Description of the three-dimensional hydrodynamic model: Environmental Fluid Dynamics Code

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Outline

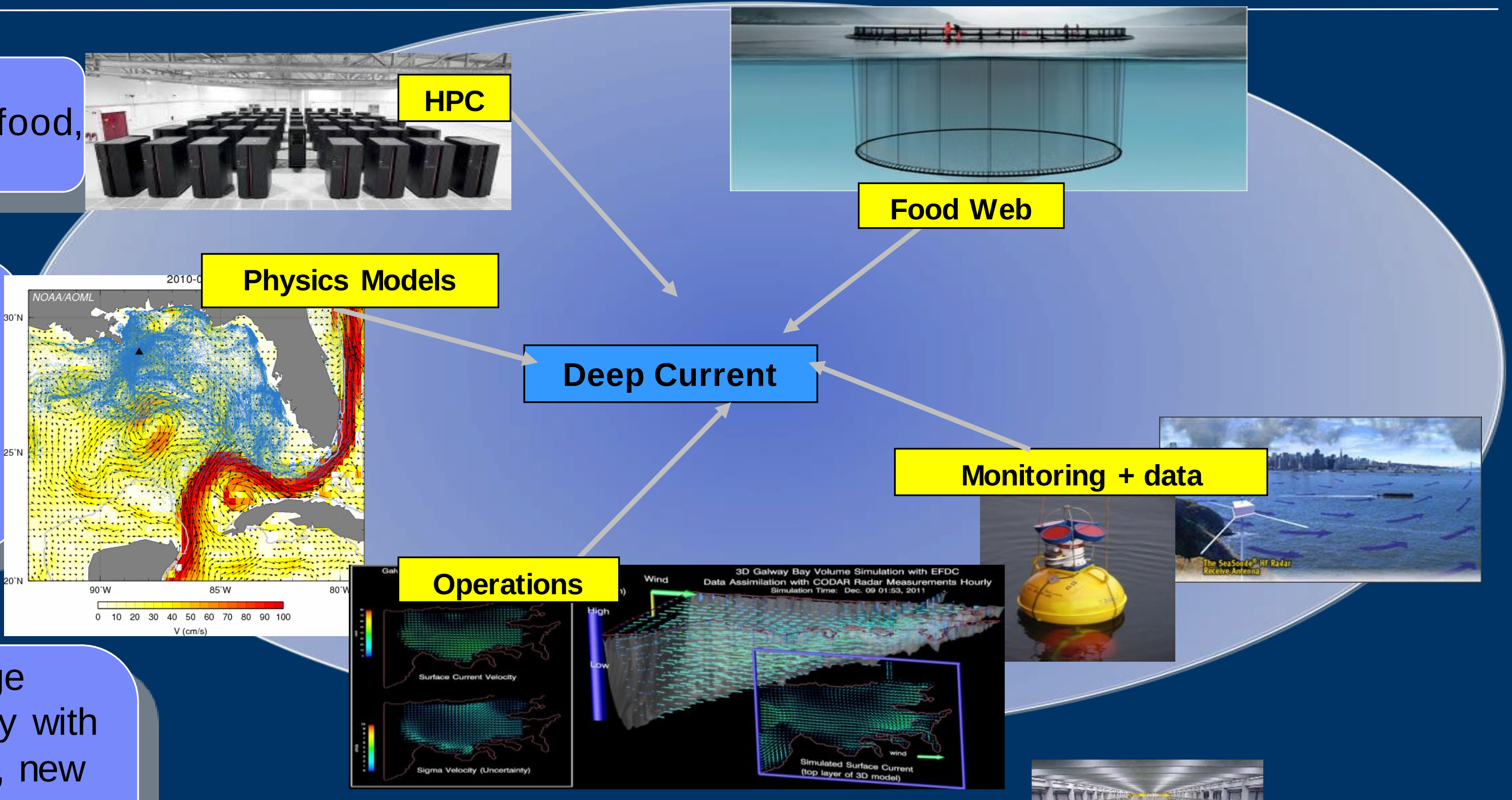
- Introduction
- Development History
- Capabilities
- Hydrodynamic Modeling
- Example Applications
  - Straight Channel
  - Galway Bay

IBM DeepCurrent

Oceans are increasingly viewed as a resource for food, water, and energy

Deep Current High resolution, real-time ocean circulation forecasts to support critical operations for marine-based businesses

Objective: Challenge large scale simulation capability with high-resolution data sets, new sensing modes with high density coverage and development of new physics/numerical models



Environmental Fluid Dynamics Code (EFDC)

- The EFDC model is a public-domain surface-water modeling system incorporating fully integrated hydrodynamics
- EFDC can be used for 1D, 2D, or 3D simulations of rivers, lakes, estuaries, coastal regions
- Original Philosophy (Dr. John Hamrick):
  - Transport stuff – salinity, larvae, nutrients, sediment, contaminants
  - Transport stuff for a long time on cheap computers
  - All in one application
  - Industry rather than academic code

EFDC – Development history

- Developed by Dr. John Hamrick at the Virginia Institute of Marine Science (VIMS) with primary support from the State of Virginia
- 1988: EFDC began as a barotropic code
- In 1996, the pubic-domain version was released with Primary Support from US EPA
- 2002: US EPA releases EFDC-Hydro
- 2010: Sandia National Laboratories releases SNL-EFDC with extended water quality, sediment transport, and capabilities to represent MHK devices
- 2017 IBM Research Ireland releases “DeepCurrent” extending EFDC with MPI parallelization, data assimilation schemes, 3D visualization integration and capabilities to represent aquaculture installations
- Currently used by federal, state, and local agencies, consultants, and universities

EFDC Capabilities

- EFDC resolves circulation and transport in complex environments
  - ✓Estuaries, rivers, lakes, and coastal waters
- EFDC simulates:
  - ✓Scalar transport:
    - Dye-tracer
    - Temperature
    - Particles
    - Water-quality variables
  - ✓Density stratification due to:
    - Salinity
    - Temperature
    - Sediment concentration

EFDC capabilities

- Directly coupled sediment and contaminant transport and fate models
  - Multiple sub-model options
- Simulates wetting and drying of flood plains, mud flats, and tidal marshes
- Integrated near-field mixing zone model (jet and plume injections)
- Recirculating boundary conditions
- Simulates hydraulic control structures such as dams and culverts
- Simulates wave boundary layers and wave-induced currents

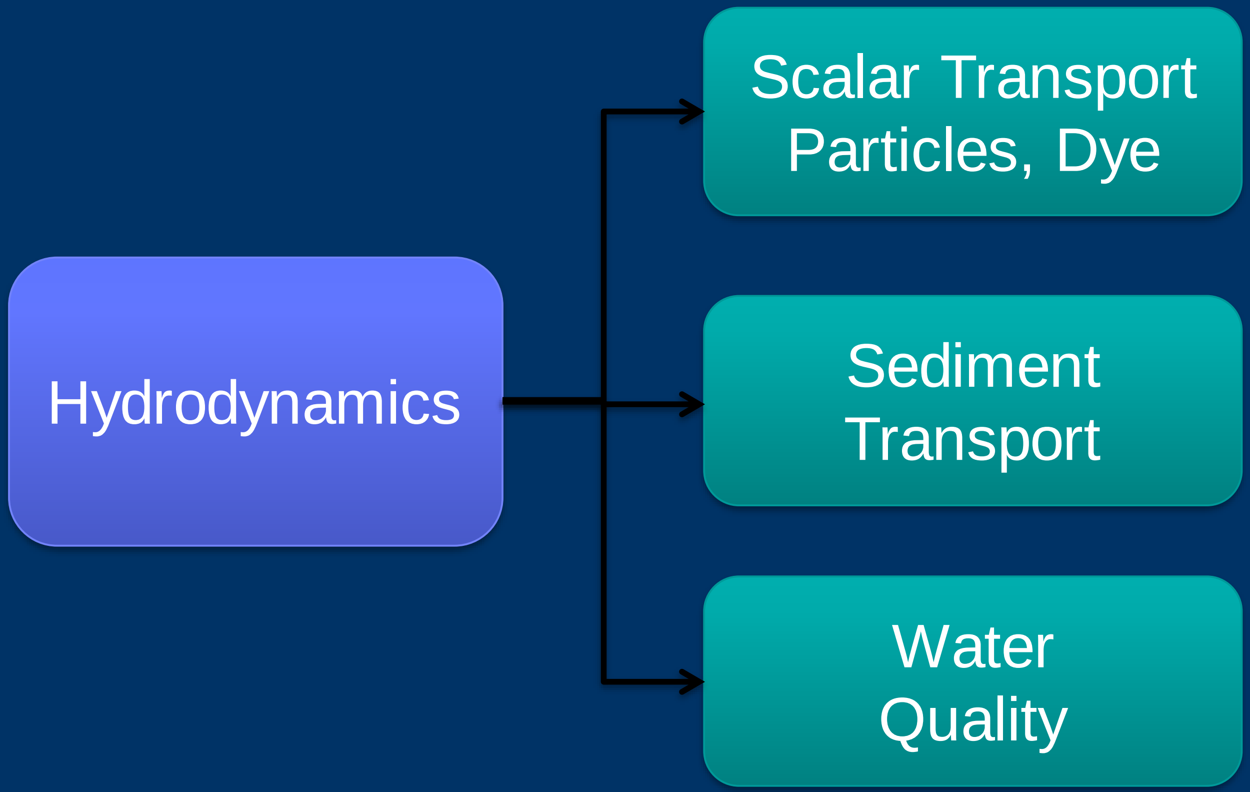
EFDC – Sandia National Laboratories extensions

