Physical Controls on Dissolved Oxygen and Inorganic Carbon Dynamics in Estuaries: Insights from Simplified Numerical Models

Malcolm Scully
Woods Hole Oceanographic Institution
mscully@whoi.edu

OCB Summer Workshop
June 24-27, 2019

Motivation:

1) Hypoxia in estuaries is a growing issues of major economic importance.
2) Estuaries are thought to be globally important sources of CO_2, but large uncertainties remain in these estimates.

Goal:

Use idealized numerical models to provide insight into how estuarine physics modulates low dissolved oxygen (hypoxia) and impacts oxygen and carbon fluxes.

a) Part 1 – Simulations of oxygen dynamics in Chesapeake Bay
b) Part 2 -- Simulations of coupled O_2/DIC in estuary with idealized bathymetry.

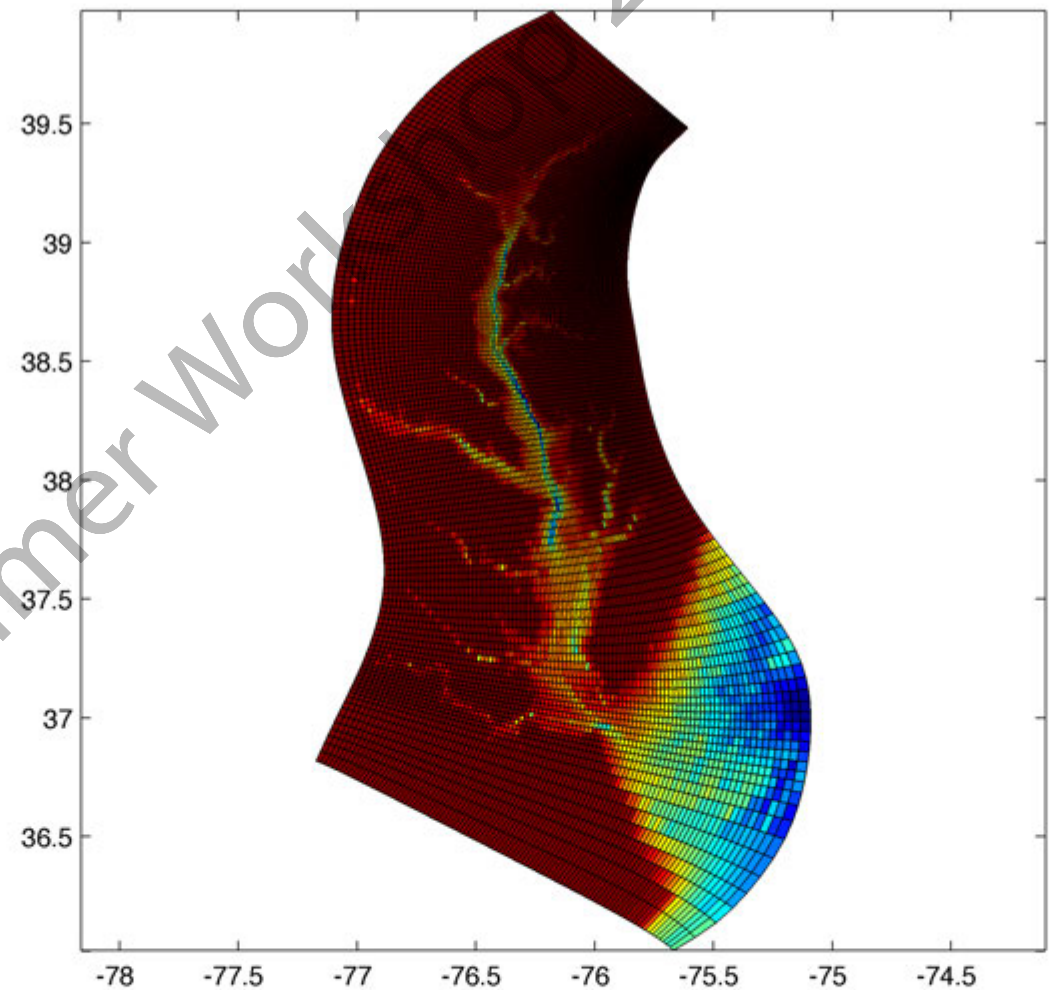
Conclusions:

<u>**Physics are important**</u>

Part 1: Simplified Dissolved Oxygen Modeling in Chesapeake Bay

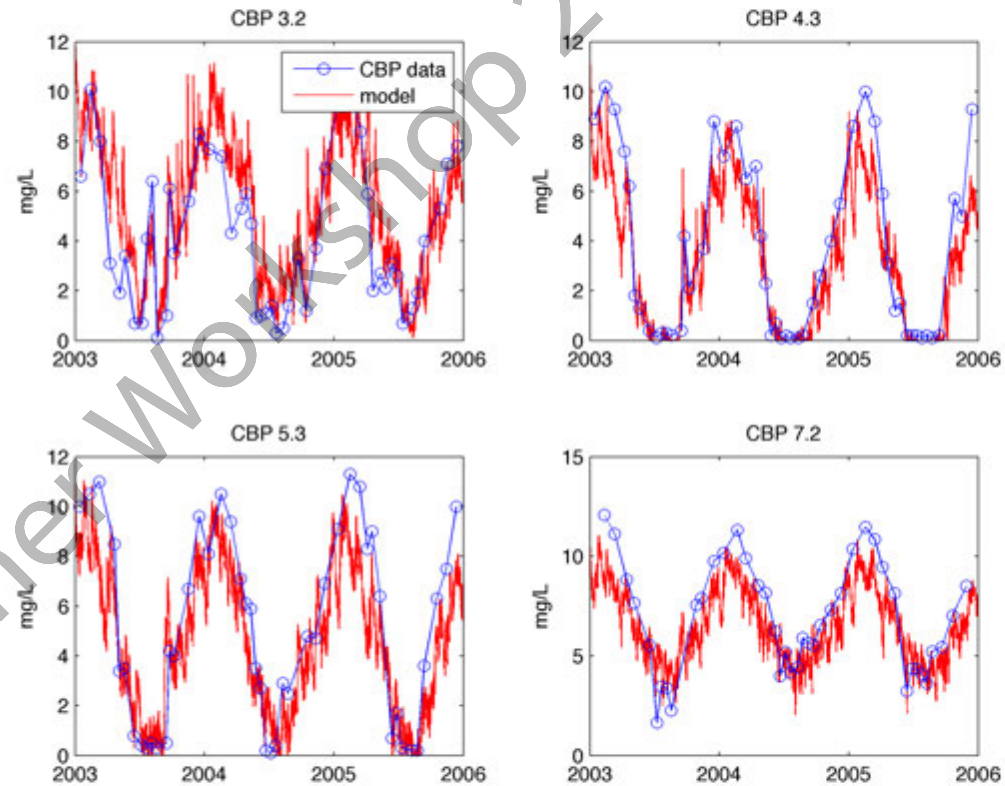
<u>Model forcing</u>

- Realistic tidal and sub-tidal elevation at ocean boundary
- Atmospheric forcing from NCEP NARR model
- Observed river discharge for all tributaries.
- Temperature and salinity at ocean boundary from World Ocean Atlas.
- **<u>Very simple</u>** oxygen model



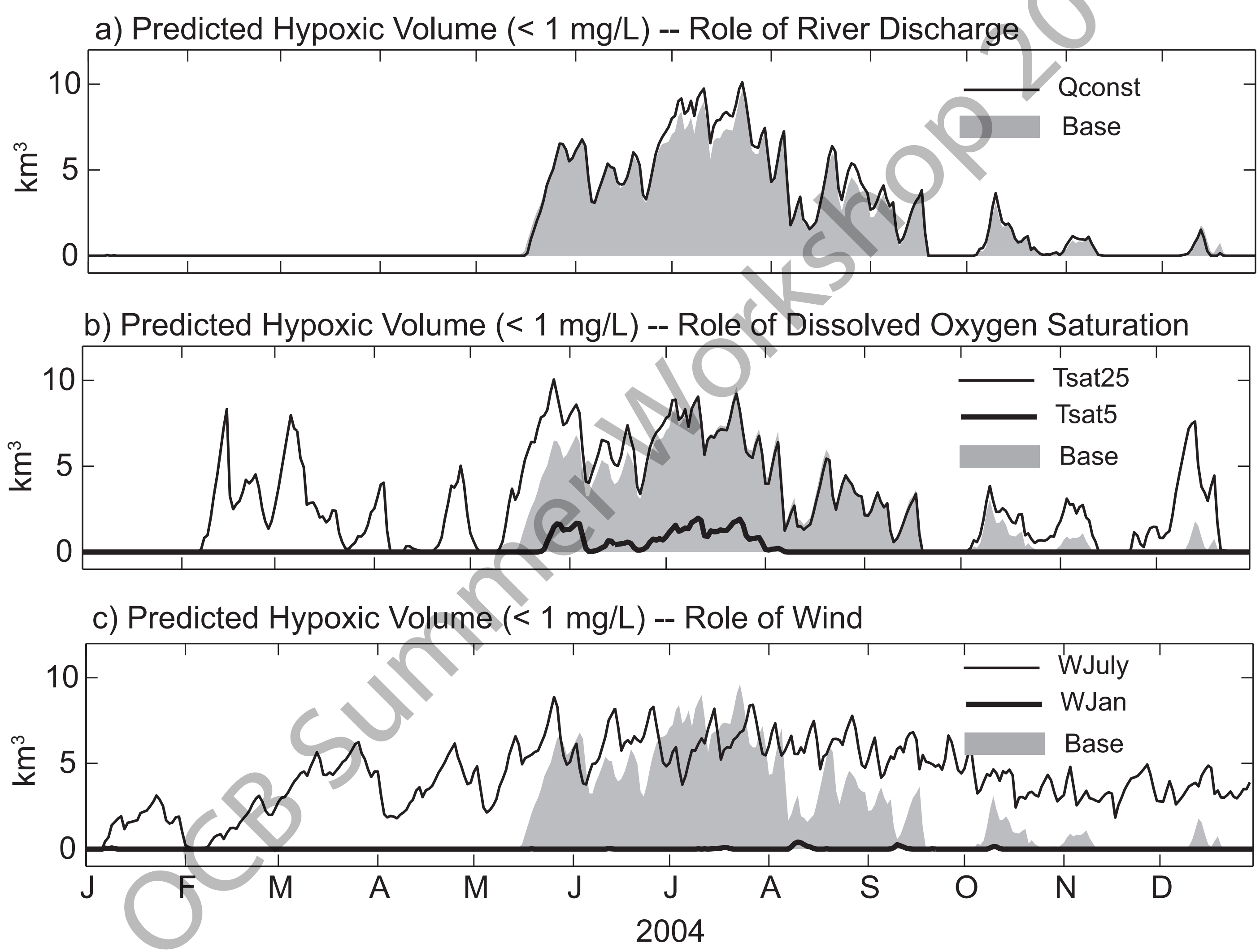
Simplified Dissolved Oxygen Modeling in Chesapeake Bay

- Oxygen is introduced as an additional model tracer.
- Oxygen consumption (respiration) is constant in time and space (~0.4gO_2/m^3/day) .
- No oxygen consumption outside of estuarine portion of model
- No oxygen production.
- At both surface and open boundaries, O_2 concentration is set to saturation.
- No negative oxygen concentration and no super-saturation.



