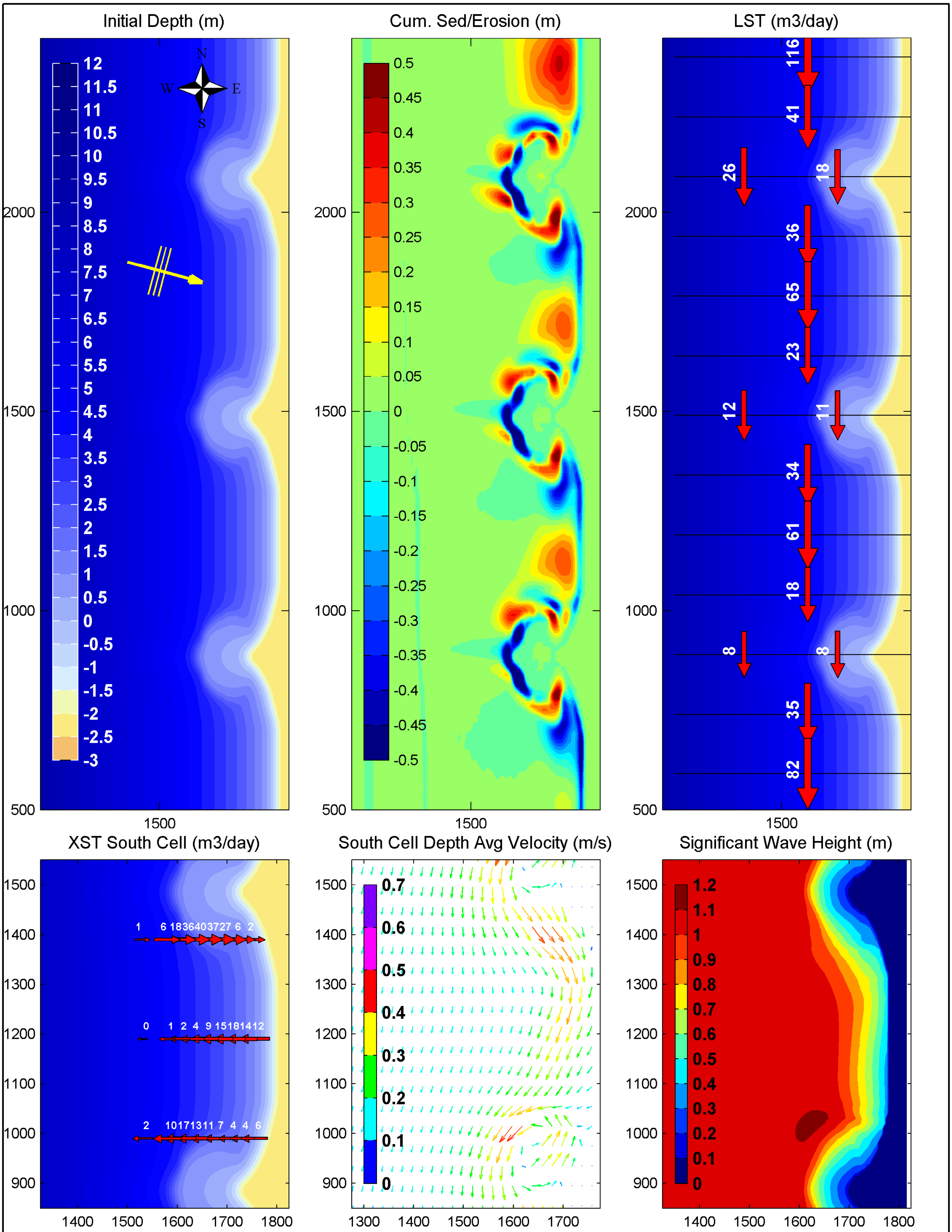
Deltares
Delft Hydraulics



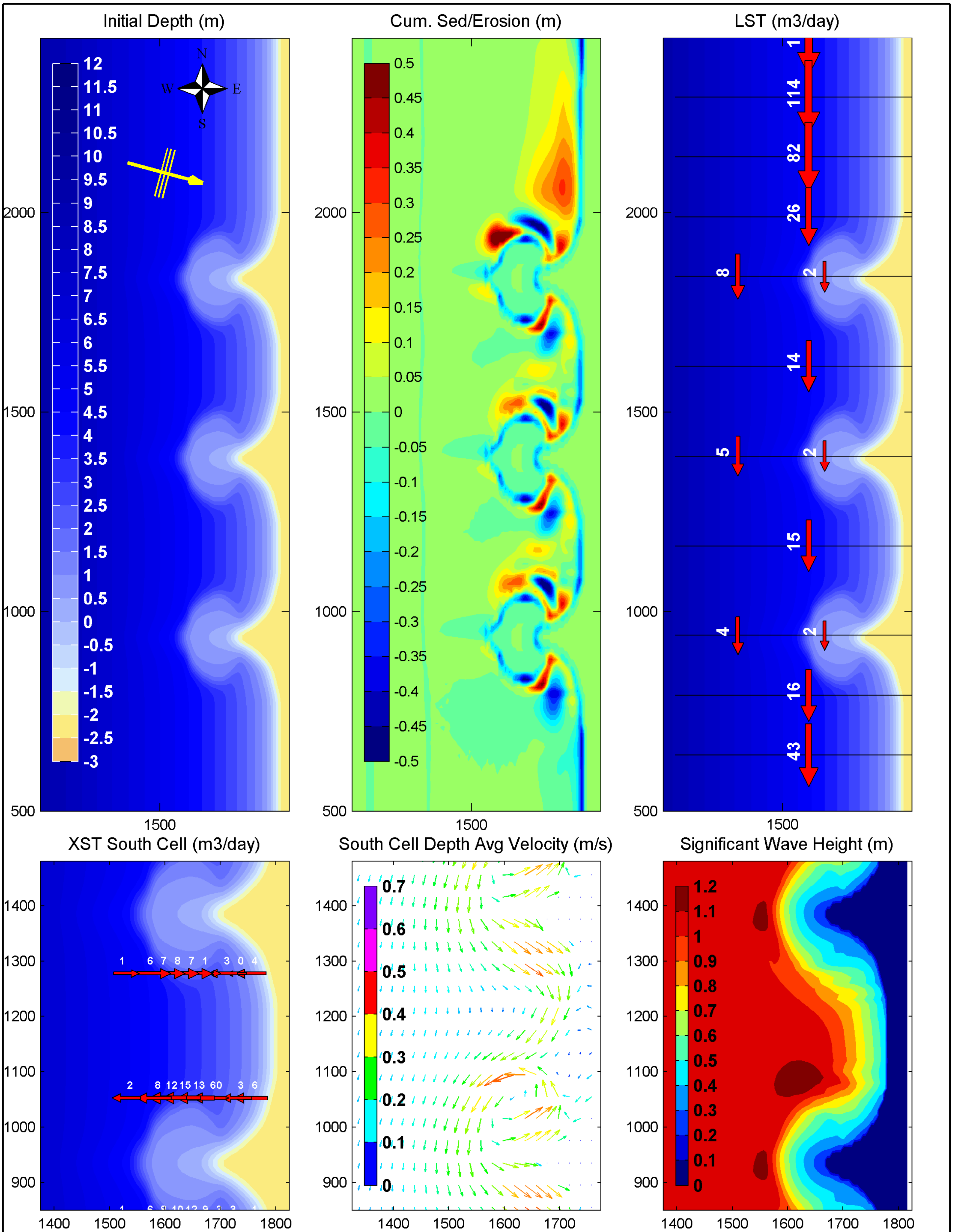
FORCING: Hs 1m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Bay 300.040, Reef 200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

RUN ID#	G01
BAY SIZE	
DATE	24/05/2012

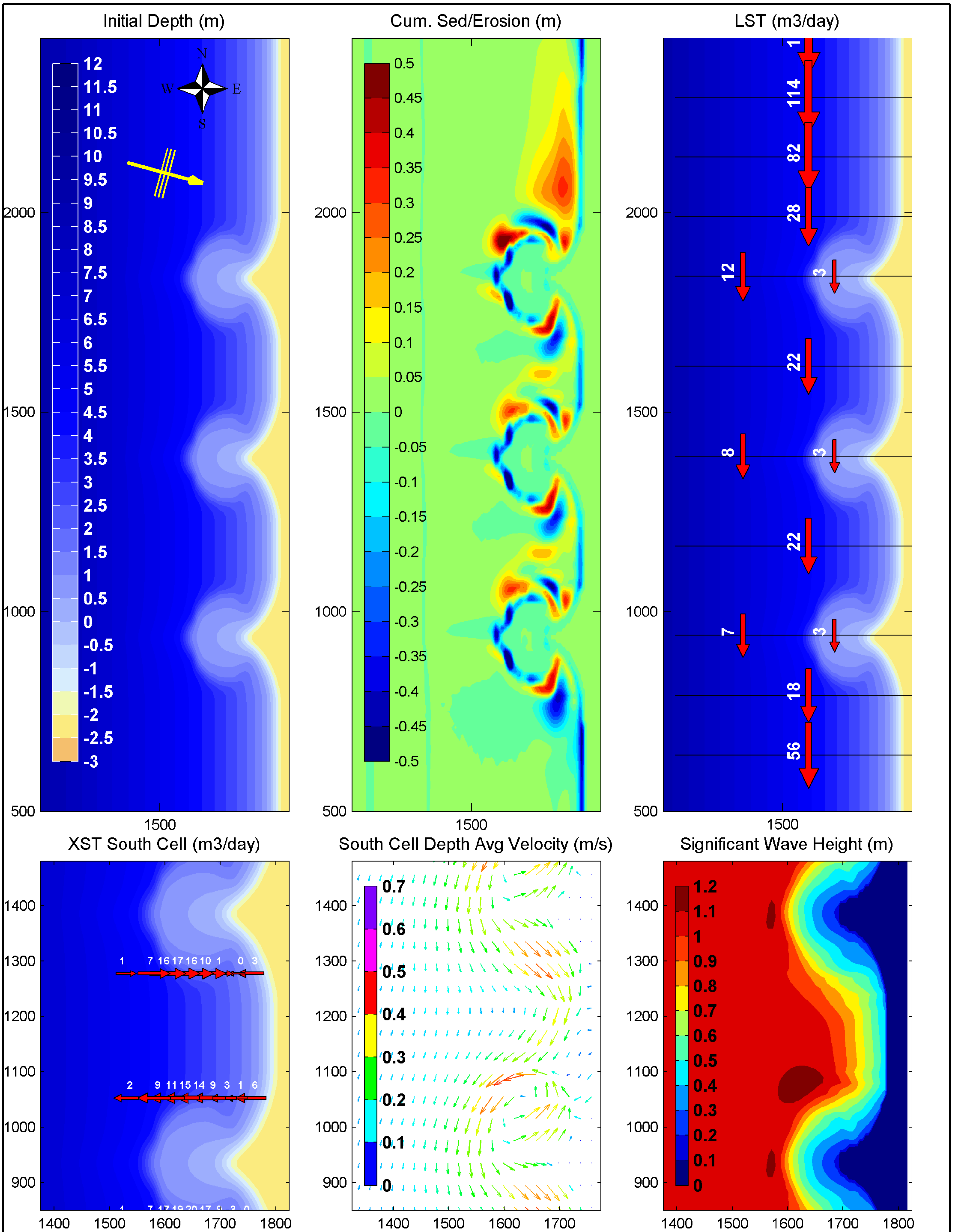
Deltares
Delft Hydraulics



FORCING: Hs 1m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 600.080, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G03
	BAY SIZE	
Deltares Delft Hydraulics	DATE	24/05/2012

