Tidal-Driven Dynamics and Mixing Processes in a Coastal Ocean Model With Wetting and Drying

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May 24, 2010

Overview

- A wetting and drying (WAD) scheme has been implemented in POM (WAD-POM) and was tested for 1- and 2-D cases, including hydraulic jumps, dam-break problems, and a comparison with analytical solutions
- A full 3-D of WAD-POM, including stratification, rivers, winds, and realistic coastlines, has been applied to Cook Inlet, Alaska, where it has successfully simulated 10-m-range high tides, mudflat flooding, and even tidal bores (Oey *et al.* 2007)
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More details in Oey (2005, 2006)

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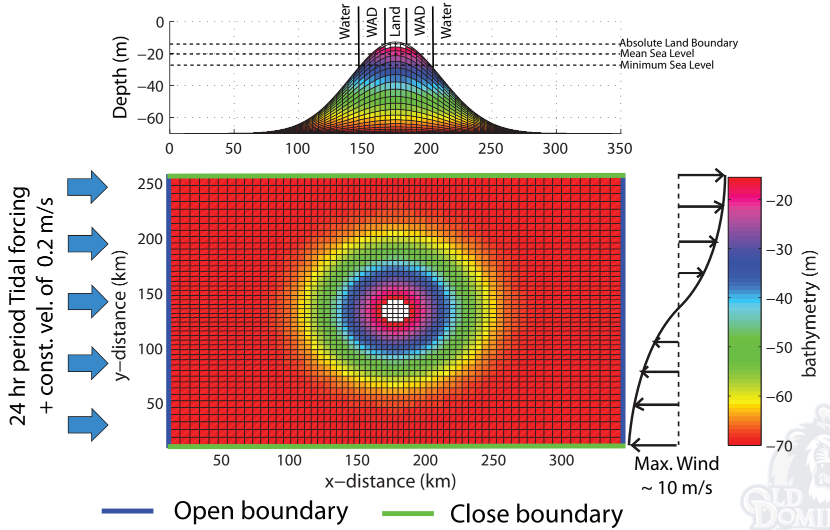
More details in Oey (2005, 2006)

http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/

Objective

- To evaluate how the tidally driven mixing processes in shallow areas around the island are affected by inundation associated with WAD and by several factors, such as tidal amplitudes, stratification, model resolution, etc.

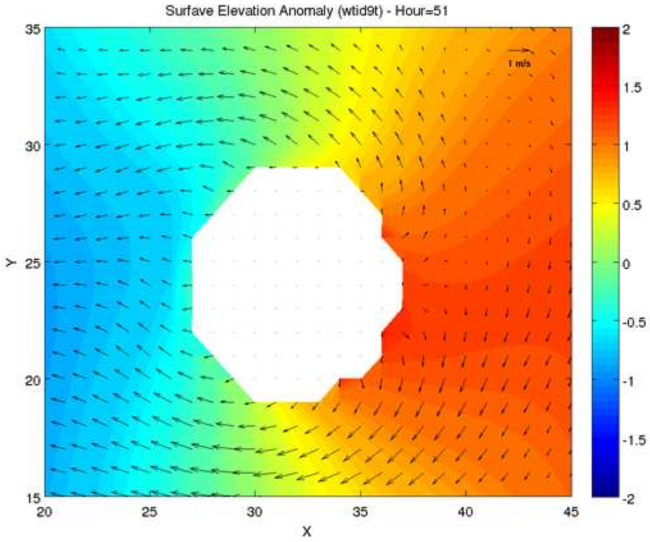
Methodology: Model setup



Methodology: Model experiments

- Grid size
  - **RM** (Standard run): medium grid size 4-8 km (65×49), 9 m tidal range, stratified, with Coriolis and with wind, **RS**: small grid size 2-4 km (131×99), **RL**: large grid size 8-16 km (33×25)
- Tidal range
  - **TR1**, **TR2**, **TR3** and **TR4** same as **RM**, but with 1 m, 2.75 m, 4.5 m and 9 m tidal range, respectively
- No stratification
  - **NS1** and **NS4** same as **TR1** and **TR4**, respectively
- No Coriolis
  - **NC1** and **NC4** same as **TR1** and **TR4**, respectively
- No wind
  - **NW1**, **NW2**, **NW3** and **NW4** same as **TR1**, **TR2**, **TR3** and **TR4**, respectively

Model results: Surface Elevation Anomaly



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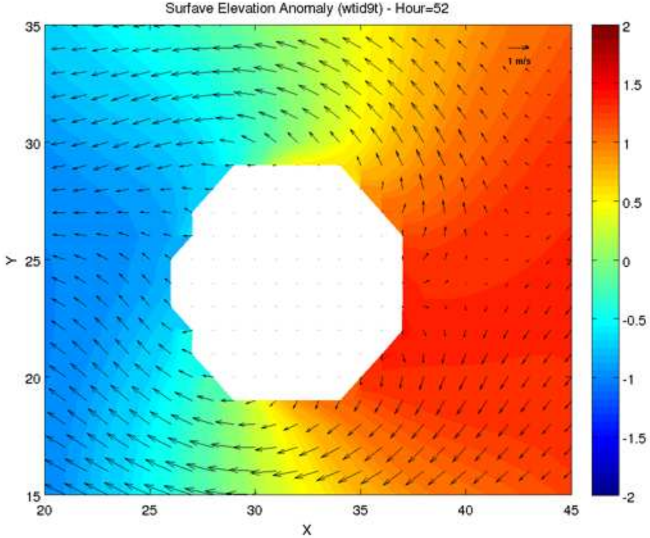

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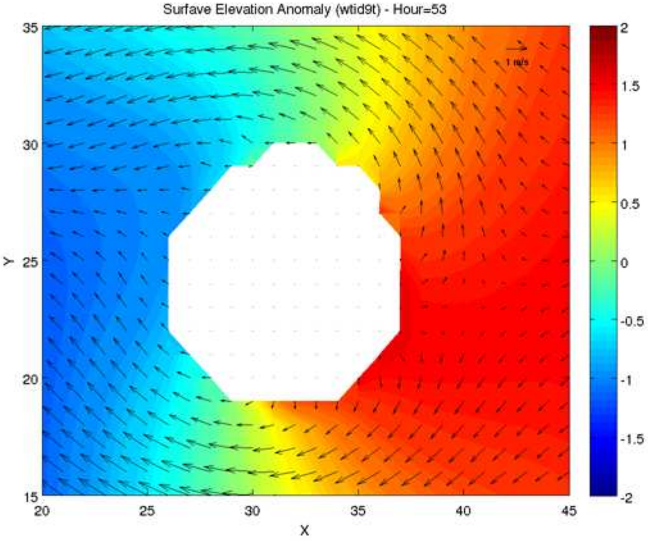

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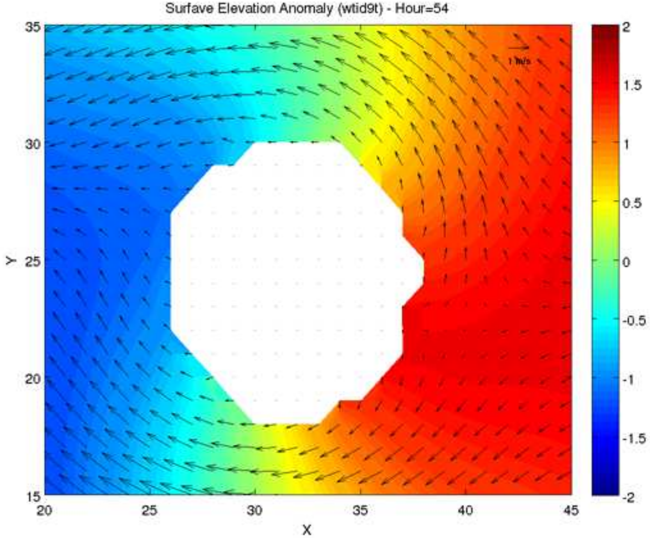

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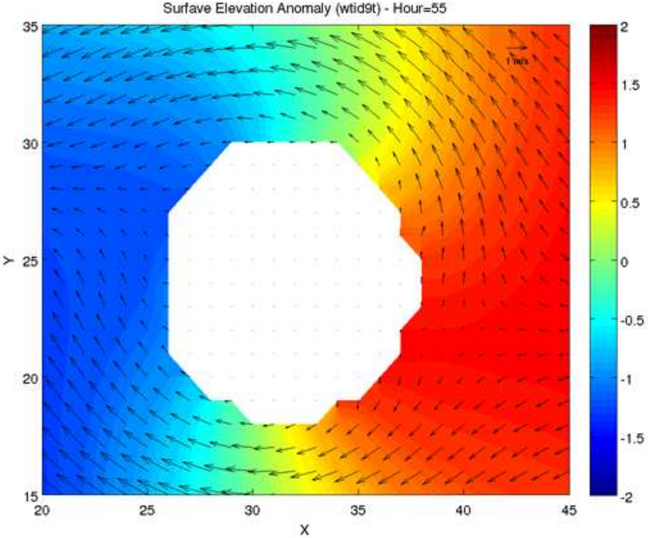

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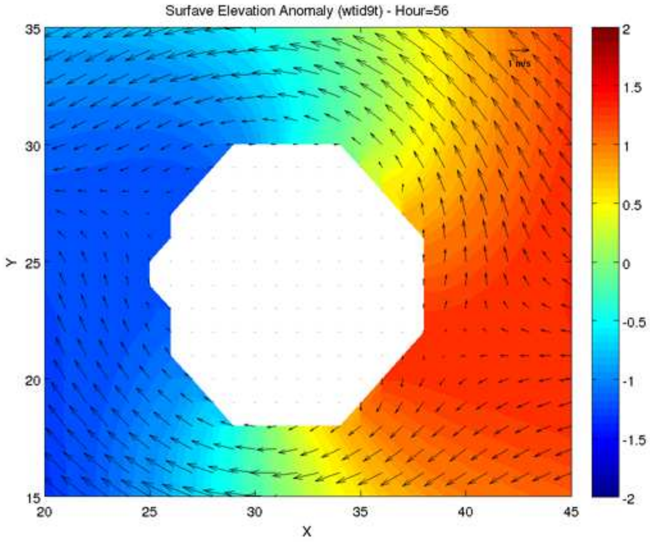