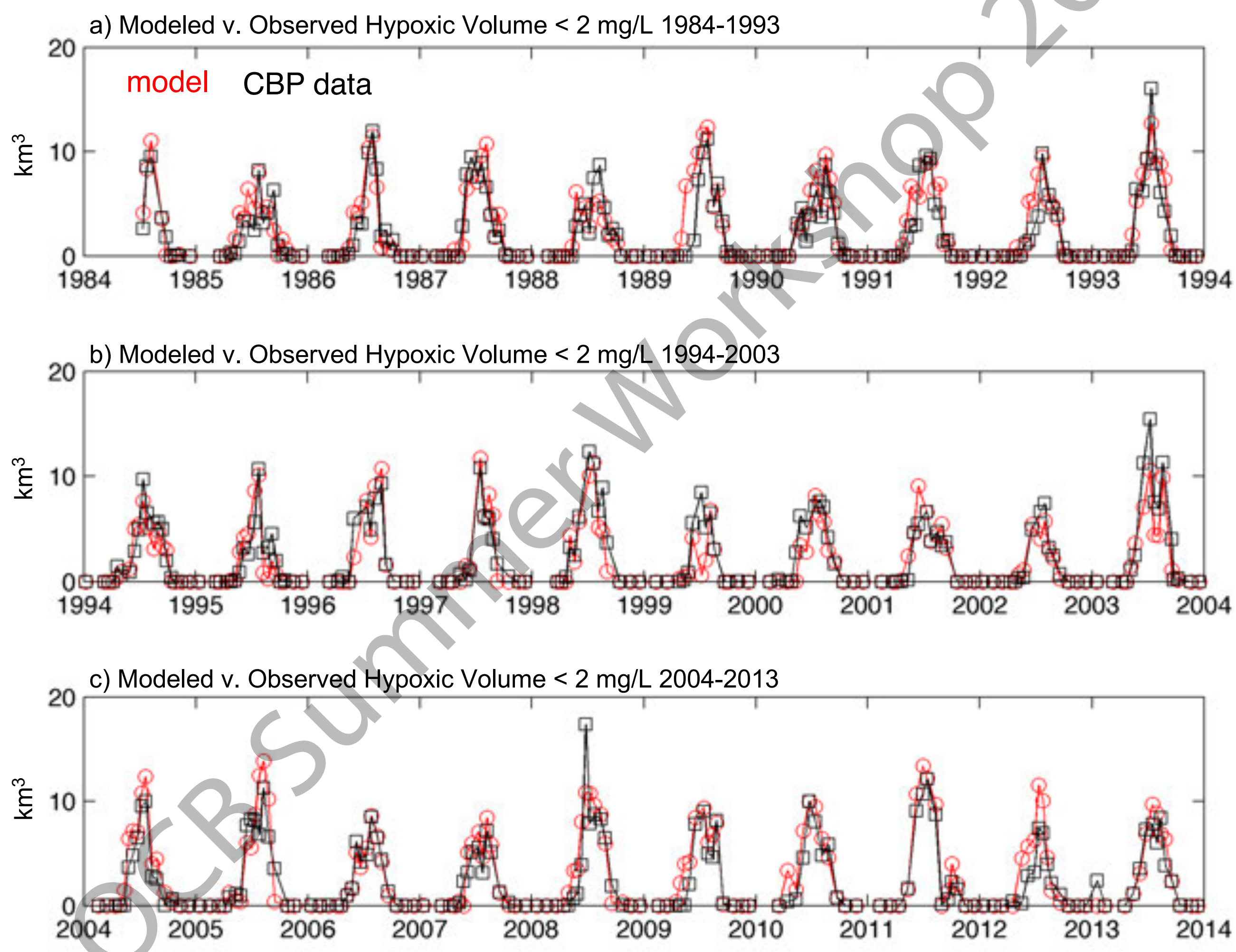
Model assumes biology is constant so that the role of physical processes can be isolated!

What Physical Variables Contribute to Seasonal Cycle of Hypoxia?



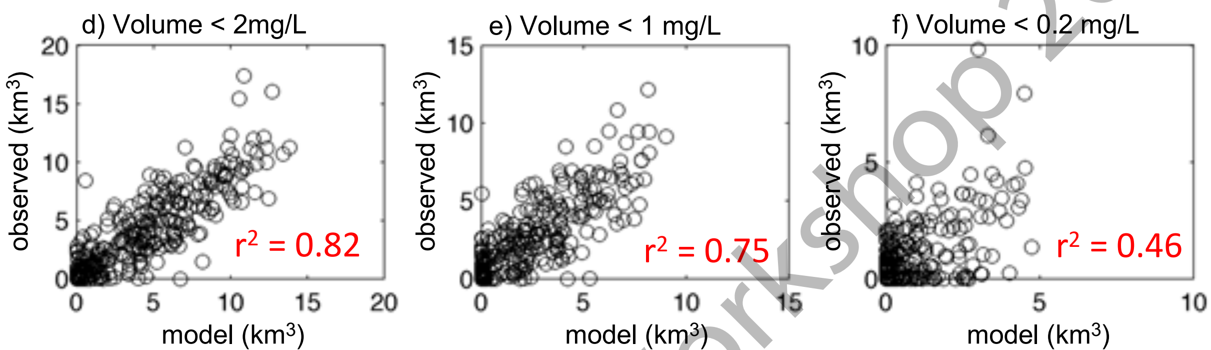
Scully JGR-2013

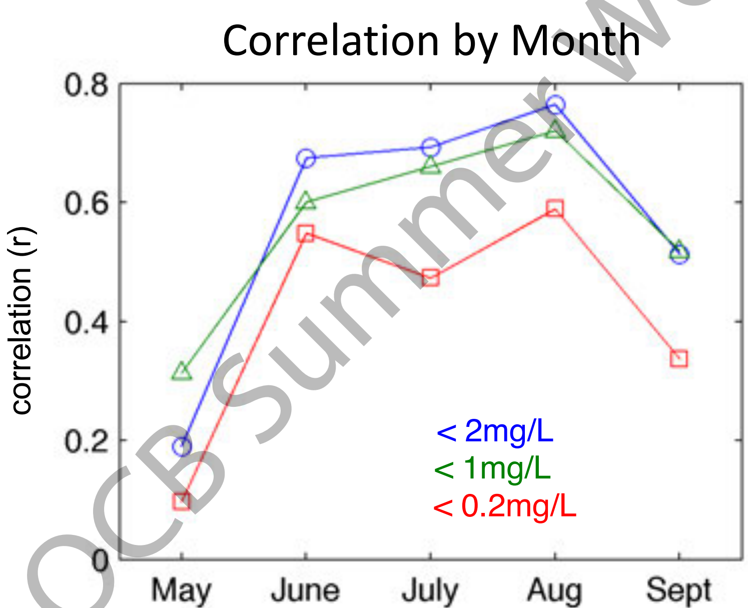
How Do Variations in Physical Forcing Impact Inter-Annual Variability?



Scully L&O-2016

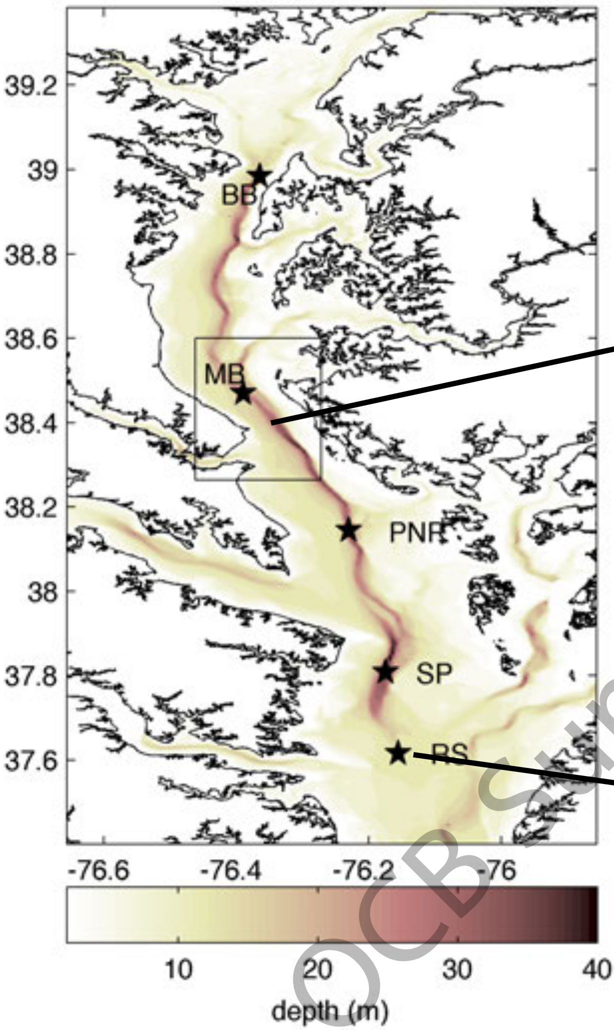
How Do Variations in Physical Forcing Impact Inter-Annual Variability?



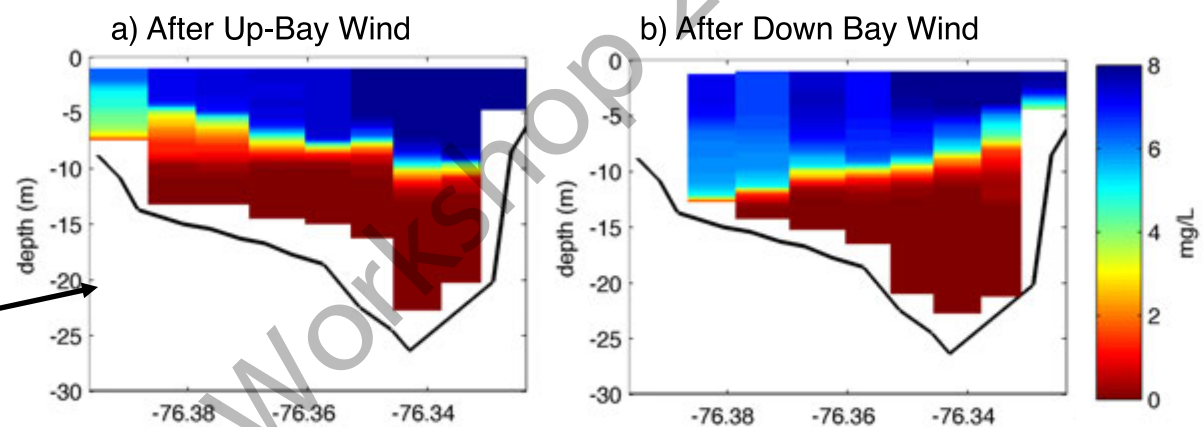


1) Model with no biological variability can capture more than 50% of interannual variability in hypoxic volume for months of July and August.
2) Variable that explains most of the variance in modeled hypoxic volume is July-August wind speed (r = -0.77).