- Extension of EFDC for predicting effects of MHK devices
- Upgrades to the water-quality routines
- Significant upgrades to the sediment transport routines of EFDC
  - When used with accurate measurements of erosion and transport mode, it provides realistic predictions of sediment transport
  - Applications of this algorithm have shown excellent agreement between both theoretical predictions and observations

EFDC – IBM Research Ireland extension

- MPI parallel implementation for deployment on HPC environment
- Load-balancing modules to provide optimal distribution across cores and minimize simulation time
- Data-assimilation modules
  - Assimilation of High Frequency Radar (HFR) measurements of surface currents
  - Assimilation of Vertical Profiler temperature data
- Coupling to high-resolution weather models (e.g., WRF) for atmospheric forcing
- Connections to Paraview and Visit for visualization & ncWMS for browser distribution and exploration
- Extensions to predict the effects of aquaculture installations on flows and transport
- Docker images for deployment on Cloud platforms (Bluemix, AWS, Azure)

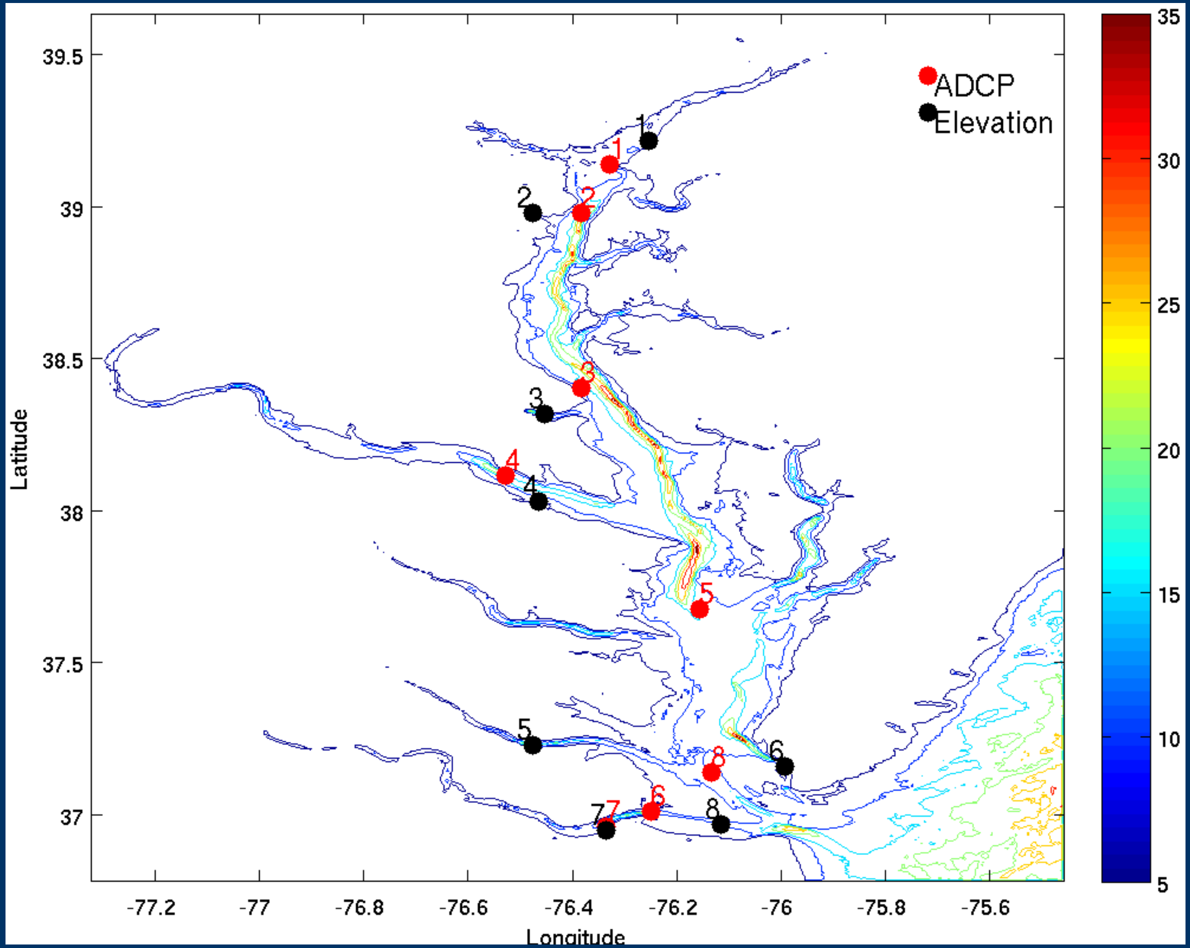
Basic EFDC Structure



Example of EFDC peer-reviewed applications

- Over 160 known applications
- Rivers – Potomac River (VA), Fox River (WI), Flint (AL), Housatonic (MA), Chattahoochee (GA), Los Angeles (CA), Penobscot River (ME)
- Lakes – Cedar Lake (IL), Lake Okeechobee (FL), Lake Jordan (NC), Coosa River Reservoirs (AL), Lake Allatoona (GA), Hartwell Reservoir (GA/SC), East River (NY)
- Estuaries - Mobile Bay (AL), Neuse River (NC), Savannah River/Harbor (GA), Charleston Harbor (SC), St. Johns River (FL), Lower Duwamish Waterway (WA), Curonian Lagoon (Lithuania), Chesapeake Bay (VA), Peconic Bays (NY), Cobscook Bay (ME), San Francisco Bay (CA)
- Coastal – Oahu (HI), Santa Cruz (CA)