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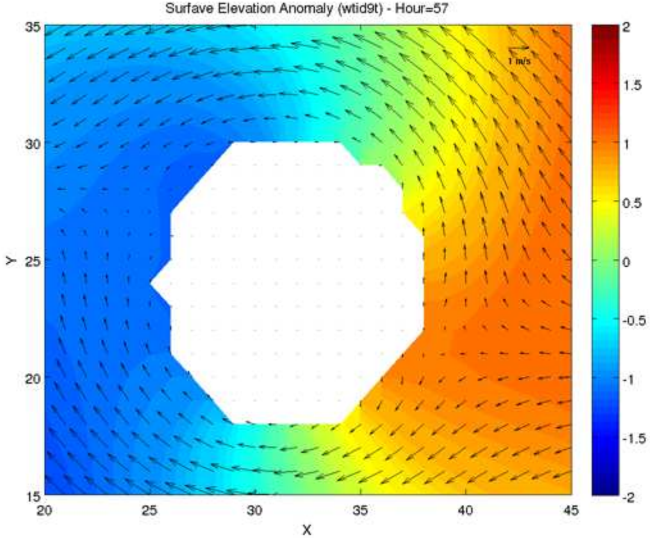

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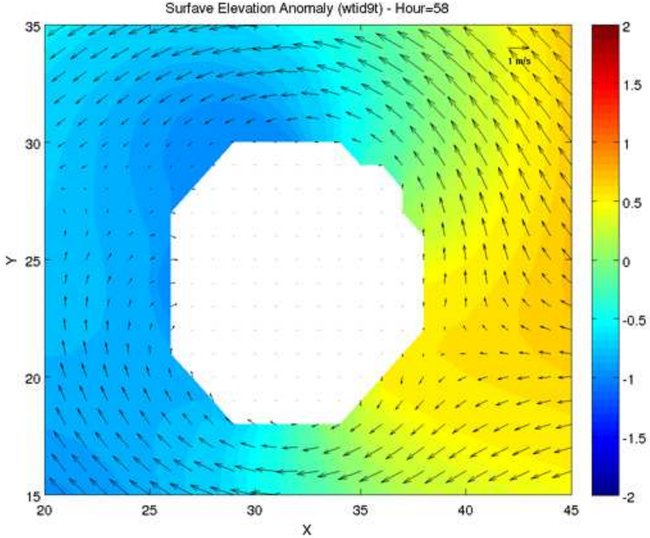

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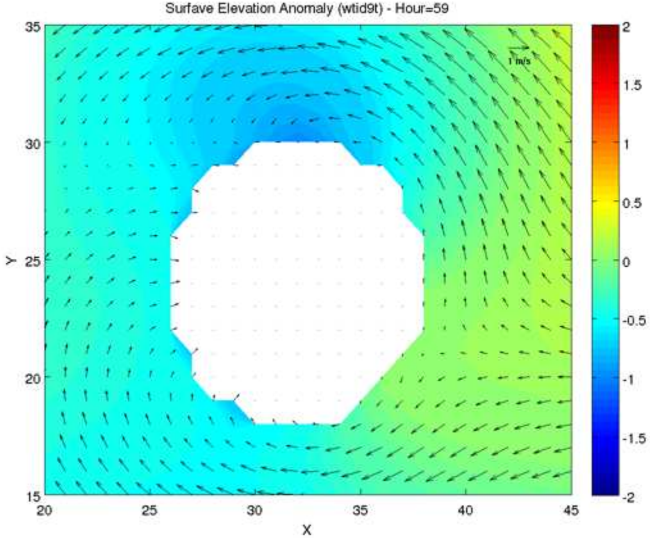

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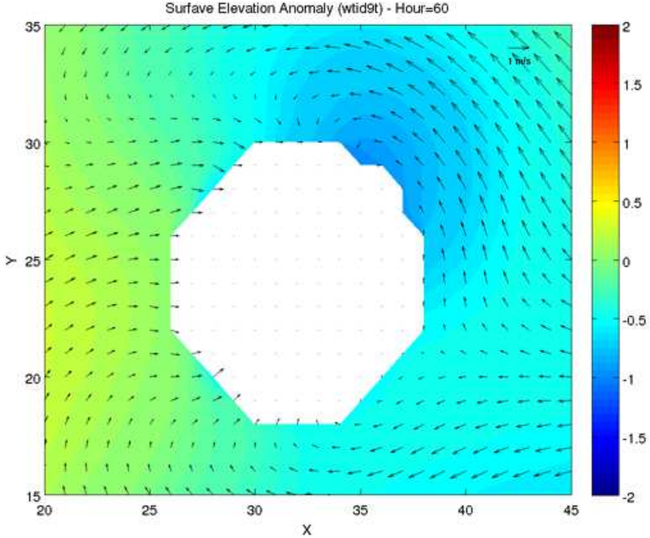

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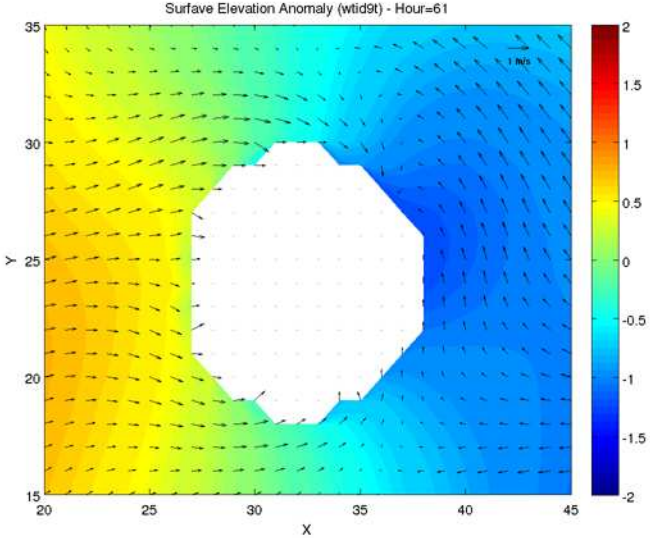

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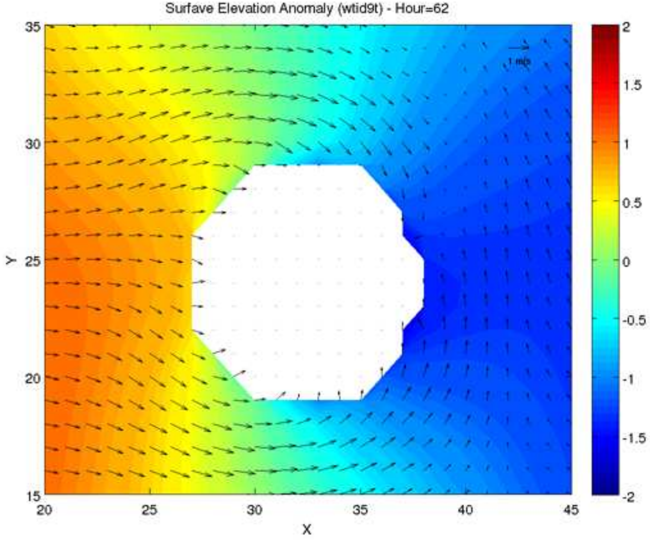

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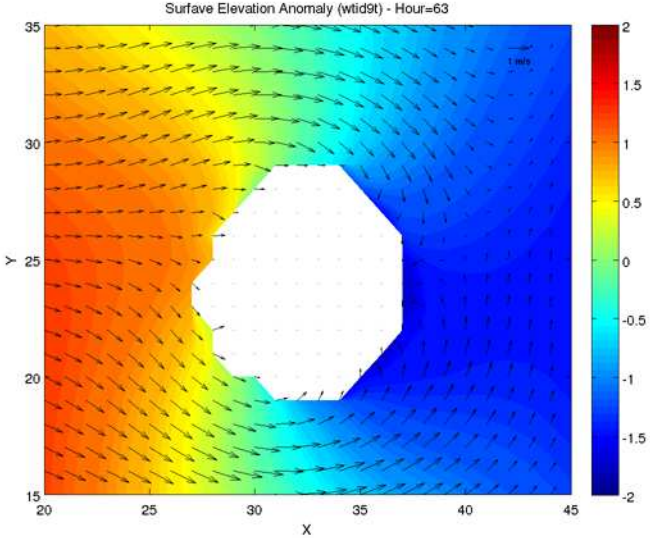

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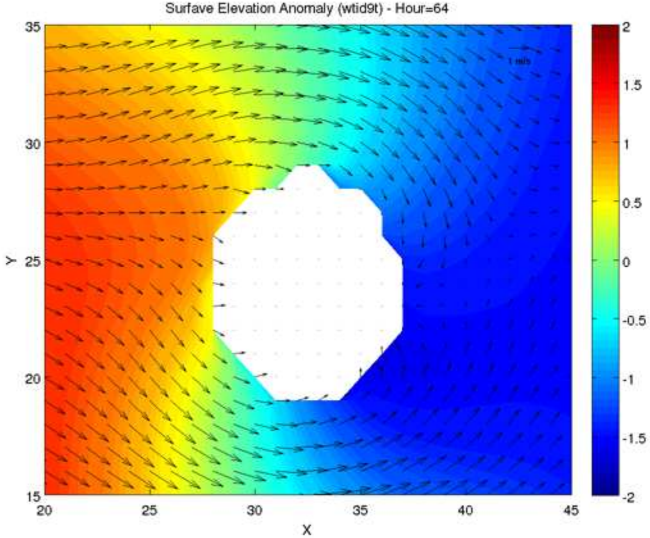