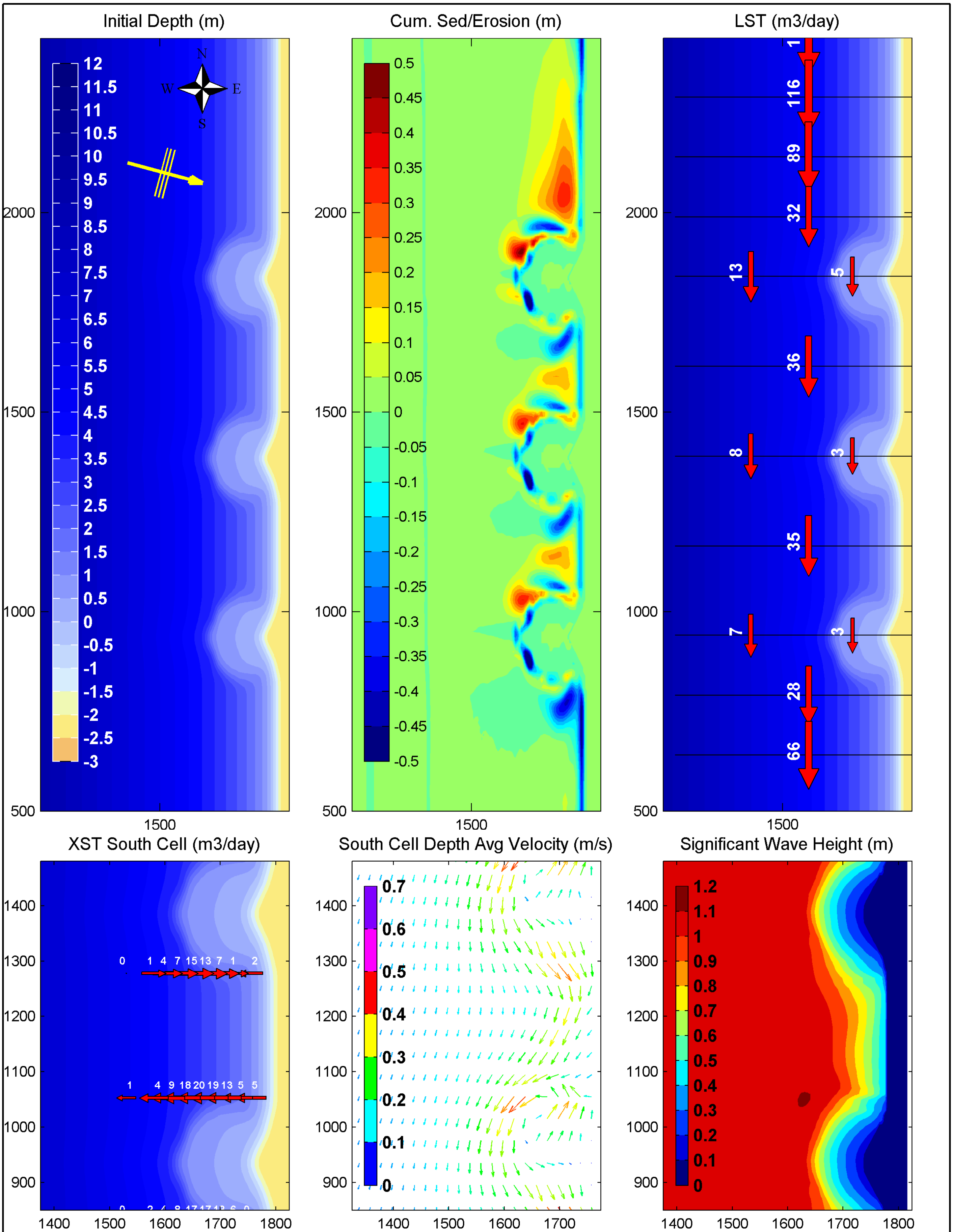


FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.115, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G05
	BAY RATIO	
Deltares Delft Hydraulics	DATE	25/05/2012

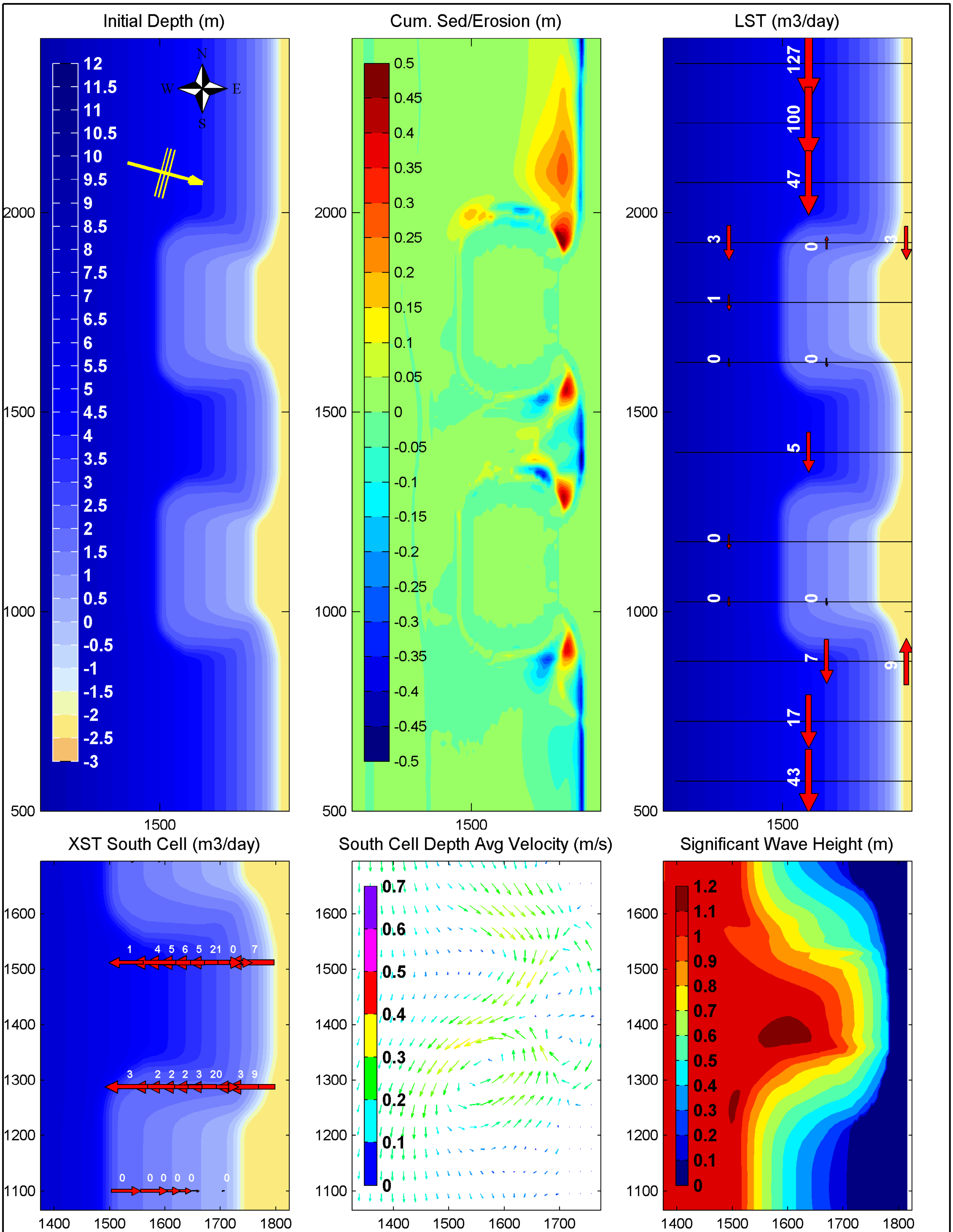


FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.90, Reef 200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