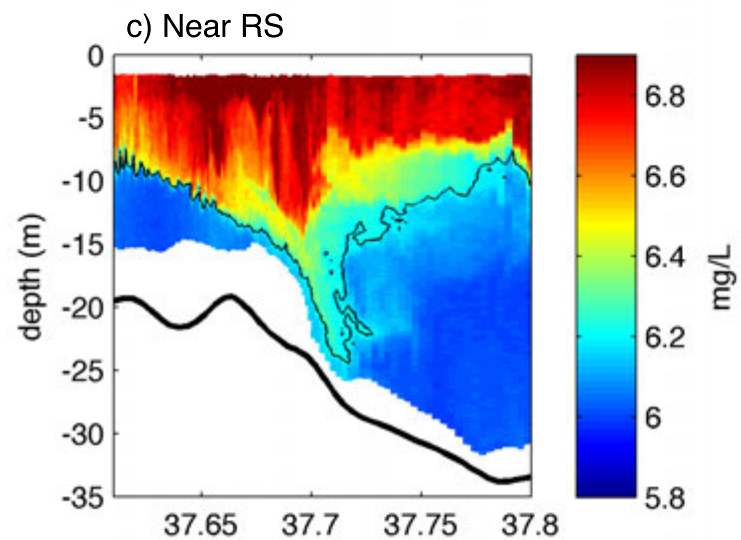
Importance of Wind Forcing



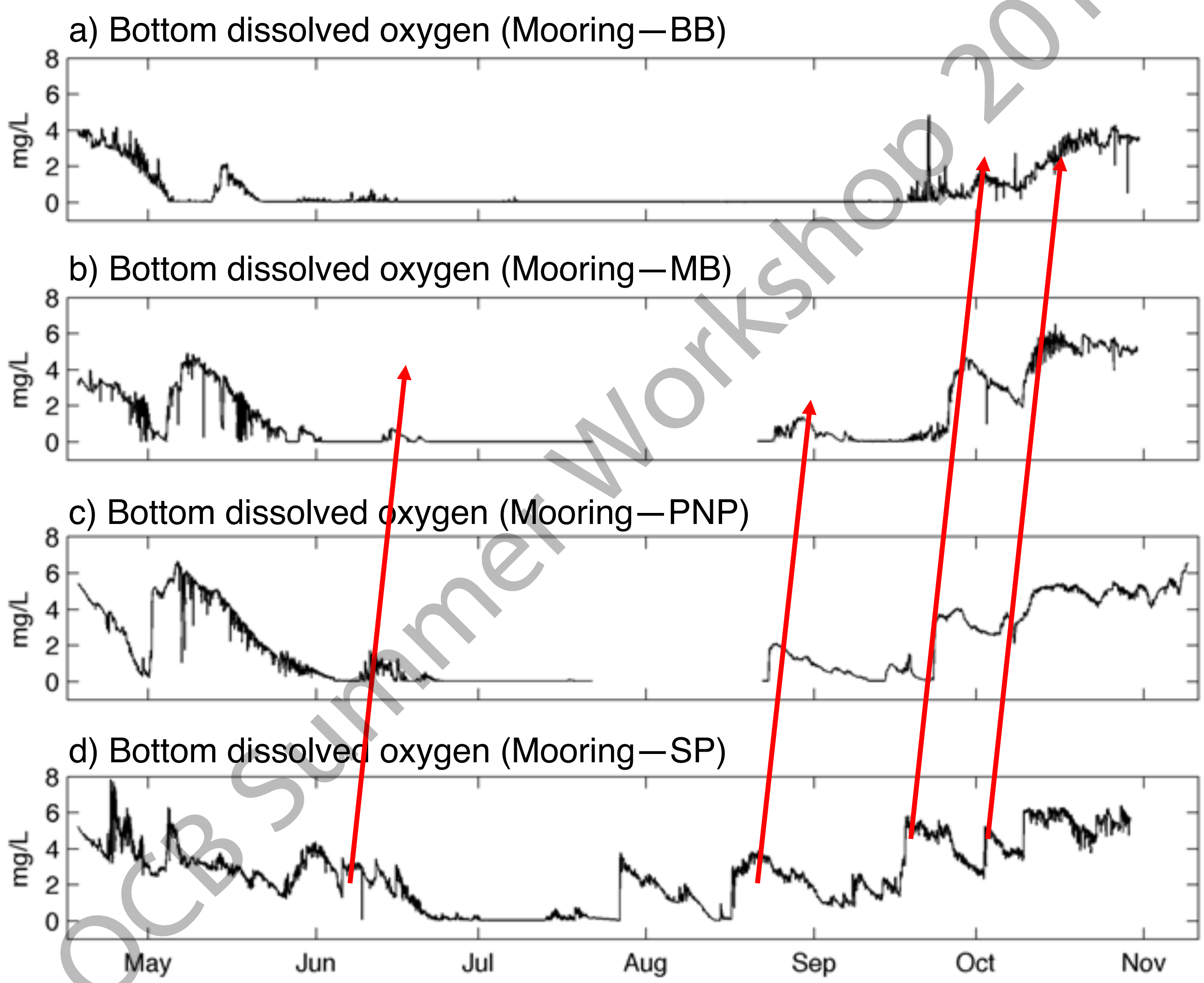
Dissolved Oxygen Data—Across Channel:



Dissolved Oxygen Data—Along Channel:

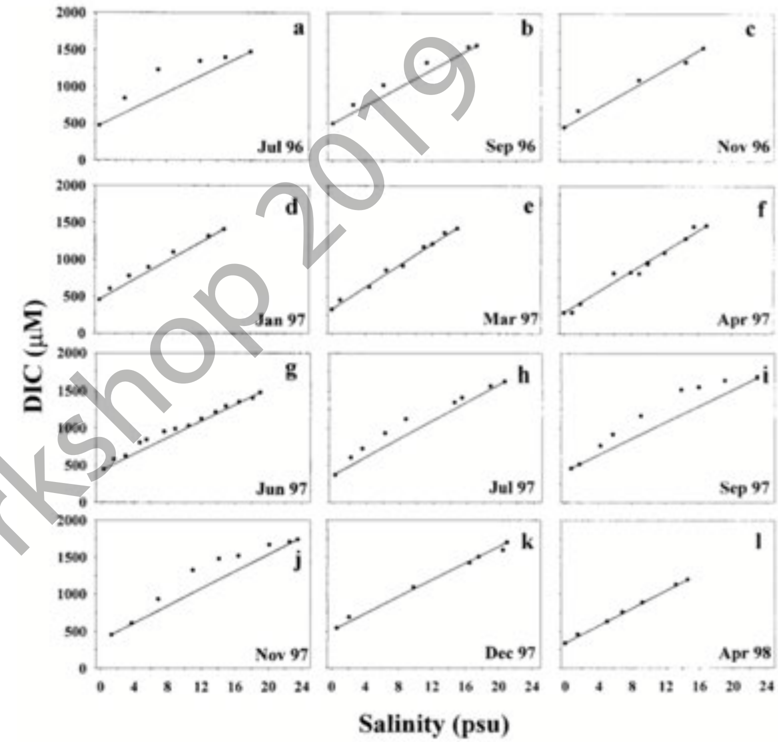


Along Bay Bottom Dissolved Oxygen Variations

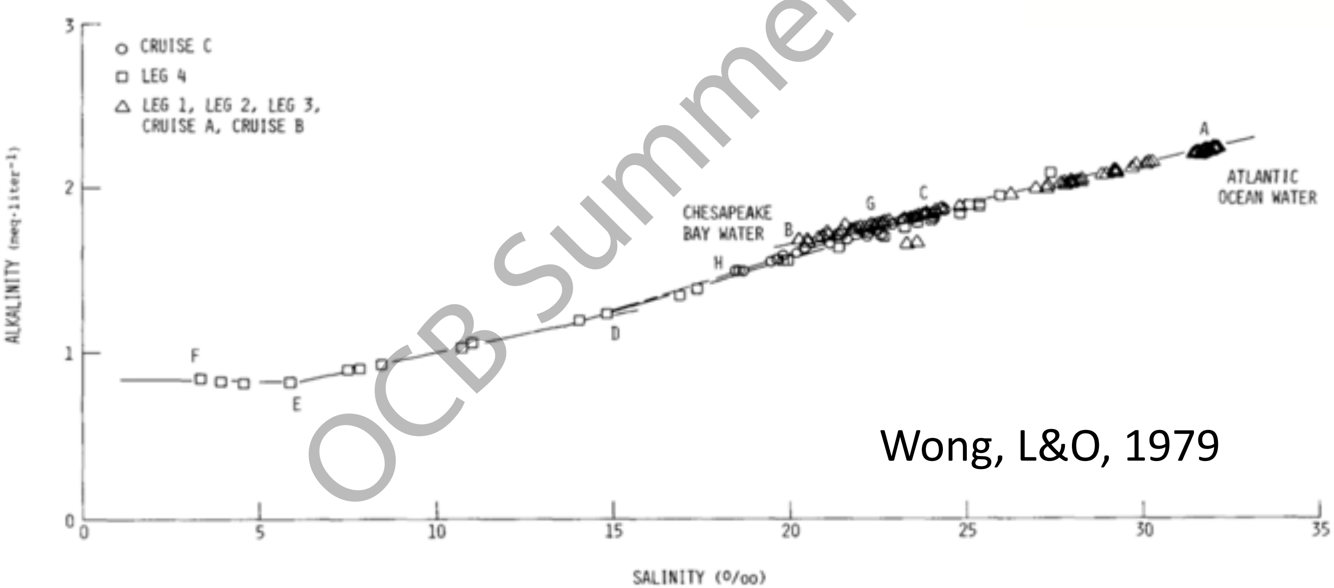


Part 2: Implications of physics to coupled DIC—O_2 Dynamics

In estuaries, DIC and alkalinity are often strongly related to salinity. Stratified estuaries will have strong vertical gradients in DIC/alkalinity and vertical mixing will result in non-linear response of carbonate chemistry.

