September 23, 2026

Towards a physically-based treatment of river inputs in MOM6
(leveraging the ALE framework)

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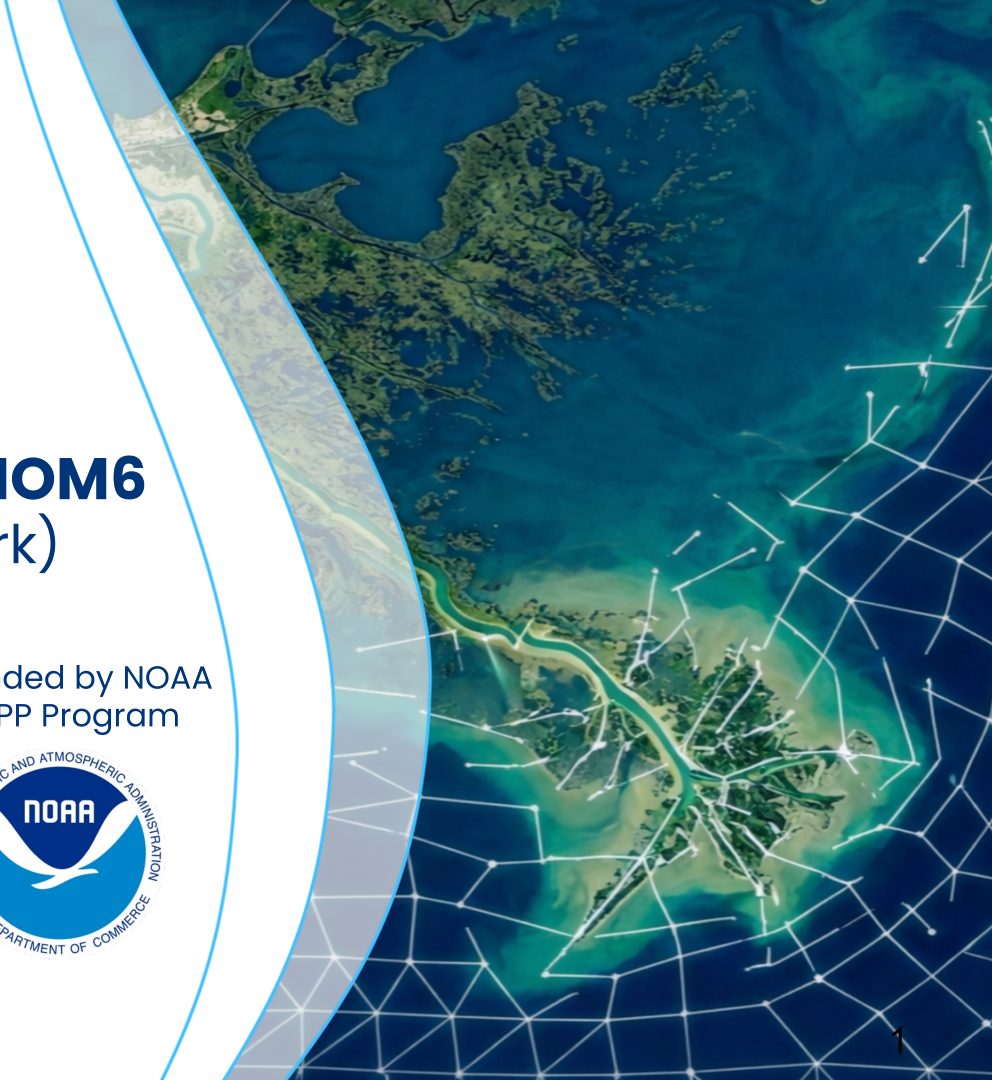


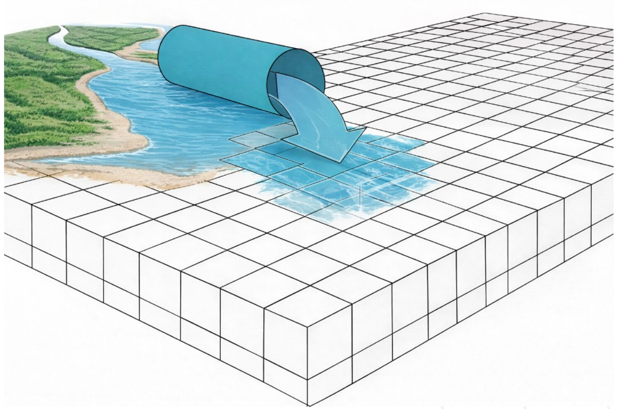
Why riverine freshwater inputs matter?