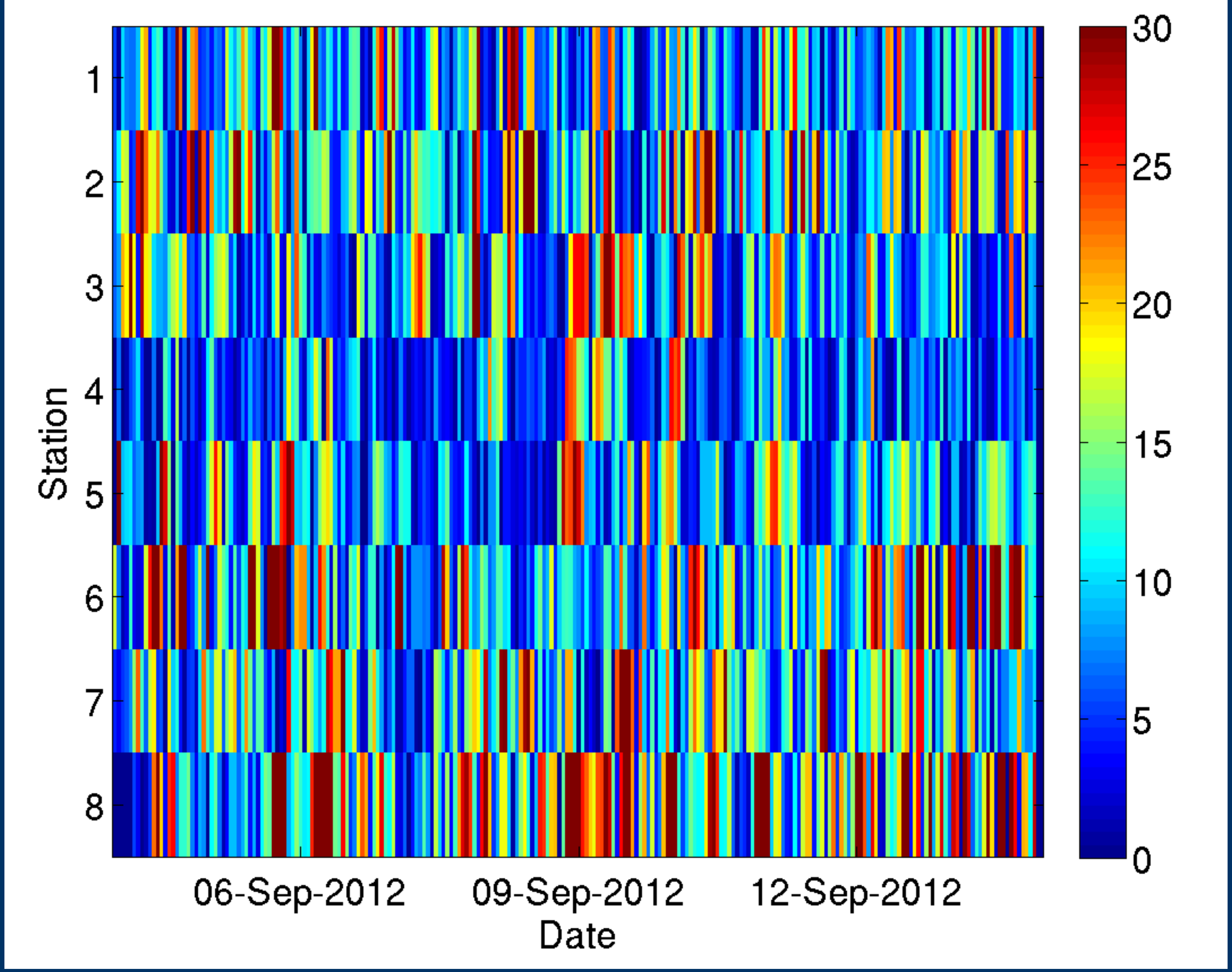
Study Site – Chesapeake Bay



- One of the largest estuaries in the world
- Extends approximately 300 km north from the ocean entrance to the Susquehanna River
- Average depth of 8 m with natural channel greater than 15 m depth extending over 60% of length
- Width varies from 6.4 km in the upper Bay to 48.3 km in the middle

Results – EFDC flow speed differentials against measurements

- With appropriate boundary conditions, a well-calibrated model can accurately reproduce hydrodynamics in the system.