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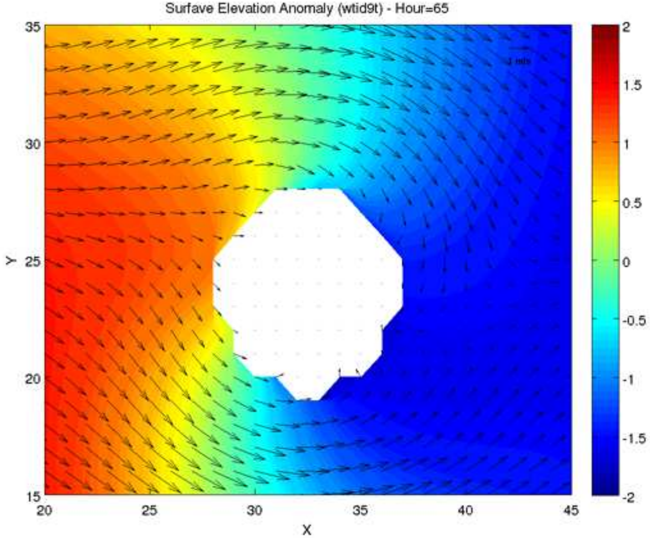

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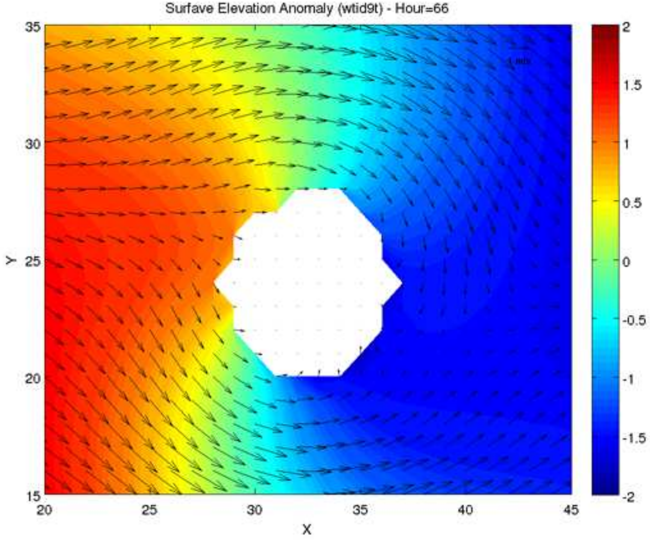

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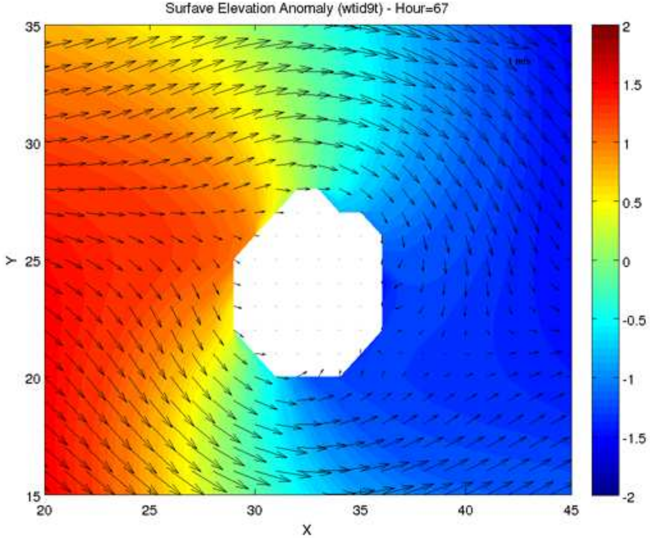

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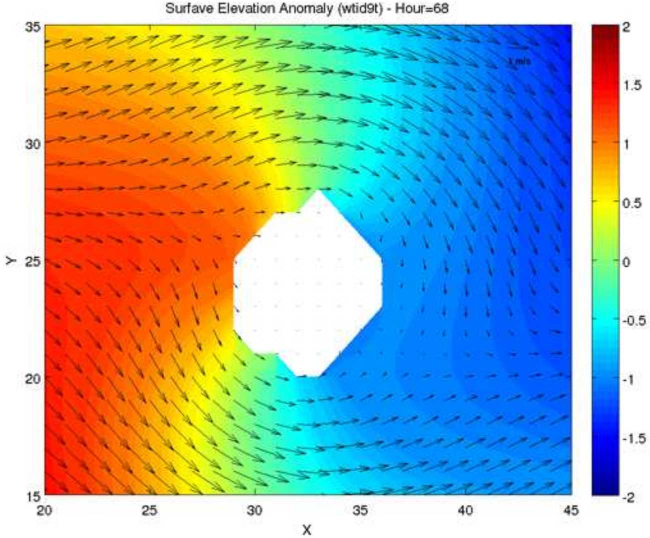

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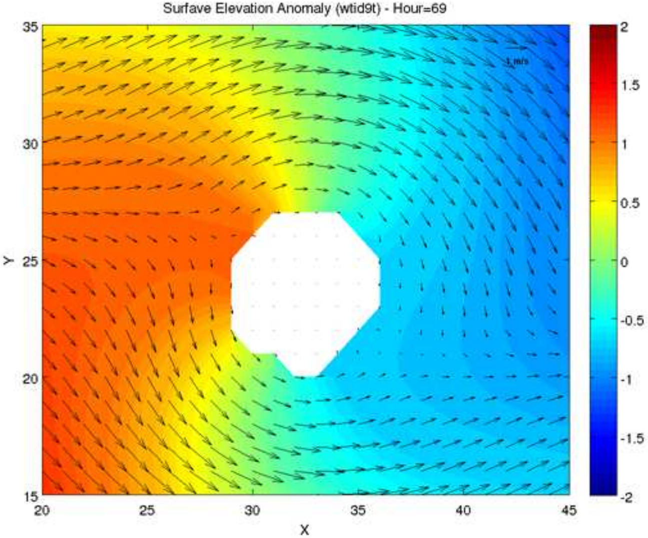

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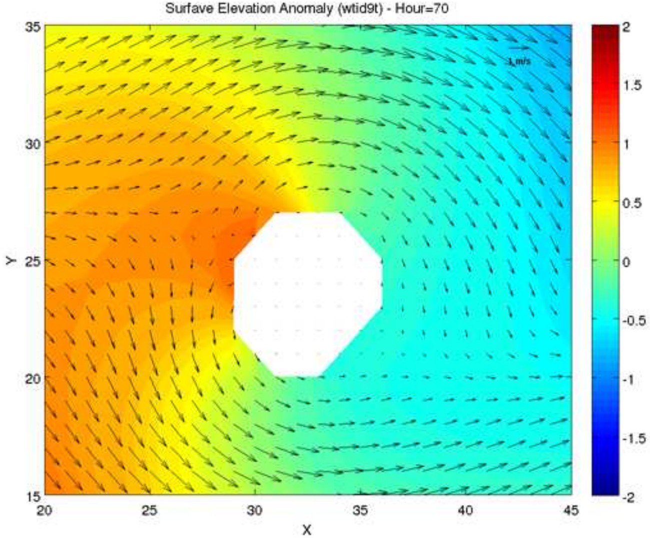

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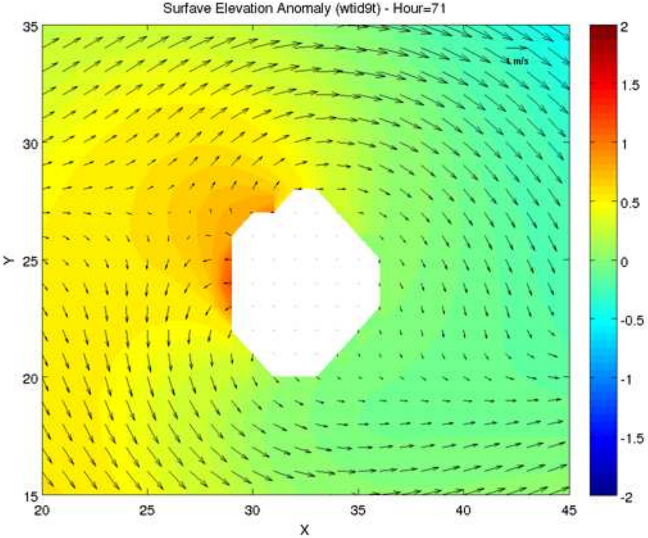

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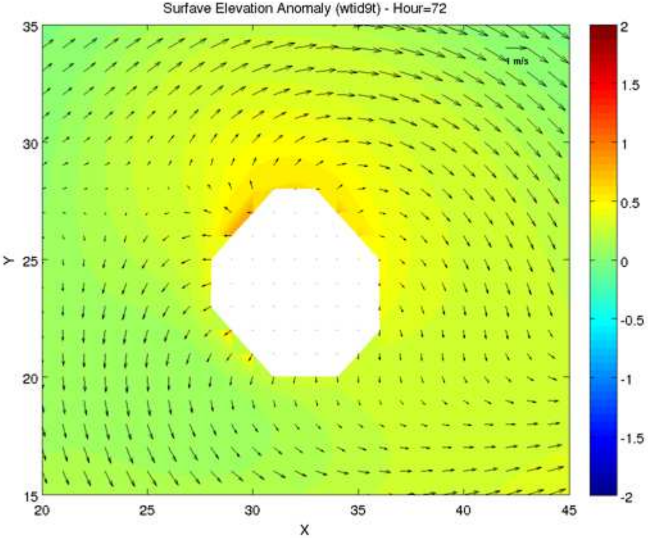

