The FOOTPRINTS of ICCH

ICCH CORE PERSONNEL

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Ole R. Sørensen, Coastal Dynamics

Hemming A. Schäffer, (65%), Coastal Dynamics

Jesper Skourup, (65%), Ship/Harbour Dynamics

Stefan Mayer, Refined flow

Lars S. Sørensen, Refined flow

Erik Andresen, (55%), Refined flow

Ole S. Petersen, (80%), Stratified flow

Julie Pietrzak, (25%), Stratified flow

Henrik Kofoed-Hansen, (30%), Wind waves

Henrik Madsen, (25%), Data Assimilation

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Dr. Ashwini Kumar Otta, formerly Delft Hydraulics, The Netherlands, Jan. 97 - Sept. 98

Dr. Antoine Garapon, formerly Ecole Centrale Nantes, France, Oct. 1995 - Aug. 1998

Dr. Yehuda Agnon, Technion, Israel Institute of Technology, Israel, Period: Aug. 1996 - Sep. 1997

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Dr. John Christoffersen, Danish Maritime Institute, Denmark, May 1994 - Sept. 1995

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Dr. Thomas Hardy, James Cook University, Australia, Aug. 1996 - Mar. 1997

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A number of individuals from DHI

ICCH



FIVE YEARS THAT MADE A DIFFERENCE



The International Research Centre for Computational Hydrodynamics (ICCH), hosted by the Danish Hydraulic Institute (DHI), was established late 1993 with a five year grant from The Danish National Research Foundation (DG). This publication highlights some of ICCH's achievements.

The main objective of ICCH has been to conduct basic research within the field of coastal and ocean engineering. The topics treated concern hydrodynamics, transport processes and numerical techniques, and the research activities have been classified under the following headings

- Coastal Dynamics
- Refined flow with free surface dynamics
- Stratified Flow
- Ship and Harbour Dynamics
- Wind Waves
- Data Assimilation

From the very beginning, ICCH has been based on the concept of mixing national and international researchers with a multi-disciplinary background, and on the establishment of a number of research working groups dealing with different aspects of computational hydrodynamics. The working traditions at ICCH have favoured cooperation, not only within the individual research groups but also between the different groups. This tradition has proven to be one of ICCH's strongest points, as it has had the effect of inspiring the individual researchers and raising the overall level of research. One successful example of interaction is the subject of Nonlinear Wave Dynamics, which has been studied in the framework of Deterministic as well as Stochastic evolution equations, Boussinesq equations, Boundary Integral equations, and Navier-Stokes equations and with an additional feed-back from the research (at DHI) on wave generation techniques for laboratory test facilities. Another example is the subject of Stratified Flow, which has benefitted from the mixture of researchers with an oceanographic, a fluid mechanic and a numerical background. During the last five years ICCH has established contacts and collaboration with leading groups in a number of countries throughout the world. The number of visiting researchers has been steadily increasing and the Centre has become recognized as an attractive environment for research at a high international level. The visiting researchers have contributed significantly to the advances of ICCH both directly through their specific research and indirectly through their different perspectives.

ICCH's researchers have all made a tremendous and dedicated effort, resulting in valuable contributions and frontline research with a significant impact on the scientific field. Today, a leading international position has been established within the areas of *Coastal Dynamics* and *Refined flow with free surface dynamics.* International recognition is strongly supported by four evaluation reports from 1997 and one recent letter of recommendation from the ICCH review committee indicating the high quality of the research. These reports include phrases like 'research at the cutting edge' and 'a remarkable centre of excellence'.

Regrettably, ICCH will terminate by March 1999. Most of the core personnel will, however, disperse to various departments at DHI, who will get the opportunity to benefit from their skills and research experience. Research within the topics of Coastal Dynamics and Refined flow will continue at the Department of Mathematical Modelling (IMM) at the Technical University of Denmark (DTU), where a new professorship and a small research group in Computational Hydrodynamics will be established. This initiative will be financed partly by DG and partly by the Danish Technical Research Council, and hopefully it will ensure that the footprints of ICCH will lead to further insight and scientific achievements in the years to come.

solse.