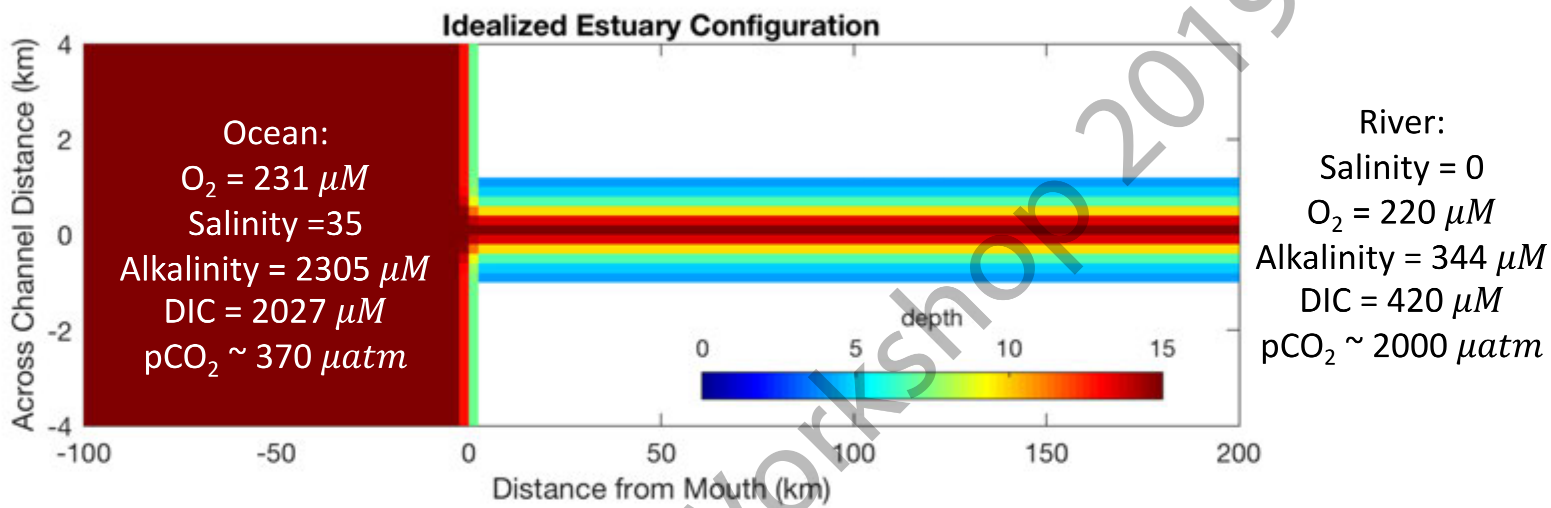


Raymond et al, 2000



Wong, L&O, 1979

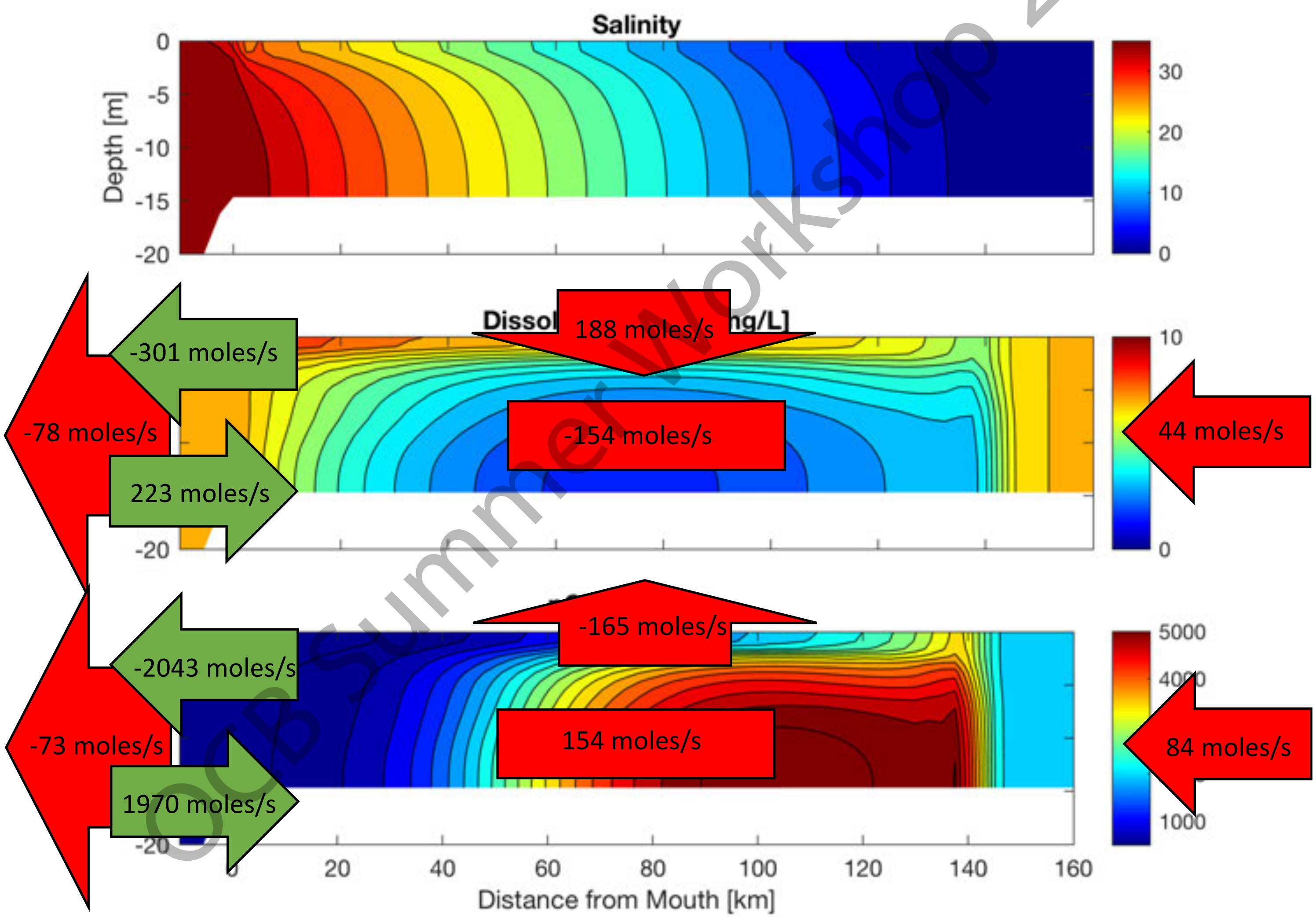
Model for Coupled Oxygen-DIC Dynamics



1) Gross Primary Production based on simple P-I curve (produces/consume O_2 and DIC). No nutrients, phytoplankton, zooplankton, etc….
2) Community Respiration is constant in time and space and selected to give a prescribed Net Ecosystem Metabolism (NEM).
3 DIC, alkalinity at river and oceanic boundaries is prescribed (constant in time). Riverine water is super-saturated with pCO_2.
4) Alkalinity is conservative (no sources/sinks).
5) Carbonate chemistry equilibrium Millero (1995).
6) Air sea flux is calculated using estuarine piston formulation of Raymond et al (2000).
7) Systematically vary: 1) Tides, 2) River Discharge, 3) Wind, 4) GPP and CR (holding NEM constant)

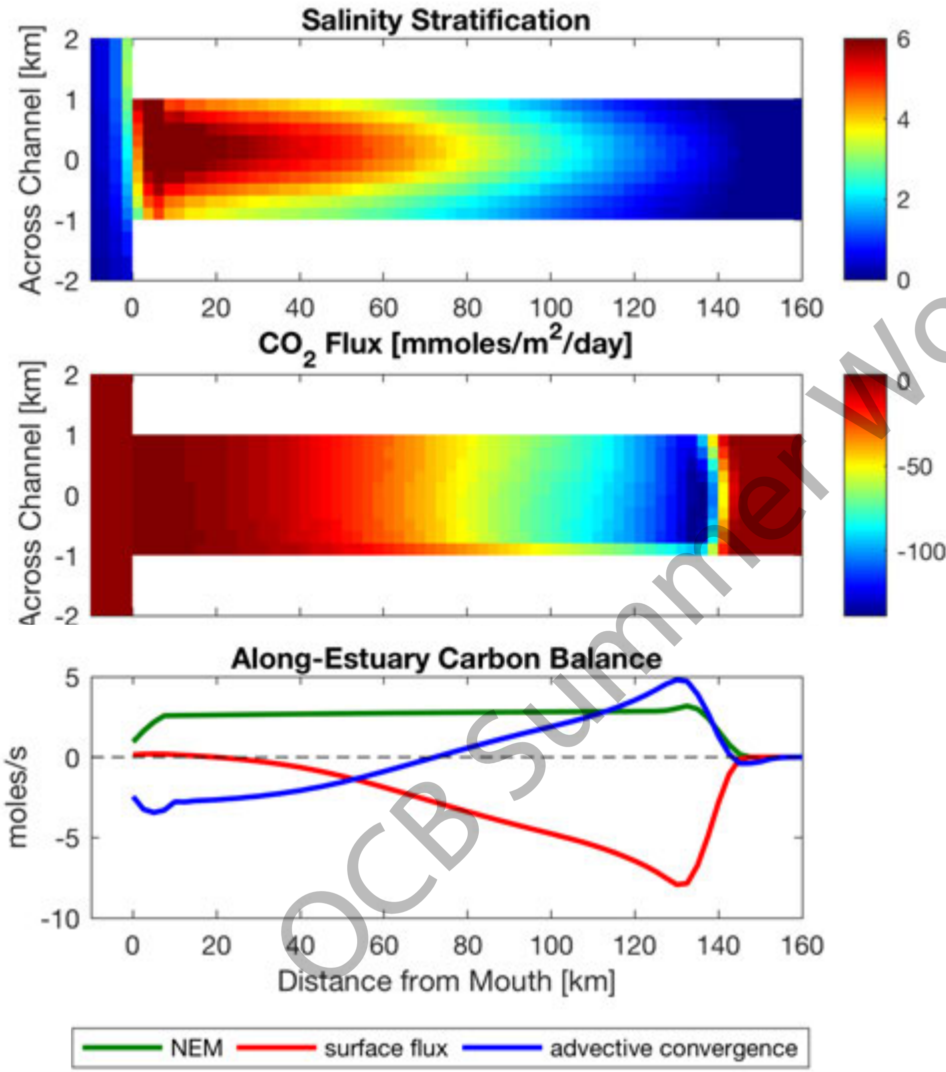
Example Model Run:

Simulation = Tidal Amplitude = 0.3m; River Discharge = 200 m^3/s; Wind = 4 m/s (rotating); NEM = Heterotrophic



Example Model (cont)

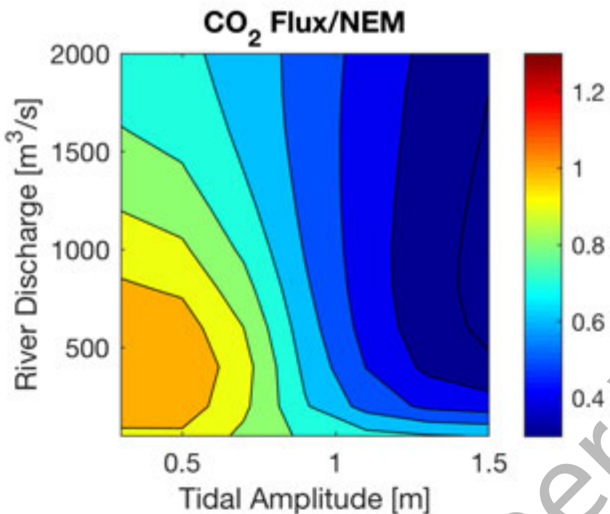
Simulation = Tidal Amplitude = 0.3m; River Discharge = 200 m^3/s; Wind = 4 m/s (rotating);NEM = Heterotrophic

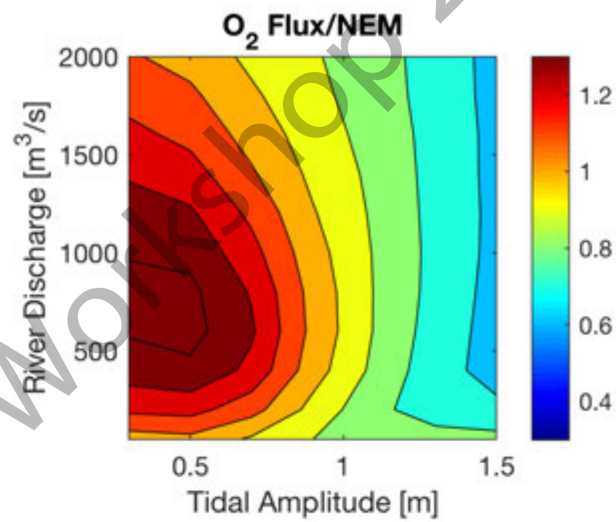


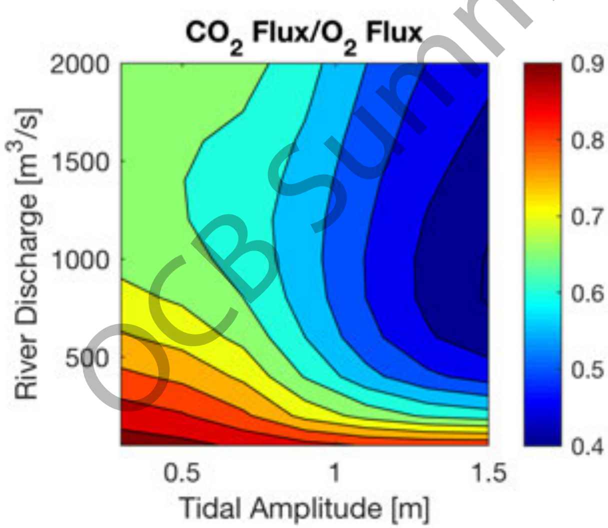
1) Even though NEM is spatially uniform, there is significant along-estuary variability in gas flux. This variability must be balanced by convergence/divergence in advective transport.
2) Stratification prevents vertical mixing allowing buildup of high pCO_2 in bottom waters, which is advected up estuary and outgassed where stratification is weaker.
3) In lower estuary, O_2 flux is outward but CO_2 is ~ 0, where high pH/Alkalinity ensure that $\Delta DIC >> \Delta CO_2$.