- **Drive stratification & mixing**
  Freshwater lowers salinity → creates strong density gradients → alters mixing and air–sea exchange;

- **Fuel ecosystems (and hazards)**
  Deliver nutrients & pollutants → boost productivity but also drive hypoxia;

- **Shape fisheries**
  Define water masses → influence habitats and boundaries of coastal fisheries.

Current models oversimplify river inputs

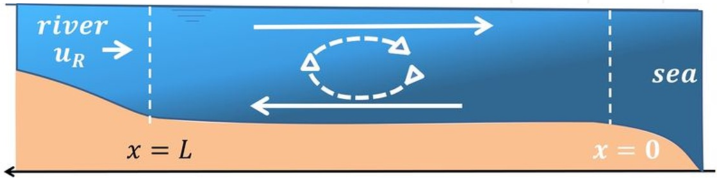


Current Models

River discharge is often introduced *ad hoc*; either as "augmented precipitation" over some arbitrarily prescribed area or injected directly into a single grid cell → failing to represent estuary mixing and transport processes.

Actual Processes

Accurate estuary modeling must capture key dynamics: two-layer exchange flow, internal mixing/upwelling, tidal mixing, and dynamic salt intrusion.



Source: Coastal Wiki (coastalwiki.org)

Goal → Objectives → Impact

Goal: Improve representation and evaluation of riverine freshwater in MOM6

Year 1

Year 2

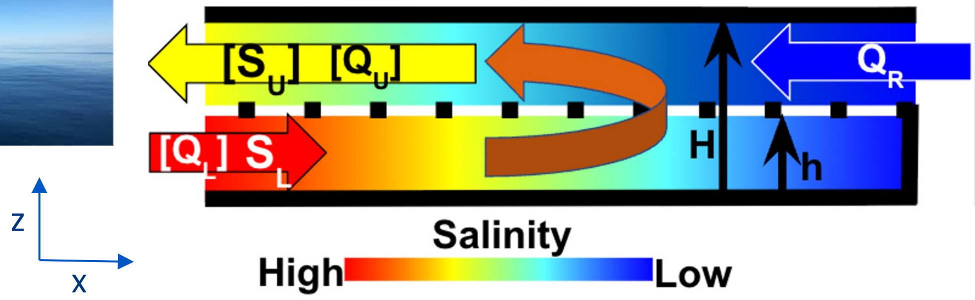
Year 3

Impact: Reduce coastal salinity and stratification biases in MOM6, directly improving NOAA's forecasting and climate projection skill.

Estuary Box Model (EBM) control equations

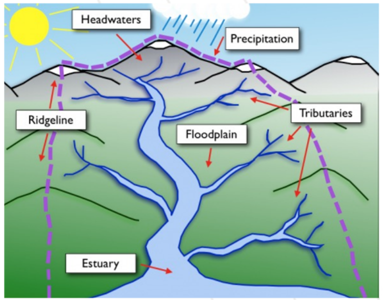
Open ocean

Estuary



Schematic courtesy of Qiang Sun

Head of estuary



Continuity: $$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

Salinity balance: $$\frac{\partial (uS)}{\partial x} + \frac{\partial (wS)}{\partial z} = \frac{\partial}{\partial x}\left(K_H \frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_V \frac{\partial S}{\partial z}\right) \tag{2}$$