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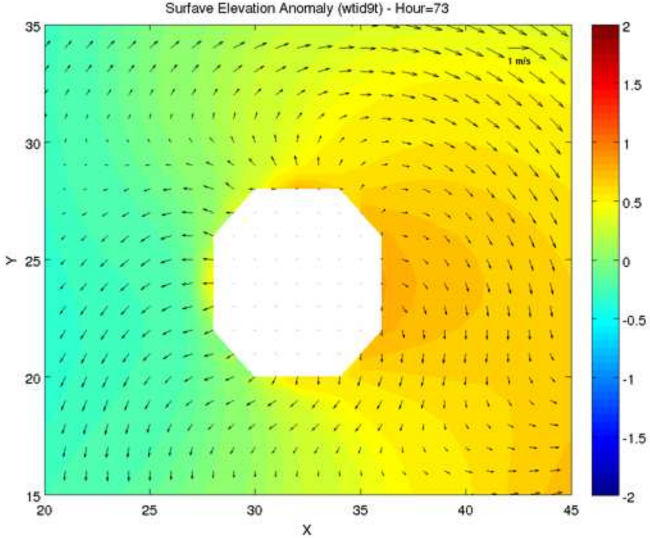

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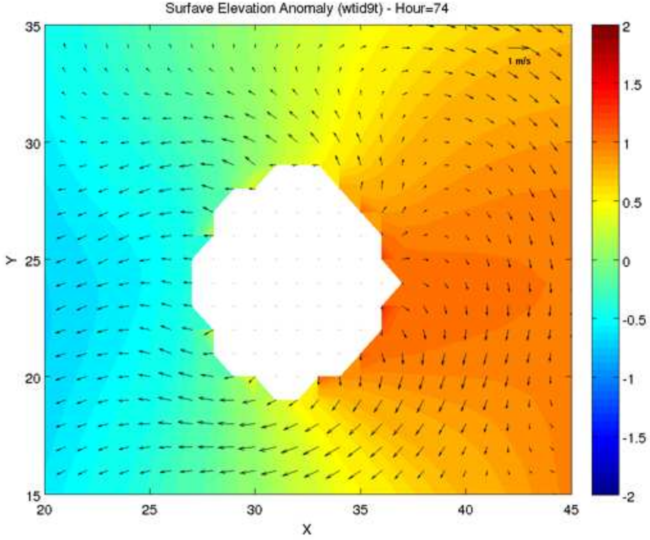

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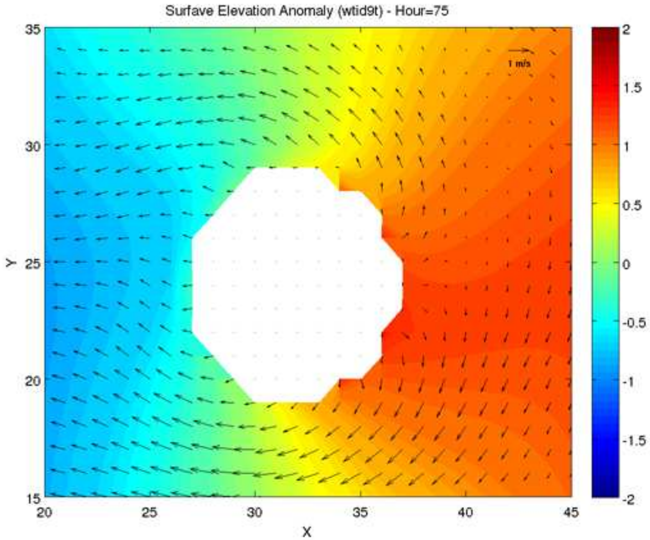
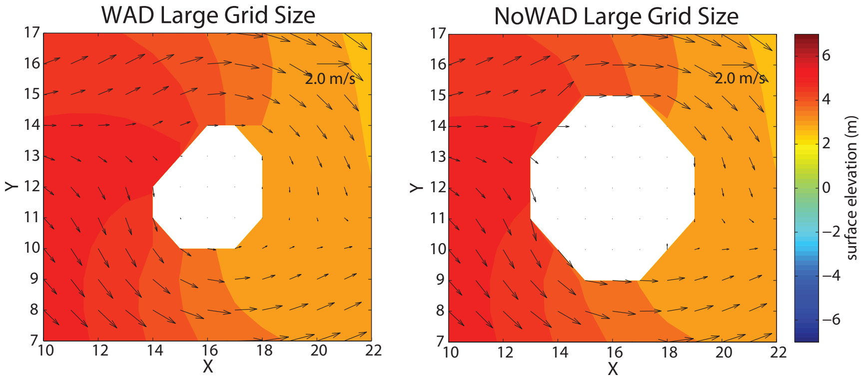


The effect of model grid



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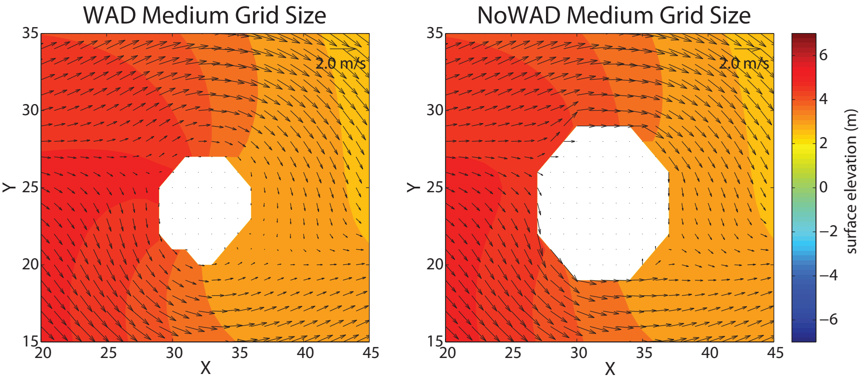

- The inundated area may be somewhat unpredicted (WAD)
- High discrepancy between WAD and NoWAD, especially near the coast (∼ 20 cm)

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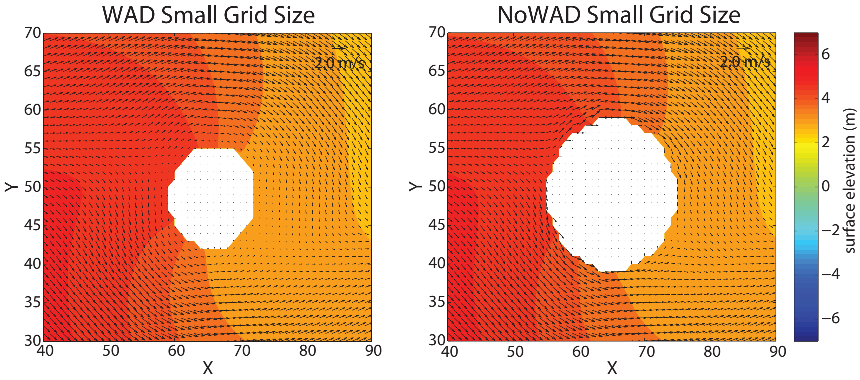

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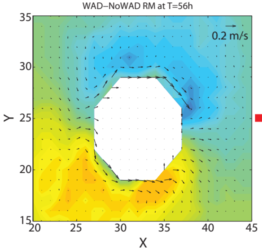
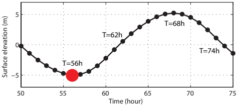
WAD-NoWAD: surface elev. & velocity





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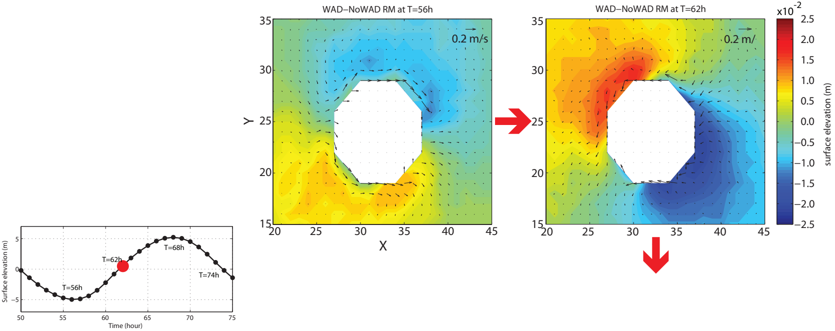

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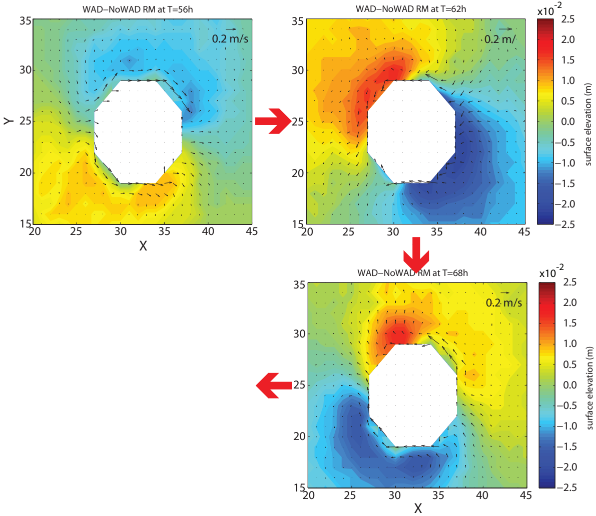