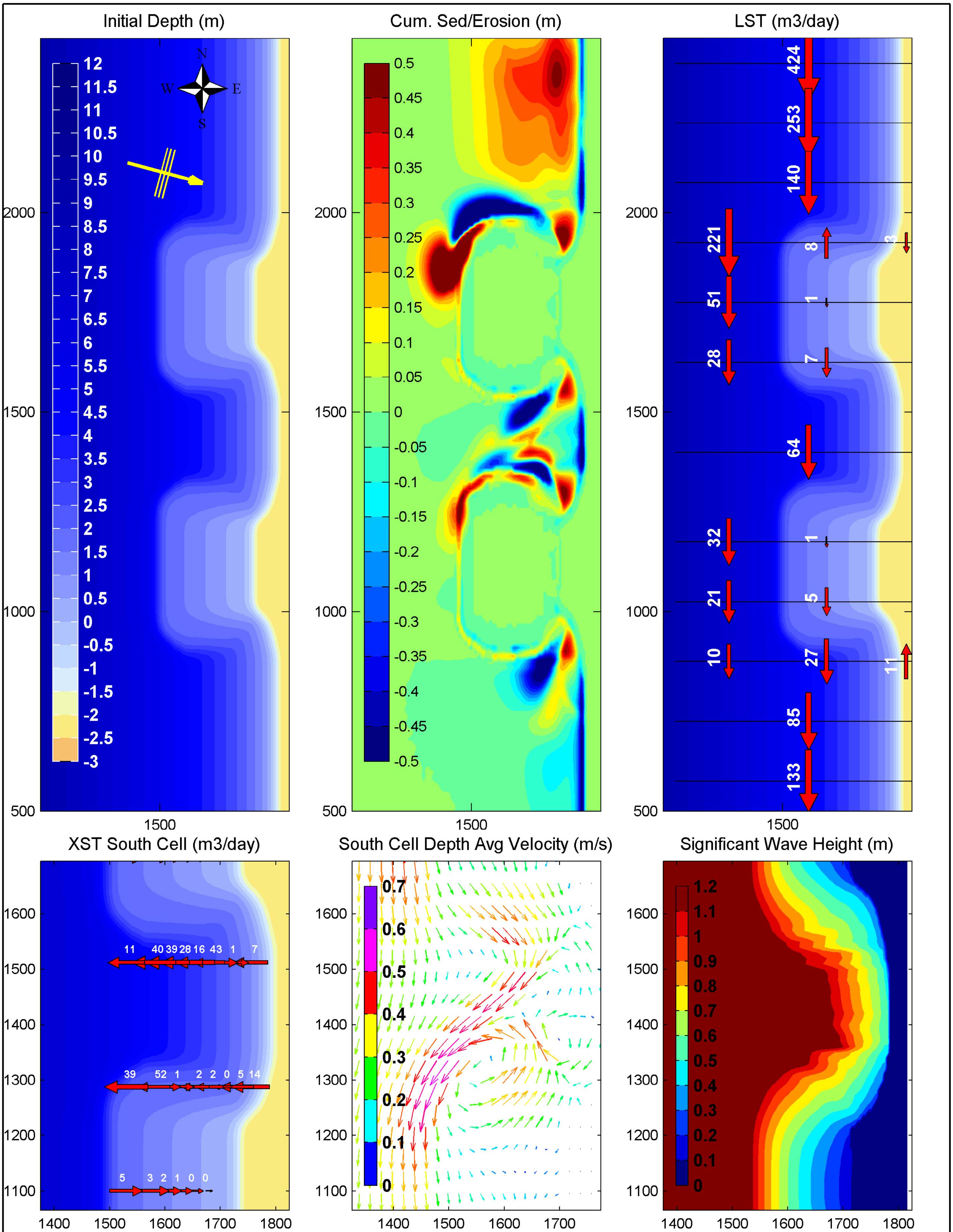
RUN ID#	G06
BAY RATIO	
DATE	25/05/2012



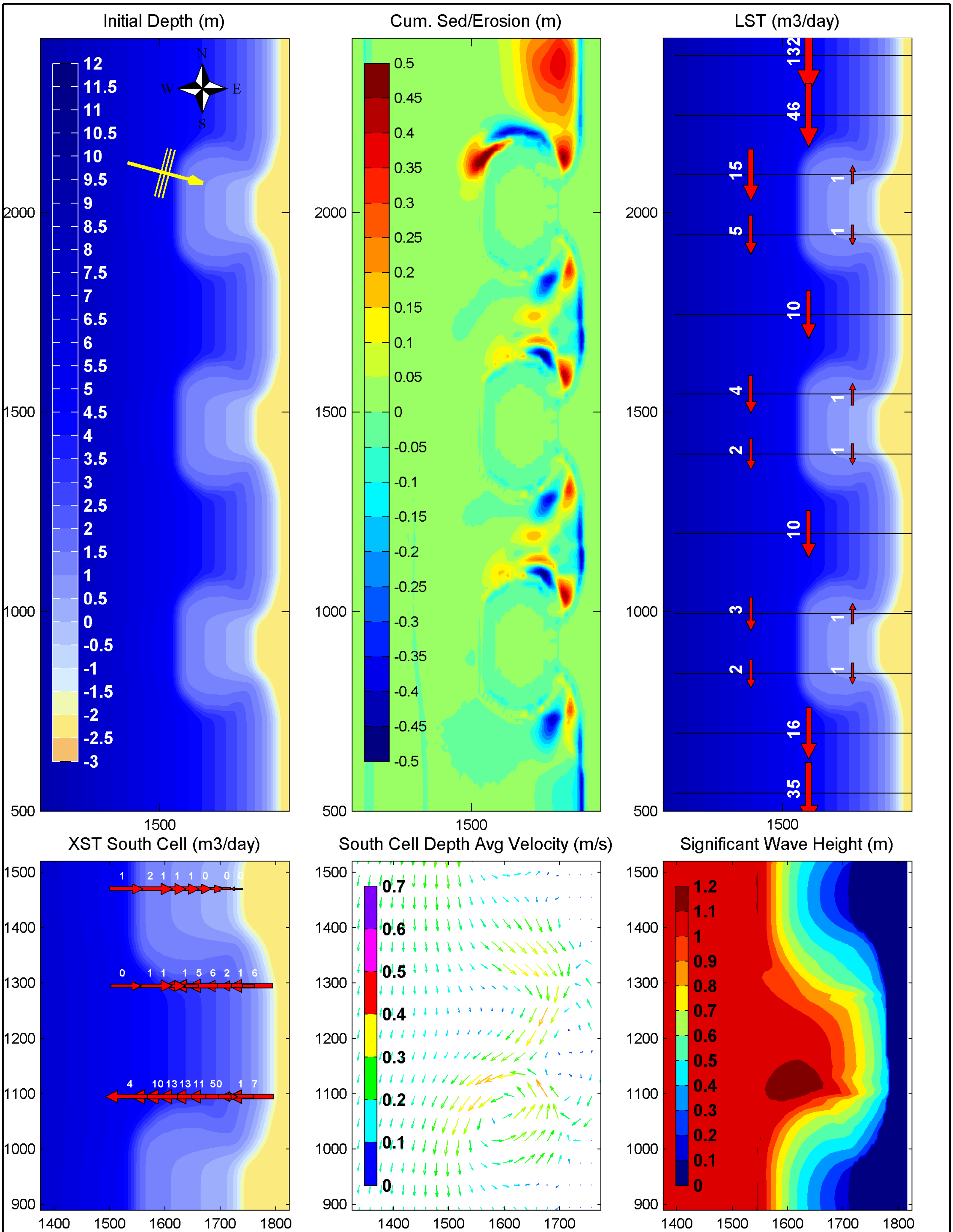
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.40, Reef 200.100 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G07
	BAY RATIO	
Deltares Delft Hydraulics	DATE	25/05/2012



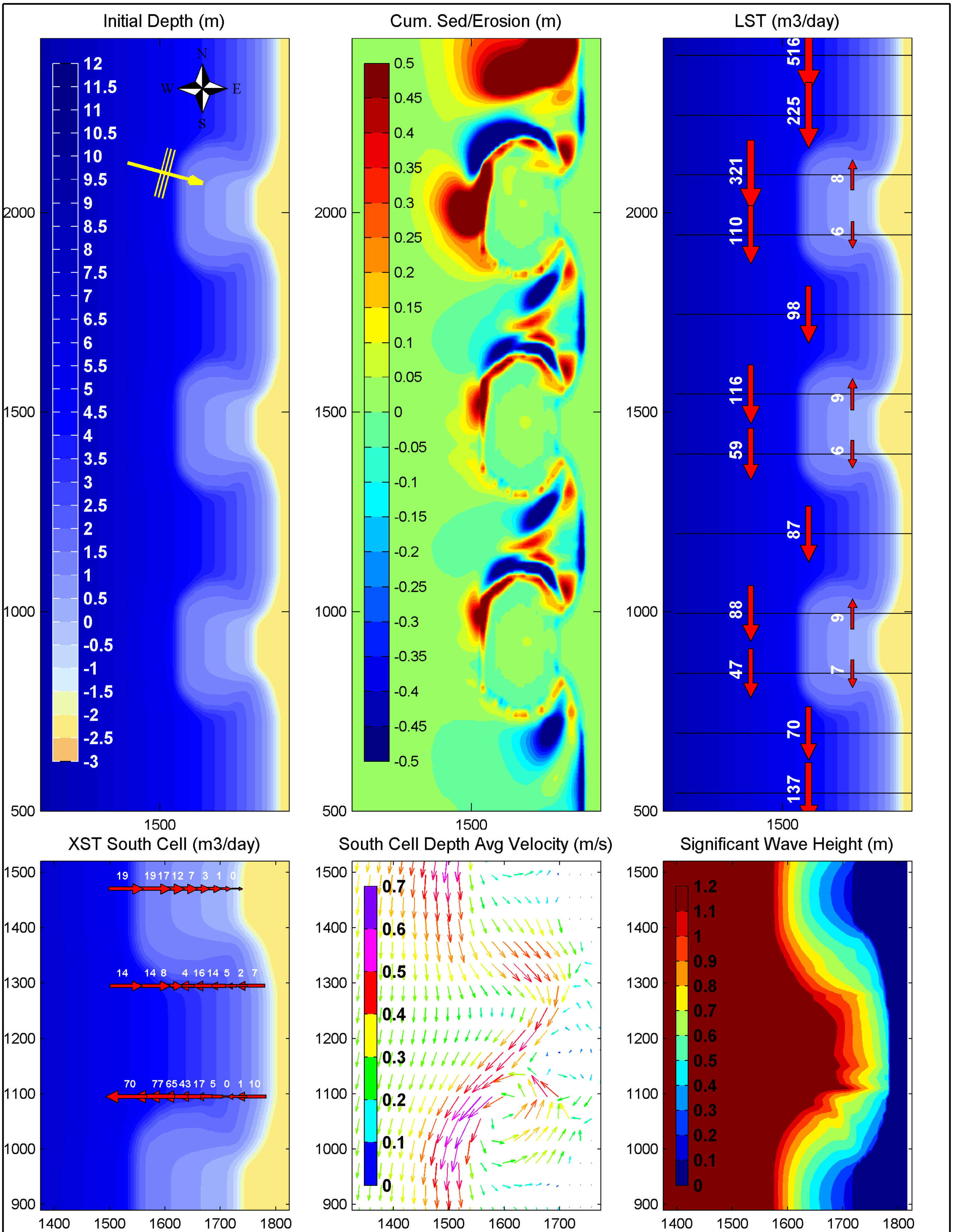
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 400.200 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID# G08
	REEF SIZE
Deltares Delft Hydraulics	DATE 25/05/2012



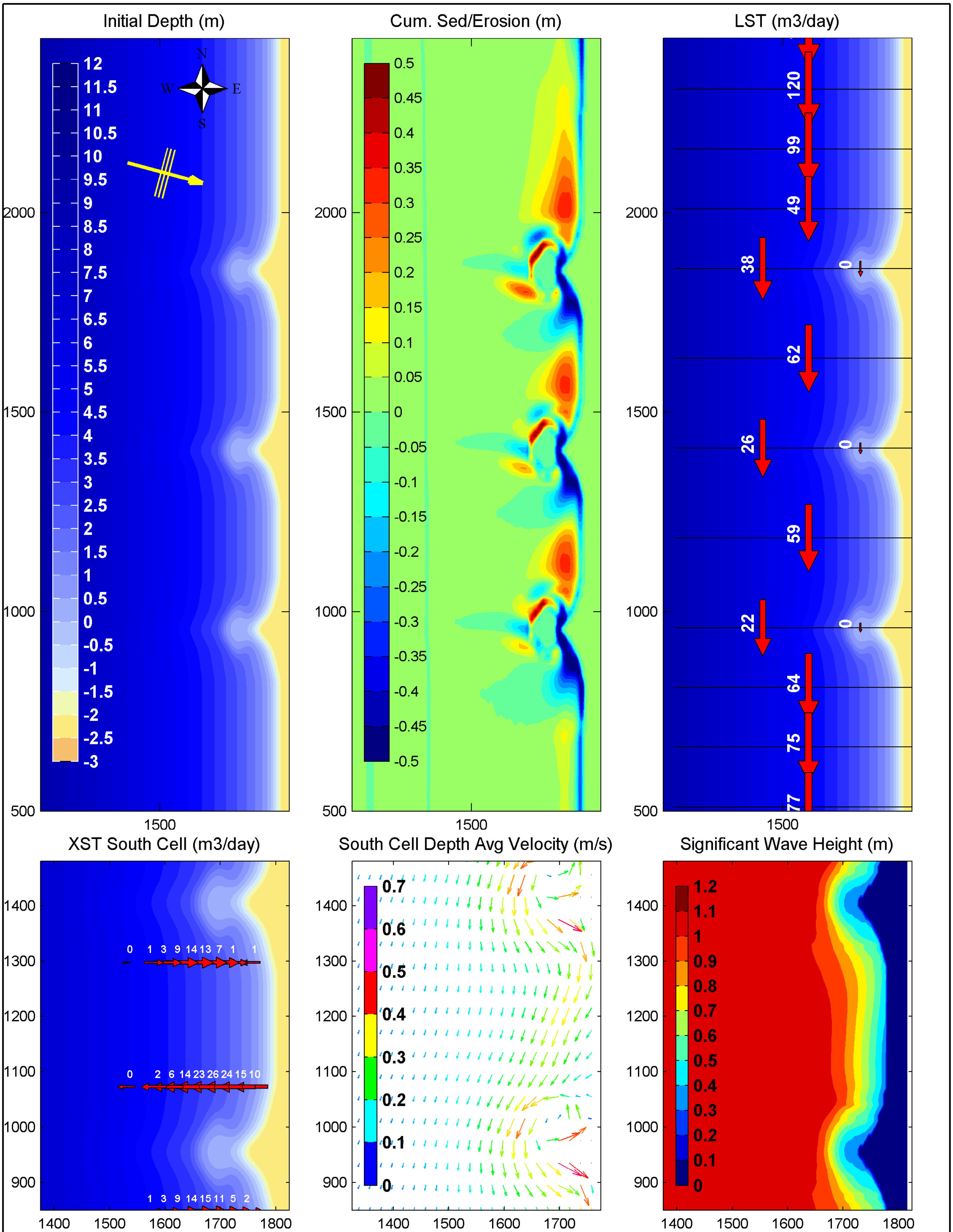
FORCING: Hs 1.5m, Tp 12s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 400.200 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G08a
	REEF SIZE	
	DATE	25/05/2012