Per Madsen Hørsholm, March 1999

COASTAL DYNAMICS

Through an intensive research effort ICCH has established an internationally leading position in the description of non-linear, irregular waves in coastal areas, including the surf zone. This research has focused on the formulation of new and very accurate wave equations (so-called higher-order Boussinesq equations) and on the development of new and effective numerical methods for solving them. The principle behind Boussinesq equations is to eliminate the vertical dimension in the flow description without loosing important effects like the influence of the vertical acceleration on the wave propagation. This principle was initially introduced by the French mathematician Boussinesq in 1872, and DHI was among the first to develop numerical models following this idea.

Since 1978 this type of model has been an important tool for the computation of wave agitation in harbours due to irregular waves. The range of application was, until recently, limited to non-breaking shallow water waves without currents and to weakly non-linear processes. However, this has changed significantly during the past 5-10 years, as new formulations have opened up a much wider range of applications.

This development includes the computation of wave transformation for highly non-linear, irregular multidirectional waves from deep water, through the surf zone and all the way up the beach, or to the harbour quay. Wave breaking can be included in various ways and ICCH has developed a method based on the concept of the surface roller; a bulk of water carried forward by the breaking wave. The first order physics are captured by the inclusion of an additional momentum flux term in the horizontal momentum equation along with a heuristic approach to the determination of rollers. The wealth of physical phenomena and the accuracy to which they are modelled is surprising considering the relative simplicity of the mathematical formulation. Wave-current interaction, which is important in tidal inlets and in the surf zone, is

also included. The new formulations are so realistic that even details like the generation and release of low-frequency energy due to primary wave transformation can be computed. This is of significant importance for harbour resonance, ship movements and coastal processes. A list of wave phenomena which have been studied at ICCH is given below:

- Wave-wave Interaction
 - Nonlinear, Irregular, Multidirectional Waves
 - Triad Interactions (energy exchange)
 - Harmonic generation
 - Generation of low frequency waves
 - Harbour Resonance
- WAVE-CURRENT INTERACTION
- Doppler shift
- Shoaling, Refraction
- Wave Blocking
- Wave-wave interaction in ambient currents
- SURF ZONE DYNAMICS
 - Nonlinear, Irregular, Multidirectional Waves
 - Breaking and dissipation
 - Set-up/set-down
 - Swash Oscillations (runup)
- Surf Beat (low frequency waves)
- Wave-induced nearshore circulations

The recent significant progress in surf zone hydrodynamics has made it feasible for ICCH to develop a new generation of coastal sediment transport models in cooperation with the Department of Hydrodynamics and Water Resources (ISVA), Technical University of Denmark.

Coastal morphology can be divided into large-scale phenomena such as bed evolution in the coastal zone including bars, rip channels and developments around structures; and small-scale phenomena such as travelling bed forms, backfilling of trenches and local scour around structures. The modelling of sediment transport in the coastal zone took an important step forward almost 15 years ago with the introduction of depthaveraged models of the hydrodynamics associated with wave induced currents and tidal currents. To a large extent, however, conventional morphology models are still based on a relatively primitive representation of the wave field using a phase-averaged approach. This leaves something to be desired from a physical point of view, since some important phenomena are not well represented e.g. the behaviour of suspended sediment in irregular waves and the effect of low frequency wave motions on the cross-shore sediment transport.

The new generation of deterministic sediment transport models developed by ICCH in cooperation with ISVA is based on a quasi-3D phase-resolving concept for the combined wave, current and sediment transport interaction. The models have been successfully verified on a v ariety of cases involving erosion as well as accretion giving a significant improvement of profile modelling compared to conventional phase-averaged approaches.