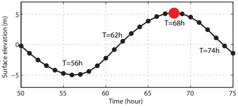

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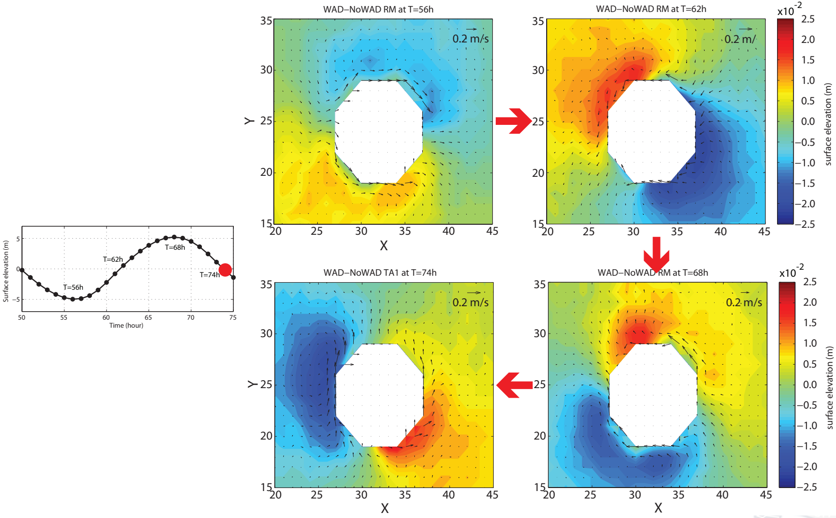
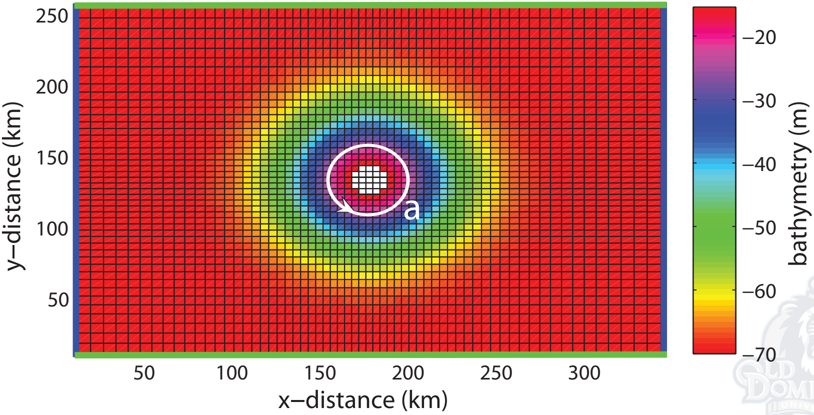


Hovmöller diagram

Signal propagations around island and basin



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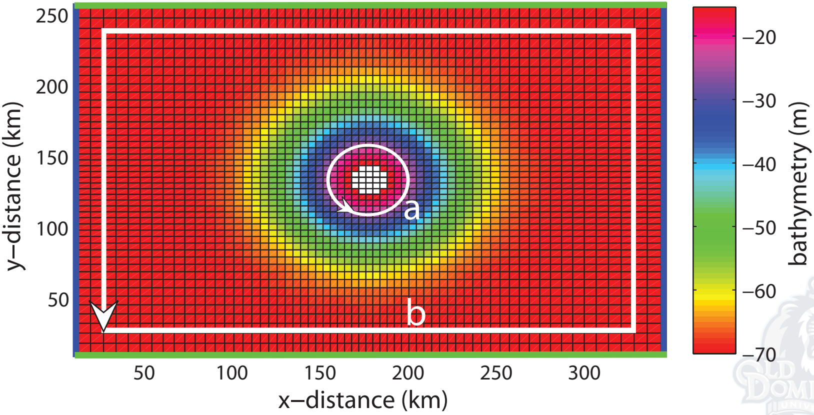

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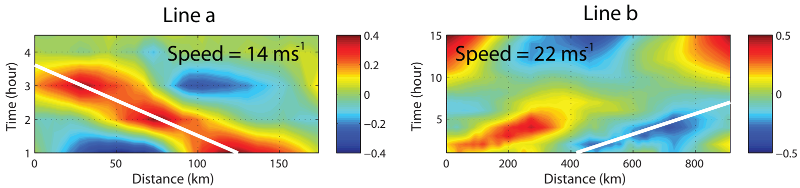
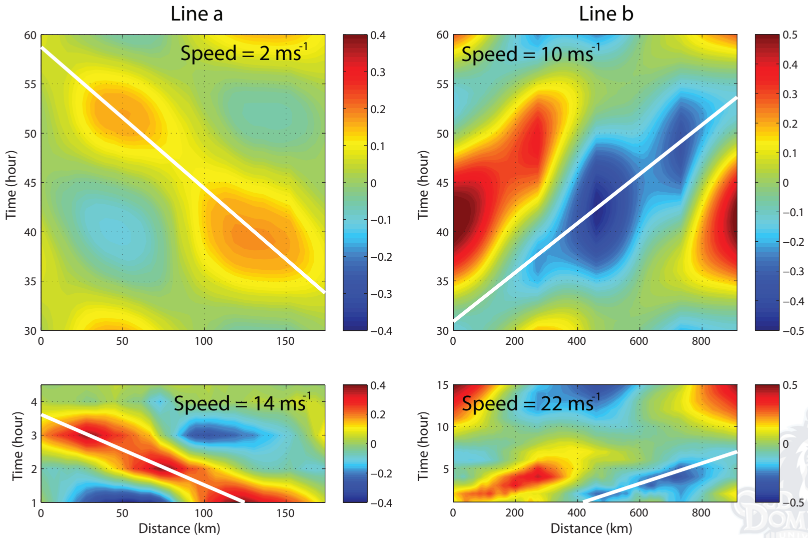


- The average depths along lines a and b are approximately 12 and 50 m, the propagation speeds of gravity waves:

$$C_a = \sqrt{gH_a} \approx \sqrt{9.81 \times 12} = 11 \quad \text{m/s}$$
$$C_b = \sqrt{gH_b} \approx \sqrt{9.81 \times 50} = 22 \quad \text{m/s}$$

- Waves act like surface gravity waves

Hovmöller diagram



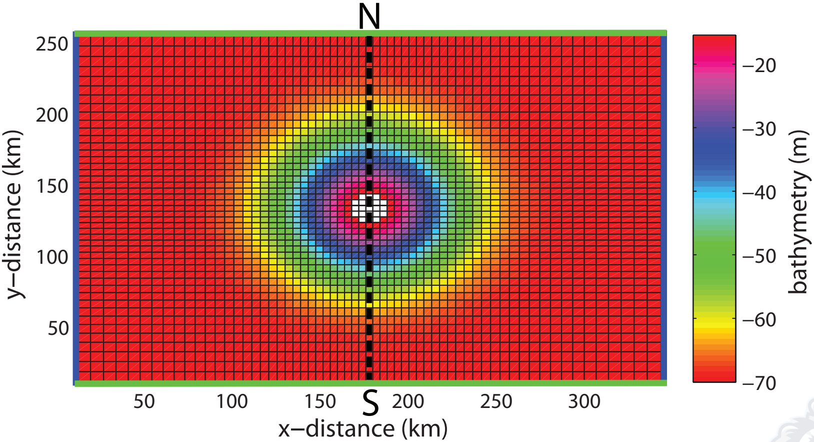
Hovmöller diagram

- The lengths of lines a and b are approximately 175 and 915 km, the expected propagation speeds for the along channel flows:

$$C_a = \frac{X_a}{T} \approx \frac{175\,\text{km}}{24\,\text{hr}} = 2.03 \quad \text{m/s}$$
$$C_b = \frac{X_b}{T} \approx \frac{915\,\text{km}}{24\,\text{hr}} = 10.59 \quad \text{m/s}$$

- Waves are dominated by the tidal period ($T = 24$ hours)

Influence of WAD on velocity



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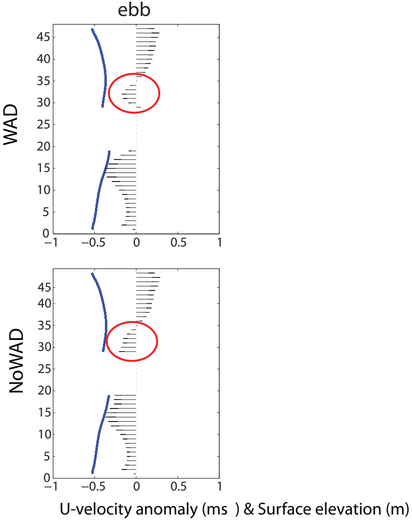

- During low tide: strong velocity shear near the island appears in WAD case as flow slows down in the shallower area, while velocity remains high in NoWAD case

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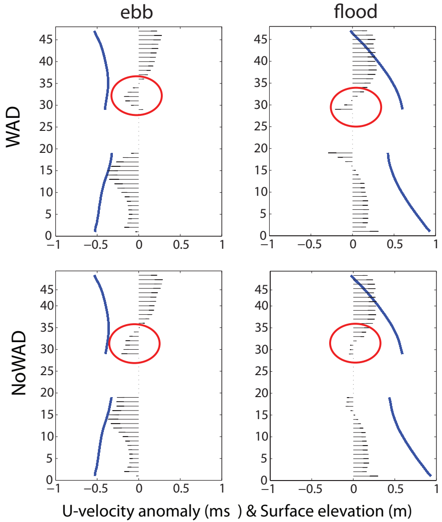
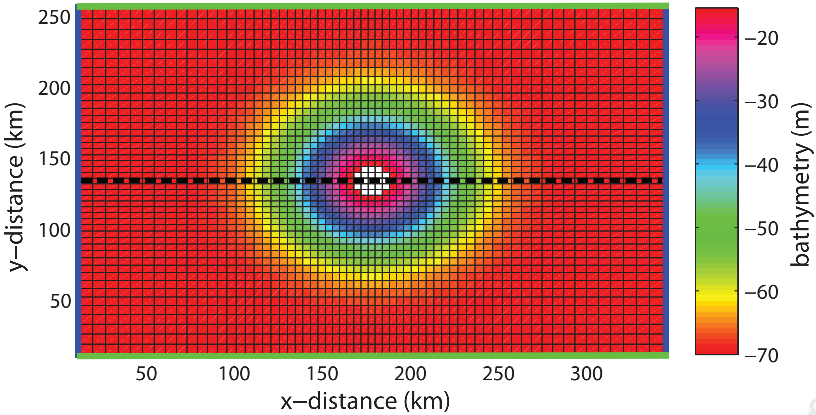