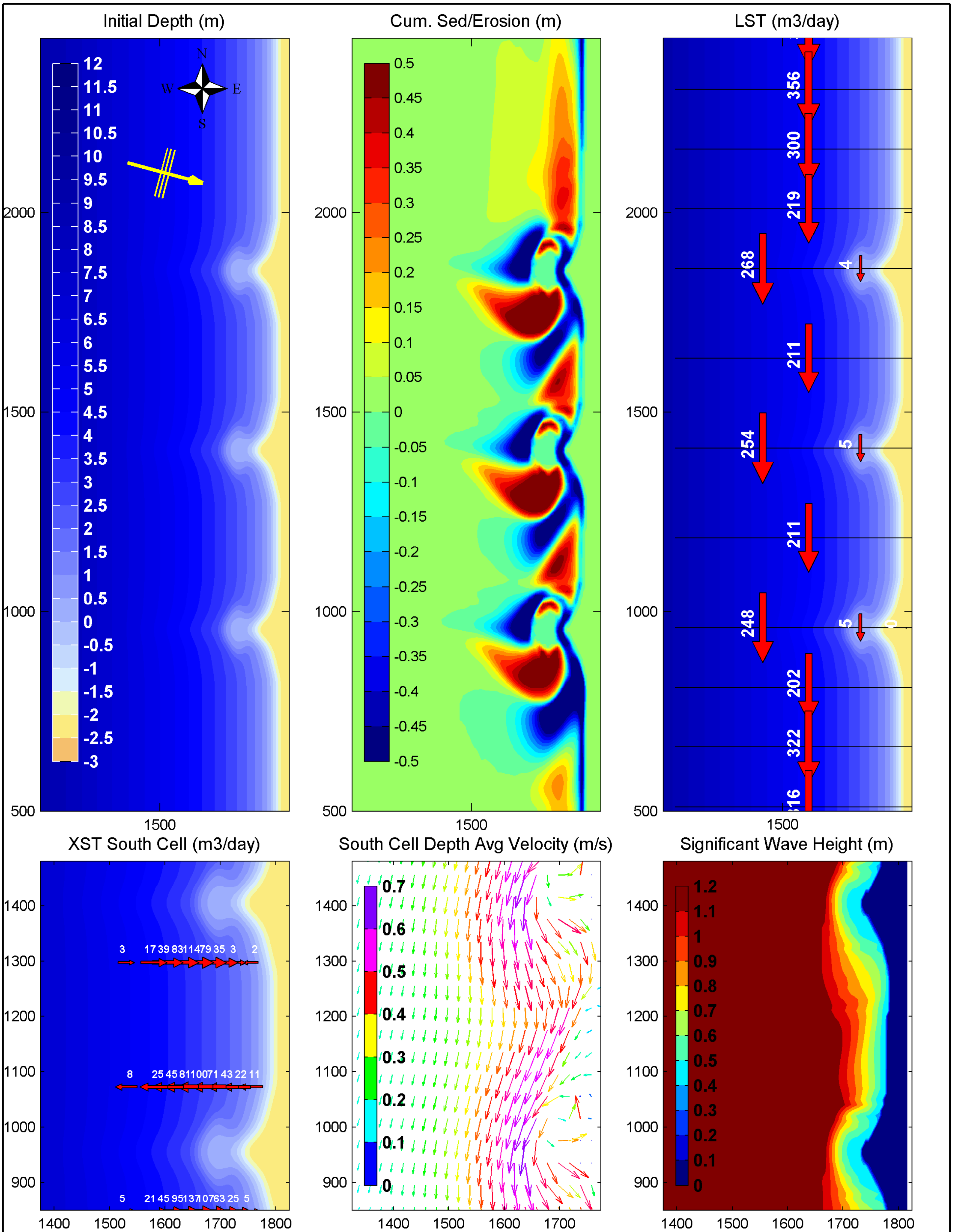
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 300.150 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G09
	REEF SIZE	
Deltares Delft Hydraulics	DATE	25/05/2012



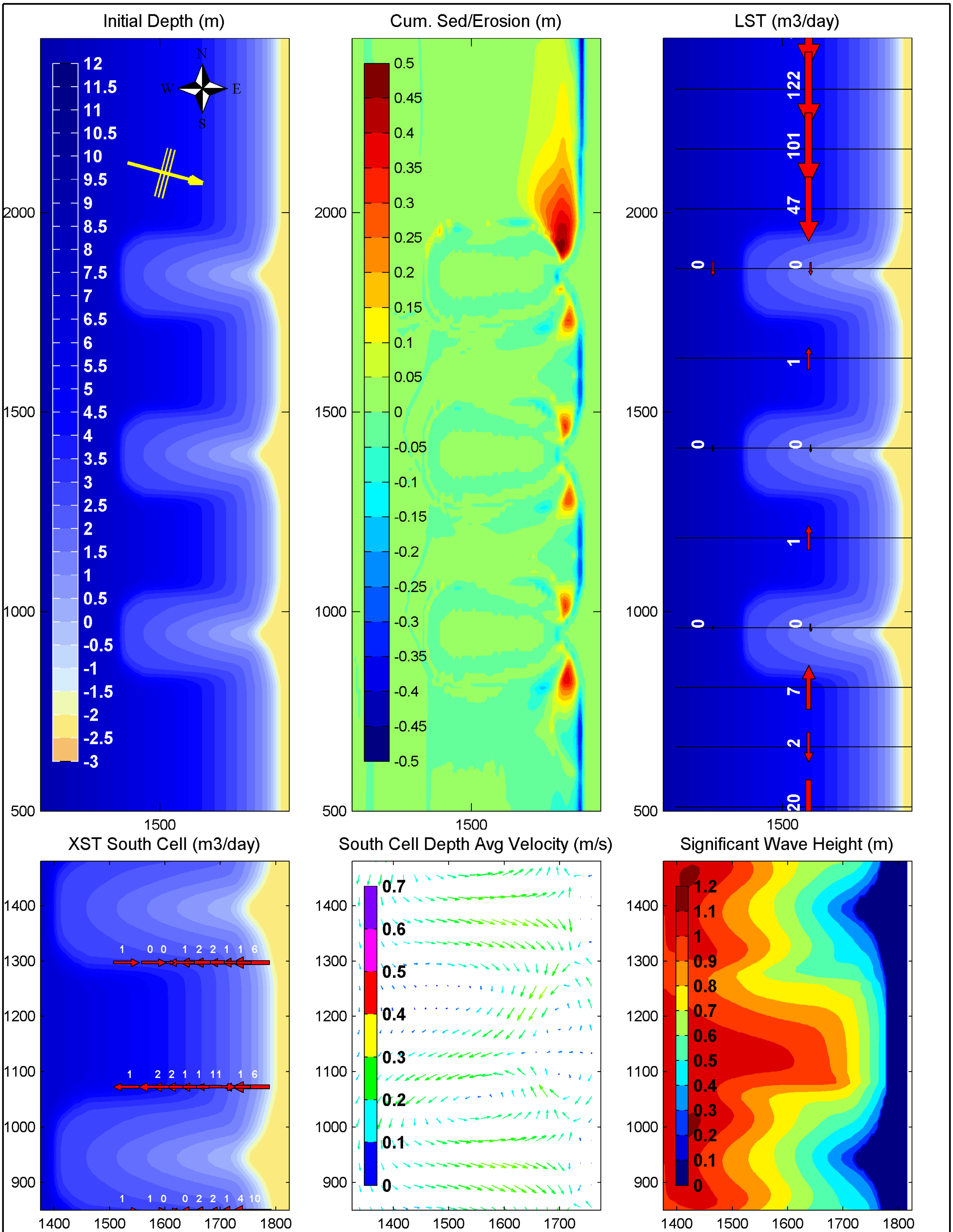
FORCING: Hs 1.5m, Tp 12s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 300.150 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G09a
	REEF SIZE	
Deltares Delft Hydraulics	DATE	25/05/2012



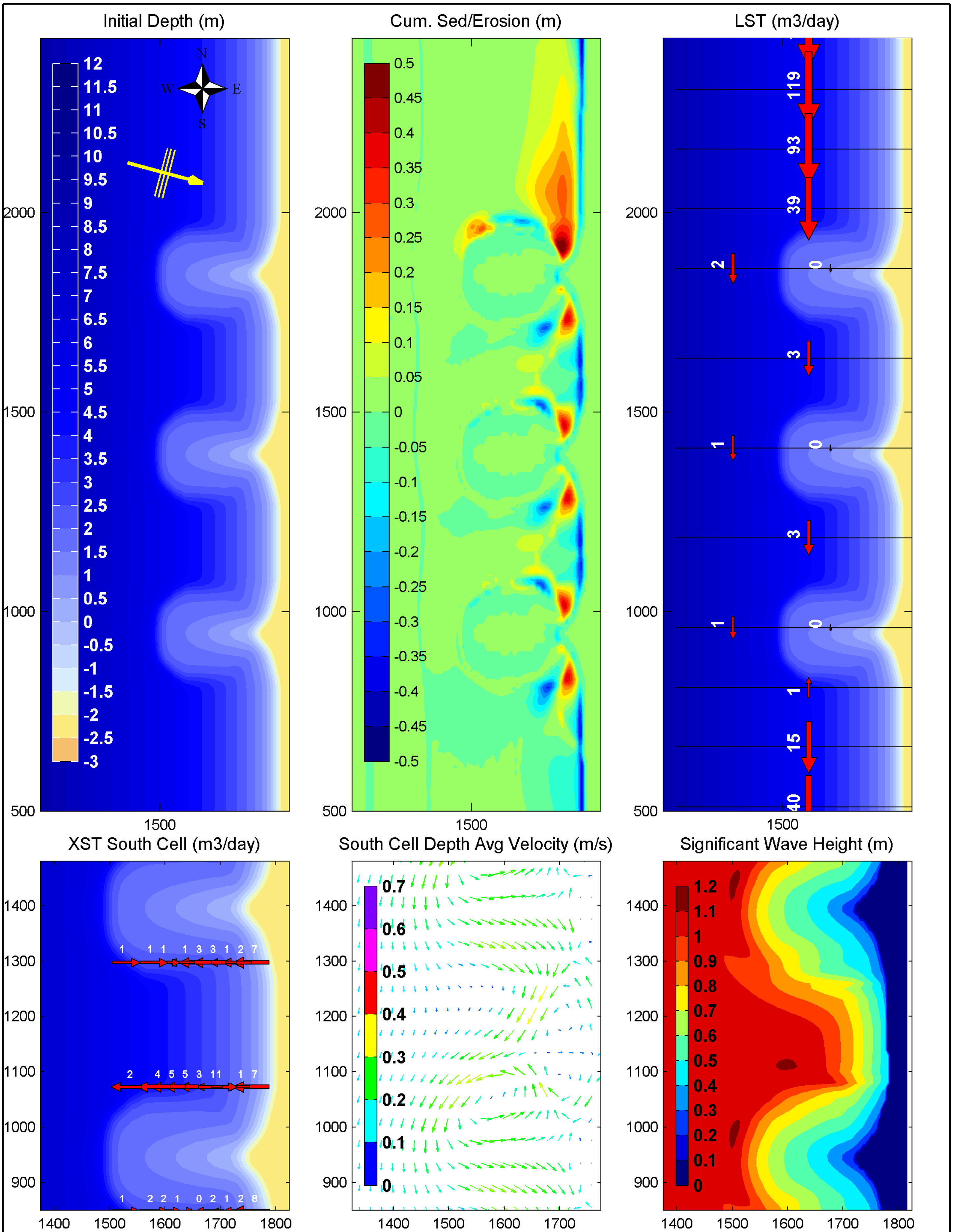
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 100.50 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G10
	REEF SIZE	
	DATE	25/05/2012