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Multidirectional irregular waves on a beach with a detached breakwater. Computations made by a Boussinesq model with wave breaking. Top Panel: Computed surface elevations including surface rollers (shown in white). Bottom panel: Wave-induced vortex (wave-averaged net flow) behind the breakwater.





Sequence of a breaking wave off the coast of Bali Photo by Per Madsen

COASTAL DYNAMICS

Fig. 2

As Fig 1 but with unidirectional, regular, incident waves. LEFT: Computed surface elevation. **RIGHT: Photo from** experiment by Mory and Hamm (1997). Note that the wave-induced vortex behind the breakwater (see Fig 1) interacts with the incoming waves and results in the kink in the wave fronts seen in the experiment as well as in the computation.









Fig. 3

Morphological development due to regular wave impact on a highly erosive initially plane sloping beach.

A) Evolution of sand bars. The bars develop and tend to move offshore with the depth over their crests increasing in time. New bars continuously develop onshore of the previous bars. B) Schematic drawing of the concept of the mathematical model.

Fig. 4

Bichromatic incident waves breaking on a plane beach. Time-space trajectories of surface rollers together with the shoreline motion. A) 12 waves per group; B) 30 waves per group.







Surf Beat created by bichromatic incident waves. Top panel: Shapshot of the computed surface elevation. The figure includes the envelope defining the maximum crest and trough elevations. Bottom panel: Surf beat elevation obtained by low pass-filtering the total surface elevation. The figure includes a series of snapshots covering one wave group period.





Wave-wave interaction over a submerged bar. Computations made by a Boussinesq model. Top panel: Perspective time-space representation of the computed surface elevations (time increasing upwards, covering two wave periods). Middle panel: Bathymetry. Bottom panel: Computed and measured spatial variation of first and second harmonics. Notice (from top panel) that the incoming monochromatic wave pattern (to the left) is changed into an interference pattern with free super-harmonics (to the right) due to the release of bound harmonics over the bar crest. The two different phase speeds of the primary wave and the free second harmonic show up as the cross pattern on the down wave side of the bar.



Wave blocking by an opposing current. Computations made by a Boussinesq model. Bottom panel: Bathymetry. Middle panel: Contours of the computed surface elevations in a time-space representation (time increasing upwards, covering 27 wave periods). Top panel: Snapshots of the spatial distribution of surface elevations covering one wave period and forming the wave envelope. The incoming monochromatic waves propagate (from left to right) from a deeper region onto a shallow shelf. When the speed of the opposing current exceeds the group velocity of the incoming waves they will be stopped and a reflected wave train will be generated. The reflected waves are generally shorter, higher and steeper than the incoming waves, and while their energy propagates in the direction of the current (from right to left), their wave crests travel very slowly in the opposite direction.



Wave blocking in Lillebælt, Denmark Photo by Hemming Schäffer

REFINED FLOW WITH FREE SURFACE DYNAMICS

One of the most comprehensive and successful research activities at ICCH has been the development of an advanced numerical Navier-Stokes solver for the computation of three-dimensional, unsteady, turbulent flows in connection with complex geometries. The model stands out when compared with most CFD-codes because of the inclusion of the dynamics of the free water surface. This allows for the computation of the forces and moments excerted on structures by the combination of non-linear waves and currents. The model features a flow-adaptive curvilinear grid which allows for moving boundaries; Volume of Fluid representation of free surfaces which allows for mixing of air and water; multiblock formulation which allows for complex geometries; numerous advanced turbulence models such as a variety of nonlinear k- ω formulations and Large-Eddy-Simulations (LES).