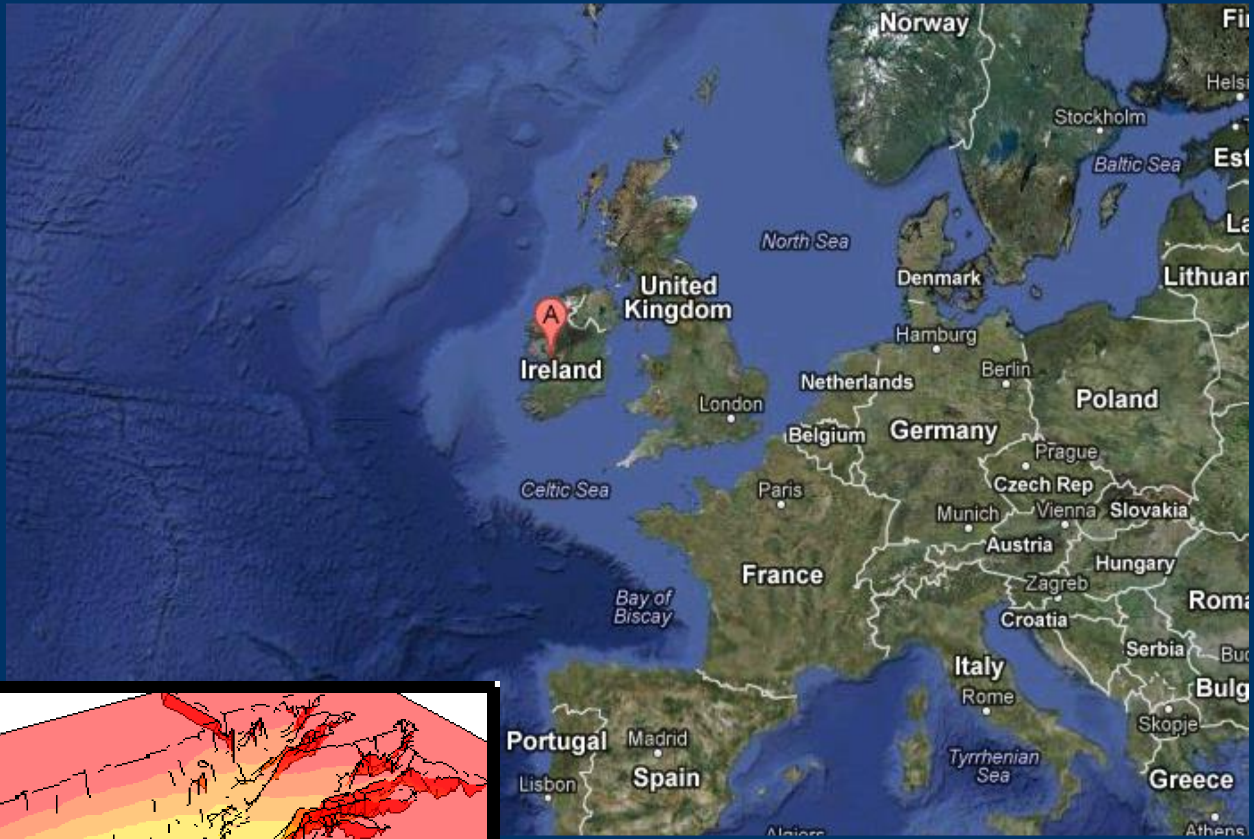


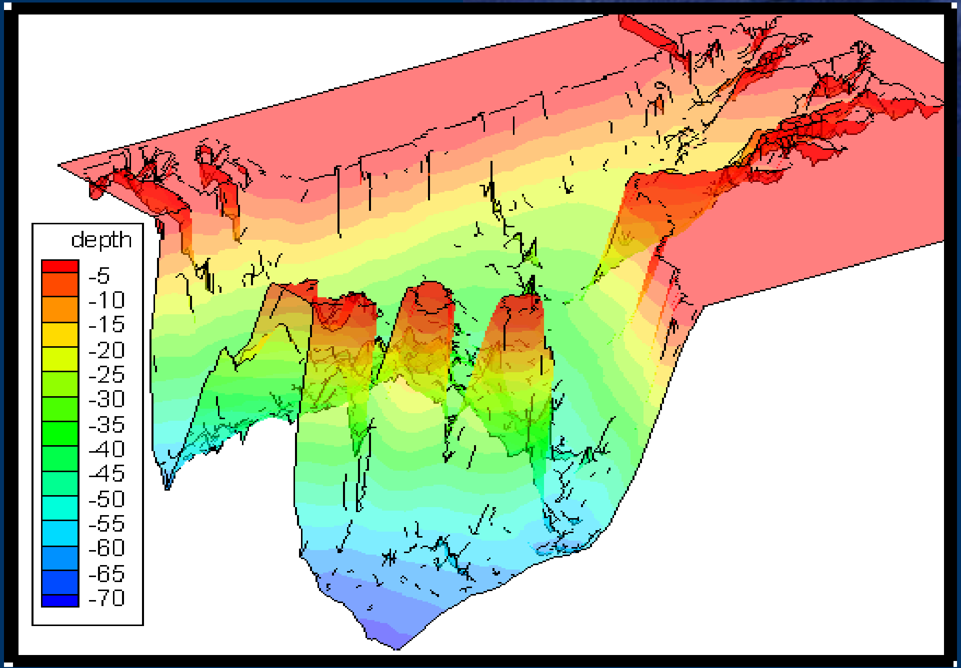
Upper Chesapeake

Lower Chesapeake

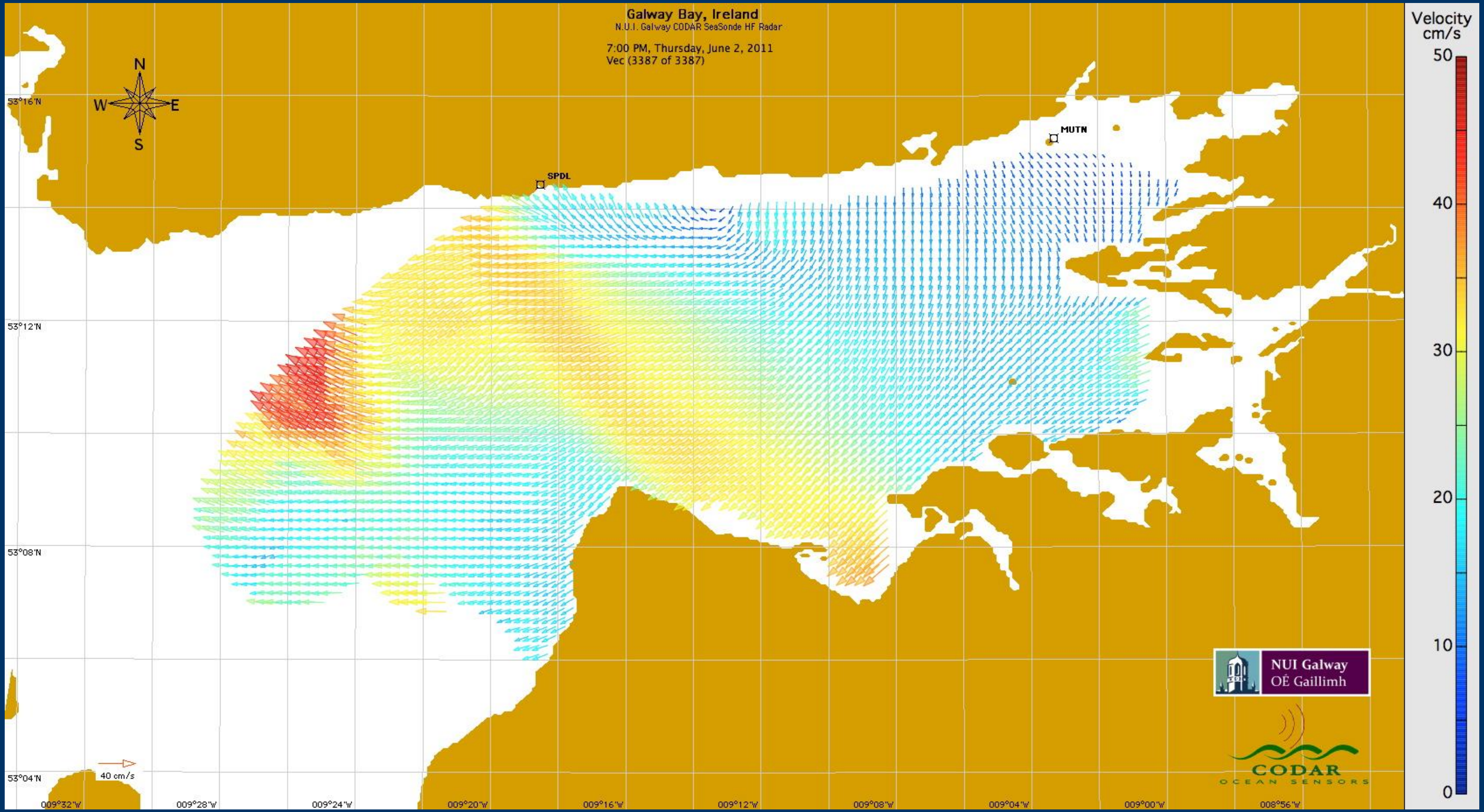
Galway Bay – Data assimilation to improve forecasts

- Complex forcing requires accurate specification of boundary conditions of: (1) incoming flows from open ocean, (2) surface forcing of winds and atmospheric heating, and (3) river inflows
- Model input data are incomplete and uncertain
- Leverage sensor measurements to improve model forecasts via data assimilation