Combined Effect of Tides and River Discharge

Simulations = Systematically vary tidal amplitude and river discharge, while holding wind (4 m/s) and NEM (heterotrophic) constant



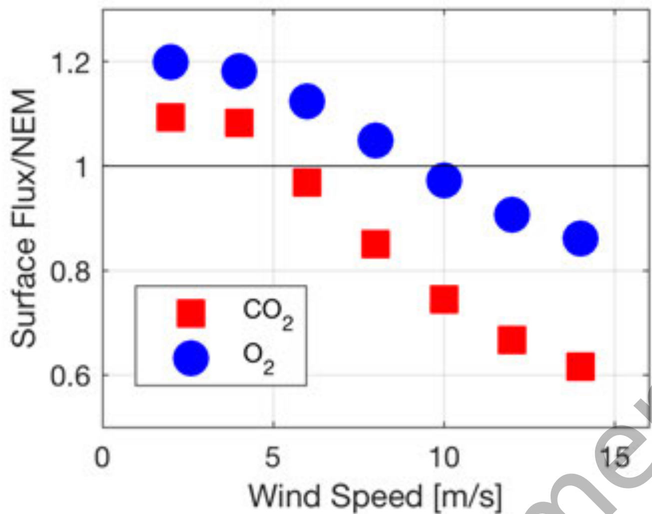


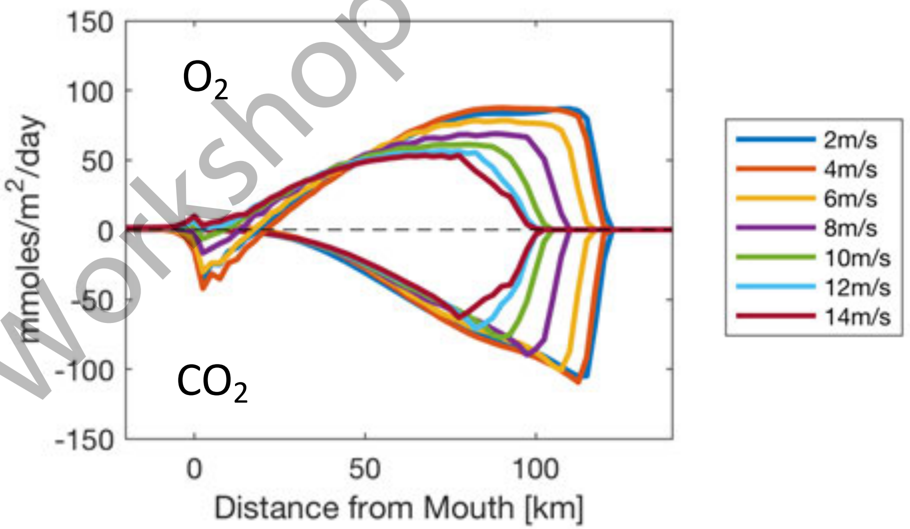


1) Fraction of NEM that is exchanged via atmosphere varies strongly with tide and river forcing.
2) Magnitude of CO_2 flux is always lower than O_2 flux and CO_2 flux is reduced more with increased tidal mixing and river discharge

Effect of Winds

Simulation = Tidal Amplitude = 0.5m, River Discharge = 200 m^3/s; Constant NEM (heterotrophic); Rotating winds of constant magnitude (2 – 14 m/s)



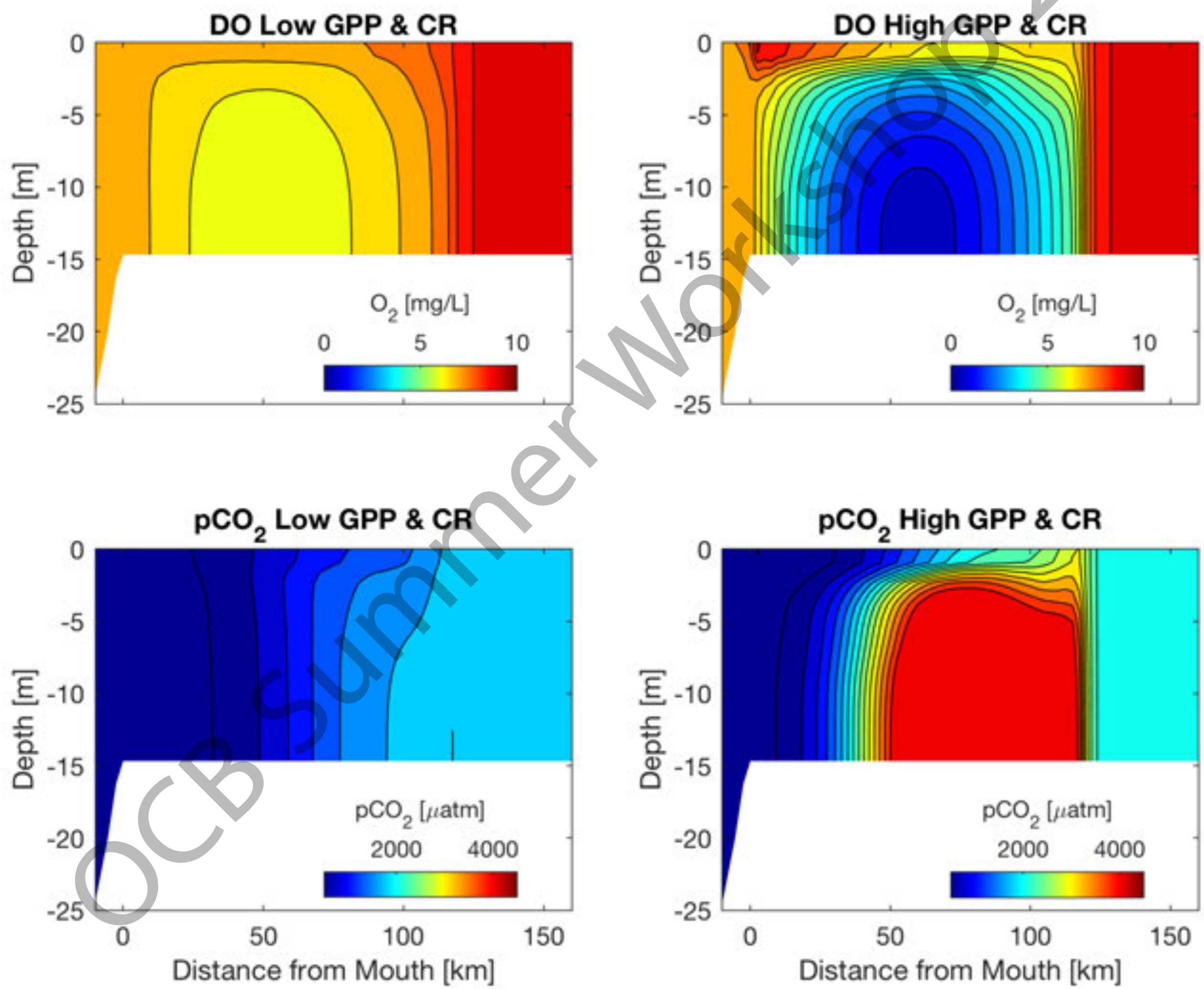


1) Consistent with tidal mixing, wind mixing tends to reduce magnitude air-sea outgassing/ingassing of CO_2/O_2.
2) The impact of wind mixing on surface concentration is greater than increase in piston velocity.
3) Magnitude of CO_2 flux is consistently smaller than O_2 flux, and difference increases with intensity of mixing, consistent with greater conversion of CO_2 to HCO_3^- and CO_3^{2-}.
4) Largest differences between O_2 and CO_2 fluxes in high salinity/alkalinity region of estuary.

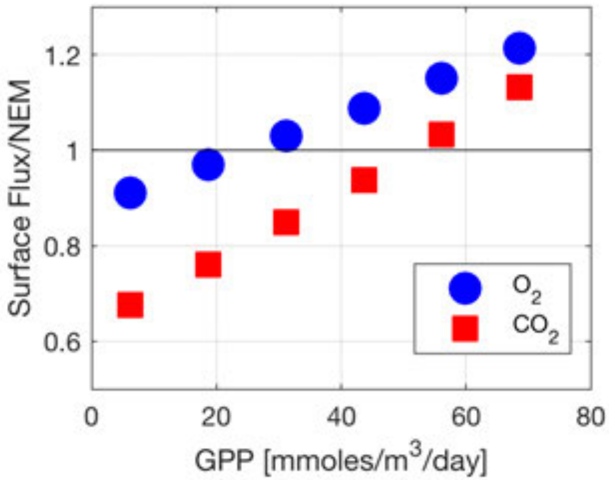
Effect of Biological Rates (GPP and CR)

Tidal Amplitude = 0.5m, River Discharge = 200 m^3/s; Wind = 4m/s

Value of NEM is **Heterotrophic and held constant** , but GPP and CR are varied

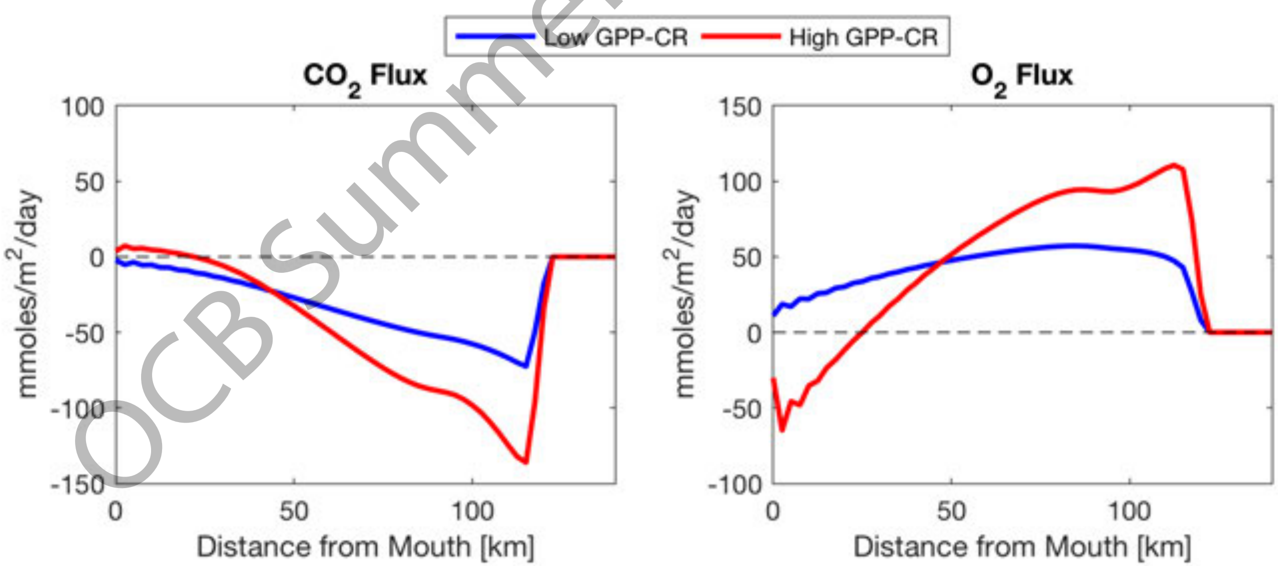


Effect of GPP/CR (cont)



CO_2 Flux: For low GPP/CR 70% of NEM is outgassed and 30% is advectively exported to ocean. However, as GPP/CR increases, export at mouth decreases and more HCO_3 is converted to CO_2 (presumably in hypoxic bottom waters) and as a result, 130% of NEM is outgassed (mostly in upper estuary).

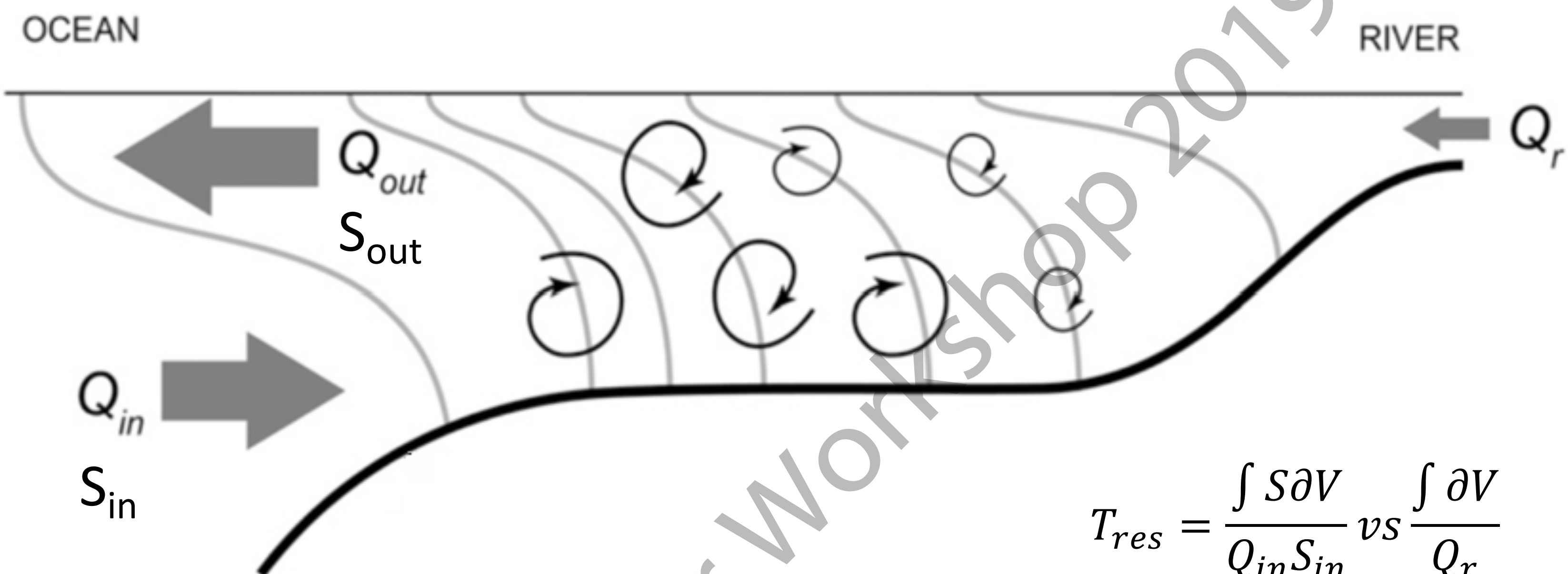
O_2 Flux: For low GPP/CR 90% of O_2 demand is from atmospheric influx. As GPP/CR increase more O_2 is exported ocean at the mouth and atmospheric influx exceeds NEM. However, variation in flux are smaller for O_2.