Potential energy (PE) balance: $$\frac{\partial (uPE)}{\partial x} + \frac{\partial (wPE)}{\partial z} = \frac{\partial}{\partial x}\left[K_H \frac{\partial (PE)}{\partial x}\right] + \frac{\partial}{\partial z}\left[K_V \frac{\partial (PE)}{\partial z}\right] - K_V g \frac{\partial \rho}{\partial z} - g\frac{\partial K_V \rho}{\partial z} + wg\rho \tag{3}$$

EBM parameterization

Algebraic solutions (see Sun et al., 2017 for additional details)

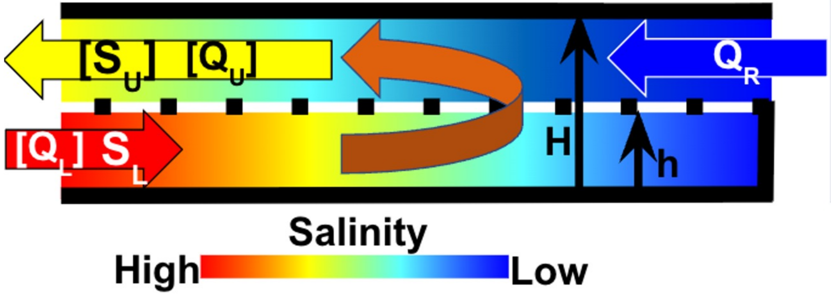
$$Q_U = Q_R - Q_L \quad (4)$$

$$S_U = \frac{-Q_L S_L}{Q_U} \quad (5)$$

Knudsen Eqs.

$$\lambda_3 Q_L^3 + \lambda_2 Q_L^2 + \lambda_1 Q_L + \lambda_0 = 0 \quad (6)$$

Schematic courtesy of Qiang Sun



$$\lambda_3 = -H$$

$$\lambda_2 = 2Q_R(2H - h) + a_2 Q_t H$$

$$\lambda_0 = -0.048\, a_1 \left(\frac{WHc^4}{Q_R S c^2}\right)^{1/3} H^2 W (Q_R + a_2 Q_t) Q_R$$

$$\lambda_1 = 0.096\, a_1 \left(\frac{WHc^4}{Q_R S c^2}\right)^{1/3} H^2 W Q_R - Q_R(2H - h)(Q_R + a_2 Q_t) - a_2^2 \frac{Q_t^2}{4} H$$

Tunable parameters:
a_1, a_2, H, h, W

Forcing terms: Q_R and S_L

Output: Q_U and S_U

Key parameters for top 20 rivers

Table 2

EBM parameters for top 20 rivers in POP2 of CESM, where W is the width, H is the height and h_* is the layer depth ratio(h/H) for the box dimensions. The a_1 and a_2 are the dimensionless coefficients for vertical mixing and tidal pumping in the EBM.

River Name	W (m)	H (m)	h_* (-)	a_1 (-)	a_2 (-)	References to get annual mean S_{UM}
Amazon	50,000	21.8	0.5	1.00	0	Geyer (1995)
Congo	9740	8.0	0.5	1.04	2.57	Eisma and Van Bennekom (1978)
Orinoco	17,000	10.0	0.5	1.52	0	Bone et al., (2011)
Changjiang	28,870	7.4	0.5	1.59	0	Zhang et al. (2011)
Brahmaputra	11,000	14.0	0.5	0.16	0	Rao (2005)
Mississippi	4000	12.0	0.5	1.07	3.84	Georgiou and Hanegan (2013)
Yenisey	61,500	3.8	0.5	1.29	0	Burenkov and Vasil'kov (1995)
Parana	30,000	7.5	0.5	0.58	0	Fossati and Piedra-Cueva (2008)
Lena	5800	9.3	0.5	0.11	0	Cauwet and Sidorov (1996)
Mekong	15,200	6.5	0.5	1.13	0.89	Nguyen et al. (2008)
Tocantins	62,000	16.0	0.5	0.03	0	Barthem and Schwassmann (1994)
Ob	47,270	8.6	0.5	0.02	0	Burenkov and Vasil'kov (1995)
Ganges	9000	14.0	0.5	0.05	0	Rao (2005)
Irrawaddy	35,140	22.5	0.5	0.15	0	Kravtsova et al., (2009)
St. Lawrence	4680	42.9	0.5	1.03	2.57	Ingram and Ei-Sabh (1990)
Amur	20,000	14.3	0.5	0.11	0	Shevchenko et al. (2013)
Mackenzie	25,000	2.8	0.5	1.16	0.51	Emmerton et al., (2008)
Xijiang	29,000	5.2	0.5	0.28	0	Zu and Gan (2015)
Columbia	3670	10.9	0.5	1.10	1.08	NOAA buoy jtaw1
UNIFORM	2000	10.0	0.5	0.88	0	Geyer (2010)