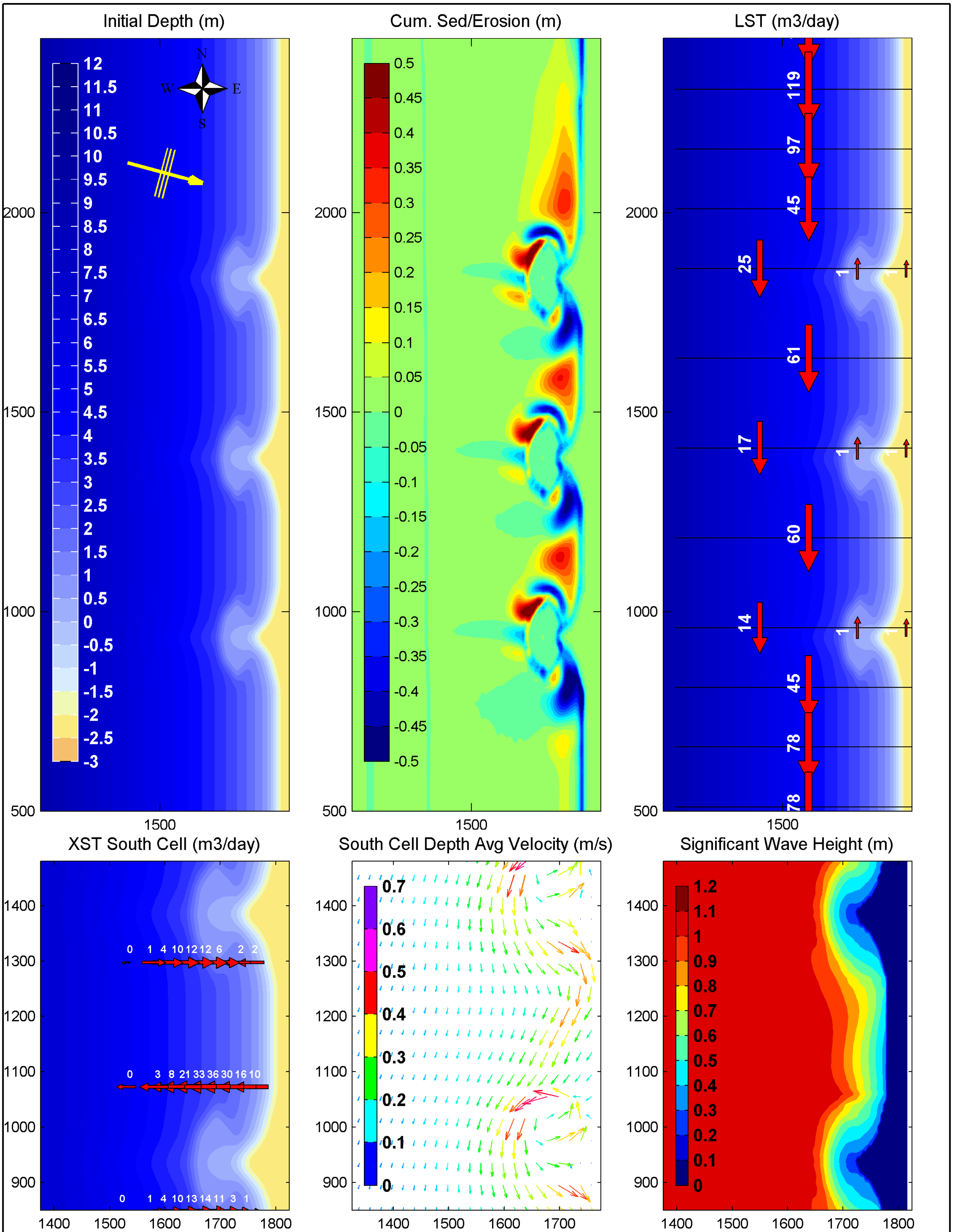
FORCING: Hs 1.5m, Tp 12s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 100.50 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G10a
	REEF SIZE	
	DATE	25/05/2012



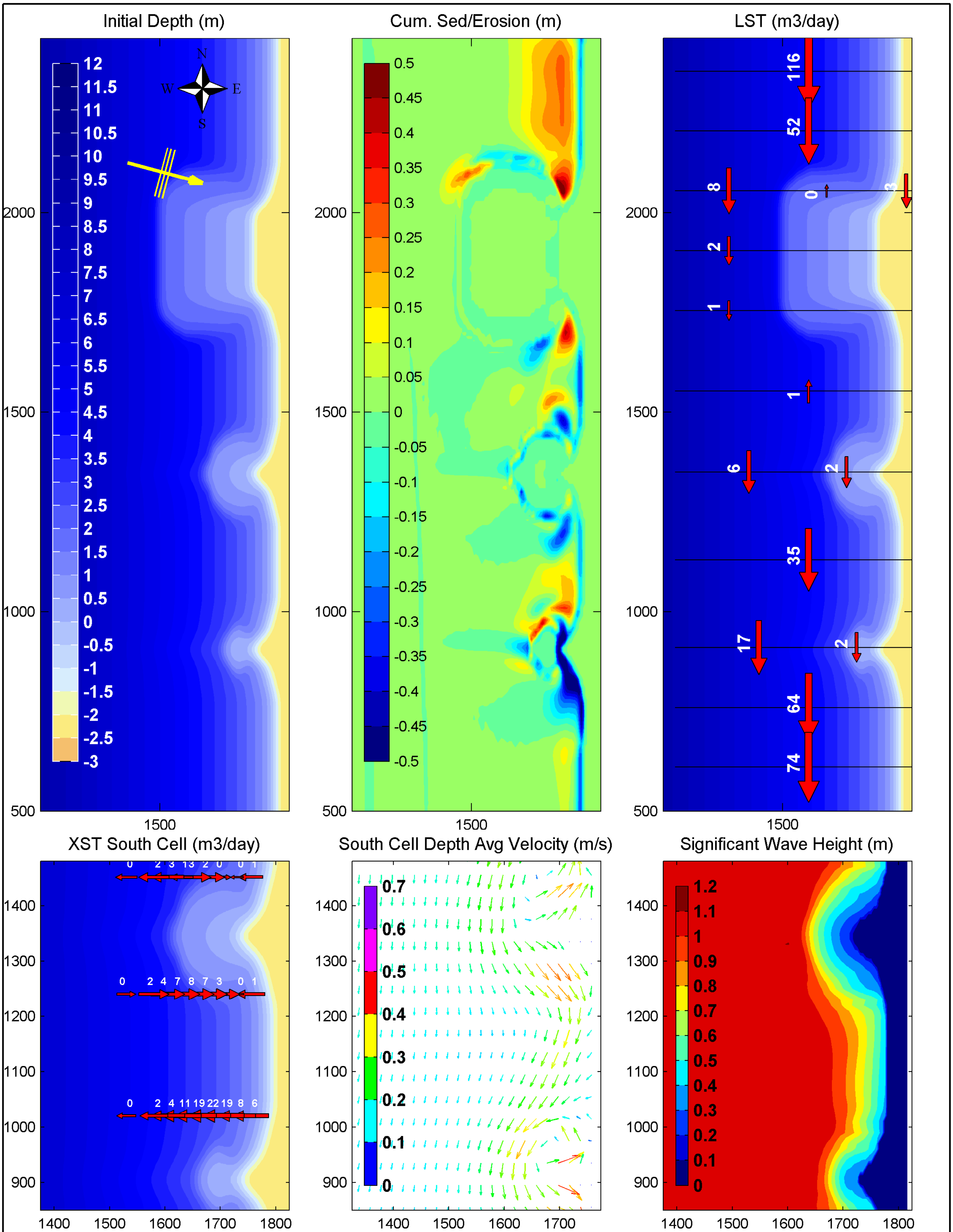
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.300 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G11
	REEF RATIO	
Deltares Delft Hydraulics	DATE	25/05/2012



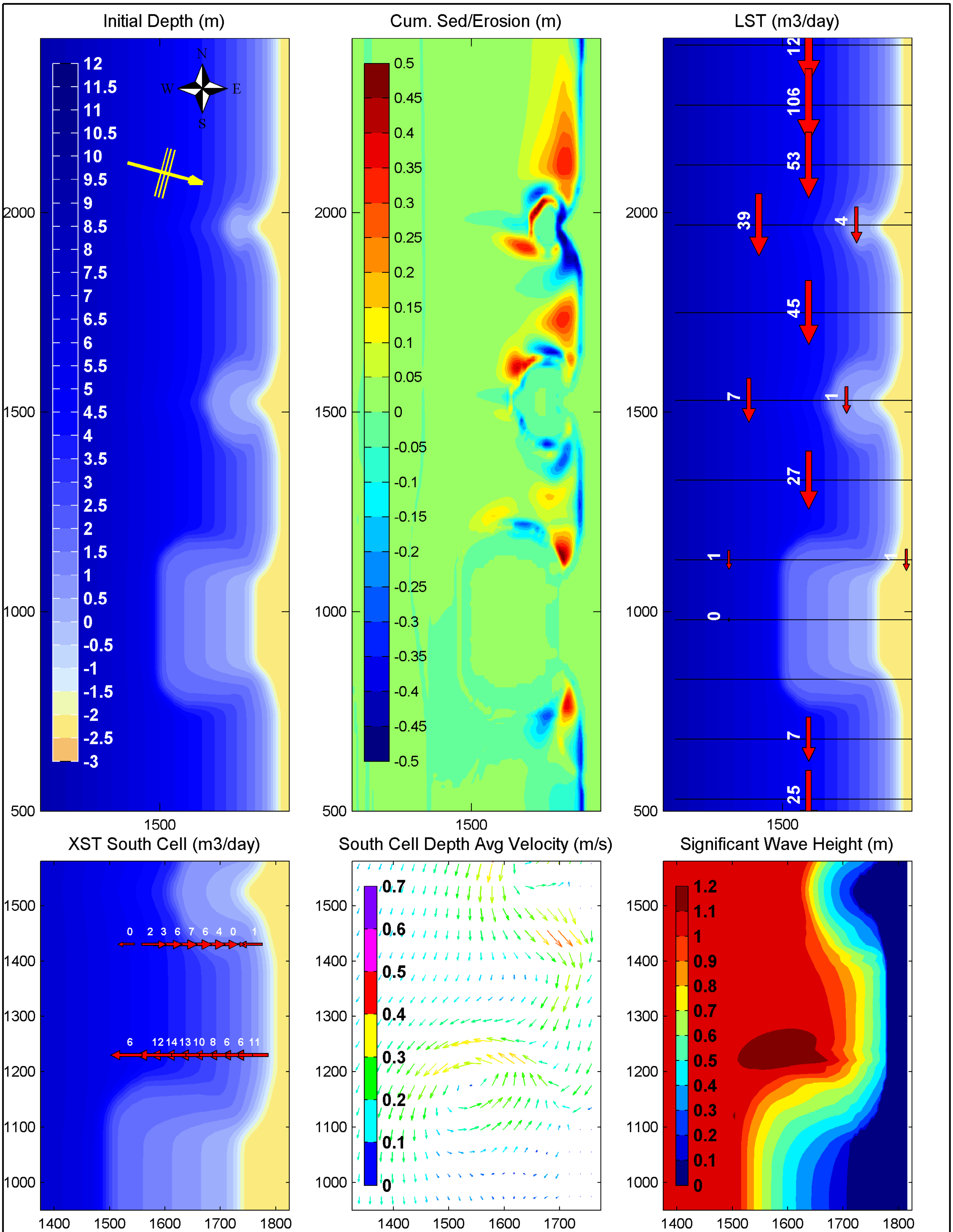
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.200 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G12
	REEF RATIO	
Deltares Delft Hydraulics	DATE	25/05/2012



