



Modeling with 2D/3D coupling to simulate the movement of a brine plume

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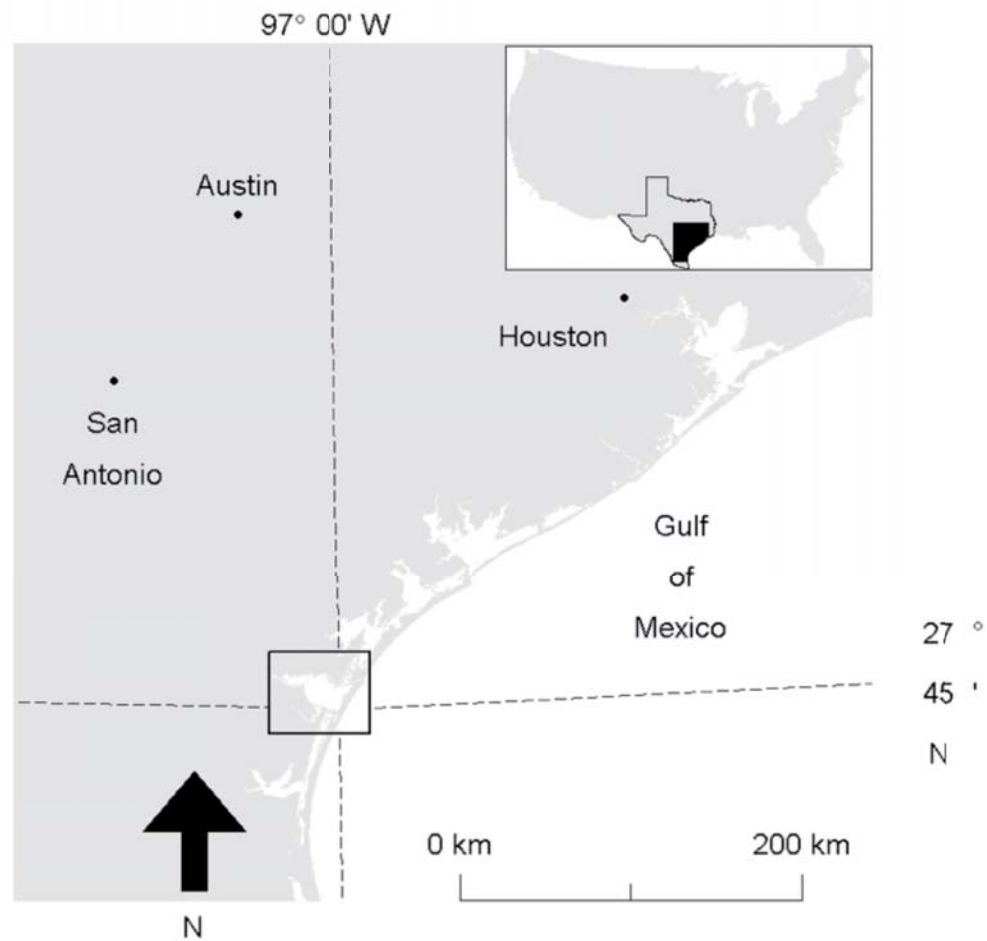


Problems

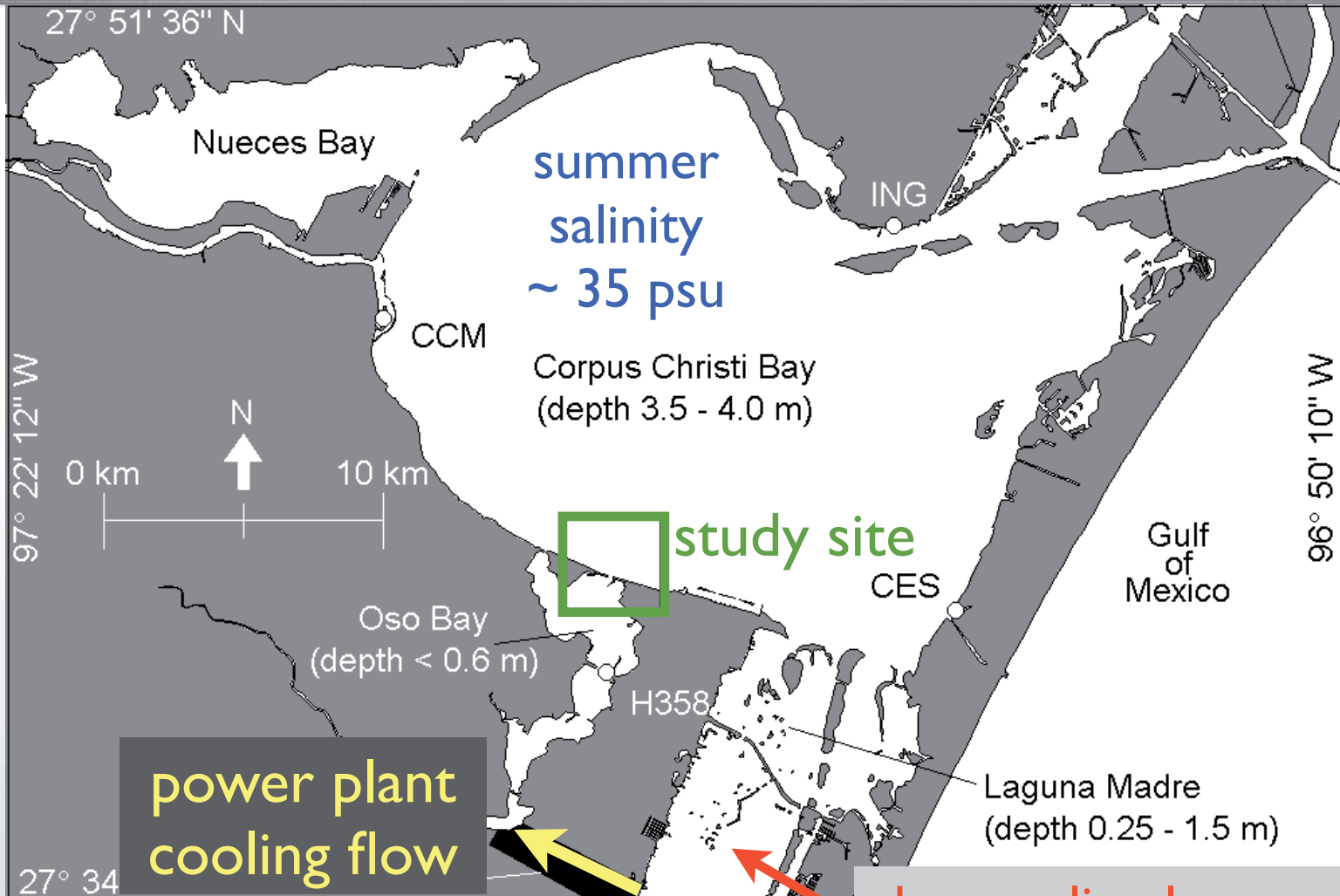
- Brine plumes may be thin layers
- Extremely fine vertical grid resolution may be required for 3D hydrodynamic models
- Turbulence models are biased towards mixing rather than entrainment