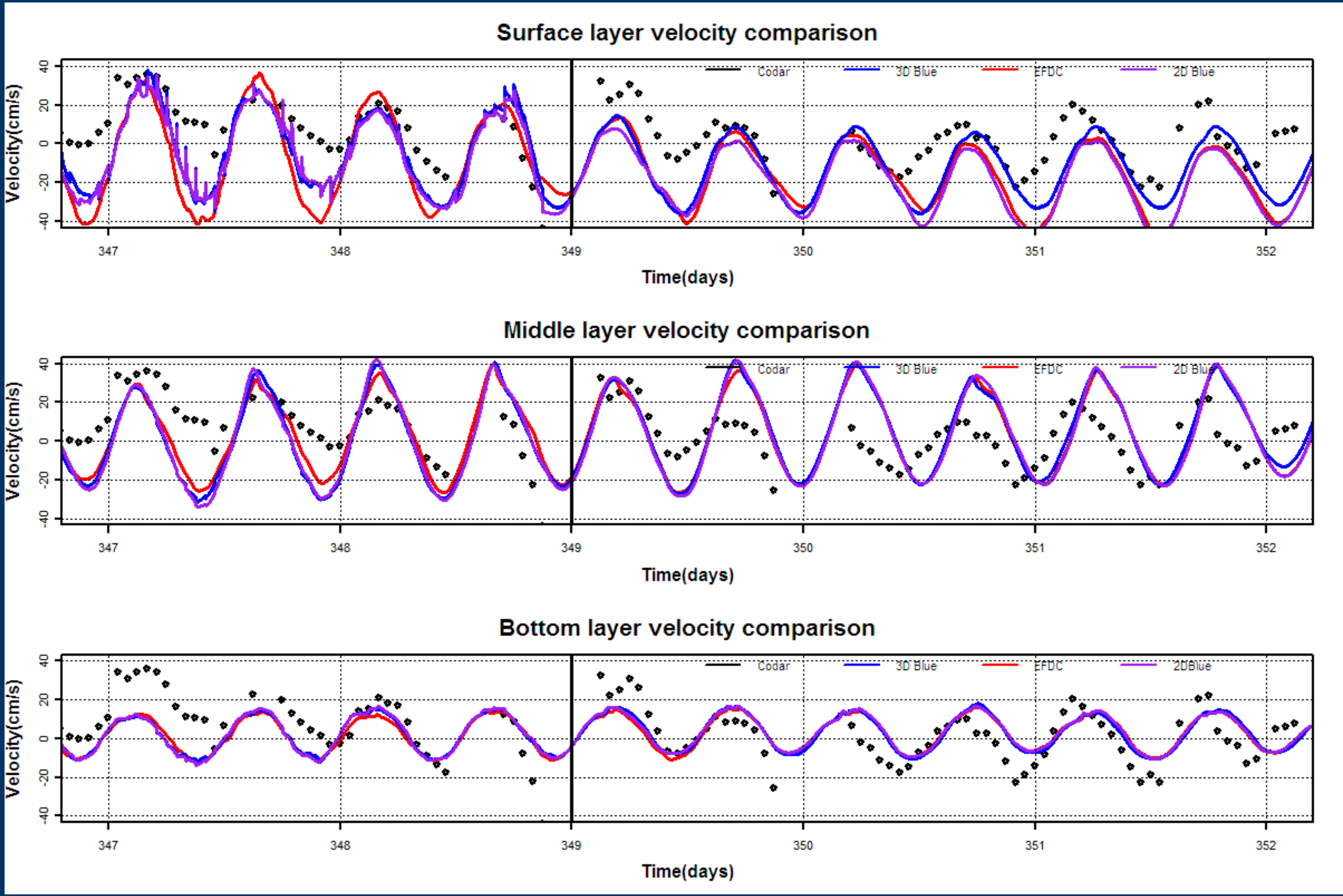




Assimilation of HFR surface current data

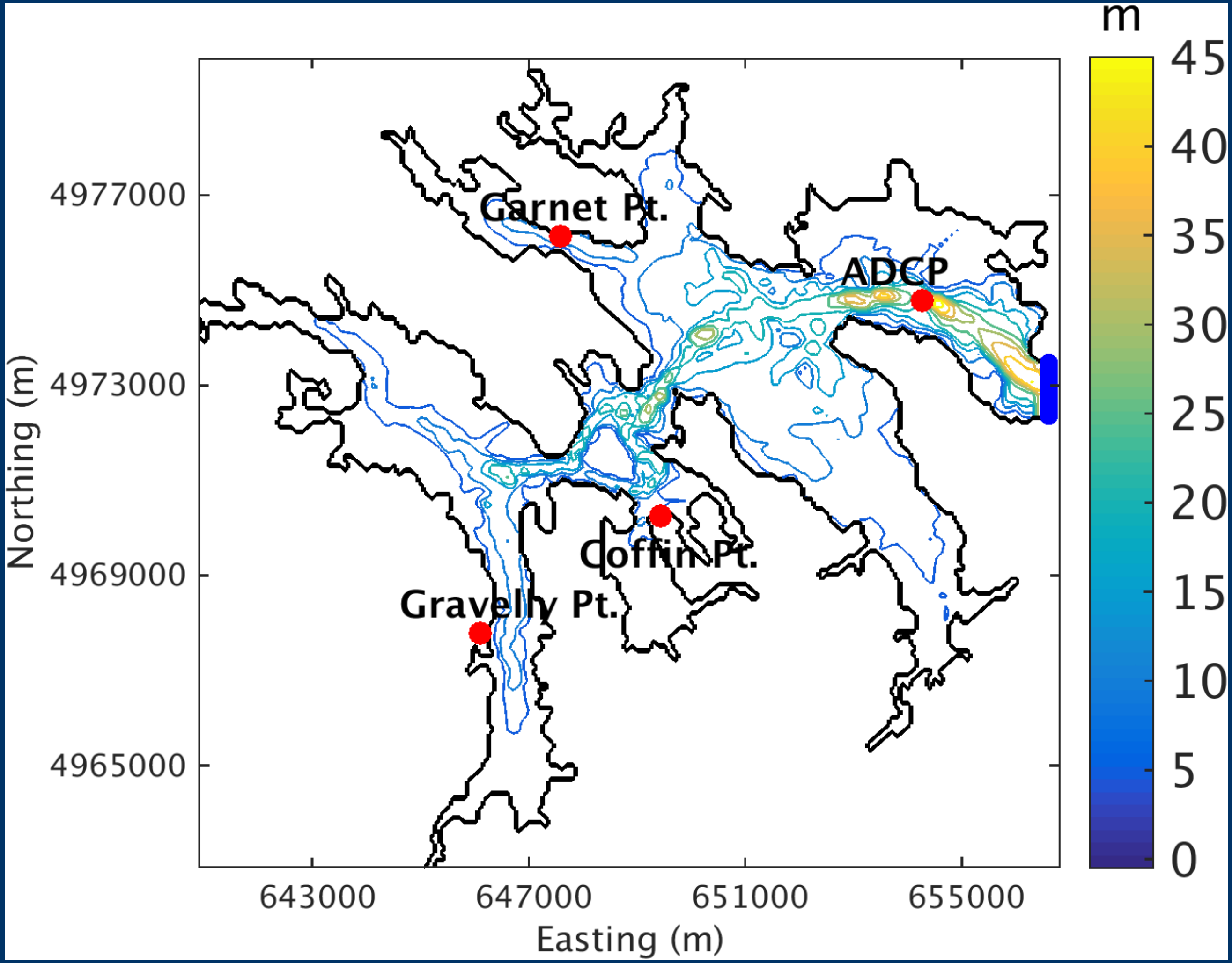


Continuous update of model forecast in real-time

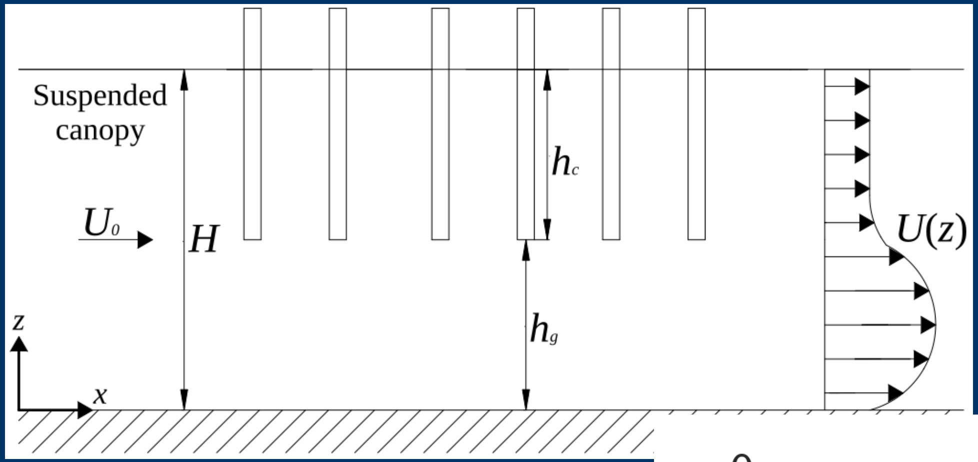


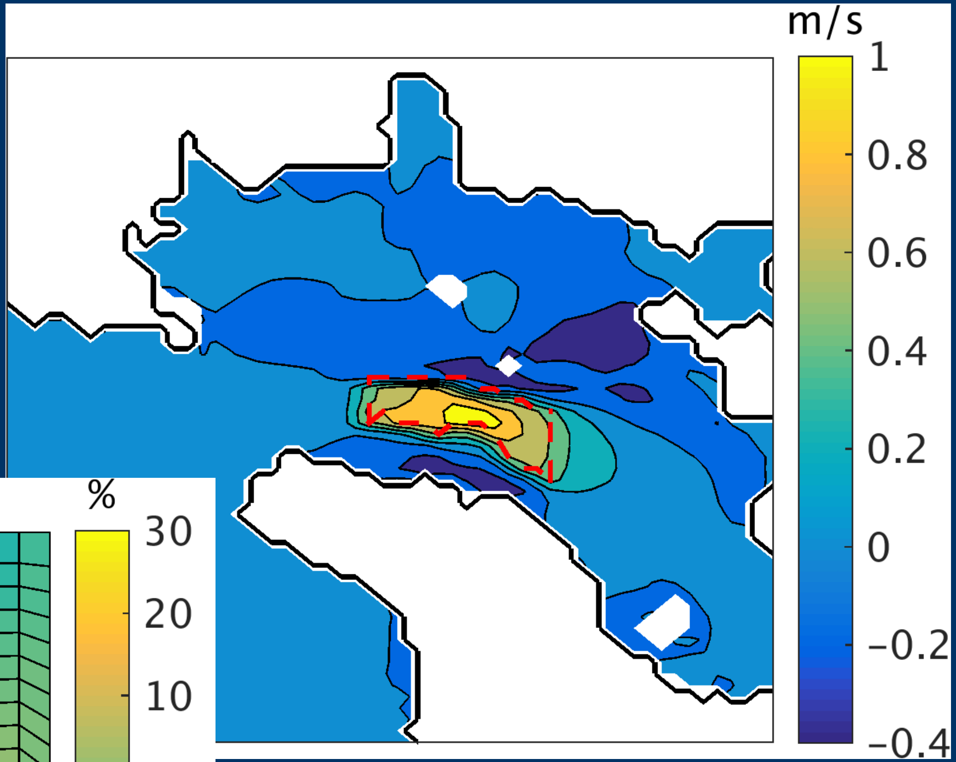
Representation of MHK and aquaculture modules – Cobscook Bay