A list of physical phenomena which have been investigated by the use of the model is given below:

- NONLINEAR WAVE MOTION
 - Wave impact on surface piercing cylinders
 - Wave-wave interaction over submerged bars
 - Instability in wave trains (Benjamin-Feir)
 - Wave-current interaction and waveblocking

- TURBULENT FLOW AND FLUID STRUCTURE INTERACTION
 - Secondary flow in a bending duct
 - Turbulent shear flow induced by wind
 - Turbulent shear flow with gravity waves
 - Early stages of wind wave generation
 - Wave-current boundary layers
 - Flow around a sailing ship
 - Flow around a surface piercing cylinder
 - Flow around a fixed submarine pipeline
 - Flow induced motion of a pipeline
 - Plunging and spilling types of wave breaking
 - Flow over a rectangular weir

A discussion of two of the most successful and innovative applications is given in the following:

Very high accuracy has been achieved for the turbulent flow around sailing tankers. The purpose of these computations is to evaluate the hydrodynamic consequences of different types of ship hulls. Flow resistance and turbulence in the propeller plane are two quantities with a strong impact on the design and optimization of the hull for reduced fuel consumption. The ICCH results obtained in this area are among the best in the literature, and have been recognized by leading researchers in the field (e.g. from Tokyo University, Tokyo Ship Research Institute and Ecole Centrale de Nantes, France).

Another exciting application of the model is to turbulent flow around submarine, free spanning pipelines and their resulting vibrations. Pipelines must be able to resist peak loads from waves and currents, as well as the continuous vibration loads from the near bed wave motion and vortex shedding behind the pipeline. The risk of resonance is present when free spans occur due to erosion and/or irregularities of the sea bed. Initial two-dimensional computations have been undertaken at ICCH using a curvilinear grid locally following the oscillating structure while still being adapted to the sea bed. Preliminary results are very promising and the Norwegian oil company Statoil has shown great interest in computations performed jointly by ICCH and DHI.

A significant research effort is still needed to further develop this model and utilize its great potential in connection with a number of interesting problems and research topics. Some examples are 1) the effects of waves and currents on fixed structures (e.g. jetties and bridge piers); 2) wave-induced motion of moored ships; 3) wave- and current-induced vibrations of fixed and floating structures; 4) hydrodynamics in the surf zone. At a later stage it is also possible that the model can be adapted to solve problems outside the marine environment, since fluid-structure interaction is a much wider field covering everything from the vibration of aerodynamic structures to the modelling of biological flows.





Measured



Fig. 8

Turbulent flow around sailing ship. Computations made by Navier-Stokes solver. Experiments by Wieghardt & Kux (1994). A) Partial view of the grid system near the bow and the stern. B) Computed streamlines and iso-wake lines near the stern. Color on the ship hull shows the pressure distribution. C) Measured and calculated speed of the longitudinal velocity at three cross-sections.



Measured

0.8

B

11

Computed

REFINED FLOW WITH FREE SURFACE DYNAMICS







Fig. 9

Flow past a surface piercing cylinder computed by Navier-Stokes solver with Large Eddy Simulation.

A) Grid system. B) Comparison of computed and measured mean

surface elevation. C) Perspective view of computed and observed surface elevations.

Photos and experiments by Y. Tsuchiya, University of Tokyo.



C













Wave impact and runup on a circular cylinder. Computations made by Navier-Stokes solver and Boundary Integral Element Method (BIEM)

- A) Perspective snapshots of the computed surface elevations.
- B) Close up snapshot.
- C) Computed and measured runup on the lee side of the cylinder.

- Computation (fully non-linear Navier-Stokes)

- Computation (2nd-order BIEM)
- Experiments by Kriebel (1992)



38/H 28/H

1.6

1.4 -

1.2 -

1.0 -

0.8 -

1

0.8

0.6

0.4

0.2

<mark>0</mark> θ/π

REFINED FLOW WITH FREE SURFACE DYNAMICS



Fig. 11

Waves in a following current over a rippled sea bed. Bottom Panel: Snapshot of the water column including four ripples and a long free surface wave. Colours indicate the level of velocity speed. Computations by Navier-Stokes solver. Top Panel: Close up showing instantaneous velocity field.