Corpus Christi Bay



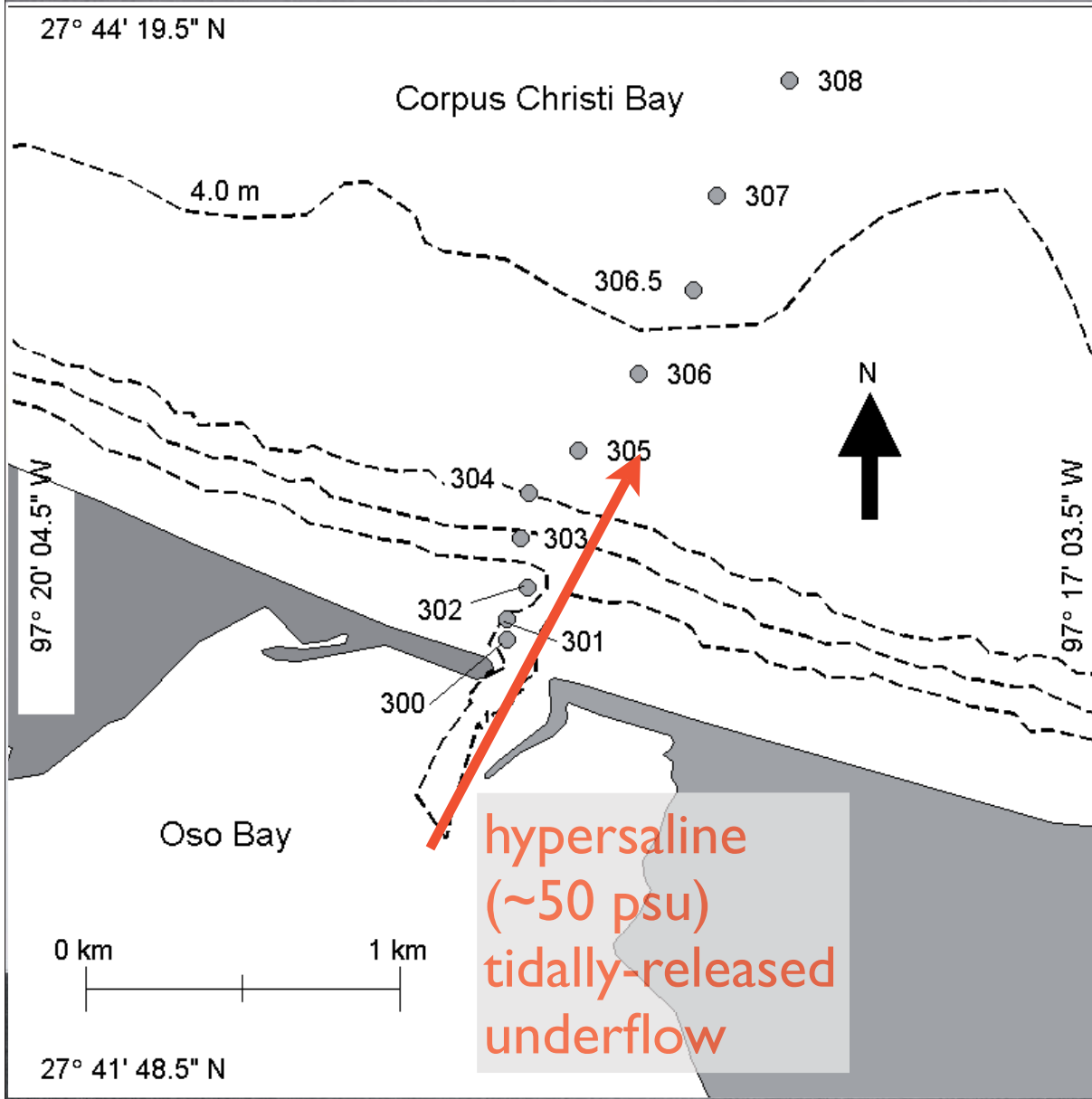
Corpus Christi Bay



power plant cooling flow

hypersaline lagoon (50-70 psu)

study site



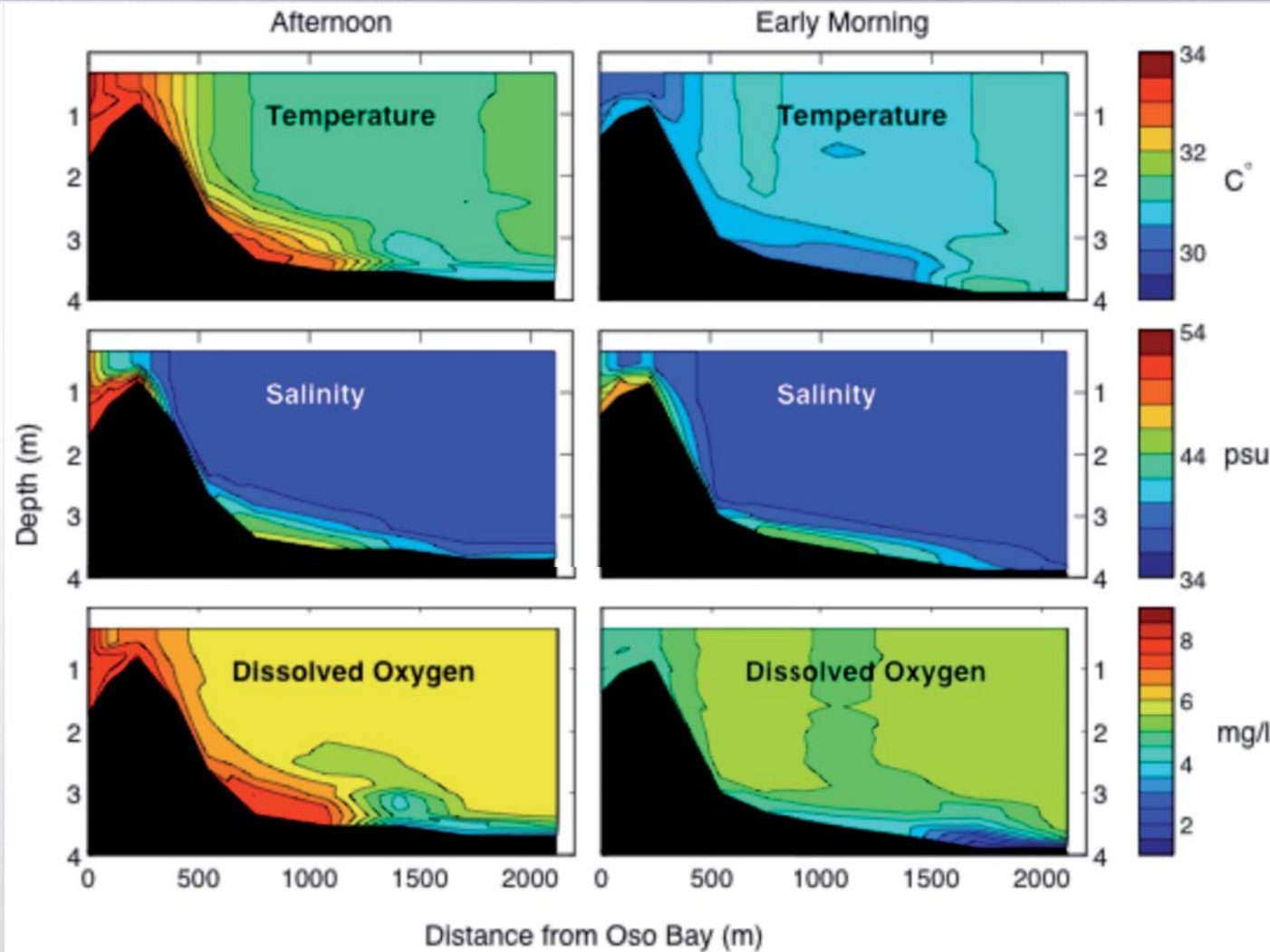
10 profiling stations

2 hour interval
between repeated
profiles

48 hour sampling



thin layer (field data)



A “natural” hyper-saline underflow similar to load from a 400,000 m³/day desalination plant

Hypoxia occurs in less than 24 hours after start of underflow

from Corpus Christi Bay (Texas) USA

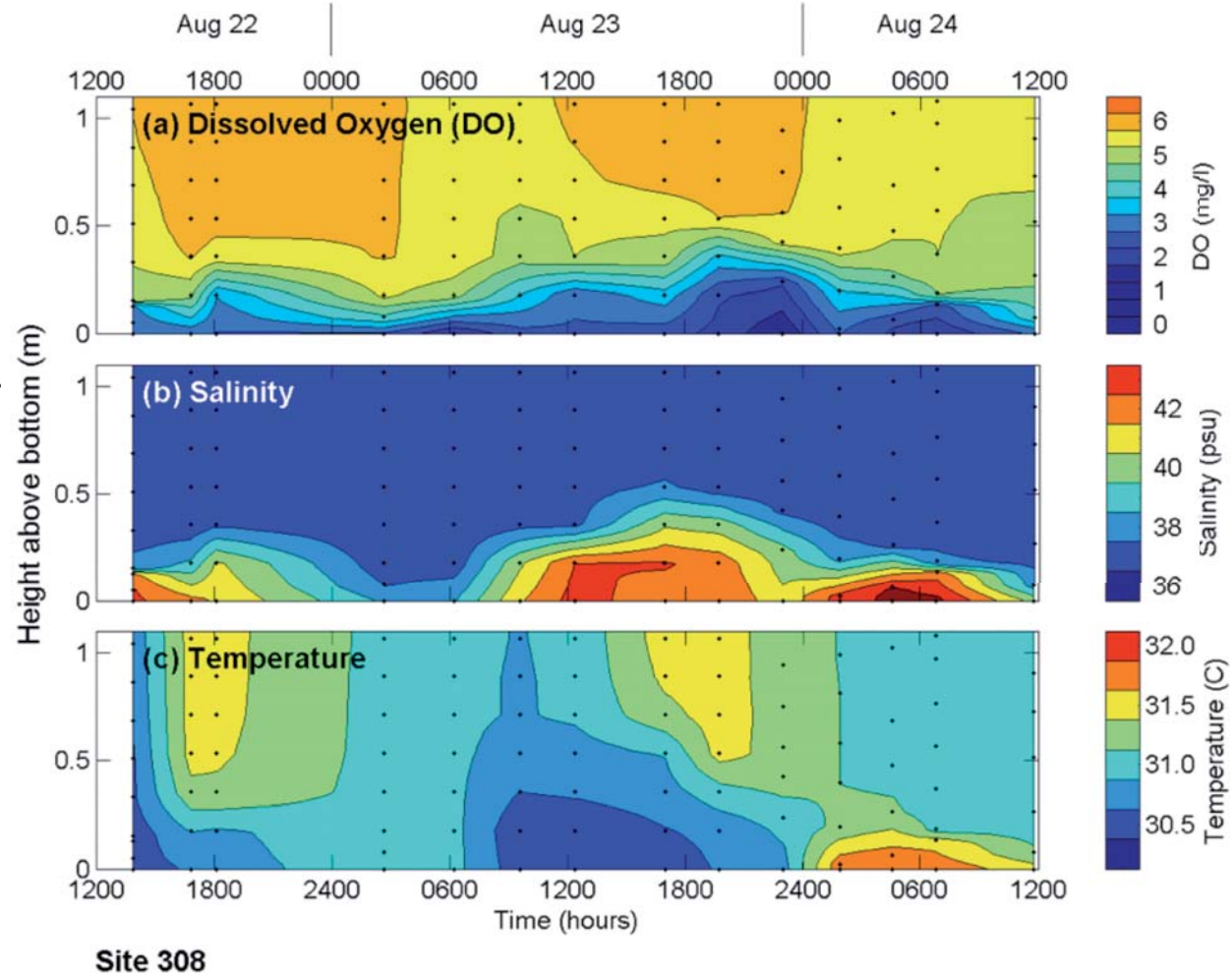


thin layer 2 km offshore (field data)



Figures show data 0 to 1 m above bottom. Layer thickness 0.3 m. Total depth is 4 m.