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 200.065 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G13
	REEF RATIO	
Deltares Delft Hydraulics	DATE	25/05/2012



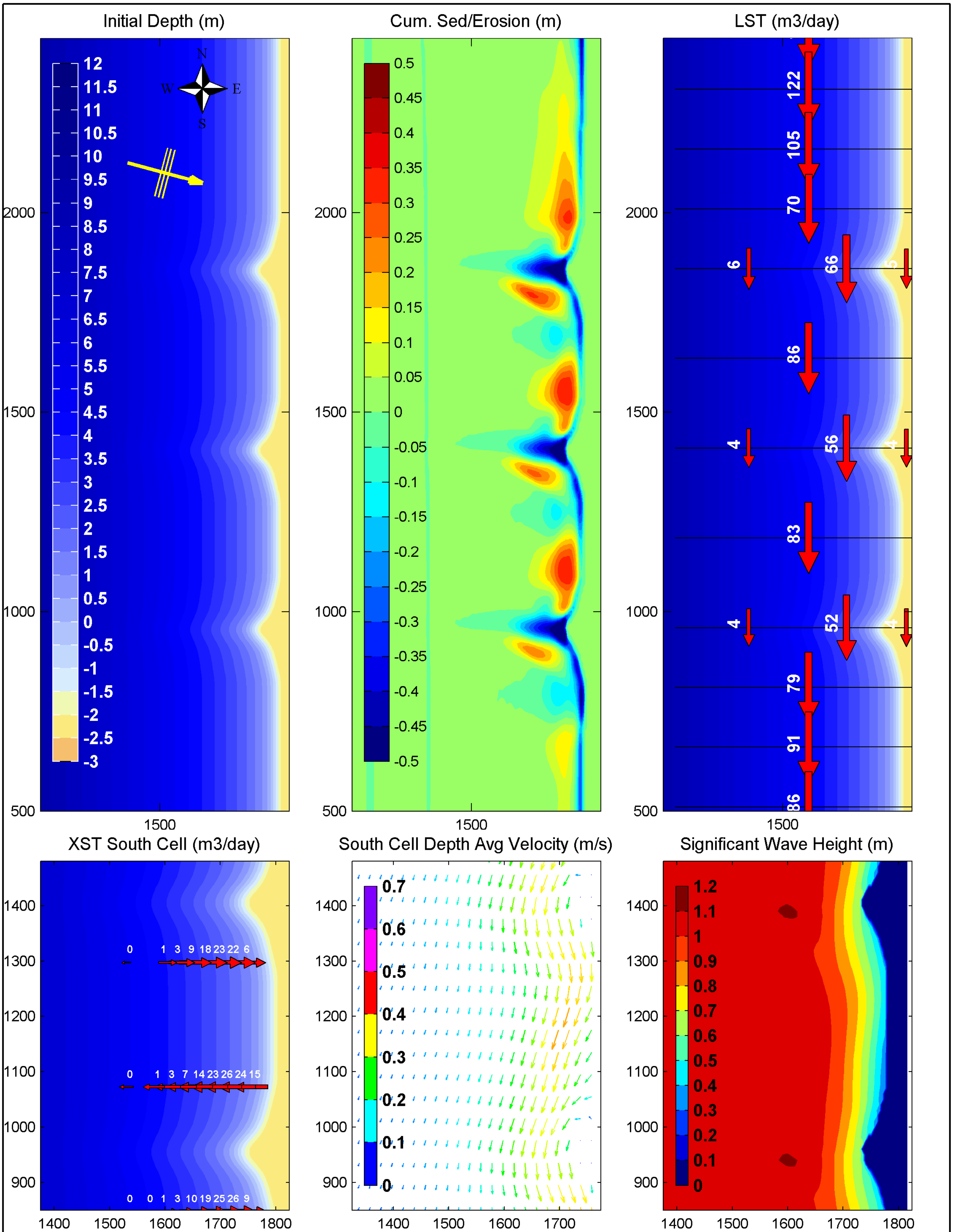
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, Reef 100.200.400 MISC: SLR 0.0m, Reef rgh 20 (Chézy)	RUN ID#	G14
	ASYMMETRY	
Deltares Delft Hydraulics	DATE	25/05/2012



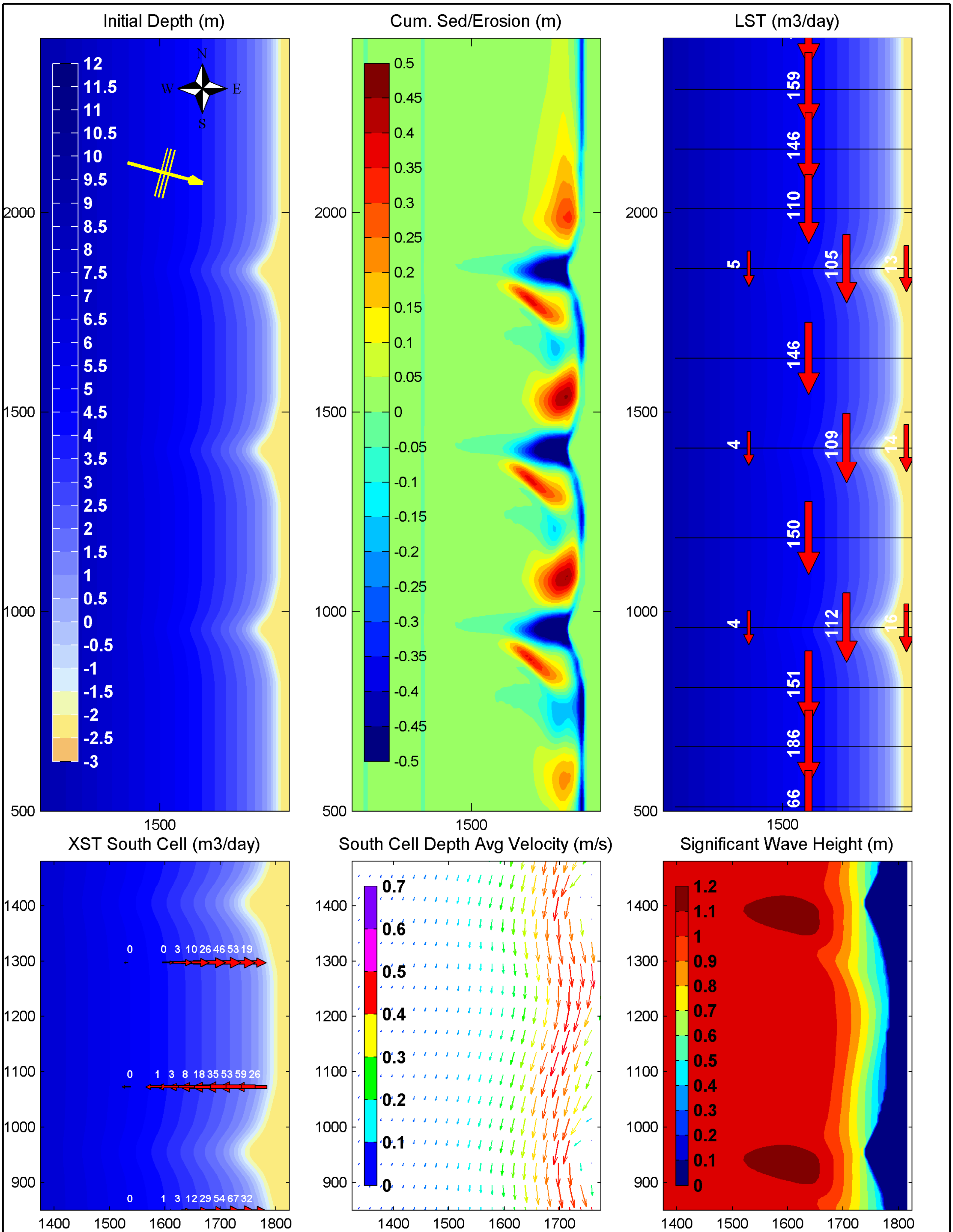
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Bay 450.60, Reef 400.200.100
MISC: SLR 0.0m, Reef rgh 20 (Chézy)