Fig. 12

Volume-of-Fluid representation of the free surface. Computations made by Navier-Stokes solver including a mixture of air and water. The plotted free surfaces are contours of fluid fraction equal to 0.5. Notice that the water flowing over the weir enters the pond and penetrates it to the ground level.

Flow induced vibration of a pipeline, which is elastically suspended near the sea bed. Computations made by Navier-Stokes solver with multiblock curvilinear flow-adaptive grid. Top panel: A close up of the grid system. Middle and bottom panel: The vorticity field is visualised at two instants within a vibration period.







STRATIFIED FLOW

Estuaries and the upper layers of the sea are often strongly influenced by density differences from either temperature or salinity variations which can be decisive for the flow and transport processes.

In a joint effort ICCH and DHI have developed a hydrostatic 3D oceanographic model based on an adaptive boundary conforming grid. The hydrostatic approximation, which is relevant where vertical accelerations are small, allows the use of very efficient 3D flow solvers. Various vertical coordinate transformations have been investigated to allow the sea surface and the sea bed to be coordinate surfaces and providing a dense resolution in different parts of the fluid domain depending on the actual interest e.g. sediment transport near the sea bed or mixing layers in the upper part of the fluid.

In general, the assumption of a hydrostatic pressure is not valid and in this case more advanced methods are necessary. ICCH has developed a very efficient and accurate model, solving the full Navier-Stokes equations on nested 3D Cartesian grids. The model uses a multigrid fractional step technique and includes stratification, rotation and advanced turbulence closures. The hydrodynamic model has been used as a platform for Large Eddy Simulations (LES), which is an emerging technique that potentially may supplement observations and experiments on stratified flows. This method relies on a resolution of a significant part of the turbulence, the largest eddies, and it reproduces some of the fine details of the turbulence and mixing providing estimates of fluxes and more complex non-linear statistics.

Some examples of physical phenomena related to stratified flows, which have been addressed at ICCH, are:

- Mixing and turbulence in stratified flows
- Structure and entrainment in a shallow water jet

- Flow and mixing in gravity driven currents
- Mixing and internal waves in wind driven flows
- Rayleigh-Benard convection
- Penetrative convection in the ocean

In the following we shall discuss the example of penetrative convection - a situation that may arise when the water surface overtopping a stable stratification with denser water in the deeper parts, cools down and creates a statically unstable surface layer. This sets up turbulence convection roll-cells and sinking plumes that penetrate and slowly entrain the denser bottom water. In the marine environment such processes can be responsible for the vertical mixing in the upper layers of the sea. This situation, which is experimentally well documented, has been used as a benchmark test for the numerical LES model and the overall agreement with observations has been found to be most satisfactory. In addition, comprehensive simulations have demonstrated that convection at ocean scales and the resulting vertical mixing may be inhibited by the rotation of the earth when the mixed layer is very deep. The physical mechanism appears to be a restriction of the size of the roll-cells when the depth of the mixed layer becomes comparable to the so-called Rossby radius.



Fig. 14

Large eddy simulation of a shallow water jet penetrating into stagnant ambient water.

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Large eddy simulation of entrainment in rotating convective turbulence. A) Temperature in a vertical section showing the chaotic patterns that develop during the simulation. B) Development of surface temperatures after onset of cooling, displaying characteristic large slowly evolving structures. Red is hot, blue is cold. C) Development of a horizontal isodensity surface displaying the footprints of the downwelling plumes and evidence of increasing internal wave activity.