- During low tide: strong velocity shear near the island appears in WAD case as flow slows down in the shallower area, while velocity remains high in NoWAD case
- During high tide: as the water drains from the flooded island, there are very strong currents in WAD case

effect of tidal amplitude on temperature



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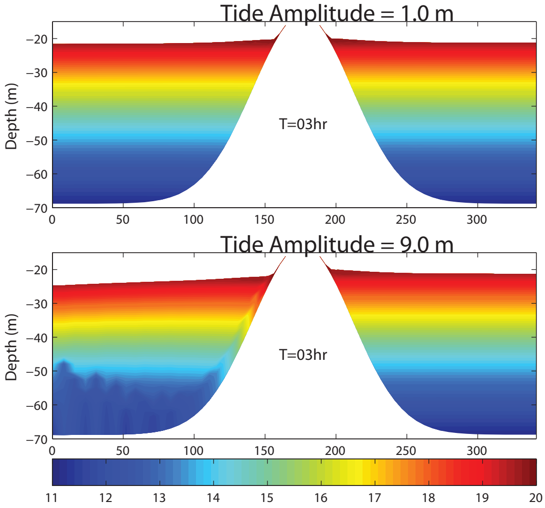

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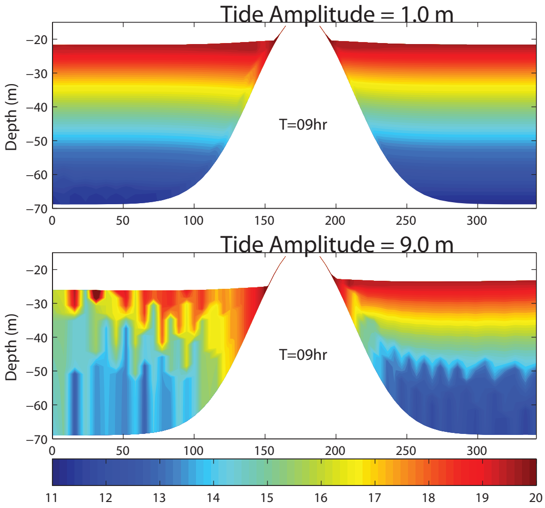

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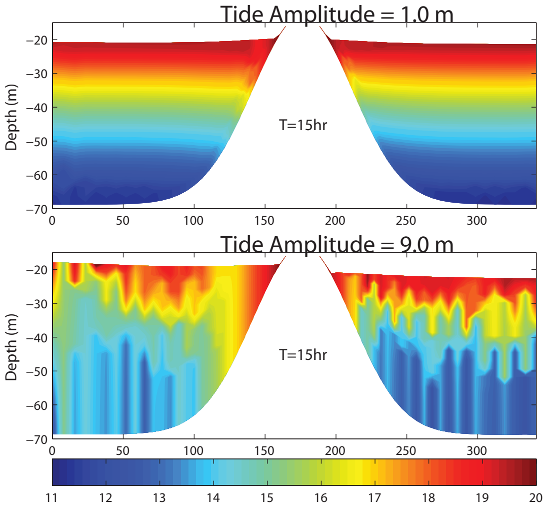

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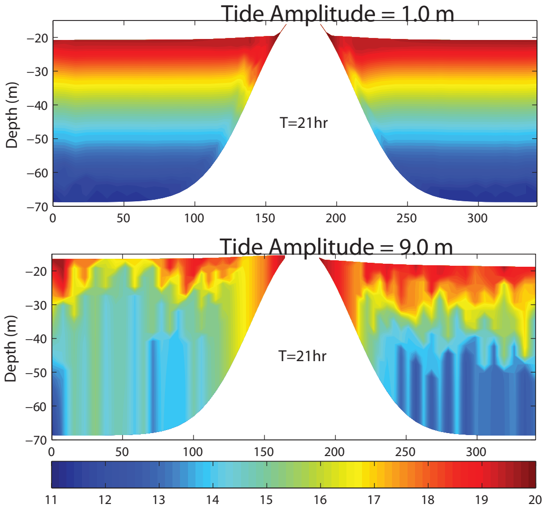

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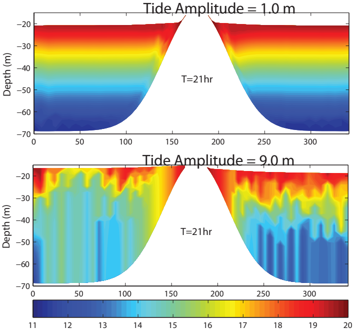
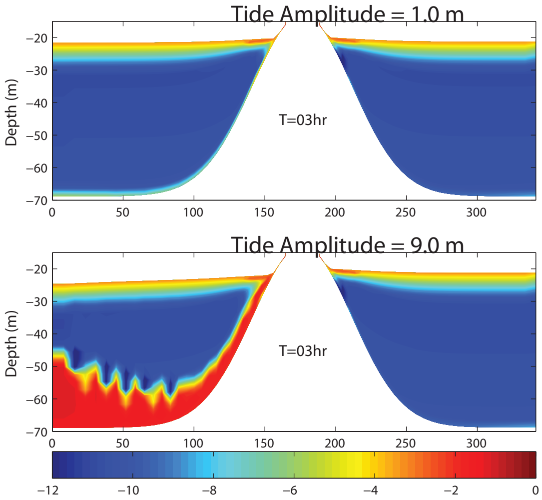


- The temperature structure for large tide case is totally destroyed within 1 day, while the stratification still remains for small tide case, except near the island
- The asymmetry wrt. the direction of the incoming tides
- Large temperature changes occur in front of the island

effect of tidal amplitude on K_M (in log scale)



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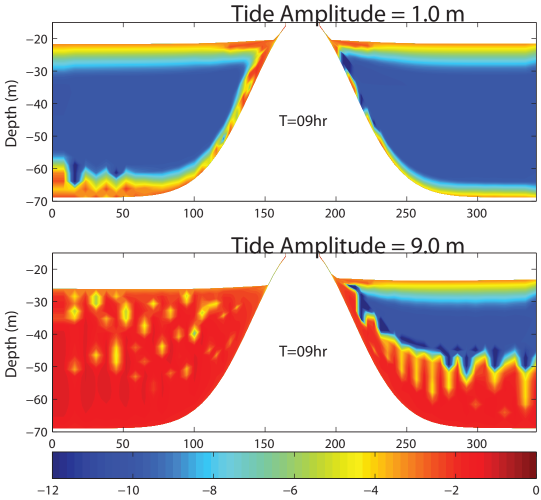

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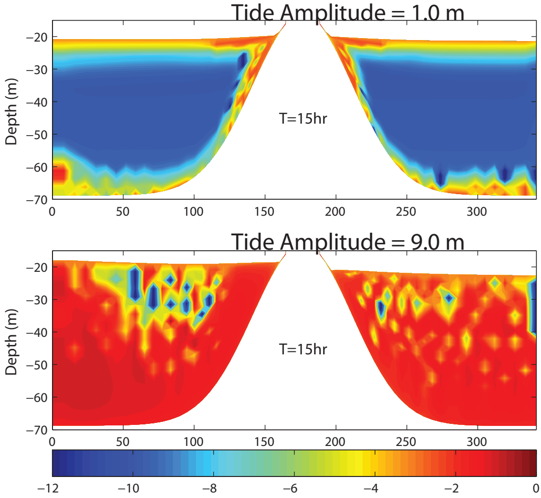

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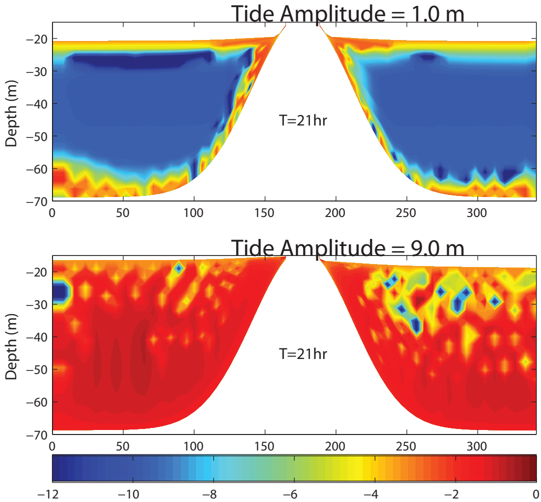
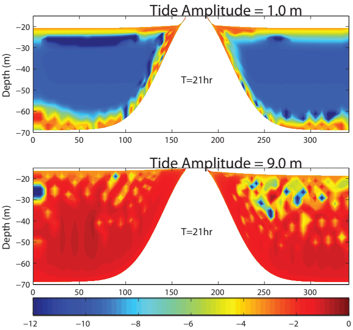
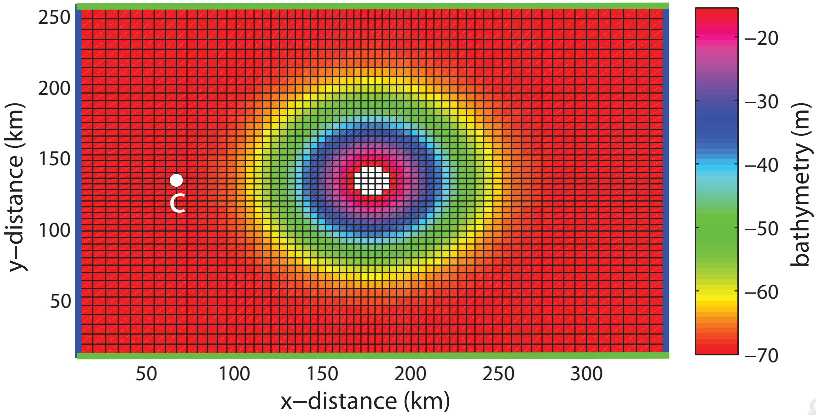


effect of tidal amplitude on K_M *(in* log *scale)*



- The strong influence of the tidal amplitude on mixing processes is clearly seen in the development of both SML and BBL
- The strong tidal-induced bottom mixing in 9.0 m tide amp. case causes the SML and BBL to merge after ∼ 9 hours (eastern side) and ∼ 15 hours (western side)

temperature and $\log K_M$ *evolution in time*



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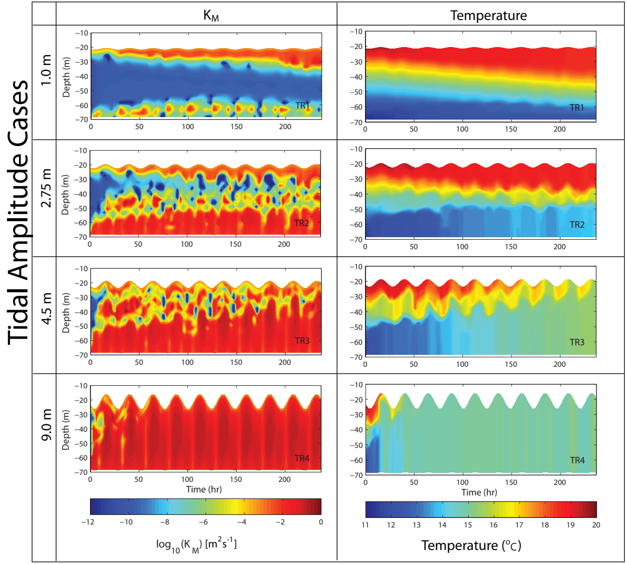