(Sun et al., 2017)

Implementing the EBM in MOM6

- Preliminary results
- Initial tests in a global ocean/sea-ice model; not the ideal framework for validation

Continuous equations

Thickness tendency:

$$\frac{\partial h}{\partial t} = -\,\mathrm{DIV}(h\mathbf{u}) + \underbrace{q_R}_{\text{river input}} + \underbrace{(q_U + q_L)}_{\text{exchange flow}} + \text{other sources/sinks} \quad (7)$$

Tracer tendency:

$$\frac{\partial (hC)}{\partial t} = \mathrm{Advec} + \mathrm{Diff} + \underbrace{C_R q_R}_{\text{river input}} + \underbrace{(C_U q_U + C_L q_L)}_{\text{exchange flow}} + \text{other sources/sinks} \quad (8)$$

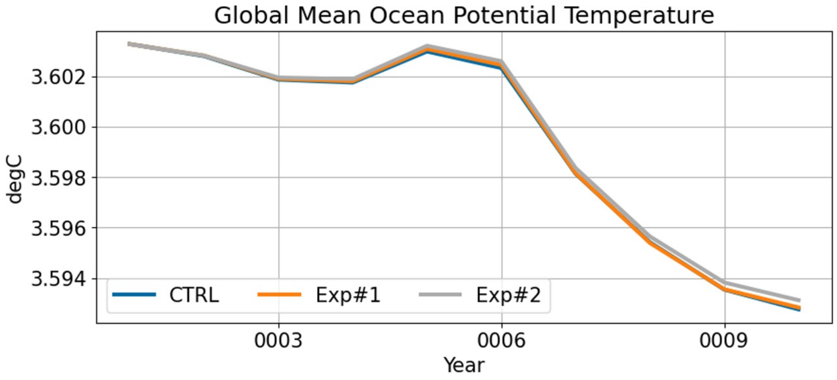
Steps for implementing the EBM in MOM6

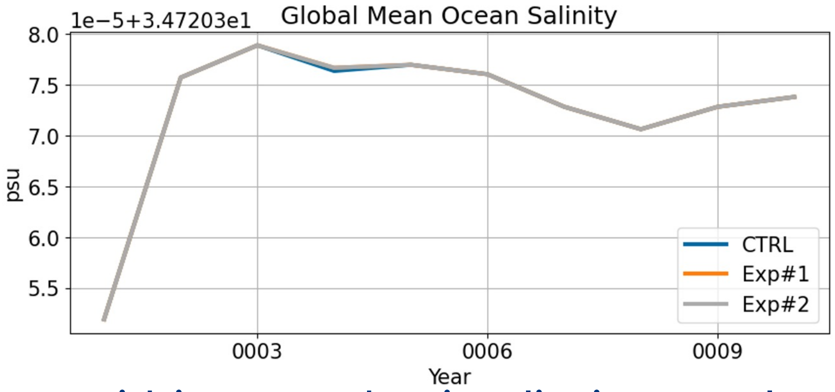
1. Decouple inflow and outflow → separate river from other FW fluxes (precipitation, evaporation, etc);
2. Distribute runoff vertically over a specified upper layer thickness (h_U);
3. Add runoff as a point source rather than spreading over a prescribed radius;
4. Parameterize estuarine mixing (exchange flow) and return derived fluxes to MOM6 as vertically distributed source-sink terms;
5. Remove buoyancy contribution due to river forcing from the boundary layer schemes (ePBL and KPP);
6. Generalize the scheme to work with passive tracers.