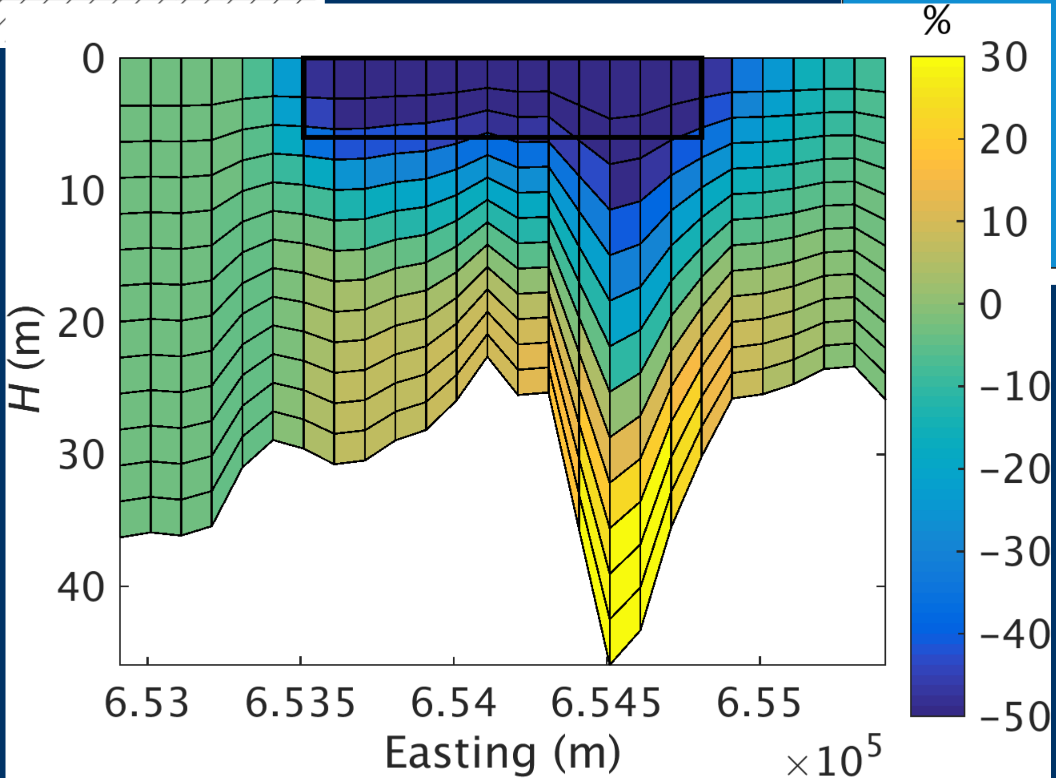
- Cobscook Bay is well known for vigorous tidal currents, abundant ocean production, and a diverse ecosystem
- Resultant high currents and suitable temperatures make the Bay highly suitable for aquaculture developments
- Further, the large tidal range and nearly enclosed nature provides obvious potential for tidal energy generation
  - EFDC to investigate viability and effects of aquaculture and MHK installations on flows and material transports



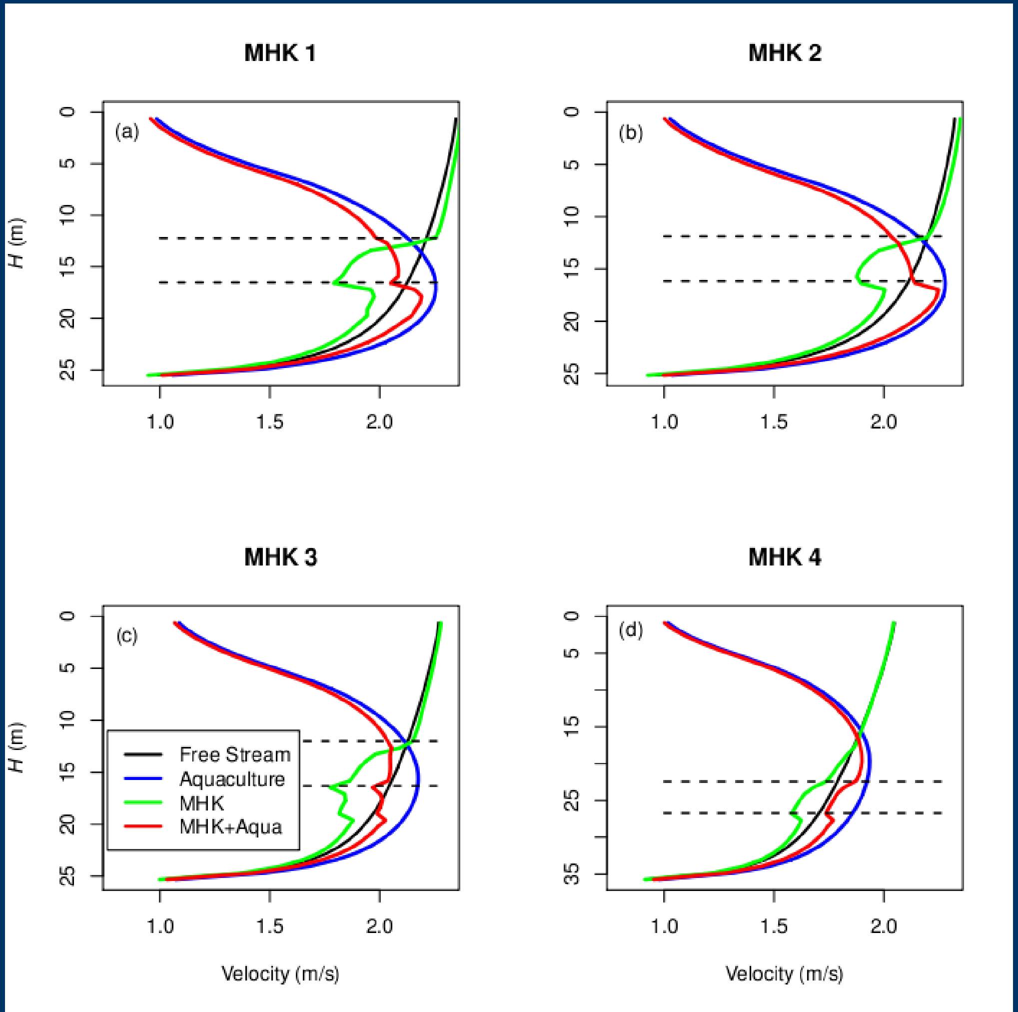
Effects of aquaculture installations on flow







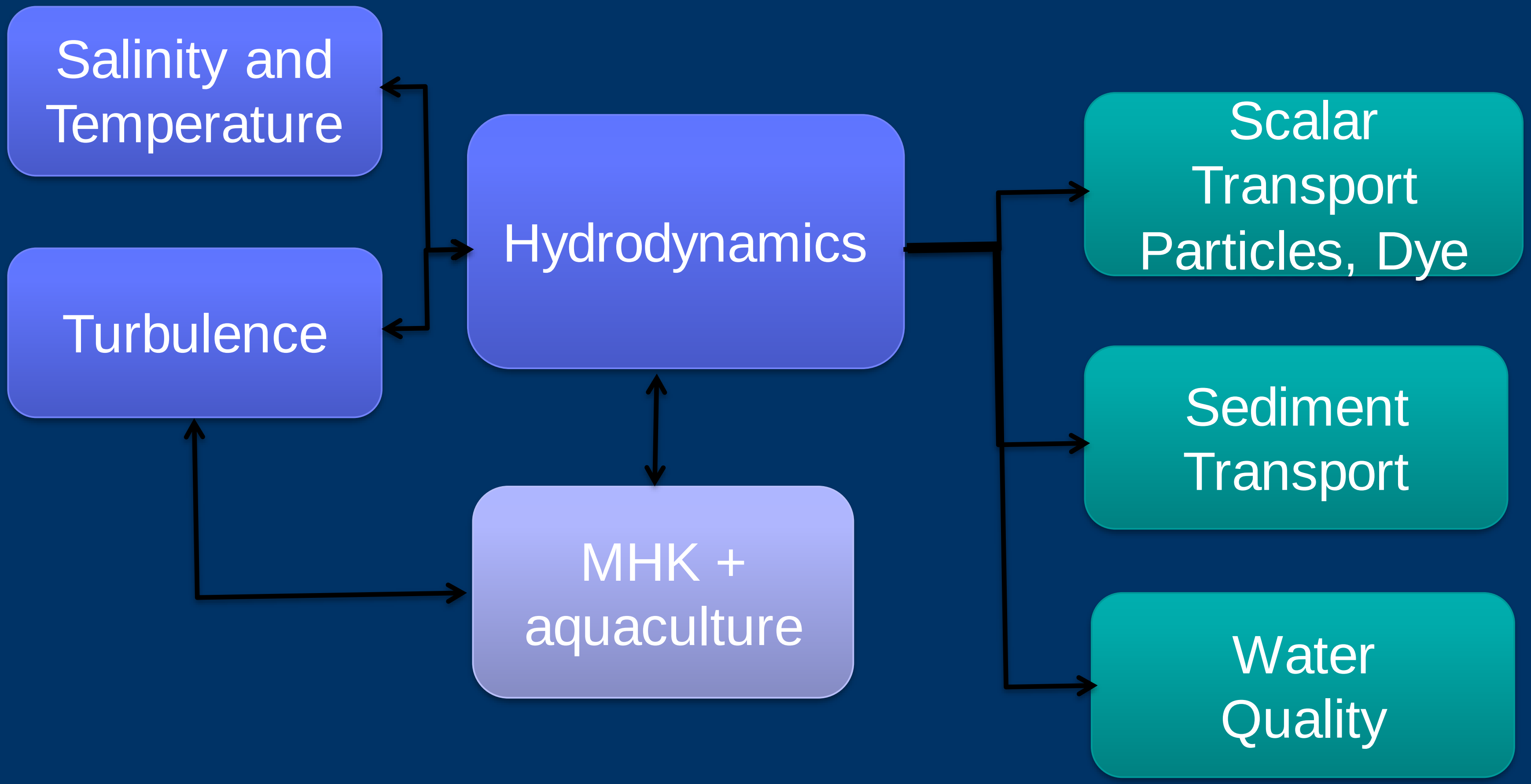
Effects of MHK devices on flow and power generation