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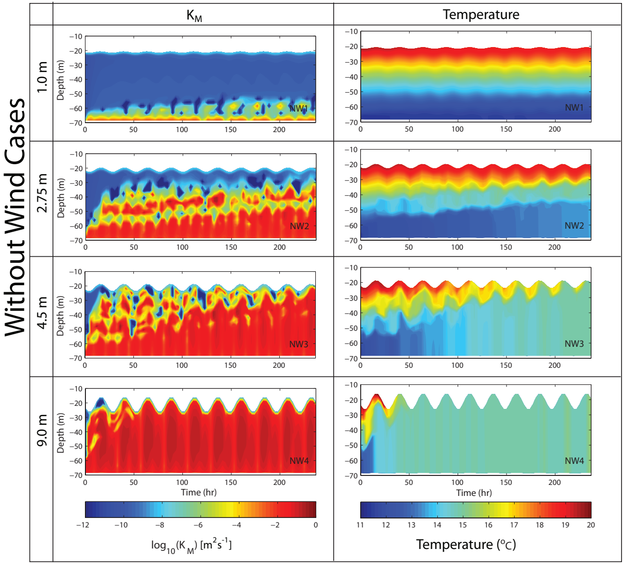

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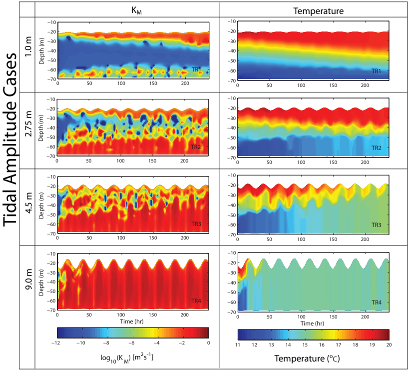
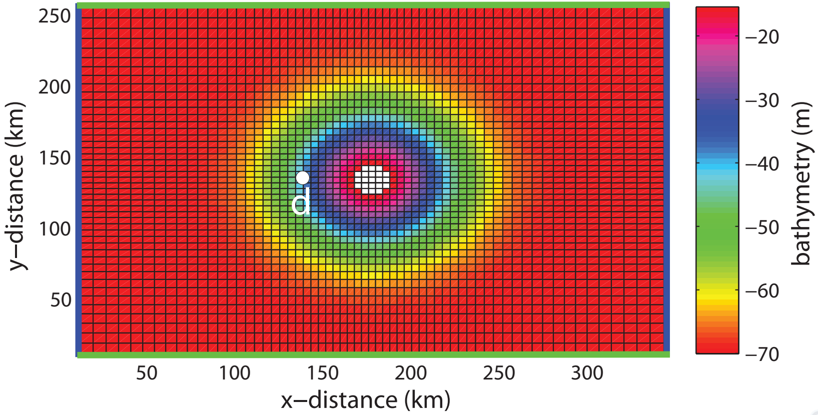
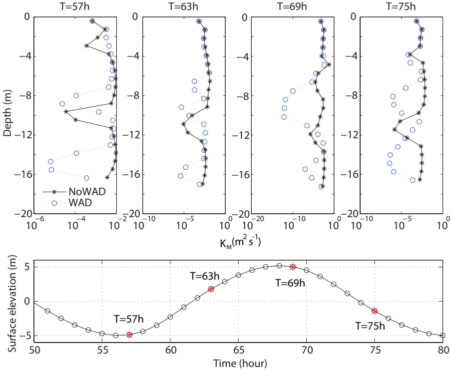


- For small tide: 1.0 and 2.75 m cases (with wind), the thickness of SML tends to increase with time, causing the thermocline to deepen, while for large tide: 4.5 and 9.0 cases, the thickness of BBL tends to increase with time, causing the thermocline to shallower
- For small tide cases (no wind), no SML, while for large tide cases, the results are similar to the cases with wind

K_M *profiles for 1 m tidal amp. (in* log *scale)*



K_M *profiles for 1 m tidal amp. (in* log *scale)*



- Additional mixing in NoWAD case may result from more reflection of waves from the vertical wall compared with more absorption of energy when waters are allowed to flow up the slop in WAD case

Vorticity equation

The dynamic balance in the model will be analyzed through the vertically integrated vorticity balance equation

$$\overbrace{\frac{\partial}{\partial t}\left(\frac{\partial \bar{v}D}{\partial x}-\frac{\partial \bar{u}D}{\partial y}\right)}^{\text{tendency}}+\overbrace{\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y}}^{\text{advection and diffusion}}+\overbrace{\frac{\partial f\bar{u}D}{\partial x}+\frac{\partial f\bar{v}D}{\partial y}}^{\text{Coriolis}}$$

$$=\underbrace{\frac{\partial P_b}{\partial x}\frac{\partial D}{\partial y}-\frac{\partial P_b}{\partial y}\frac{\partial D}{\partial x}}_{\text{JEBAR}}+\underbrace{\left(\frac{\partial \tau_y}{\partial x}-\frac{\partial \tau_x}{\partial y}\right)_o-\left(\frac{\partial \tau_y}{\partial x}-\frac{\partial \tau_x}{\partial y}\right)_b}_{\text{surface and bottom stress}},$$

where f is Coriolis parameter, $D=\eta+H$ is the water column thickness, H is the water depth relative to say mean sea level, η is the surface elevation, (A_x, A_y) are horizontal advection and diffusion terms, $(\tau_x, \tau_y)_o$ and $(\tau_x, \tau_y)_b$ are the surface and bottom stress, respectively.

Vorticity equation

P_b is the bottom pressure defined by

$$P_b = g\eta + \int_{-H}^{\eta} \rho g \mathrm{d}z,$$

where ρ is the density and g is the gravitational constant.

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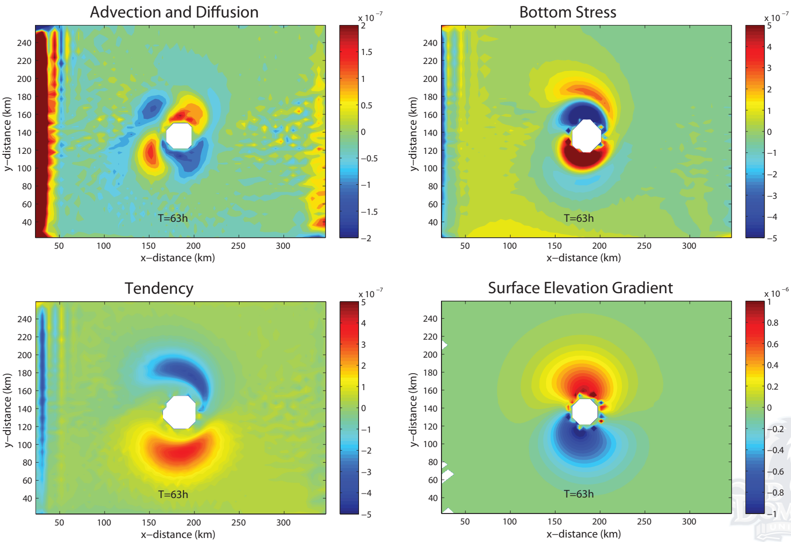
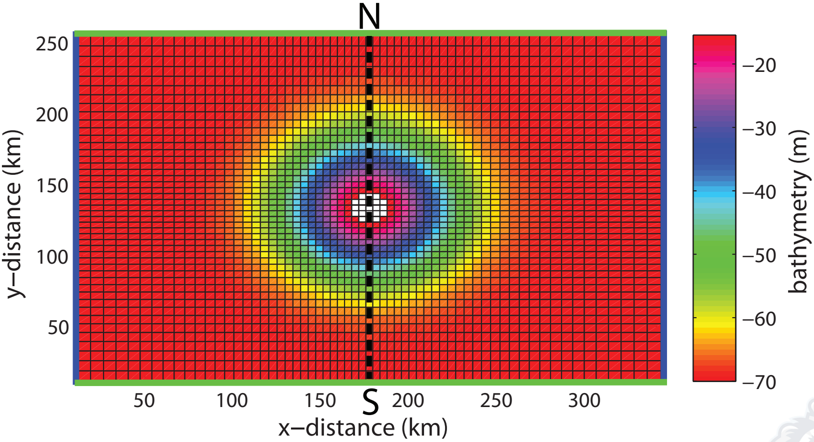
More details in Ezer and Mellor (1994, 2000)