RUN ID#	G15
ASYMMETRY	
DATE	25/05/2012

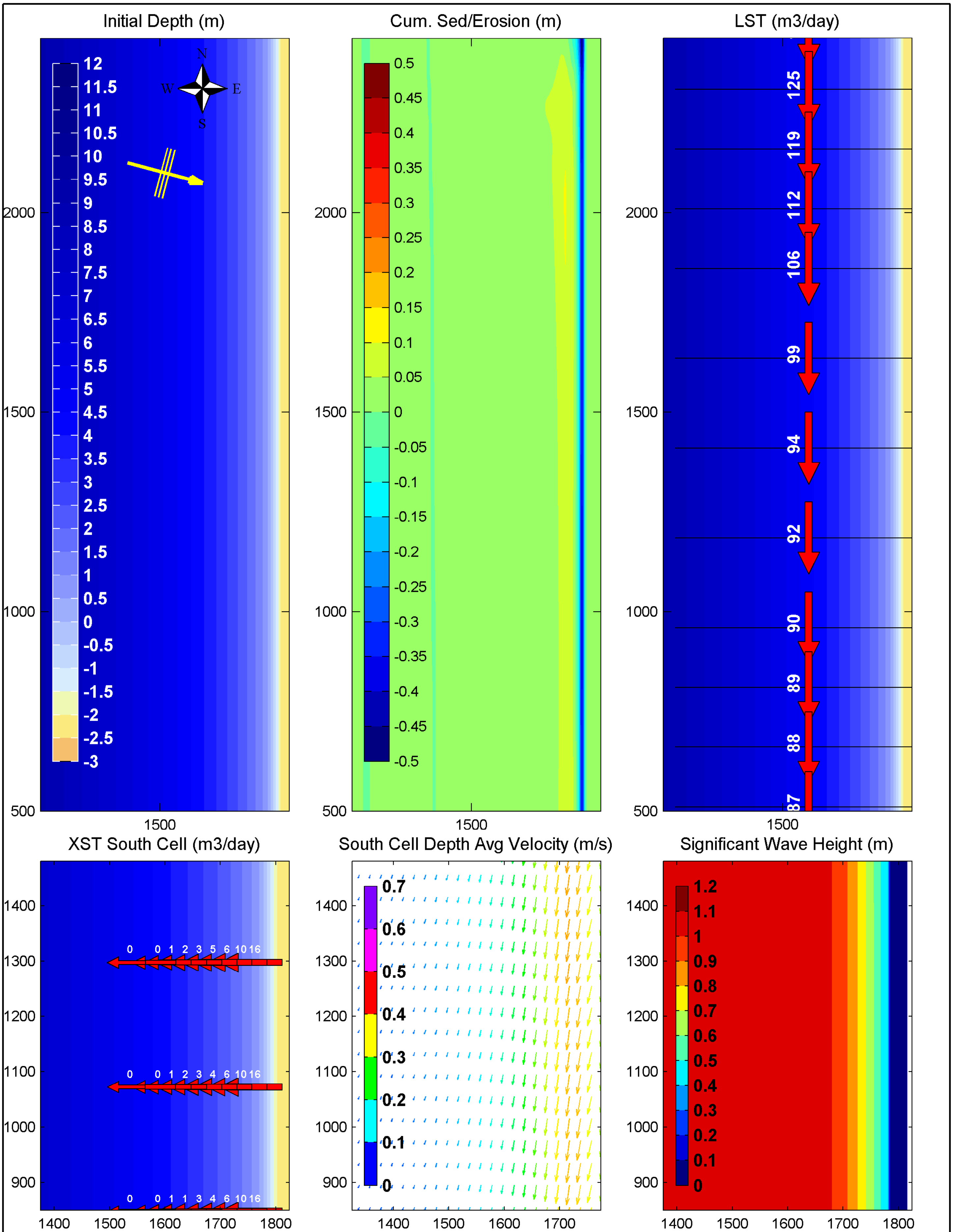
Deltares
Delft Hydraulics



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, No Reef MISC: SLR 0.0m, Reef rgh n/a (Chézy)		RUN ID#	G16
		REFERENCE (NO REEF)	
		DATE	25/05/2012



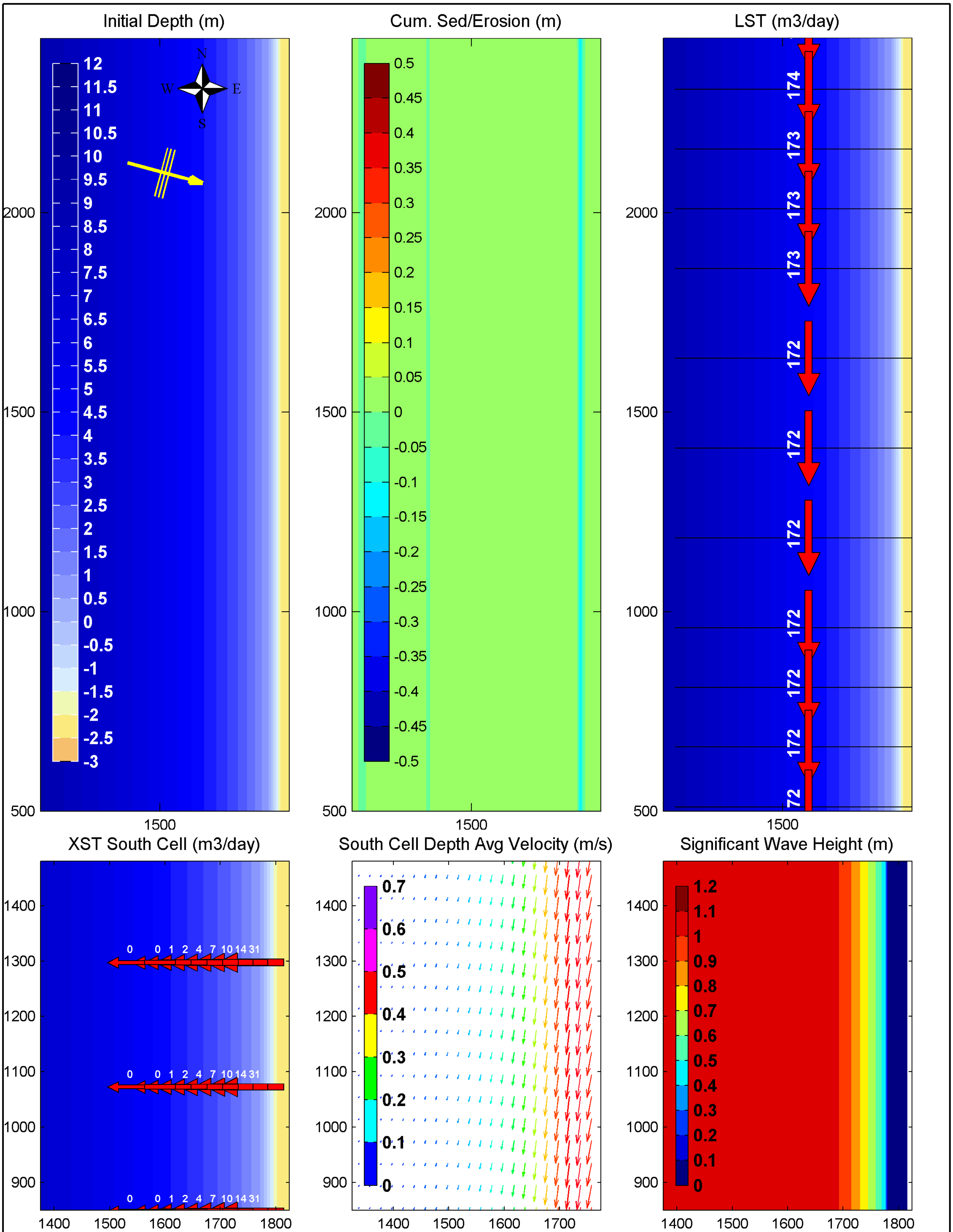
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Bay 450.60, No Reef MISC: SLR 0.0m, Reef rgh n/a (Chézy)	RUN ID#	G16r
	REFERENCE (NO REEF Rerun)	
Deltares Delft Hydraulics	DATE	25/05/2012



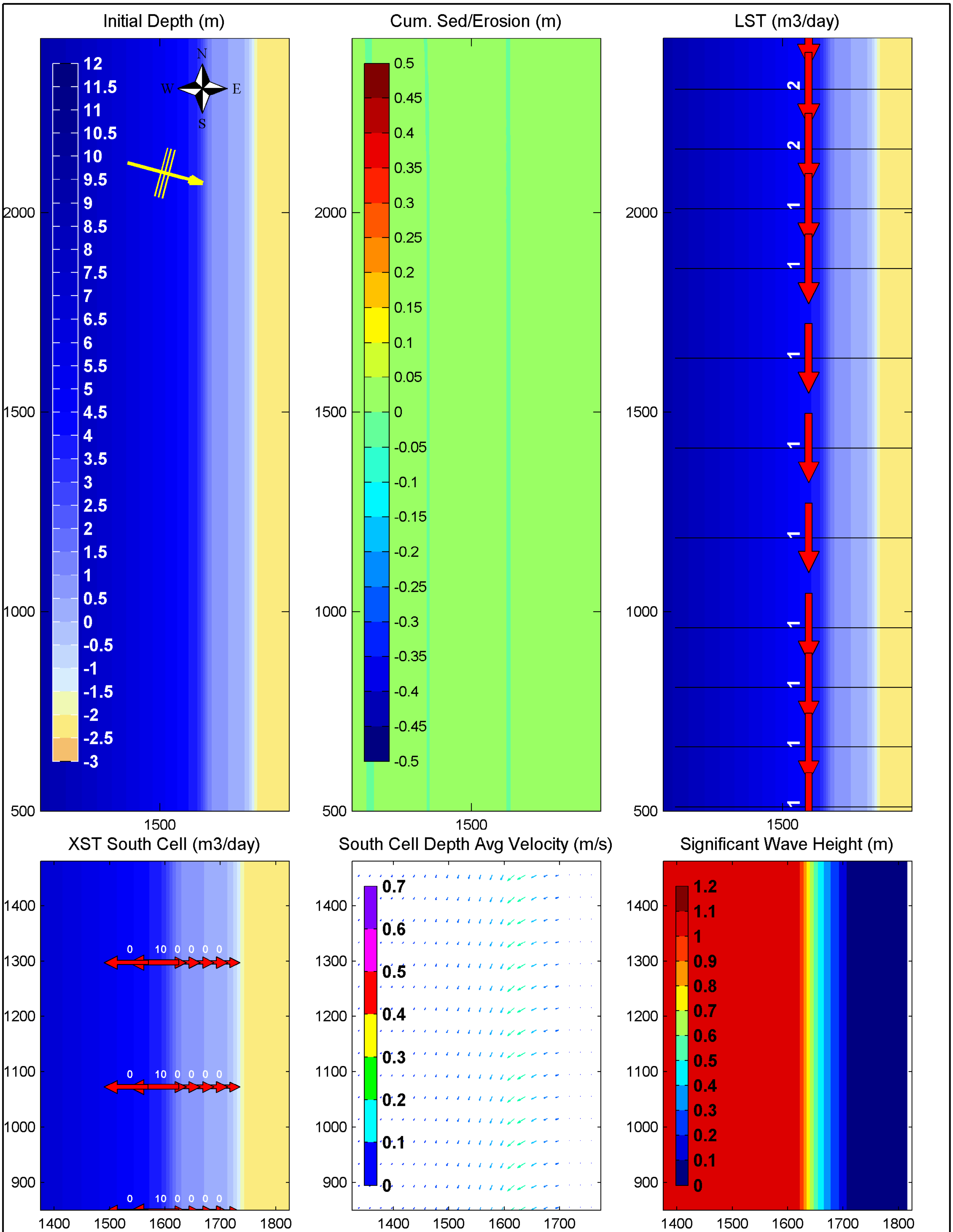
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Longshore Uniform
MISC: SLR 0.0m, Reef rgh n/a (Chézy)

RUN ID#	G17
REFERENCE (UNIFORM)	
DATE	25/05/2012

Deltares
Delft Hydraulics



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Longshore Uniform MISC: SLR 0.0m, Reef rgh n/a (Chézy)	RUN ID# G17r REFERENCE (UNIFORM rerun)
Deltares Delft Hydraulics	DATE 25/05/2012