Tidally-released pulses of 50 psu hypersaline water result in thin layer of 42-45 psu water that caps the sediments and results in hypoxia



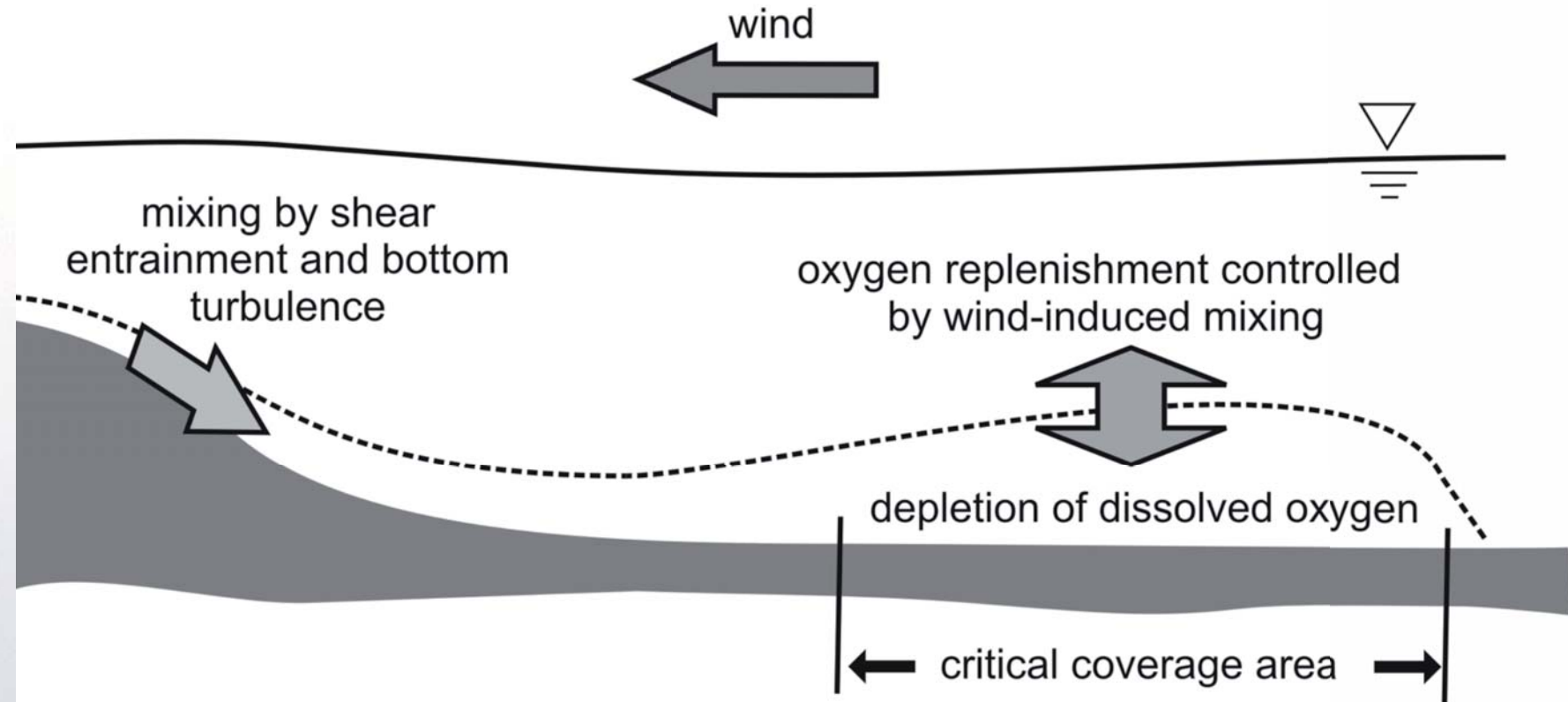
from Corpus Christi Bay (Texas) USA



when brine movement slows

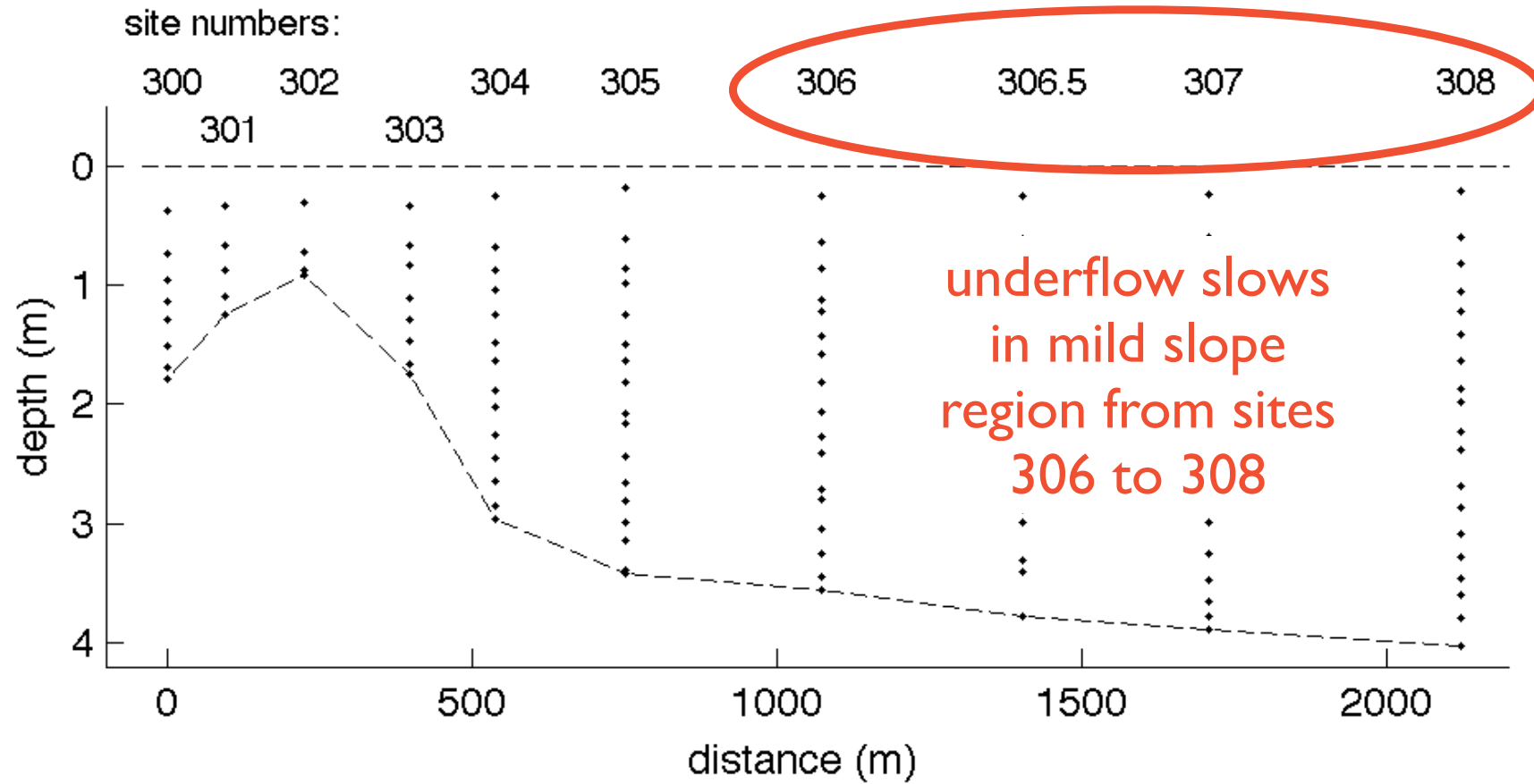


Erosion of brine layer along mild slope is determined by ambient turbulence rather than gravity-current mixing





sampling profiles





underflow destruction time scale (wind)