Time

SHIP AND HARBOUR DYNAMICS

This research area covers nonlinear wave motion in harbours and the interaction between waves and floating vessels in the harbour environment. While nonlinear wave motion in harbours including harbour resonance can be simulated very accurately by numerical models based on depth-integrated Boussinesq type equations, the wave impact on moored vessels and their response is basically a three-dimensional problem, which calls for more refined techniques. In principle, the fully nonlinear coupled problem of wave-body interaction including mooring lines and fender forces can be solved entirely in the framework of the timedomain Boundary Integral Equation Method (BIEM), but the computational effort involved is tremendous and it prevents practical solutions. At ICCH two alternative methods for computing wave-body interaction have been investigated:

The first method is a time domain procedure which utilises frequency response functions pre-computed by a 3-D panel method developed at MIT plus a Fourier transform. Empirical coefficients are used for viscous and friction damping and a non-linear mooring system is allowed. The resultant motion of the structure is computed for a given incident wave field, which may be specified as a Fourier superposition of waves, which is appropriate for deep water cases; or it may be the result of a Boussinesq calculation, for restricted water cases. Comparison with laboratory measurements for a ship moored in an L-shaped harbour (Fig.16) shows that the model works remarkably well, providing engineering answers to real problems with modest computational effort.

The second method employs a distribution of bi-linear singularities over bi-linear panels to solve for the potential flow around a freely floating structure. The boundary conditions on the free surface and on the body are satisfied to second-order in wave steepness and to first-order in current velocity. The model is complete for a fixed structure, but only implemented to first-order in wave steepness for the freely floating case. The computational effort is order N*N, where N is the number of panels, although an order NlogN solution is partially implemented and shows promise for the future.

Another research activity, which has been conducted as a joint effort between ICCH and DHI, is the formulation, implementation and investigation of theories for active wave ab-





Wave elevation spectrum at the ship





Yaw motion spectrum

Fig. 16

The wave induced motion of a ship moored at a pier in an L-shaped harbour. Simulations are based on a hybrid model complex (see text) and the measurements are from the Danish Hydraulic Institute.

Photo of the experimental setup at DHI

Verification of a 3D active absorption system in a numerical wave tank based on the BIEM model: Perspective views and contours of instantaneous surface elevation after several periods of simulation. Oblique waves are generated at the two boundaries to the left, while at the two boundaries to the right they are reflected/absorbed (top); absorbed by quasi-3D active absorption (middle); absorbed by fully 3D active absorption (bottom).



sorption. Active wave absorption means the use of a wavemaker as a moving boundary controlled as to absorp the waves impinging on it, thus avoiding spurious reflection. DHI has recently started the development of a new shallow water experimental facility including a multidirectional wavemaker. An important part of this development lies in the control of the wavemaker in general and in active absorption of multidirectional waves in particular. The implementation of a numerical wave tank based on the BIEM method with a segmented wavemaker has proven to be an efficient and reliable way to test and further develop the active wave absorption system.

Fig. 18

Side-band instabilities in uniform wave trains (Benjamin-Feir type). Computation by a fully nonlinear BIEM model. The initial wave condition is a monochromatic deep water wave with a small disturbance added to the side-band frequencies. After several wave periods instabilities develop and energy becomes concentrated at a single peak in the wave group. This local concentration of energy moves with the group velocity which is only half the phase celerity of the individual waves. A) Snapshots of the surface elevation during 10 wave periods. B) Perspective plot of the surface elevation in a time-space representation (during 10 wave periods). Wave direction: left to right; time increasing upwards.



В



Distance

WIND WAVES

Numerical modelling of the growth, decay and transformation of wind generated waves plays an important role in hindcast and forecast of wave conditions due to the meteorological impact on oceans and coastal waters. Deterministic, phase-resolving models are generally much too computationally demanding for this purpose, and the attractive alternative is stochastic modelling.

As a starting point, ICCH has implemented a state-of-the-art 3rd generation wind wave model formulated in terms of the energy density spectrum with a discrete resolution of frequencies and directions, and with nonlinear quartet (four wave) interactions estimated by the Discrete Interaction Approximation (DIA). The model has been validated on field data

from the North Sea and from various sites in the inner Danish coastal waters. One limitation of the model is that it does not account for triad (three wave) interactions which dominate in shallow water. Another limitation is that the DIA approximation to quartet interactions is inaccurate e.g. in turning wind fields and in case of restricted fetches in finite depths.