1 - Decouple inflow and outflow and isolate runoff

Forced ocean/sea ice/waves global simulations (JRA-55; 10 years integrations)

Exp	Horizontal Spreading	Vertical Spreading	Aggregate FW	Isolate Runoff
CTRL	250 km radius	No	Yes	No
Exp #1	250 km radius	No	No	No
Exp #2	250 km radius	No	No	Yes



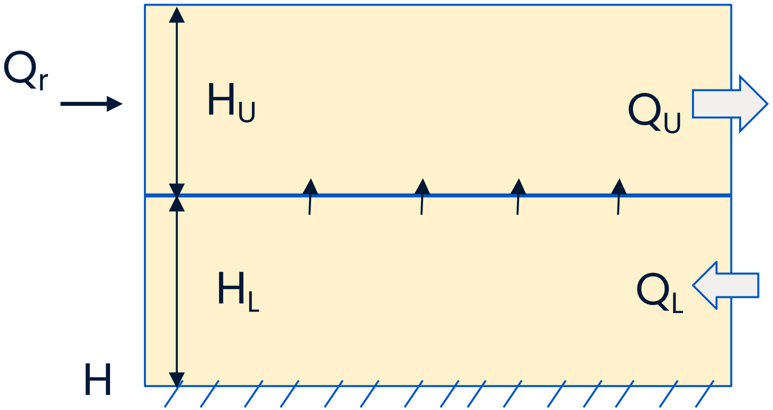


Global mean T and S differences are within perturbation limits; results are statistically indistinguishable. ✅