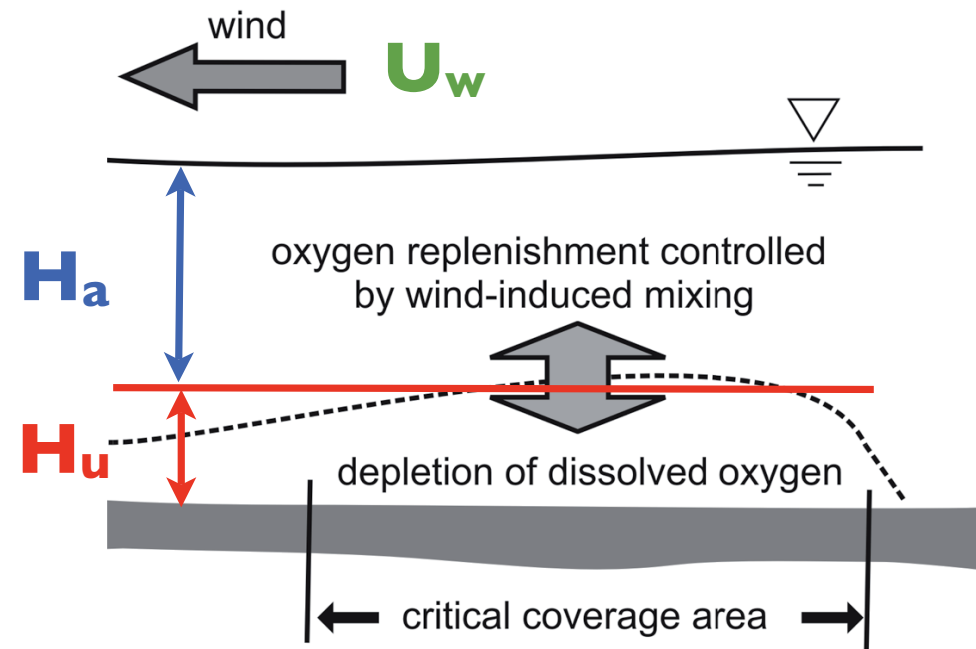


Linear time-scale for mixing underflow thickness H_u into the ambient:

$$\tau_w \sim \frac{H_u}{dH_u / dt}$$

Energy arguments provide

$$\frac{dH_u}{dt} = -C_m C_N^3 \left(C_D \frac{\rho_{\text{air}}}{\rho_0} \right)^{3/2} \frac{\rho_0}{g\Delta\rho} \frac{U_w^3}{H_a}$$



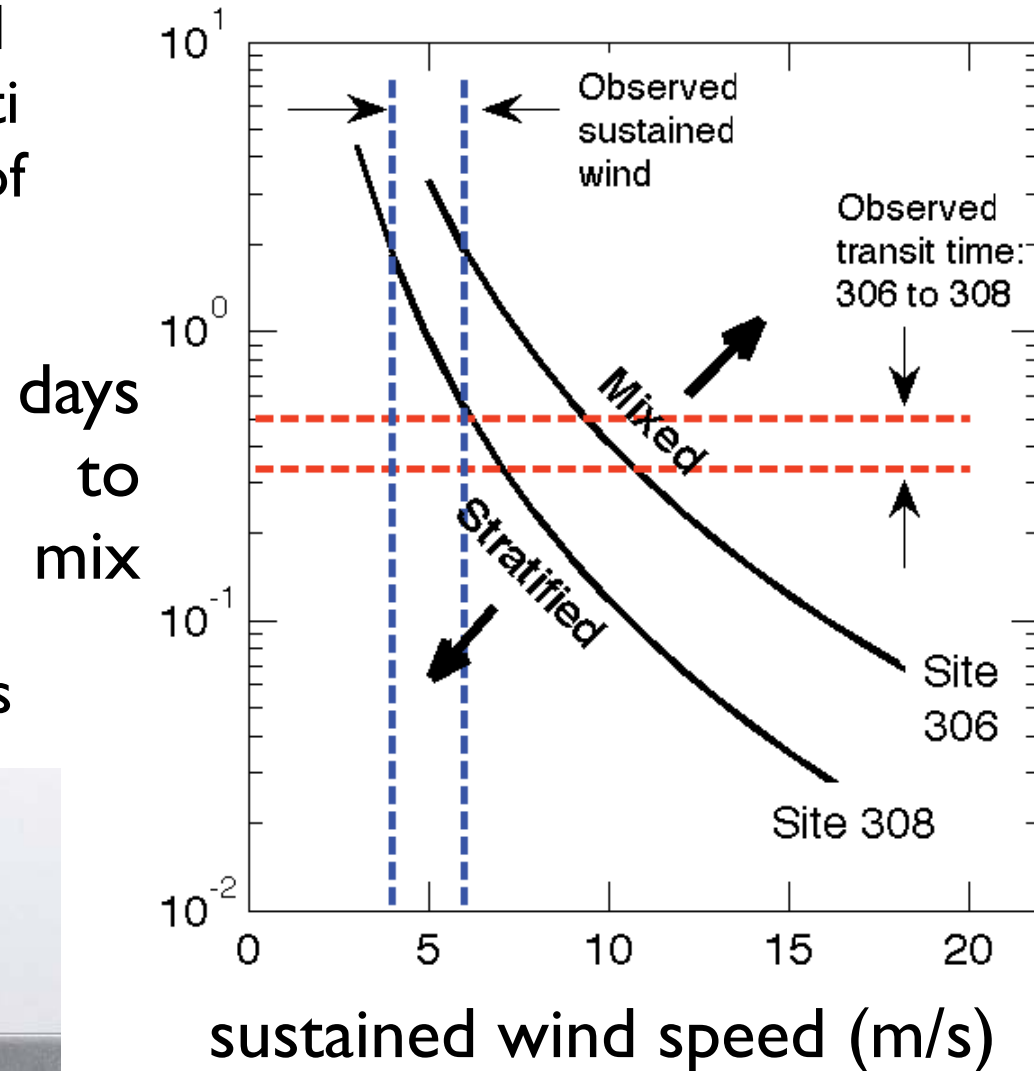


mixing time scale



Using prior formulas and data from Corpus Christi Bay for the outer 1 km of the transect, we can determine wind speeds necessary to mix the underflow during the transit between sites

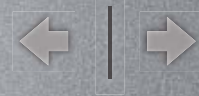
Because replenishment is faster than mixing, the thin layer is not destroyed.





Key question:

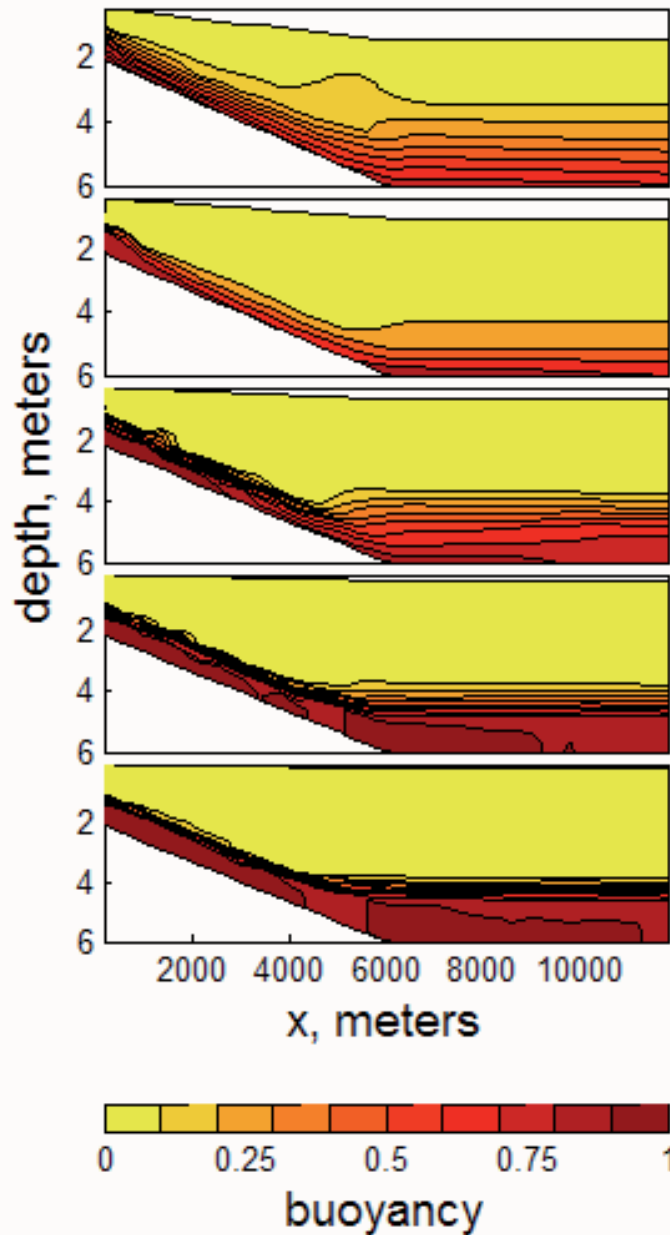
How many vertical grid layers does it take to capture the correct underflow dynamics in a 3D model?