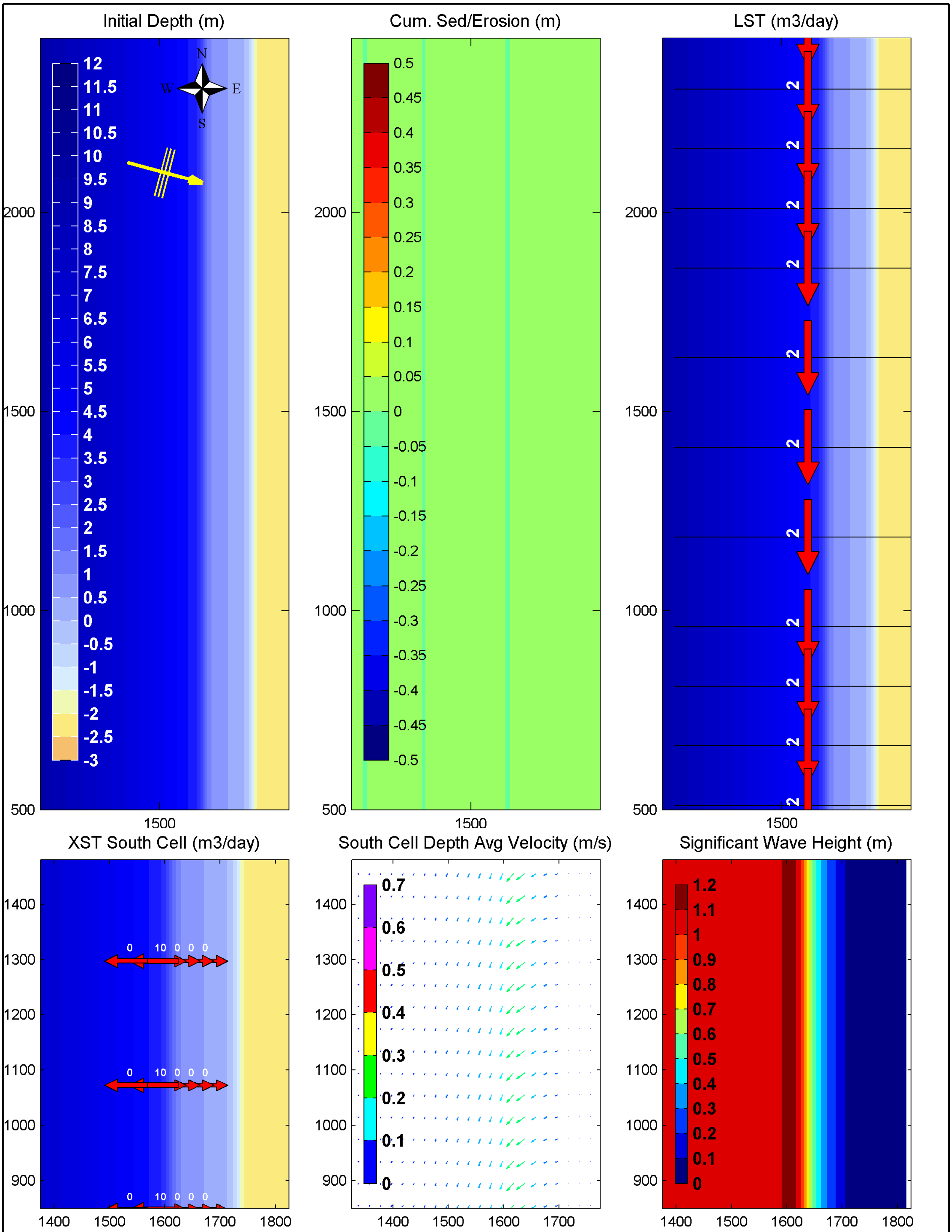
FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um
GEOMETRY: Longshore Uniform
MISC: SLR 0.0m, Reef rgh n/a (Chézy)

RUN ID# G18

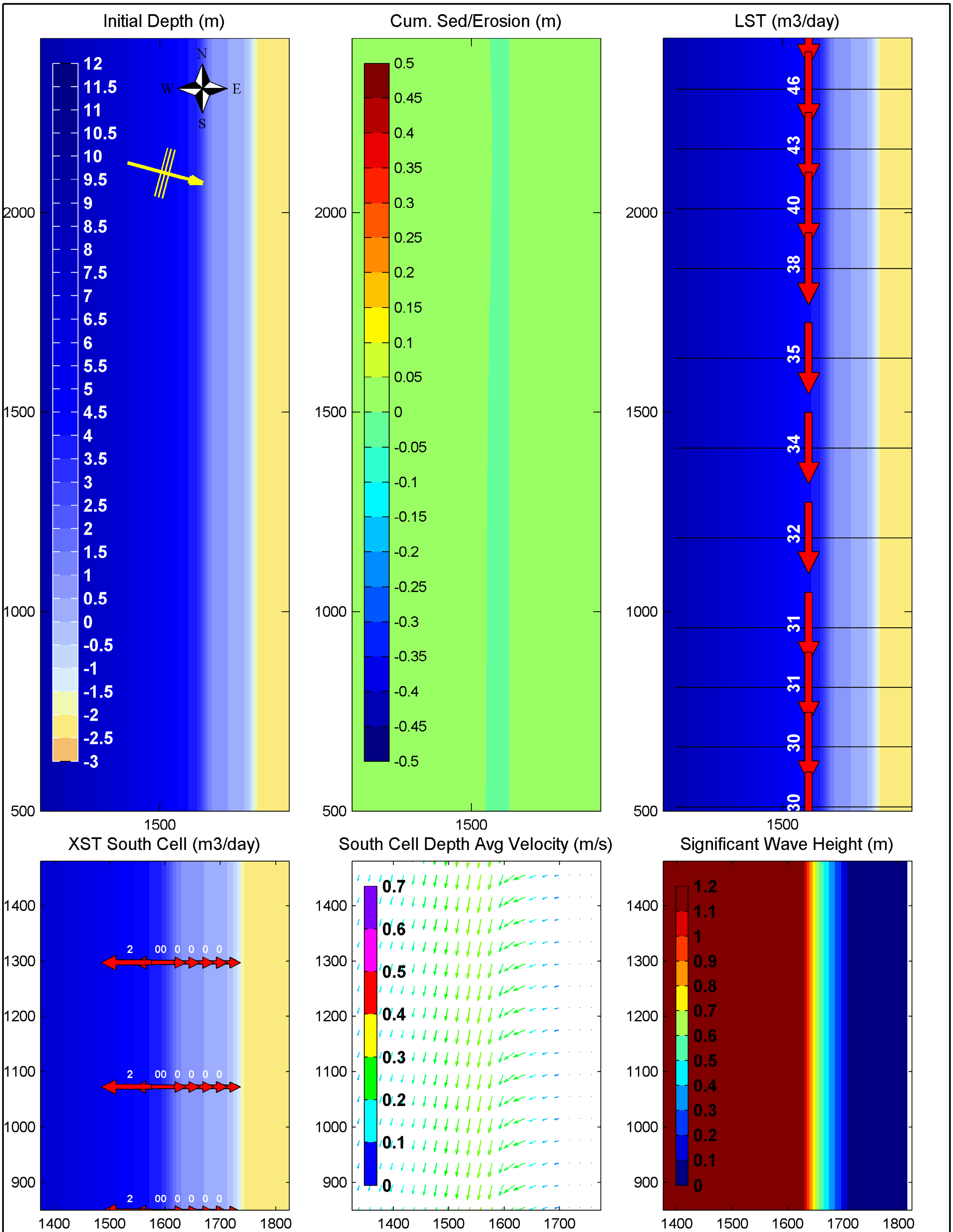
REFERENCE (FRINGE)

Deltares
Delft Hydraulics

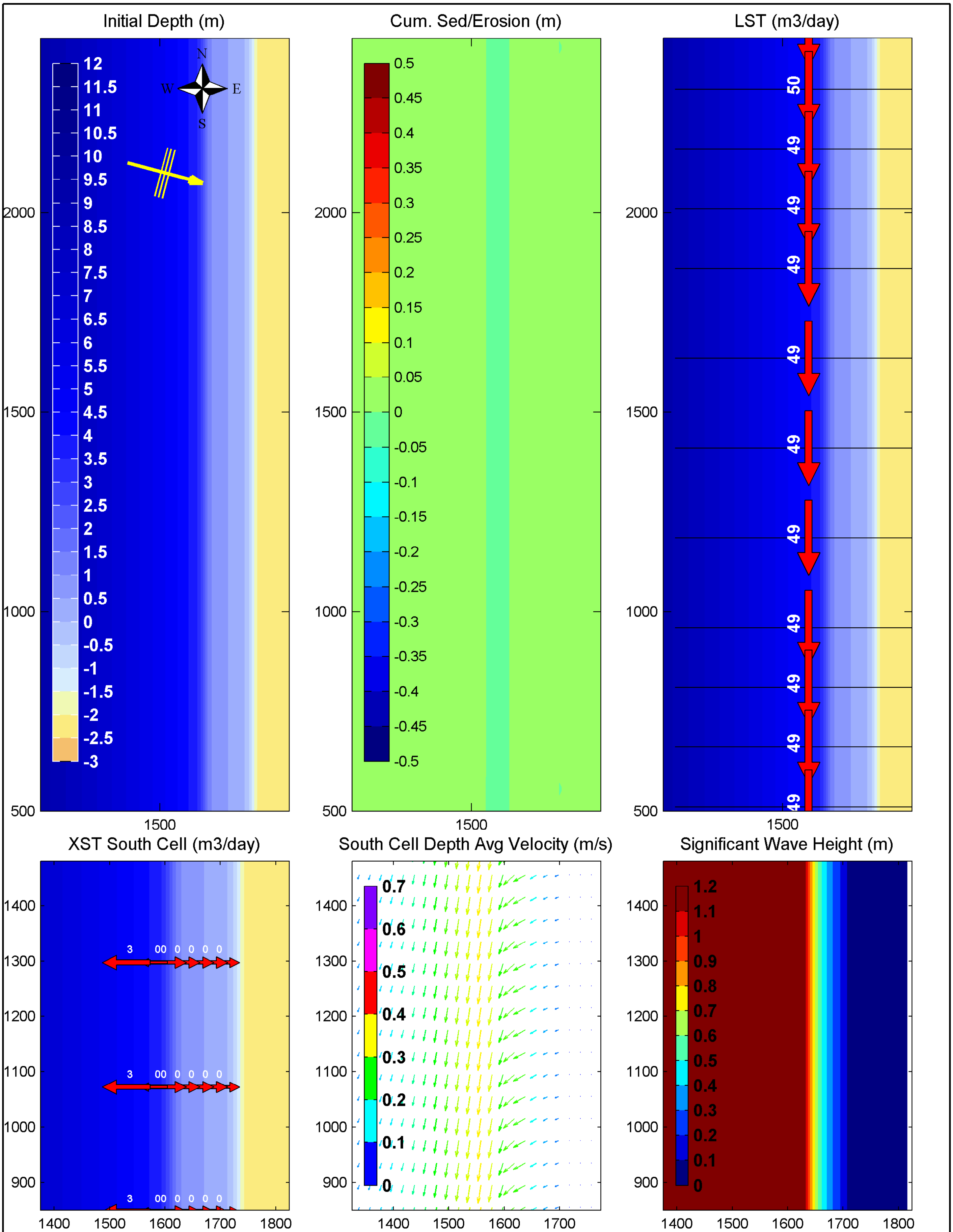
DATE 25/05/2012



FORCING: Hs 1.0m, Tp 10s, Dir 285deg, D50 375um GEOMETRY: Longshore Uniform MISC: SLR 0.0m, Reef rgh n/a (Chézy)	RUN ID#	G18r
	REFERENCE (FRINGE rerun)	
	DATE	25/05/2012



FORCING: Hs 1.5m, Tp 12s, Dir 285deg, D50 375um GEOMETRY: Longshore Uniform MISC: SLR 0.0m, Reef rgh n/a (Chézy)	RUN ID#	G18a
	REFERENCE (FRINGE)	
Deltares Delft Hydraulics	DATE	25/05/2012



FORCING: Hs 1.5m, Tp 12s, Dir 285deg, D50 375um GEOMETRY: Longshore Uniform MISC: SLR 0.0m, Reef rgh n/a (Chézy)	RUN ID#	G18ar
	REFERENCE (FRINGE rerun)	
Deltares Delft Hydraulics	DATE	25/05/2012