Connecting the estuary to the open ocean

Estuary

H_U, H_L = upper and lower layer thicknesses



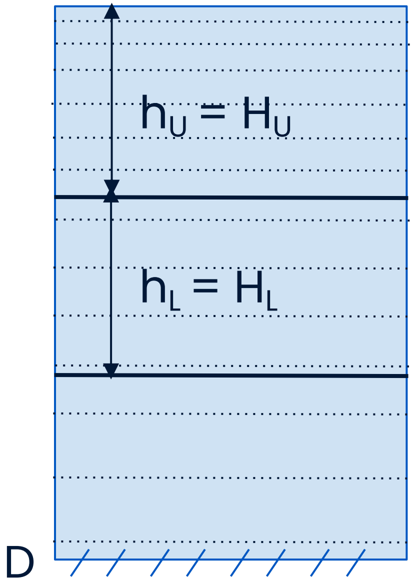
Q_r = river discharge

Q_U and Q_L = upper/lower layer flows

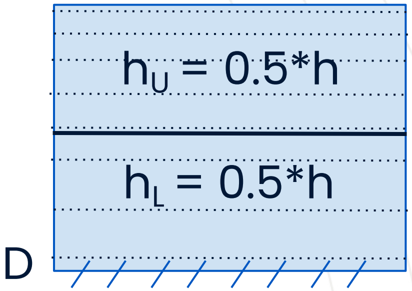
$H = (H_U + H_L)$ estuary depth

Open Ocean

Case 1: D >= H



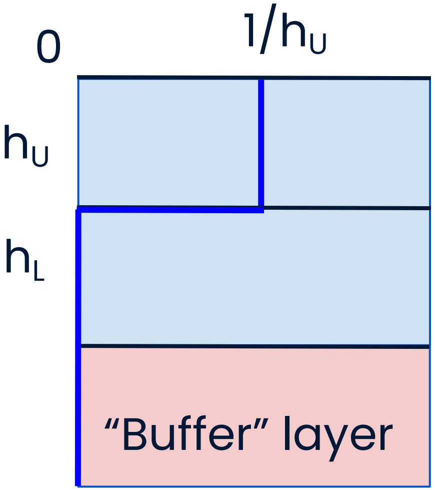
Case 2: D < H



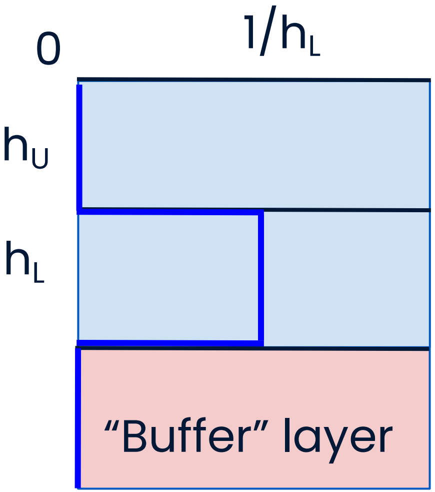
D = ocean depth

Weighting Functions (piecewise constant)

Upper Layer $\mathbf{f_U(z)}$



Lower Layer $\mathbf{f_L(z)}$



$$f_U(z) = \begin{cases} \frac{1}{h_U} & -h_U <= z < 0 \\ 0 & z < -h_U \end{cases}$$

$$f_L(z) = \begin{cases} 0 & z > -h_U \\ \frac{1}{h_L} & -(h_U + h_L) < z <= -h_U \\ 0 & \text{otherwise} \end{cases}$$

1) Remap:

$$f_U^{OCN} = \mathrm{REMAP}(f_U)$$

2) Nondimensionalize and normalize:

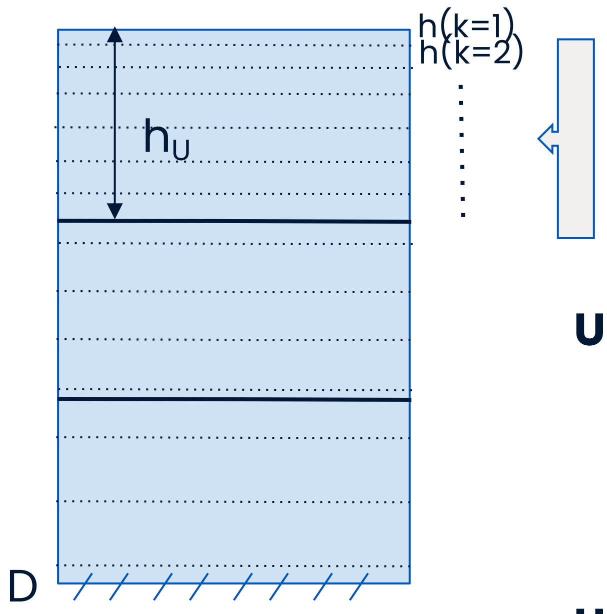
$$I_U = \sum_{k=1}^{n_z} f_U(k) h(k) \qquad f_U(k) = \frac{f_U(k)}{I_U}$$

3) Check:

$$\sum_{k=1}^{n_z} f_U(k) = 1$$

Same for $f_L(z)$

Distribute river runoff over upper layer



Distribute runoff over upper layer Q_R, T_{ref}

Update thickness (mass):