$$P = \frac{1}{2} C_T \rho A_T U^3$$

Turbine	Undisturbed (MW-hr)	Aquaculture (MW-hr)	MHK (MW-hr)	MHK + Aqua
1	1.01	1.6	0.79	1.42
2	1.77	1.97	1.28	1.78
3	2.06	2.27	1.49	2.02
4	1.96	2.33	1.5	2.07
Relative	1.00	1.19	0.74	1.05

Basic EFDC structure

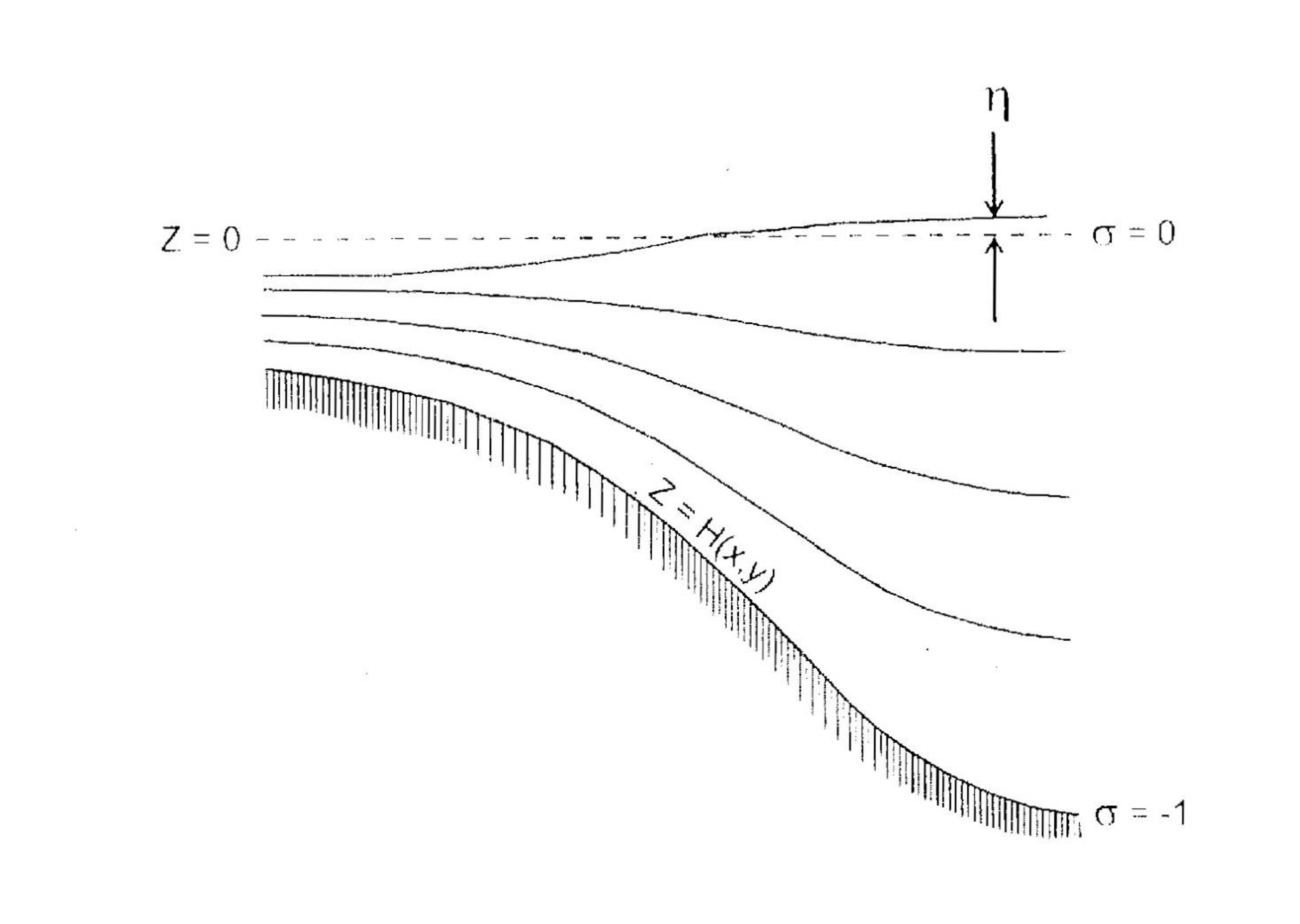


EFDC hydrodynamic module

- Fully 3D with 2D options
- Boundary-fitted curvilinear or Cartesian grids
  - σ-level or stretched bathymetry-following grid in the vertical
- Includes a turbulence closure model (Mellor and Yamada, 1982)
- Finite difference, semi-implicit solution

EFDC hydrodynamic module - Grid

- In EFDC, the sigma (σ or stretched) transformation is used to develop a “bottom following” grid.



EFDC Hydrodynamic Module

- The equations of motion and transport are turbulence-averaged.
- A statistical approach is applied, where values are decomposed into mean and fluctuating values for solution.
- Dispersion terms are introduced into the equations for flow to represent the turbulence terms.
- The turbulent equations of motion are formulated to use the Boussinesq approximation for variable density (e.g., salinity and temperature stratification)

EFDC Atmospheric Coupling

- Wind stresses can drive fluid motion (mixing and transport)
- Atmospheric coupling can drive temperature transport
  - Solar radiative heating (cloud cover considered)
  - Heat exchange as a function of air temperature and wind speed
  - Evaporative cooling
  - Long-wave radiative heat is emitted from the water column

- Atmospheric pressure affects water-surface elevation
- Heat exchange with the sediment bed

EFDC Hydrodynamic module

Three-dimensional continuity

$$H = h + \eta \qquad z^* = \frac{z}{H}$$

$$\frac{\partial H}{\partial t} + \frac{\partial Hu}{\partial x} + \frac{\partial Hv}{\partial y} + \frac{\partial w}{\partial z^*} = 0$$

Conservation of momentum - *x* component (Cartesian)

Accumulation Advection Coriolis

$$\boxed{\frac{\partial Hu}{\partial t}} + \boxed{\frac{\partial Huu}{\partial x} + \frac{\partial Hvu}{\partial y} + \frac{\partial wu}{\partial z^*}} - \boxed{fHv} =$$

$$-\boxed{H\frac{\partial p}{\partial x}} - \boxed{\left(\frac{\partial z_b^*}{\partial x} + z\frac{\partial H}{\partial x}\right)\frac{\partial p}{\partial z^*}} + \boxed{\frac{\partial}{\partial z^*}\left(\frac{A_V}{H}\frac{\partial u}{\partial z^*}\right)} + \boxed{\frac{\partial}{\partial x}\left(HA_H\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(HA_H\frac{\partial u}{\partial y}\right)} - \boxed{c_p D_p \left(u^2 + v^2\right)^{1/2} u}$$

Pressure Buoyancy Vertical-momentum diffusion Horizontal-momentum diffusion Drag resistance

X-direction momentum equation

Coriolis force

$$-fHv$$

Buoyancy

$$\frac{\delta p}{\delta z} = -gH\frac{\rho - \rho_0}{\rho_0}$$

Momentum diffusion (Vertical and Horizontal)

$$\frac{\delta}{\delta z}\left(\frac{A_v}{H}\frac{\delta u}{\delta z}\right) + \frac{\delta}{\delta x}\left(HA_H\frac{\delta u}{\delta x}\right)$$

Drag resistance

$$-c_p D_p (u^2 + v^2)^{1/2} u$$

EFDC Turbulence Transport

- Horizontal turbulent diffusivity (A_H) is determined independently using Smagorinsky's (1963) subgrid-scale closure formulation

- The second moment turbulence-closure model developed by Mellor and Yamada (1982) is used to determine the values of vertical diffusivity (A_v)

- The Mellor and Yamada model relates the vertical turbulent viscosity and diffusivity to the turbulence intensity (q), a turbulent length scale (l), and a turbulent intensity & length-scaled-based Richardson number (Ri_q)

EFDC Turbulence TransportType equation here.