3D model results (sigma grid)

Insufficient vertical grid resolution leads to weakening of gradient

Weaker gradient is more easily mixed by wind and current



2

3

5

10

15

Number of grid cells in underflow

Test of EFDC model without any mixing



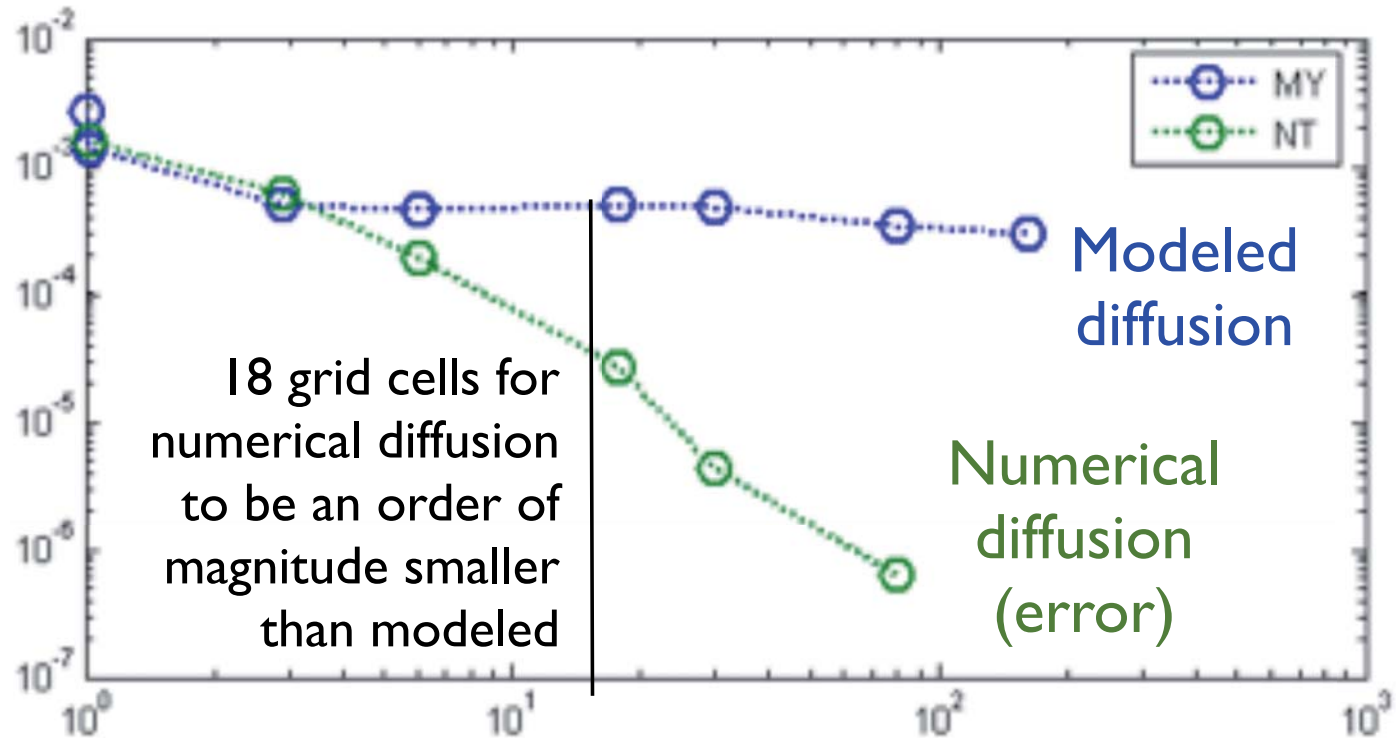
grid resolution (3D)



Entrainment Rate

Model error is biased towards weakening (diffusing) the density gradient.

Error accumulates with time.



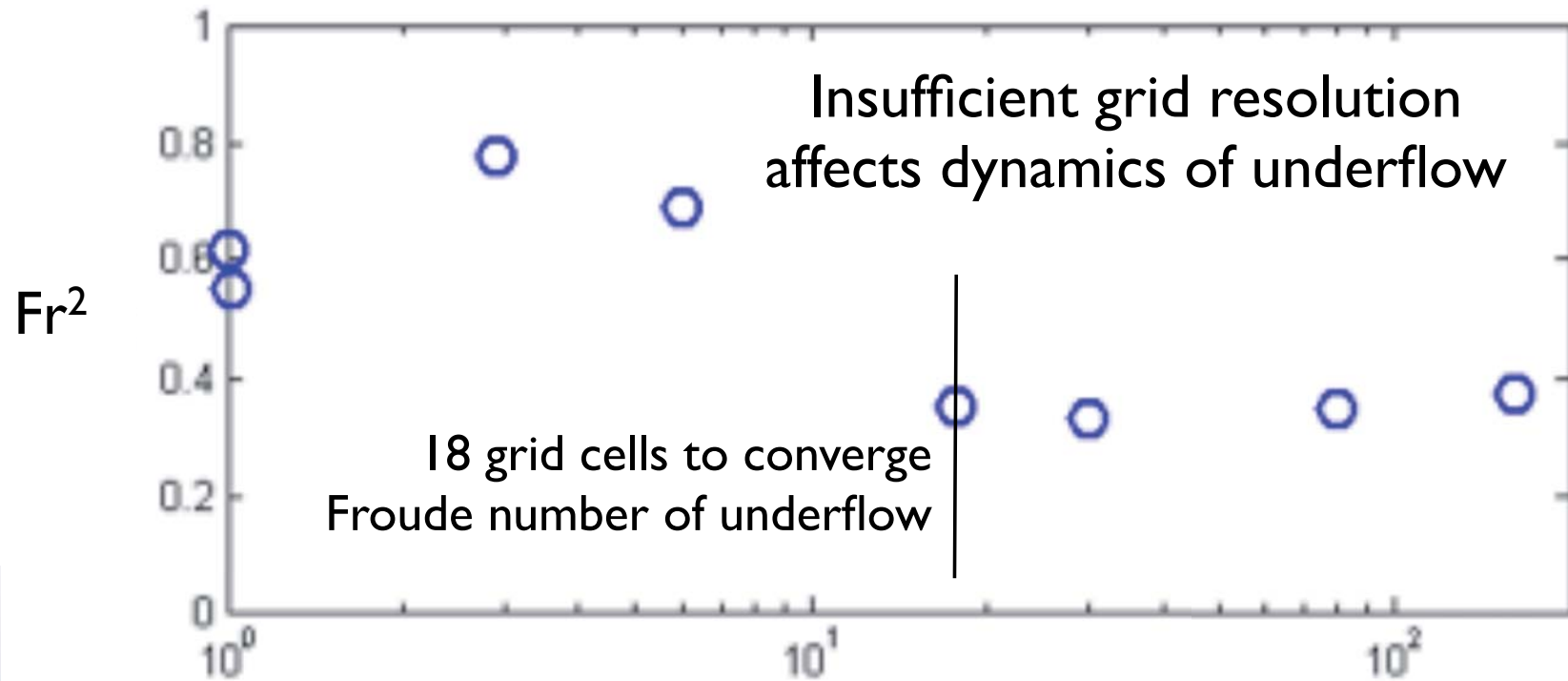
18 grid cells for numerical diffusion to be an order of magnitude smaller than modeled

Numerical diffusion (error)

Grid cells in the gravity current underflow



grid resolution (3D)