$$q_R(k) = \frac{Q_R}{A} f_U(k) \qquad (9)$$

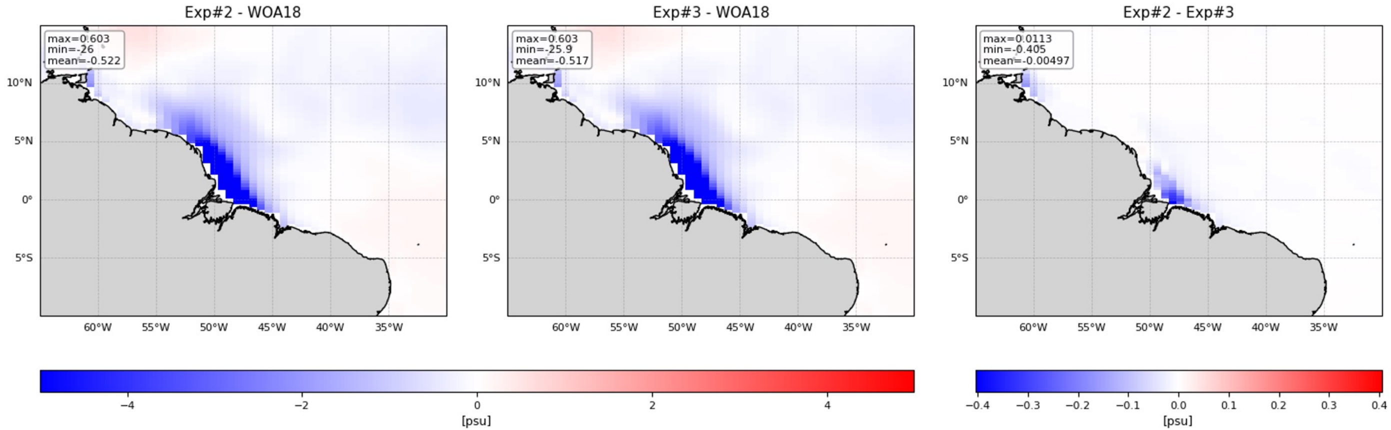
Update temperature:

$$\Delta T(k) = q_R(k) T_{ref} \qquad (10)$$

2 – Distribute runoff vertically

Exp	Horizontal Spreading	Vertical Spreading	Aggregate FW	Isolate Runoff
Exp #2	250 km radius	No	No	Yes
Exp #3	250 km radius	Yes (H = 10 m)	No	Yes

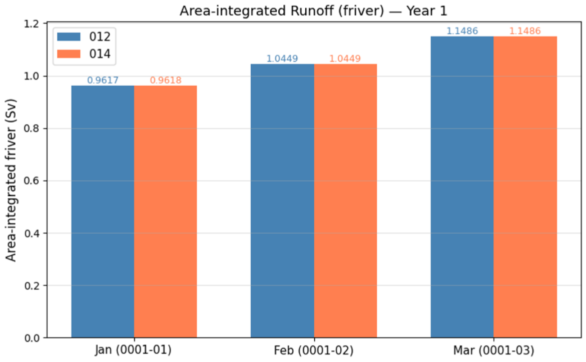
Amazon river mouth — Salinity bias [psu] at 2.5 m (k=0)