- The turbulence intensity (*k*) and length scale (*l*) are determined by solving standard transport equations

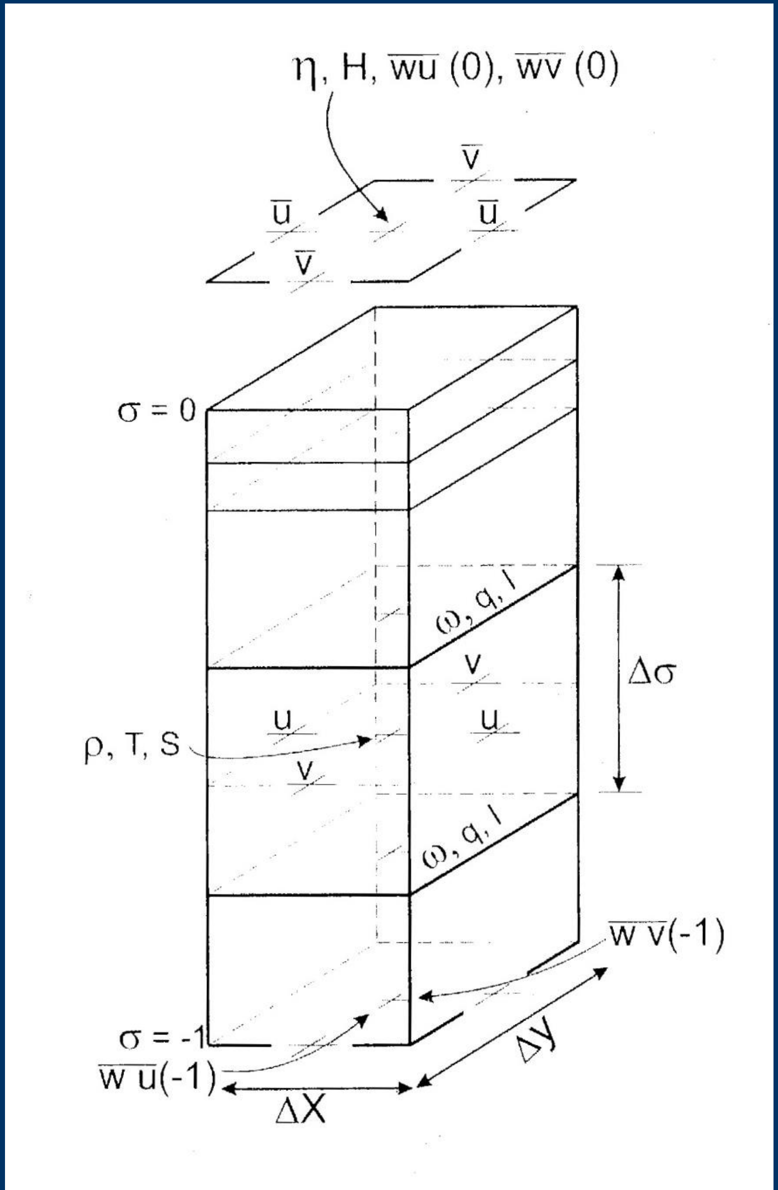
$$\frac{\partial k}{\partial t}+u\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial y}+w\frac{\partial k}{\partial z}=\frac{\partial}{\partial z}\left(\frac{A_v}{\sigma_k}\frac{\partial k}{\partial z}\right)+A_v\left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]+A_v\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}-\varepsilon$$

$$\frac{\partial kl}{\partial t}+u\frac{\partial kl}{\partial x}+v\frac{\partial kl}{\partial y}+w\frac{\partial kl}{\partial z}=\frac{\partial}{\partial z}\left(\frac{A_v}{\sigma_q}\frac{\partial kl}{\partial z}\right)+\frac{l}{k}\left[A_v\left(\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right)\right]+A_h\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}-\varepsilon F_{Wall}$$

- Model accounts for both transport and historic influences on turbulence.
- Simulates turbulence induced by convection, pressure gradients effects, shear stresses, and topographically produced.

EFDC Hydrodynamic Module Solution Scheme

- The transport equations outlined above are solved on a staggered computation “C” grid using finite differencing.
- The velocities are face centered on each cell and then *η* (i.e., water surface elevation) is solved at the cell center (i.e., node).



EFDC Hydrodynamic Module Solution Scheme

- For computational efficiency, the solution of the transport equations use a mode-splitting technique common in oceanographic models
- The theory is based on the difference in movement of fast-moving external gravity waves and slower moving internal waves in a system
- Two sets of transport equations are used to obtain a numerical solution:
  - External – Vertically integrated momentum equations are solved more frequently (~1-100 time steps) to obtain an average horizontal velocity and water-surface solution (solved on a column of water)
  - Internal – Vertically resolved momentum equations are solved at the completion of each external solution to resolve changes in the vertical structure of velocity and other water column properties (solved across model sigma layers)
- The mode-splitting technique provides a robust and efficient solution for the hydrodynamics

Model Development
Tiered Approach

- Developing a model in tiers is the most efficient and cost effective approach
- The general approach to the modeling study is outlined at the beginning of the project
- Design of subsequent tiers will be updated as the site becomes better understood

Model Development

Typical Phased Approach

- **Tier 1**: Data compilation and initial Conceptual Site Model (CSM) development
- **Tier 2**: Hydrodynamic modeling
- **Tier 3**: Transport modeling (dye, temperature, sediment, water quality, MHK)

Tier 1: Data Compilation and Initial CSM Development

- Compile and analyze available data
- Identify data gaps
- Design and conduct field studies to fill data gaps
  - Measurement of currents, waves, water levels
- Develop initial CSM for hydrodynamics

Tier 2 - Hydrodynamic Modeling

- Develop model
  - –Generate model grid and bathymetry
  - –Develop boundary conditions for model
  - –Initial testing of hydrodynamic model
  - –Calibrate and validate hydrodynamic model

- Evaluate CSM

Hydrodynamic Model – Typical Data Needs

- Geometry and bathymetry of study area
  - Bathymetry for riverine studies
  - Additional marsh topography in estuarine studies
- Inflows from upstream boundaries and tributaries
- Water-surface elevation at downstream boundaries
- For some studies, additional data needs may include:
  - Temperature
  - Salinity
  - Wind
  - Vegetation properties
  - Water-quality data

Hydrodynamic Model – Numerical grid generation

- Determine the extent of the model domain
  - Establish upstream and downstream boundaries

- Type of numerical grid depends on geometry of study area
  - Rectangular grid
  - Curvilinear grid

- Need to consider study objectives and questions when designing the numerical grid
  - Long-term, multi-year simulations
  - Areas of special interest
  - Spatial scale of remedial areas

Hydrodynamic Model – Boundary Conditions

- Data sources
  - USGS gauging stations
  - NOAA tidal stations
  - Published field studies
    - Local Universities
    - USACE
    - USGS
    - NOAA
  - Special field studies

Hydrodynamic Model – Initial Model Testing

- Quality control
  - After developing input files for upstream and downstream BCs, generate plots of the model inputs and compare to original data
- Determine maximum time-step for numerical stability
  - May be flow dependent
- Conduct short simulations over a wide range of flow and tidal conditions and verify results
  - For floodplain and inter-tidal areas, ensure that wetting/drying of grid cells is working properly
  - Animate results to examine entire study area

Hydrodynamic Model – Detailed Model Testing

- Conduct a complete modeling study
  - –Model calibration with appropriate data sets
    - Tuning of parameters to provide acceptable performance against calibration data
  - –Model validation using independent data
    - Validation of calibrated model against separate dataset and evaluation of performance
  - –Model sensitivity testing
    - Deploying model to investigate sensitivity of processes to varying model forcing functions