Conclusions:

1) A model with no biological variability can reasonably simulate bottom oxygen in Chesapeake Bay at a variety time scales.
2) The physical variable that contributes most of this variability is wind (though not through direct vertical mixing, but rather localized mixing and advection).
3) The intensity of vertical mixing plays a key roll in controlling both O_2 and DIC fluxes in estuaries. Increased tidal mixing, river discharge and wind forcing all increase the importance of advective over atmospheric exchange of CO_2 and O_2, but the partitioning of CO_2 flux responds more strongly because of underlying carbonate chemistry.
4) The simulated integrated air-sea fluxes are relatively insensitive to the gas transfer (piston) velocity, despite large differences in their wind-speed dependence.
5) Higher GPP/CR (for constant NEM) favors greater atmospheric exchange. This exchange occurs primarily in the upper estuary, where the estuarine residual circulation transports low DO/high pCO_2 bottom waters up-estuary into regions of weaker stratification where atmospheric exchange occurs.

Knudsen's Relationship:



$$T_{res} = \frac{\int S \partial V}{Q_{in} S_{in}} \; vs \; \frac{\int \partial V}{Q_r}$$

Steady State Conservation of Volume:

$$Q_{in} + Q_r = Q_{out}$$

Steady State Conservation of Salt:

$$Q_{in} S_{in} = -Q_{out} S_{out}$$

Steady State Estuarine Inflow:

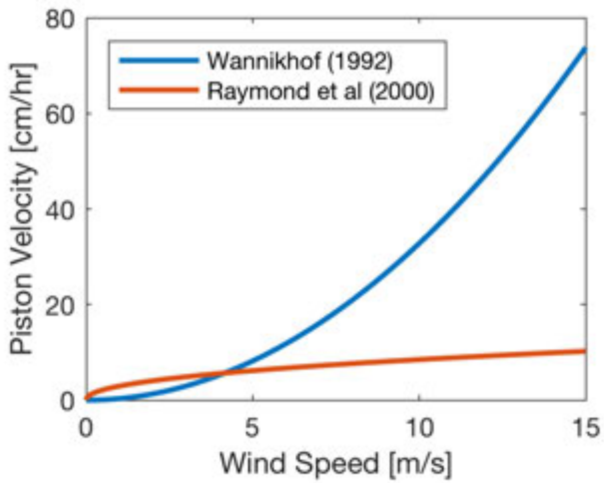
$$Q_{in} = \frac{S_{out}}{\Delta S} Q_r$$

Mixing Drives Residual Estuarine Circulation

Mixing also supplies O_2 to bottom waters, controls where O_2 and pCO_2 can exchange with atmosphere, supplies nutrients to photic zone, etc….

Estuarine circulation imports/exports O_2, DIC, DOC, nutrients, etc…

Importance of Gas Transfer Velocity (k_L)



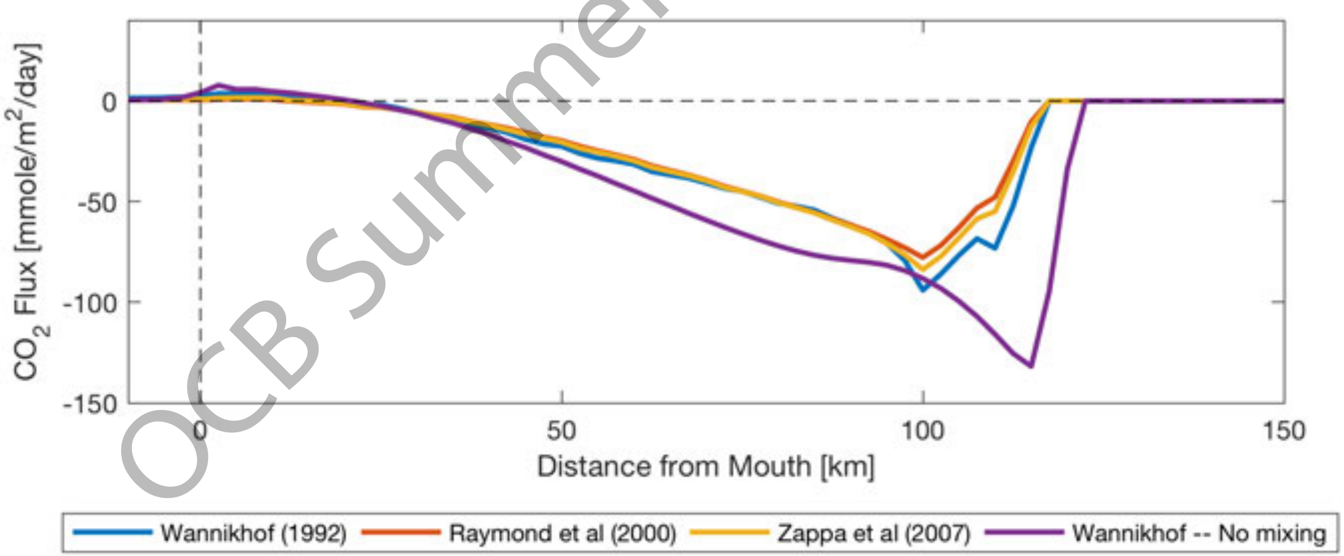
$$F = k_L \nabla CO_2$$

$k_L \sim U_{10}^2$ Wannikhof (1992)

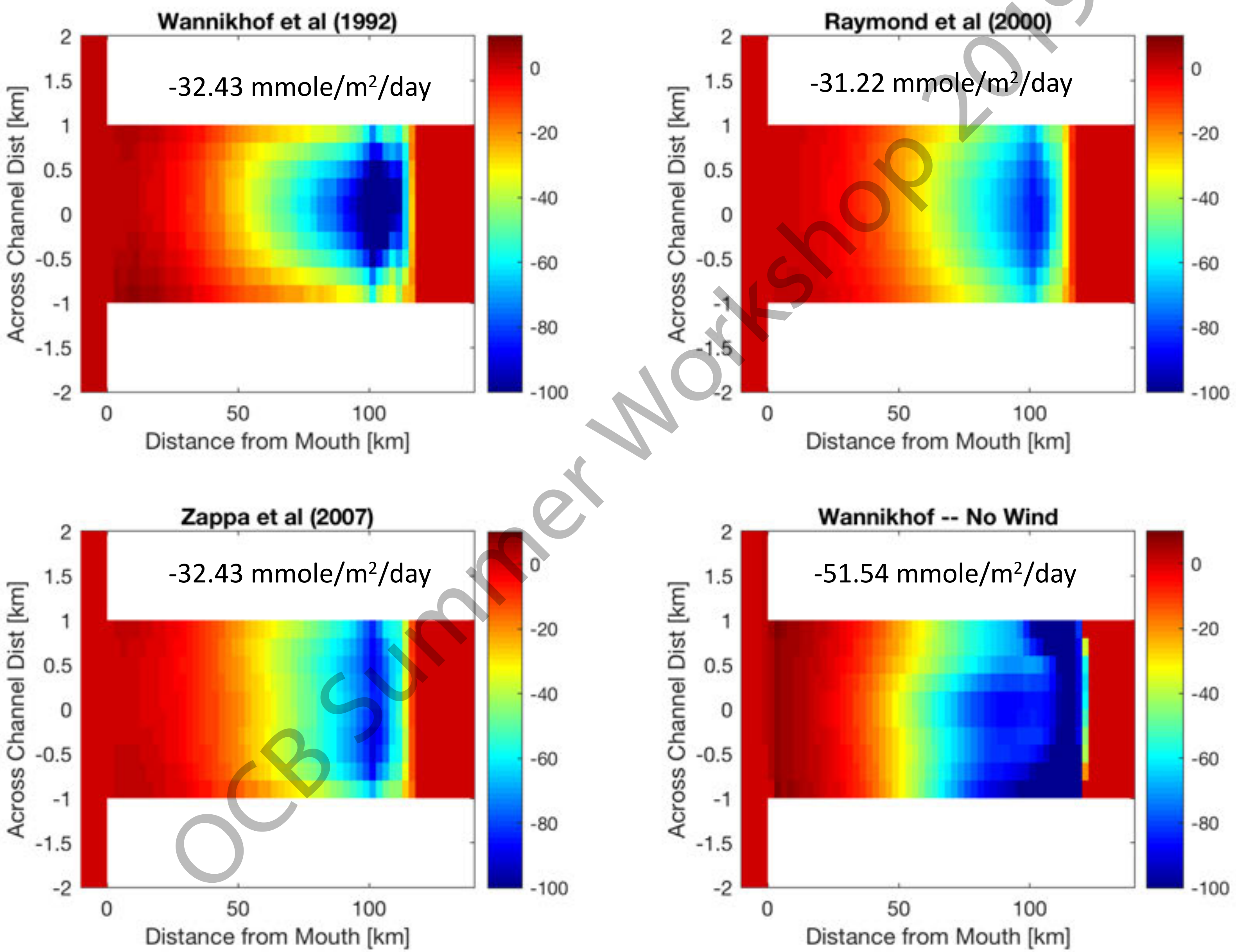
$k_L \sim U_{10}^{0.46}$ Raymond et al (2000)

$k_L \sim \varepsilon^{1/4} \sim U_{10}^{0.75}$ Zappa et al (2007)