ICCH has conducted a comprehensive theoretical study of the physics of quartet interactions following the original work by Hasselmann and Zakharov. The deterministic Zakharov equation has been re-derived and extended to allow for waves on currents in finite water depth and for deepwater waves with spatially varying Fourier components. On the basis of the extended Zakharov equations, two new



Storm surge at the Danish coastline near Rungsted Photo: Per Madsen

stochastic evolution equations, including the Boltzmann integral as a source term, have been derived. These formulations support the classical wave action balance equation, which is usually derived by the use of heuristic arguments. The effect of using the full Boltzmann integral rather than the DIA-approximation by Hasselmann has been evaluated, and the DIA has been found to be inaccurate with respect to the energy transfer towards the infragravity wave regime as well as to the high frequency tail of the spectrum. Unfortunately, solutions involving the full integral are very cumbersome and at this moment no practical alternatives to the DIA approximation are available.

In shallow water conventional stochastic formulations fail to describe the relevant physics such as wave breaking and triad interactions. Only recently (in 1997) a major breakthrough was made in this field, with the formulation of coupled evolution equations for the wave energy spectrum and the bispectrum, which retains information on the nonlinearities and the phase-coupling in the wave field. With this formulation important quantities like the skewness and asymmetry of the irregular waves can be calculated. ICCH has successfully taken an active part in this development with the derivation and implementation of two alternative formulations based on a weakly dispersive and a fully dispersive theory, respectively. In general, the accuracy of the computations is very satisfactory at least for non-breaking waves.



Fig. 19

Evolution of bispectra indicating nonlinear phase coupling between harmonics. Computations made by a stochastic Boussinesq formulation for triad interactions.

DATA ASSIMILATION

The application of numerical models is often complicated by uncertainties related to the initial conditions, the boundary conditions, and the meteorological forcing. Data assimilation is a technique that combines model dynamics and measurements to improve the knowledge of the system. In the past, data assimilation techniques have been developed and applied primarily in connection with atmospheric models and oceanic models, while only few developments have concentrated on models for estuaries, bays and coastal areas, where the dynamics are strongly influenced by the presence of land-sea boundaries, and flooding and drying of tidal areas.

The research at ICCH has concentrated on integration of data assimilation techniques into an existing hydrodynamic model solving the depth-integrated non-linear shallow water equations. In this respect two different methods based on the Kalman filter have been implemented and tested. These include (1) an extended Kalman filter based on a reduced rank approximation of the error covariance matrix using a squareroot factorisation, and (2) an ensemble Kalman filter based on a Monte Carlo simulation approach for propagation of the errors.

The two methods represent different approximations of the error covariance propagation in order to reduce the computational load, and hence providing a feasible scheme for on-line updating, e.g. in operational storm surge forecasting systems. While the first method is applicable only for weakly non-linear dynamics, the second method is particularly useful when large non-linearities and discontinuities are present, e.g. in the case of flooding and drying of tidal areas.

The data assimilation model has successfully been applied for storm surge forecasting in the North Sea. The filter has shown to be very efficient with respect to corrections of the water level in the entire model domain based on only very few measurements. In a forecast situation, the Kalman filter is adopted for assimilating data up to the time of forecast. The updated water level and velocity fields at this time are then used as initial conditions for the forecast. In the forecast period the filter is applied for propagation of model errors and for correction of the forcing terms. Besides a forecast of the state of the system, the Kalman filter also provides an estimate of the forecast uncertainty, which is very important for assessment of the quality of the forecast.







Fig. 20

Simulation of storm surge component in the North Sea with (top panel) and without (bottom panel) data assimilation. Dots indicate the positions of water level measurement stations.



Fig. 21

Time series of the storm surge component at Vlissingen according to observations and simulated with and without data assimilation.

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