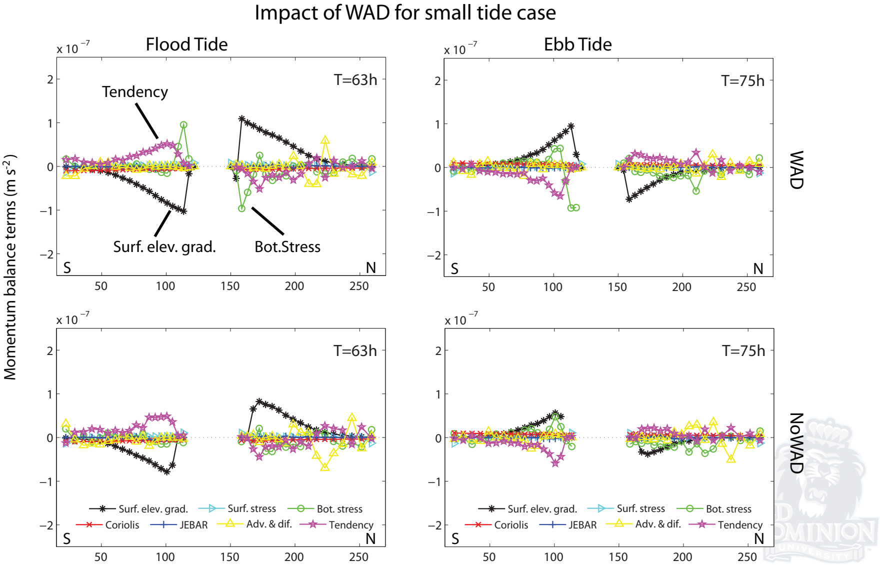
Momentum balance terms



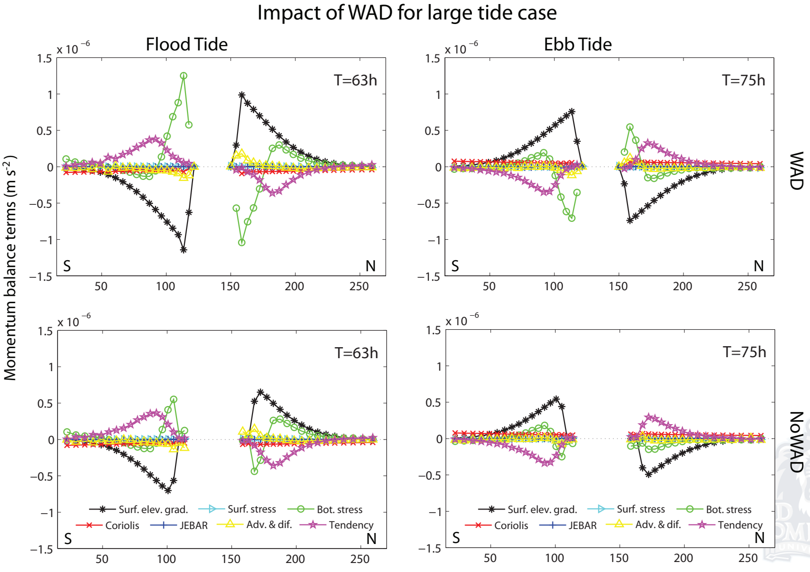
Momentum balance terms



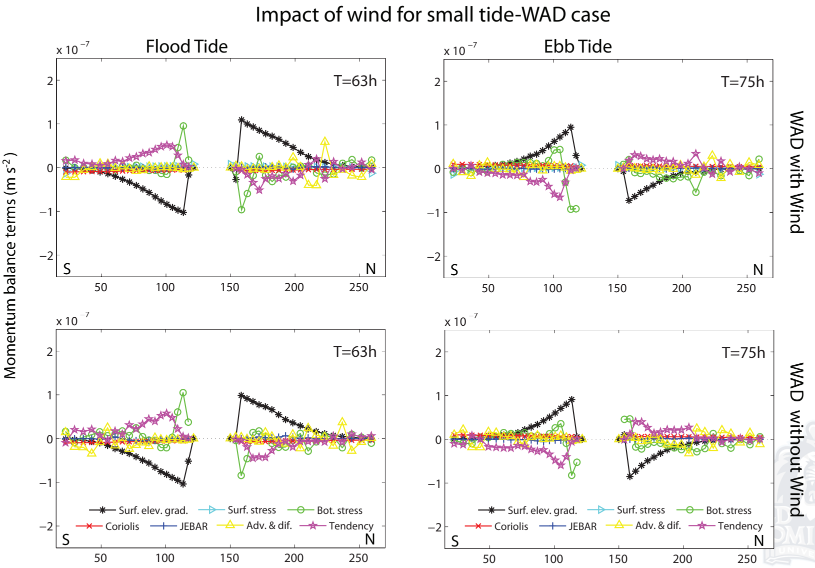
Momentum balance terms



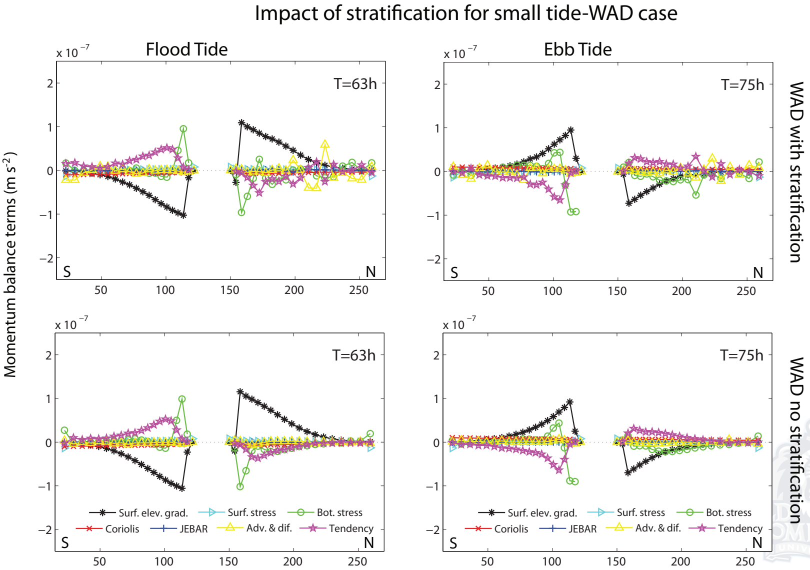
Momentum balance terms



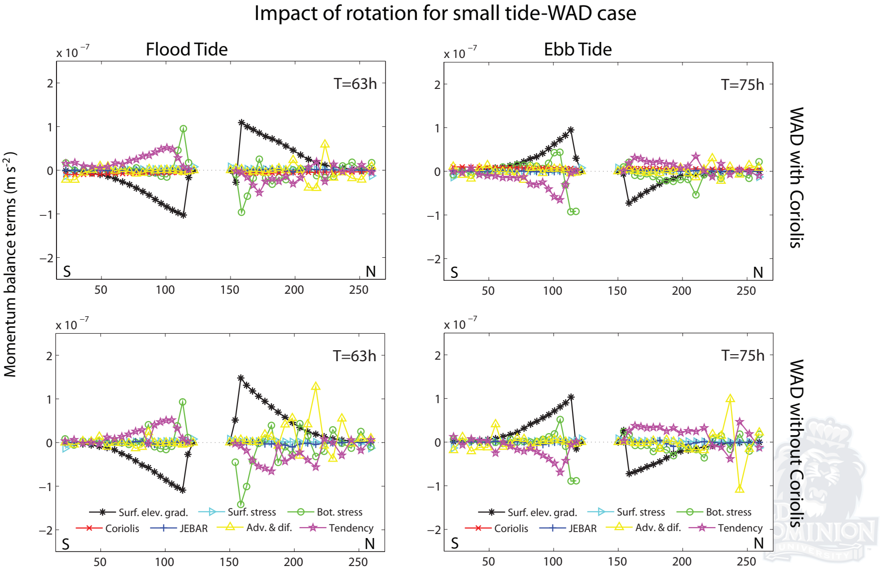
Momentum balance terms



Momentum balance terms



Momentum balance terms



Conclusions

- There exists of an asymmetric flow with large-scale counter-clockwise propagation tidal waves along the boundary, but clockwise propagating topographic gravity waves around the island
- The wave propagation speeds are initially consistent with the theoretical barotropic gravity wave speeds, but within a day or so become dominated by the tidal frequency, resulting in slower wave speeds
- The WAD impacts the amplitude of the coastal waves in an uneven way with amplitudes larger than NoWAD in the side of the island facing the incoming tide, and vice versa on the other side of the island, resulting in time dependent discrepancy between WAD and NoWAD simulations

Conclusions

- For small tides (less than 3-m range) the wind induced mixing dominates, impacting the SML, while for large tides (up to 9-m range), tidal-induced mixing dominates, impacting the BBL
- For large enough tides, the SML and BBL merge and a complete top-to-bottom mixing occurs
- Near the coast, the boundary in a NoWAD case (and in most general ocean circulation models) is an artificial vertical seawall, while in a WAD case, the energy is absorbed by the land-water interaction
- Evaluation of the momentum balance in the model shows that the surface elevation gradient, the bottom stress, and the tendency terms are the dominant terms in tidal simulation

Conclusions

- There is little difference between WAD and NoWAD at the deeper part away from the coast, especially for large tides, but within ~ 30 km from the coast, simulations with WAD show twice as large contribution from bottom stress and surface elevation gradient terms compared with a NoWAD case
- The results presented here provide a preliminary evaluation of the model with an idealized configuration, demonstrating the complex way in which WAD may affect coastal ocean simulations under different conditions and wide ranges of parameters
- More experiments with different topographies and realistic configuration and forcing are clearly needed and will follow in future studies

Acknowledgements

- The WAD model was originally developed by L.-Y.Oey, Princeton University, with support from the Minerals Management Service (MMS)
- Additional support is provided to T. Ezer by grants from NOAA's National Marine Fisheries, NOAA's Climate Programs, and the National Science Foundation (NSF)
- S. Saramul is partly supported by the Royal Thai Government

Thank you very much!

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Questions?