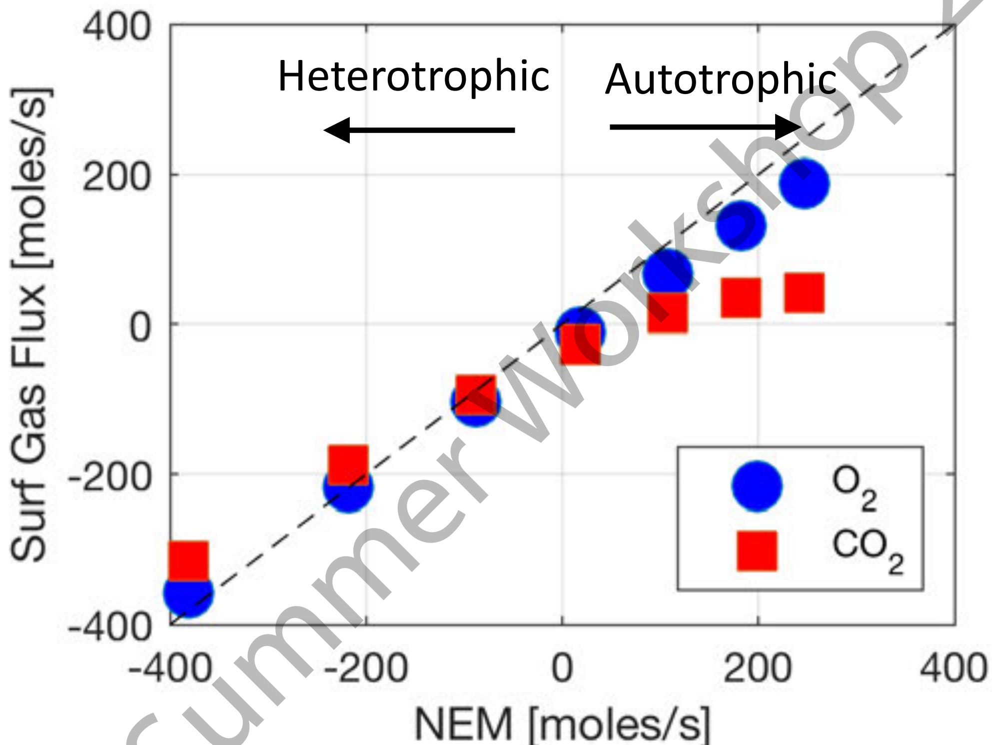
Comparison of CO_2 Flux for Simulation with Sinusoidal Wind forcing (12 m/s)



Importance of Gas Transfer Velocity (cont)



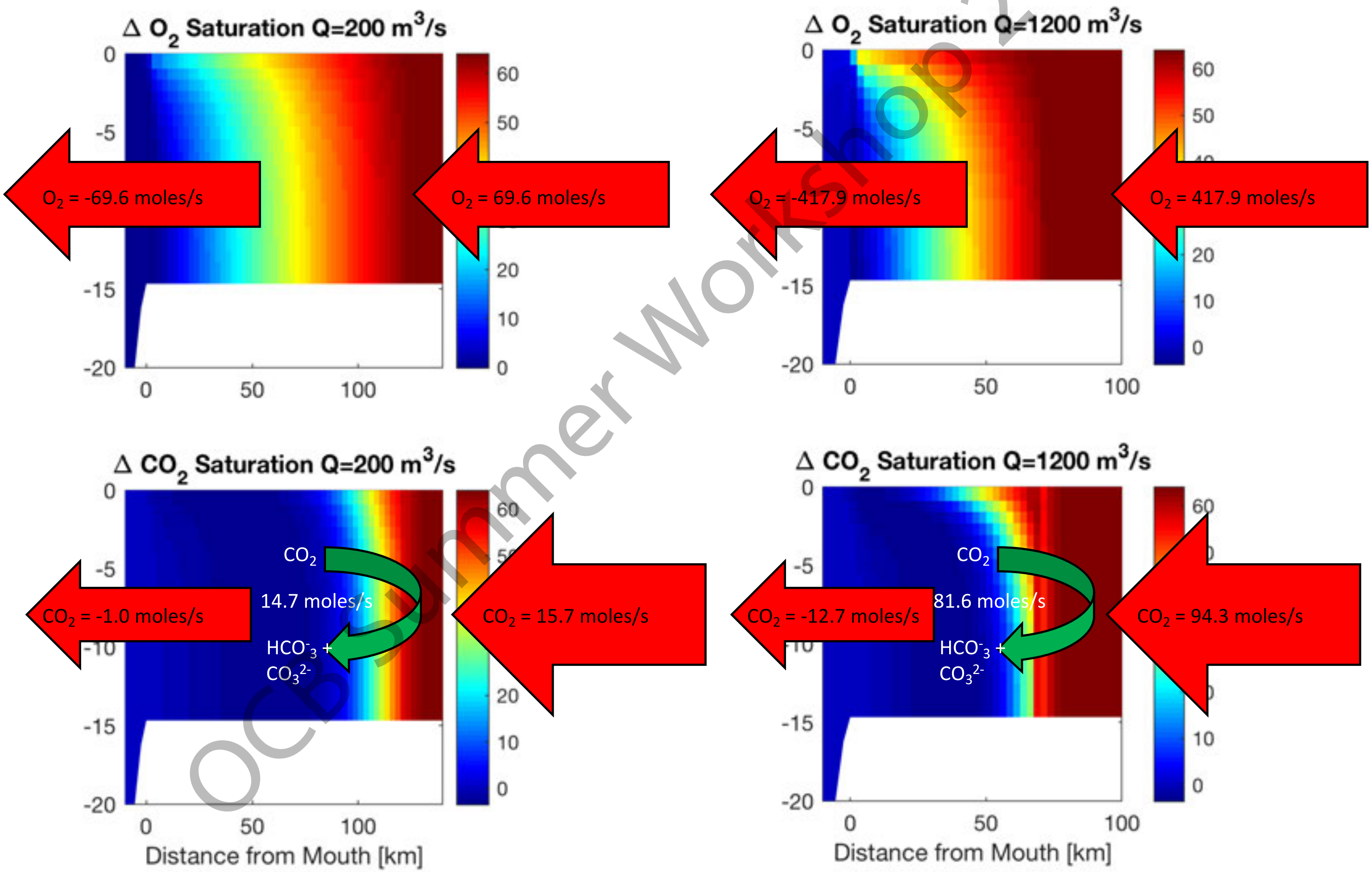
Response of Surface Gas Flux to Variations in Net Ecosystem Metabolism



1) Surface Flux of Oxygen is roughly equal to NEM for all condition, but influx of CO_2 becomes limited under net autotrophic conditions.
2) Net autotrophic conditions result in

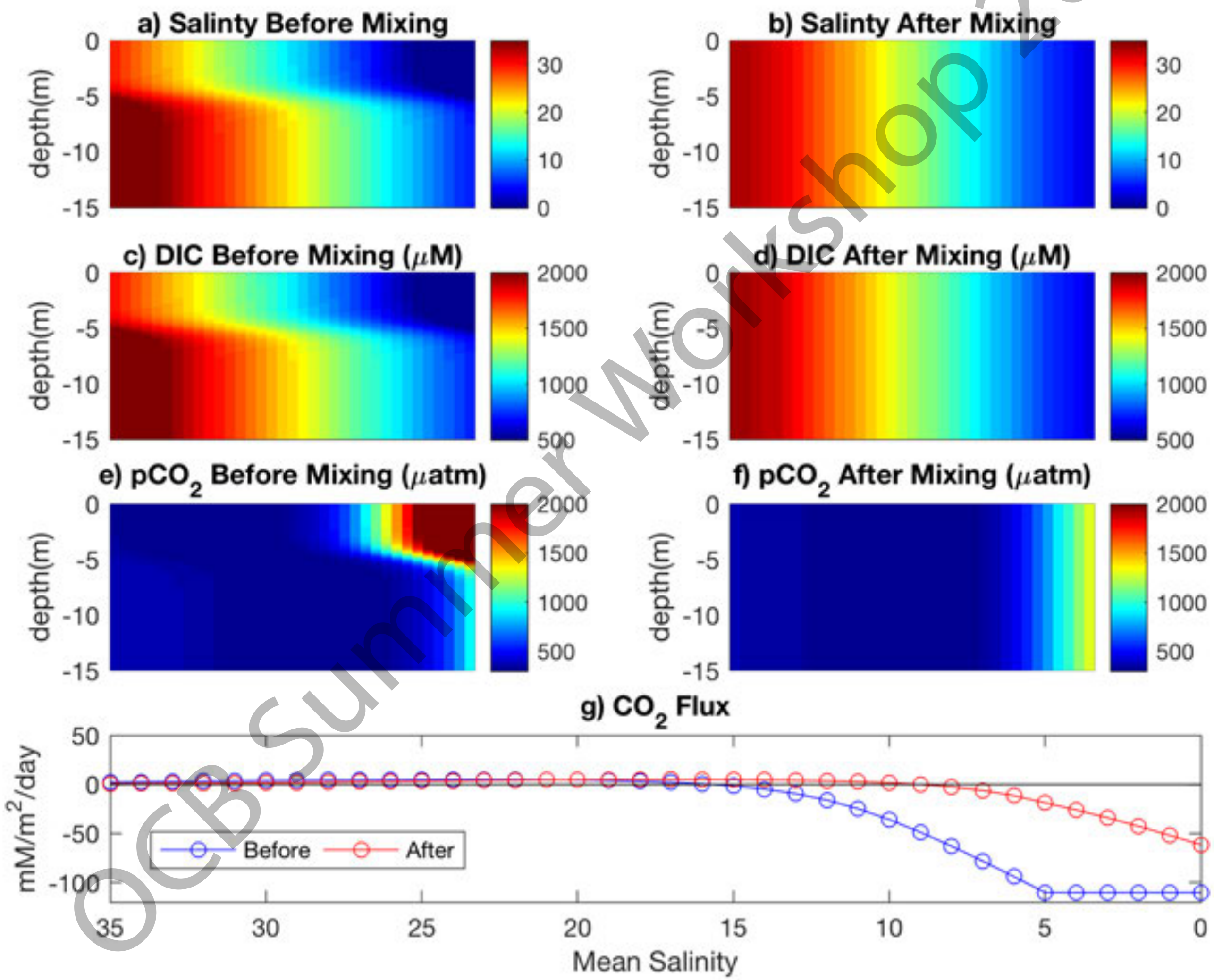
Why do oxygen and carbon dioxide responds so differently?

Simulation = No Biology, No Wind Forcing, Both O_2 and CO_2 are supersaturated in river and in equilibrium with atmosphere in ocean.