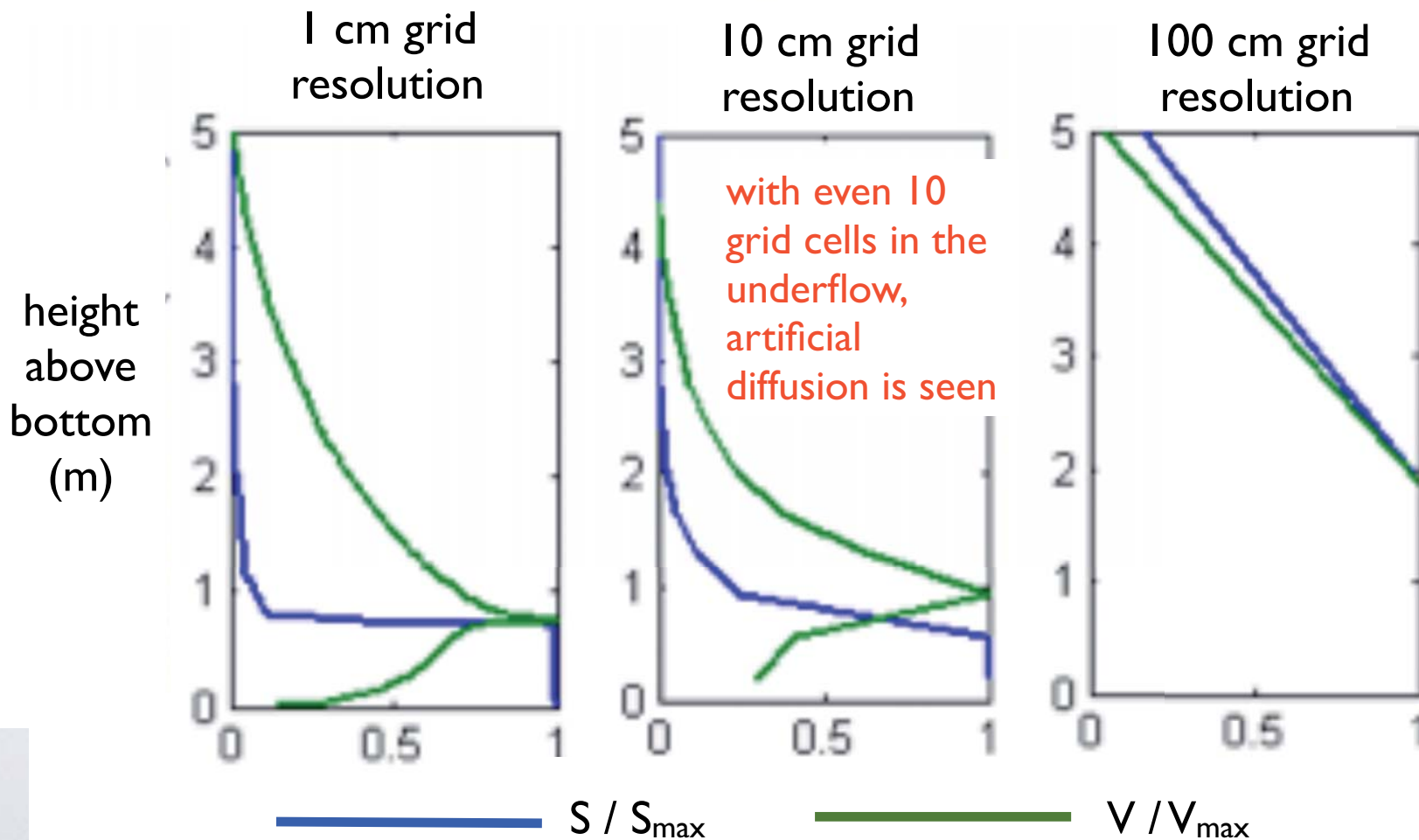


18 grid cells to converge
Froude number of underflow

Insufficient grid resolution
affects dynamics of underflow

Grid cells in the gravity
current underflow

grid Resolution (3D)



implications of thin layers and model vertical grid resolution



- Corpus Christi Bay example: 4 m deep, 0.3 m brine layer thickness; requires ~ 2 cm vertical grid resolution
- Failure to adequately resolve brine layer leads to artificial weakening of density gradient, which is easier to mix with wind-driven turbulence
- 3D models with insufficient vertical resolution are not conservative - they predict brine mixing more rapidly than will physically occur.
- Artificial weakening of brine layer alters horizontal transport, retaining a thicker, weaker layer that mixes more easily.



Poor modeling practices can lead to prediction of a brine plume that dilutes and disappears...

...but the real system may see a thin layer that caps the sediments and rapidly becomes hypoxic.

Model results may be misleading!



Coupling a 2D underflow model to a 3D model

Advantages:

- Eliminates need for small grid cells near the boundary in the 3D model.
- Eliminates numerical entrainment from underflow into ambient that artificially weakens underflow.
- Direct model control of mixing rates.
- May provide a more simple foundation for benthic boundary biogeochemistry modeling.

Disadvantages:

- Only standard in one common model (ELCOM)
- Complicated to implement and use.
- Not enough test cases exist for evolution of thin-layer plumes.
- Requires commitment to additional model development.



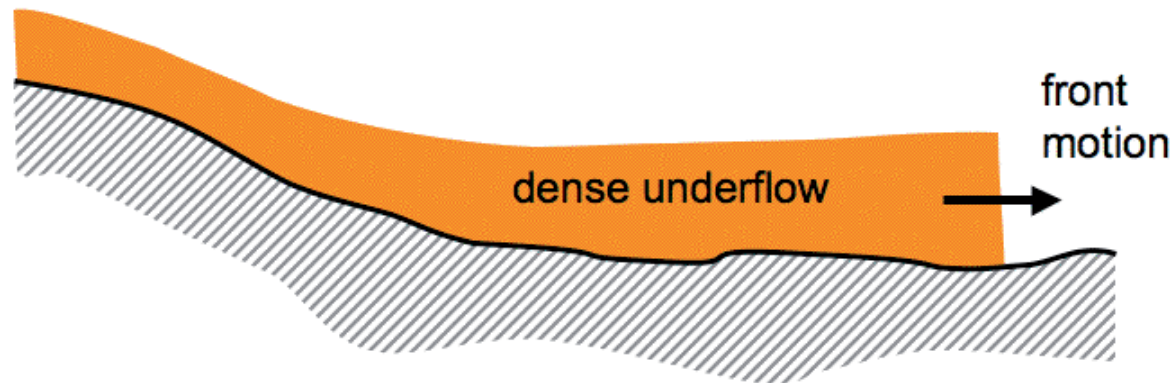
existing underflow model (ELCOM)



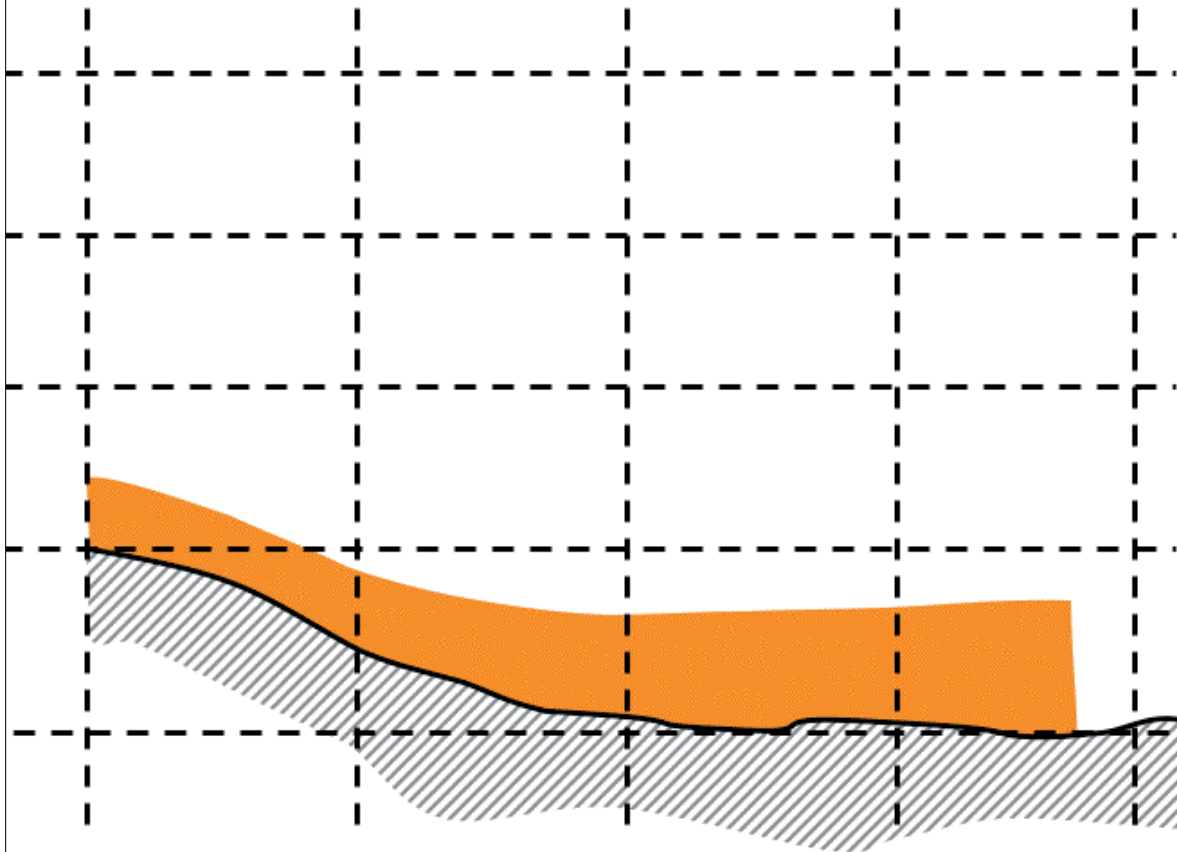
ELCOM solves depth-averaged underflow equations (2D) coupled to 3D hydrostatic Navier-Stokes equations.