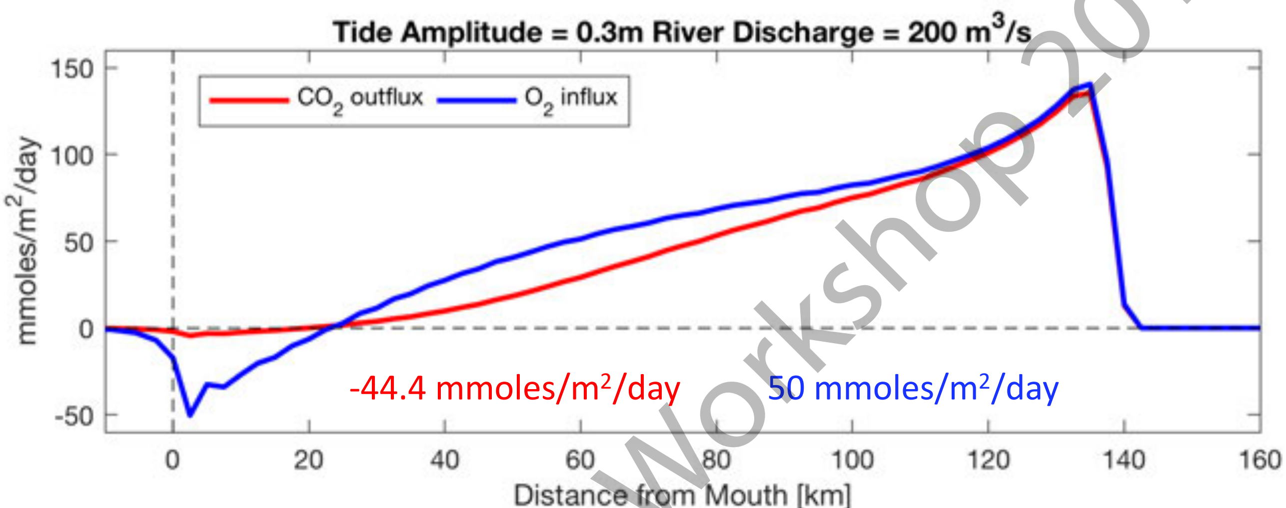


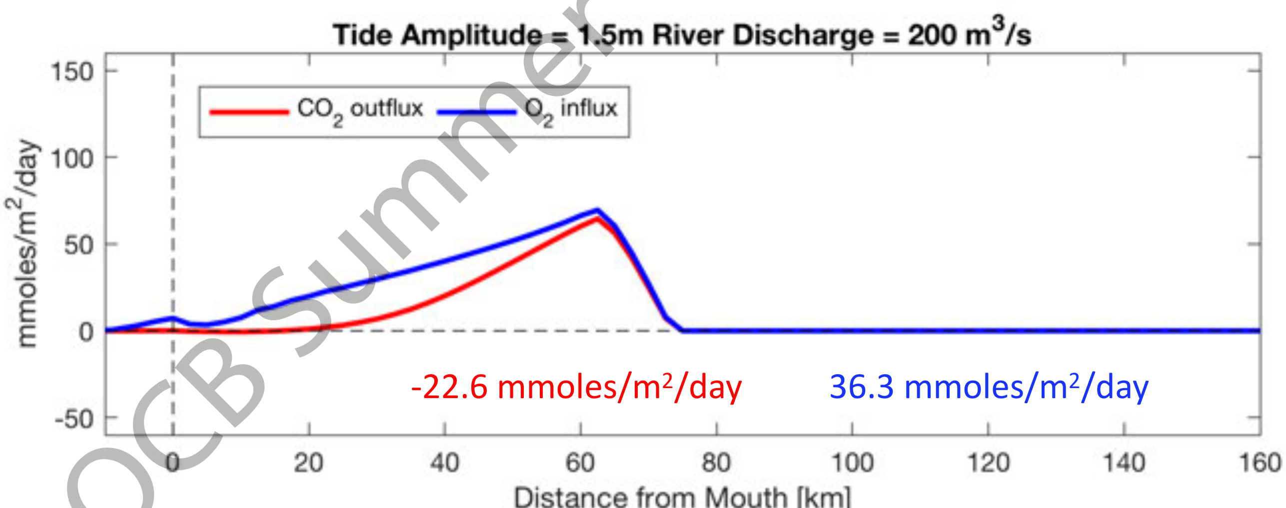
Simple conservative mixing example

[Assume DIC and alkalinity vary linearly with salinity]



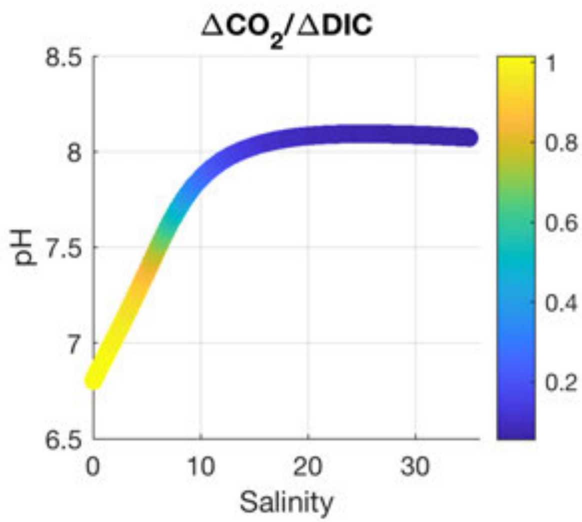
What happens if you change the intensity of mixing?

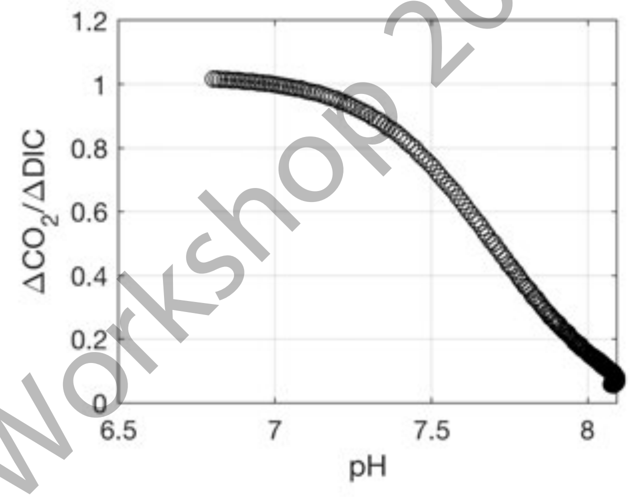




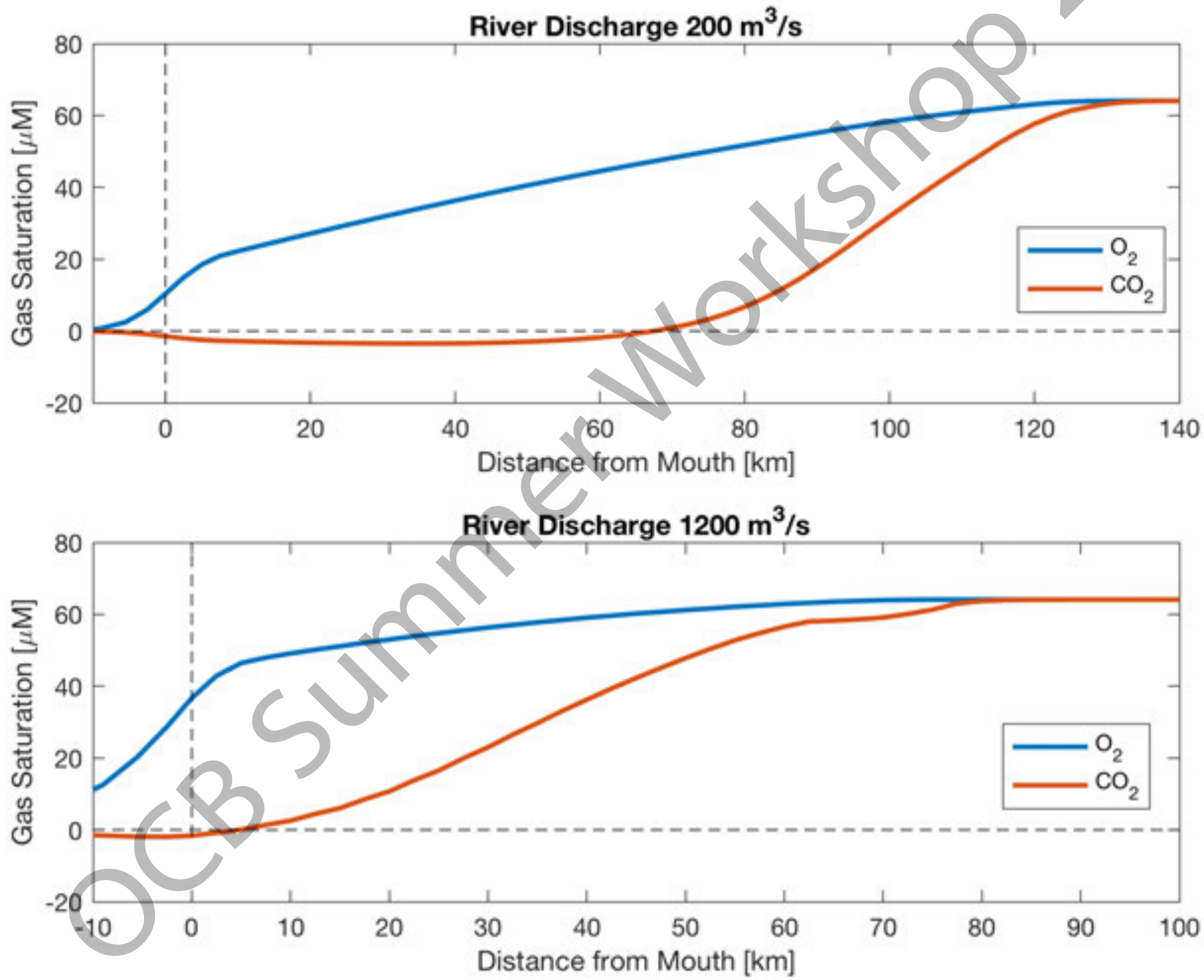
O_2 flux is reduced by 32%, pCO_2 flux is reduced by 49%

Carbonate Chemistry in the Model

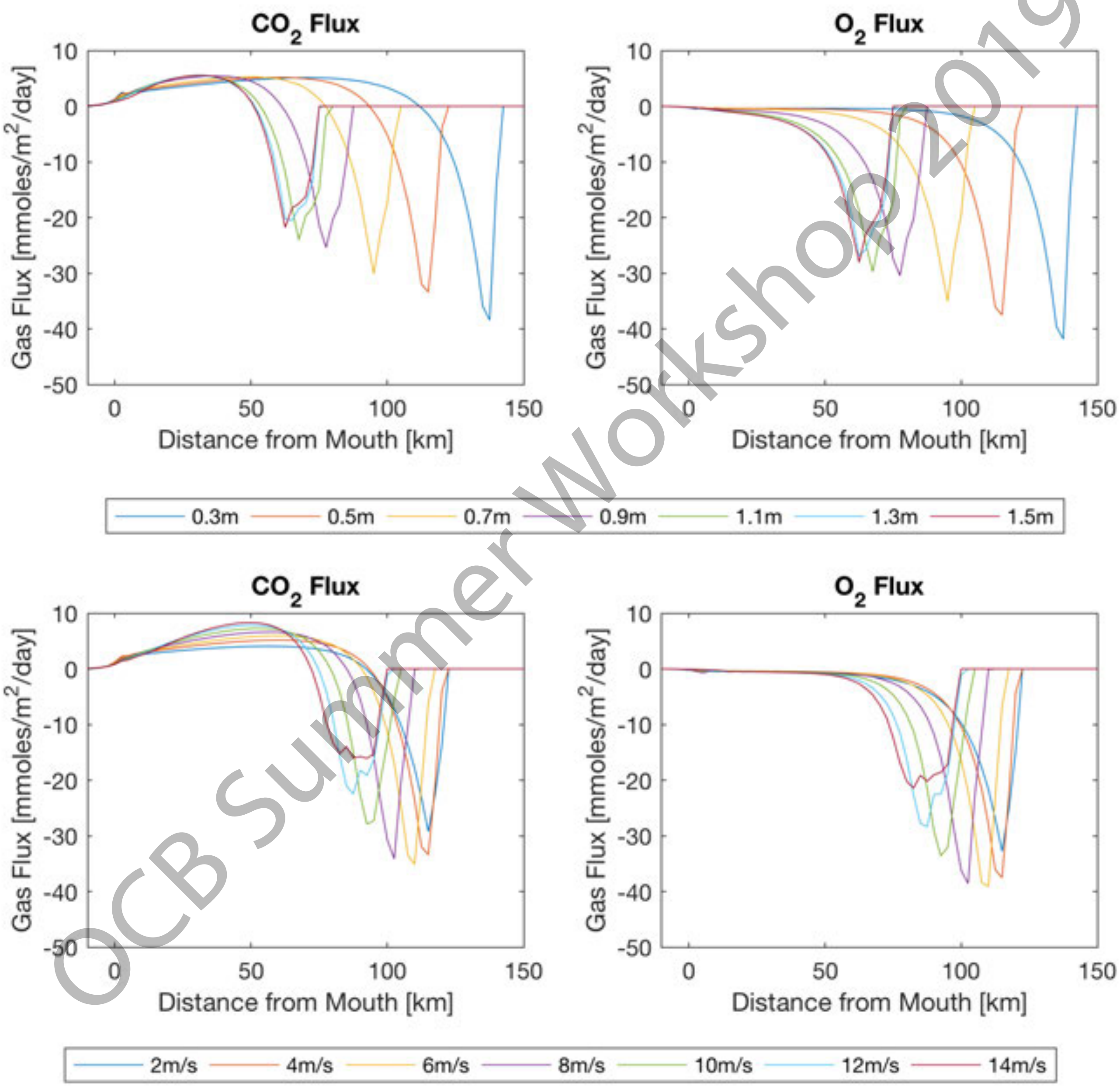




Very simple numerical simulation:
No Biology, no wind forcing, river is super-saturated in pCO_2 and O_2



No Biology, Add Wind Forcing, Super-saturated river input



Runs with no biology and super-saturated river input:

Constant wind (4m/s) and discharge (200 m^3/s)

Constant tide (0.5m) and discharge (200 m^3/s)

Constant tide (0.5m) and wind (4m/s)