- Dallimore, Hodges and Imberger, (2003) Journal of Hydraulic Engineering (ASCE), 129(10): 748-757
- Dallimore, Imberger and Hodges, (2004) Journal of Hydraulic Engineering (ASCE), 130(11): 1068-1076

ambient water



existing underflow model (ELCOM)



Apply a 3D model grid for ambient flow that does not resolve underflow





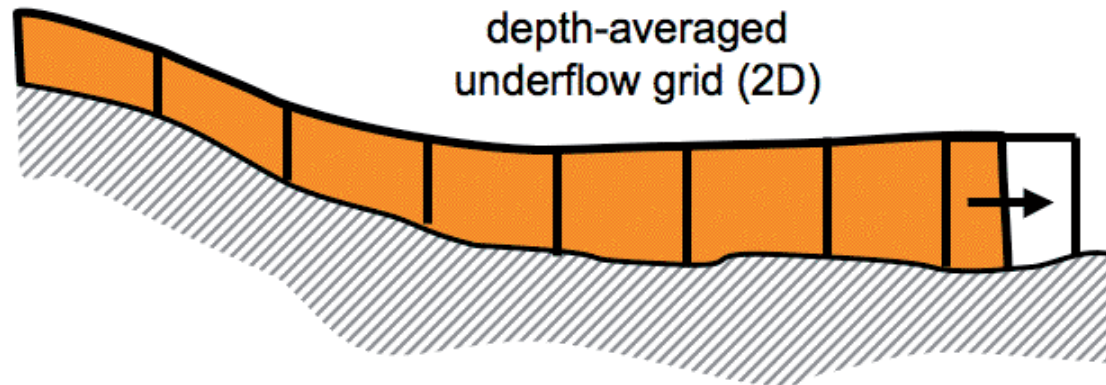
existing underflow model (ELCOM)



2D depth-averaged model uses fixed horizontal grid that follows bathymetry and underflow thickness

Similar to Bradford and Katopodes (1999) Journal of Hydraulic Engineering (ASCE) 125(10):1006-1015

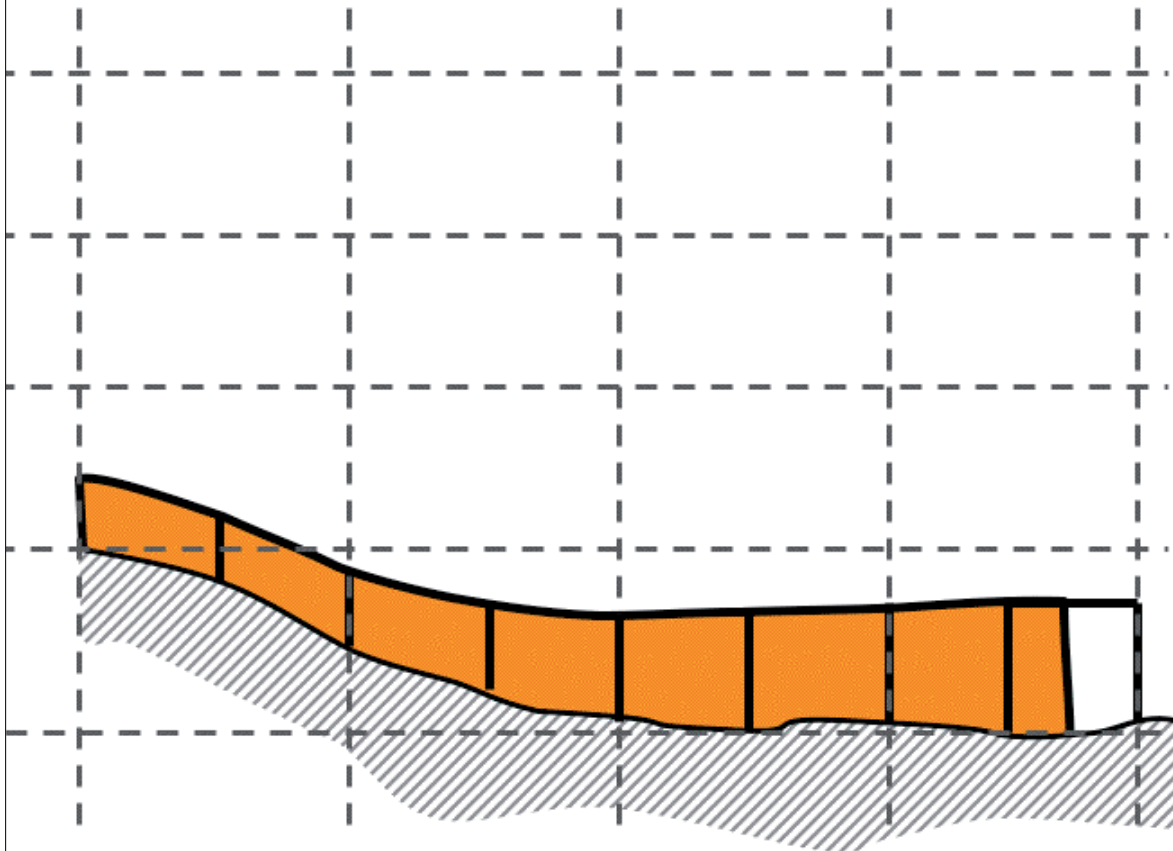
ambient water (3D)



Special treatment is required for tracking front motion in 2D



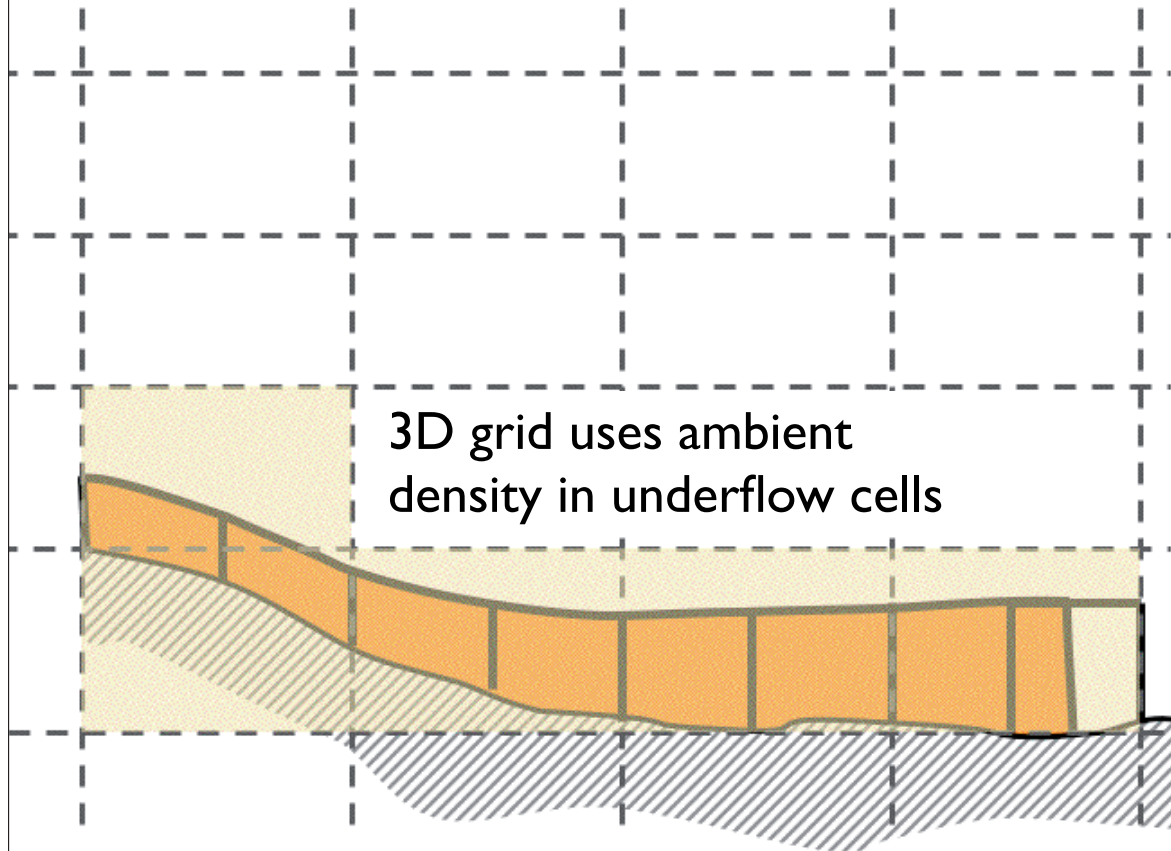
existing underflow model (ELCOM)



Overlay the 3D
and 2D models



existing underflow model (ELCOM)



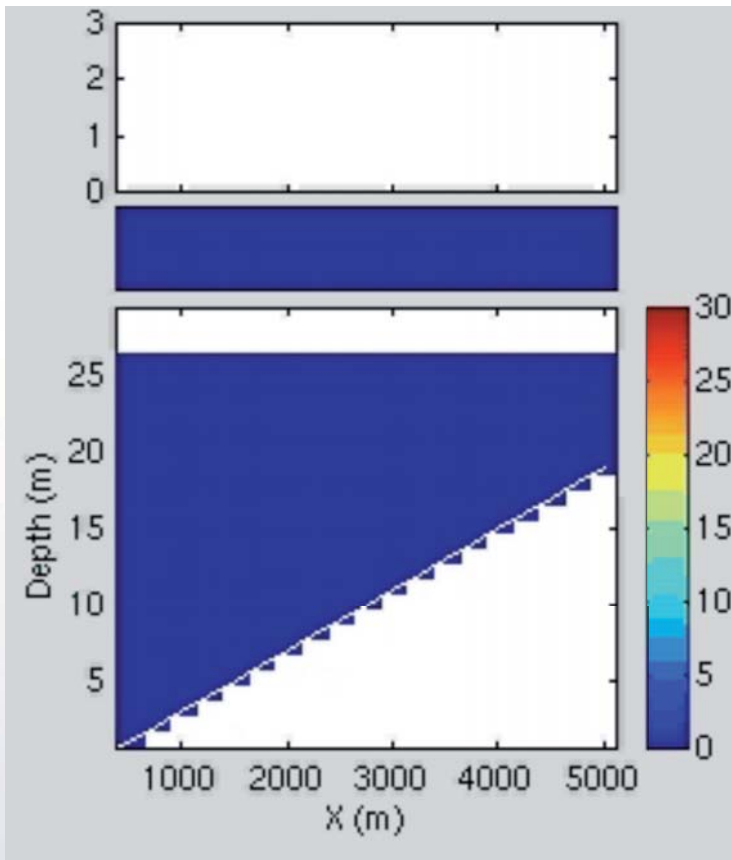
Coupling conditions needed for momentum and mass transfer.

Turbulent Kinetic Energy (TKE) model used to estimate fluxes between models

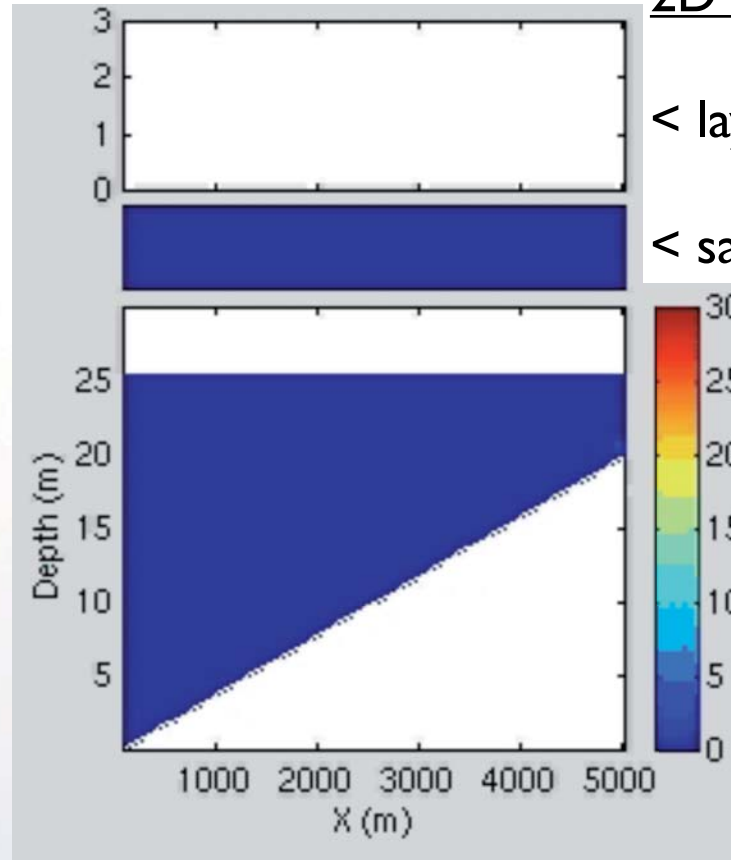
Entrainment and detrainment independently modeled rather than using ambient turbulence model



model comparison



Coarse grid 3D model



Fine grid 3D model

2D model

< layer thickness

< salinity (ppt)



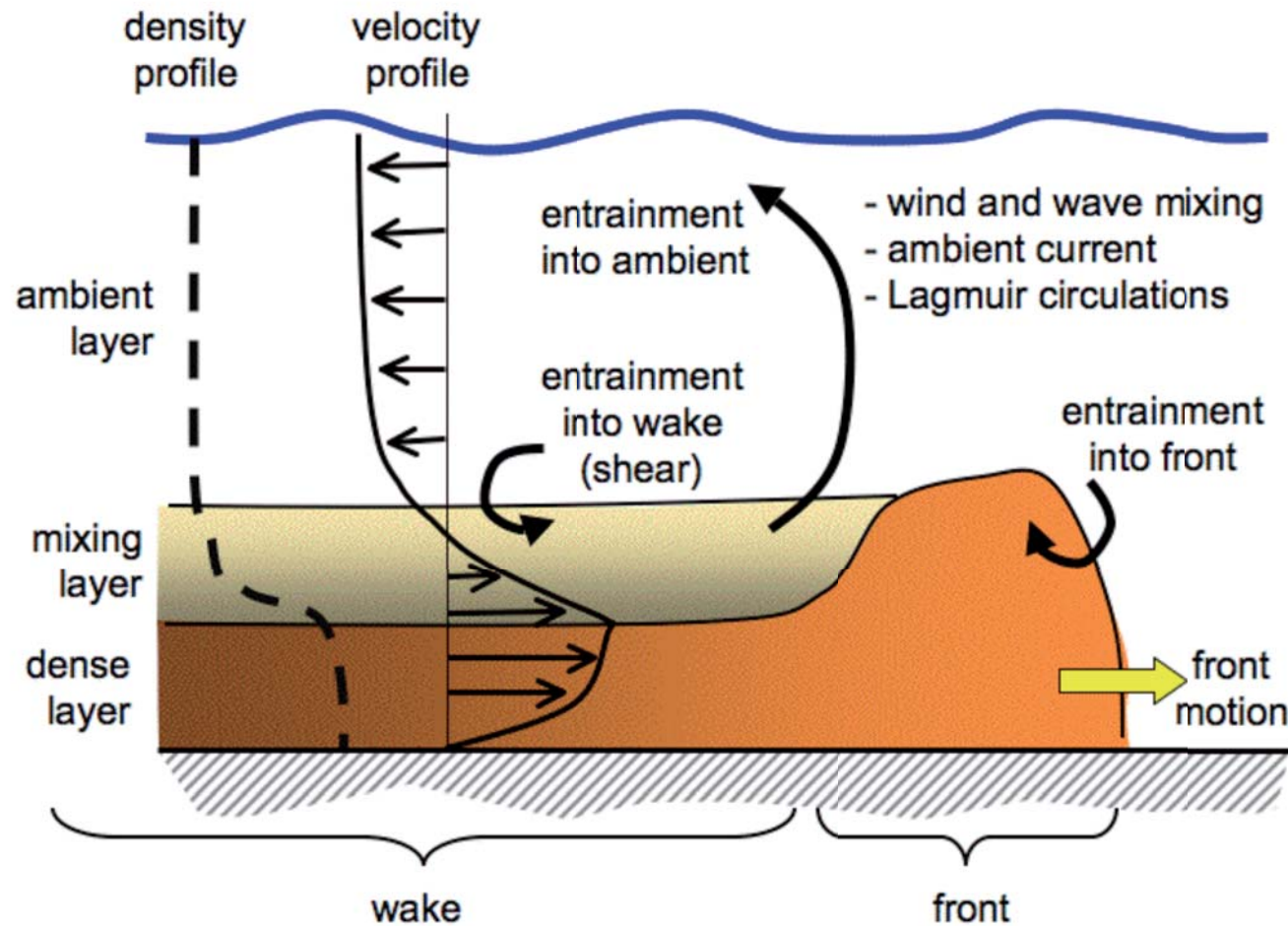
- ELCOM has been applied to Wellington Reservoir, Lake Ogawara, Lake Burragorang, and other lake/estuary underflows by Imberger's group at Centre for Water Research, Univ. of Western Australia.
- Coupling procedure is published in Dallimore papers (see prior slide)
- Has not been used on brine underflows (to my knowledge).



- Corpus Christi and Oso Bay system being modeled for Texas Water Development Board (with some NSF funding)
- Applying unstructured grid ELCIRC 3D model (not ELCOM)
- Developing 2-layer underflow model with coupling to 3D.



underflow schematic



For thin-layer underflows, the partitioning into a mixing layer and a dense layer allows us to better represent entrainment dynamics and isolation of dense fluid



- Key interest is when underflow moves slowly (very little bottom slope)
- New approach to use 2 layers to represent underflow (mixing layer and dense layer)
- Wind and shear entrain mixing layer into ambient, thereby eroding underflow.
- Bottom boundary shear affects exchange between mixing layer and dense layer
- Dissolved oxygen from the ambient cannot reach bottom until it penetrates both the mixing layer and the dense layer



take-home messages



- Ambient turbulence rather than gravity-current turbulence may dominate mixing for slow underflows.
- Ambient turbulence entrains the layer into the ambient (i.e. not a simple exchange) and may leave a thin layer of high density fluid
- Thin layers require very small vertical grid cells to resolve in 3D model.
- Coupled 2D/3D models may be a better approach than using small grid cells.
- More work is needed on coupled models before they can be considered a standard engineering approach.



- This work was sponsored by a number of grantors, including the National Science Foundation, the Texas Water Development Board, the U.S. Army Corps of Engineers and the Texas Advance Research Program.
- Much of the tough work was done by Paula Kulis and Jordan Furnans.
- Thanks to Jorg Imberger and the staff at CWR for continued use and collaboration with ELCOM.