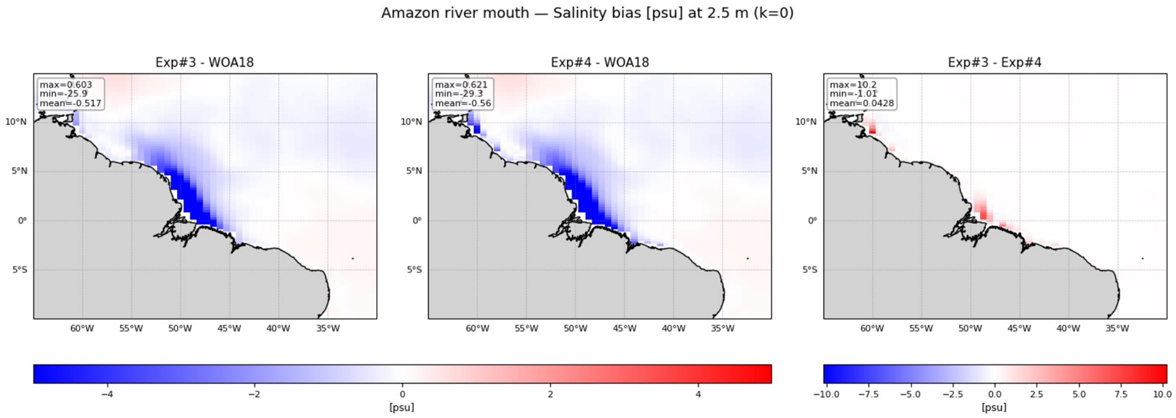


Vertical spreading has a noticeable effect on salinity near river mouths. ✅

3 – Add runoff as a point source

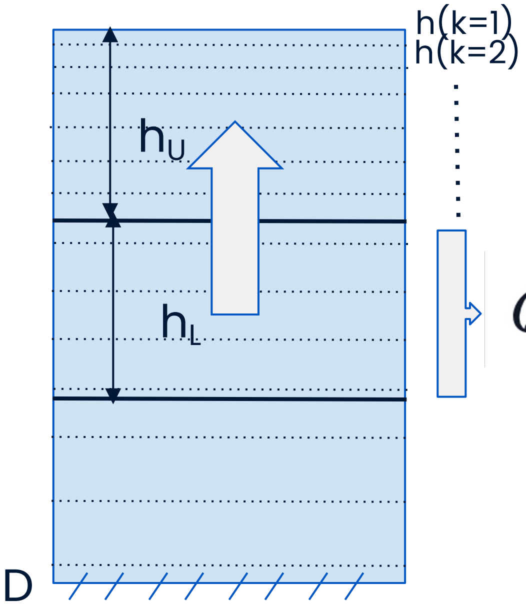
Exp	Horizontal Spreading	Vertical Spreading	Aggregate FW	Isolate Runoff
Exp #3	250 km radius	Yes (H = 10 m)	No	Yes
Exp #4	No	Yes (H = 10 m)	No	Yes





Adding point-source runoff significantly impacts near-mouth salinity while preserving the area-integrated runoff. ✅

Apply exchange flow (upper and lower layer combined)



$$Q_L, T_L, S_L$$

Update thickness (mass):

$$q* = q_U(k) + q_L(k) = \frac{Q_L}{A}(f_L(k) - f_U(k)) \quad (11)$$

Update temperature:

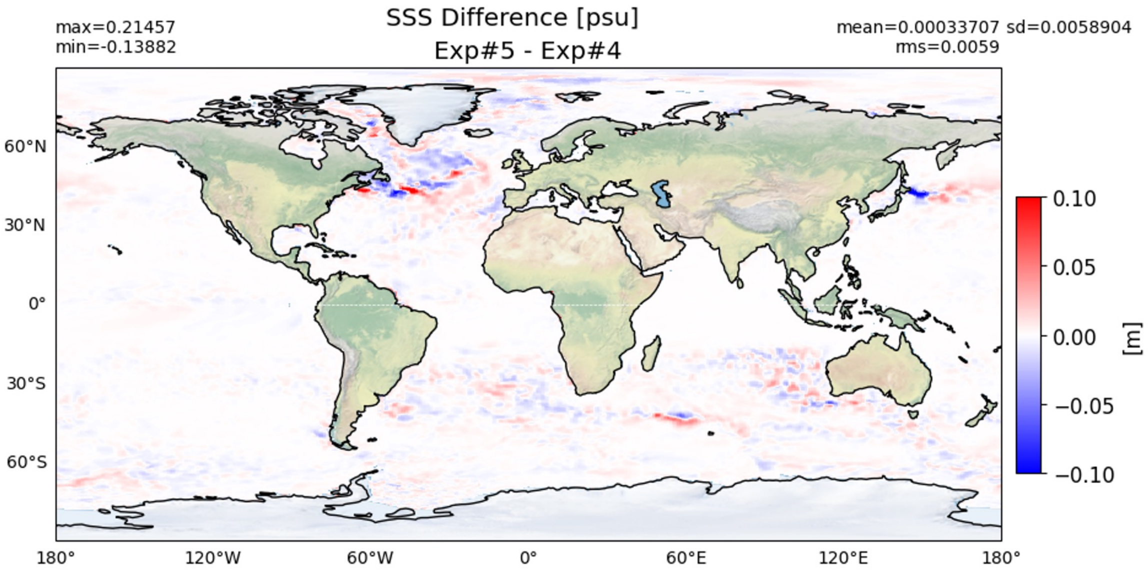
$$(T_U q_U + T_L q_L) = q^* T_L \quad (12)$$

Update salinity:

$$(S_U q_U + S_L q_L) = q^* S_L \quad (13)$$

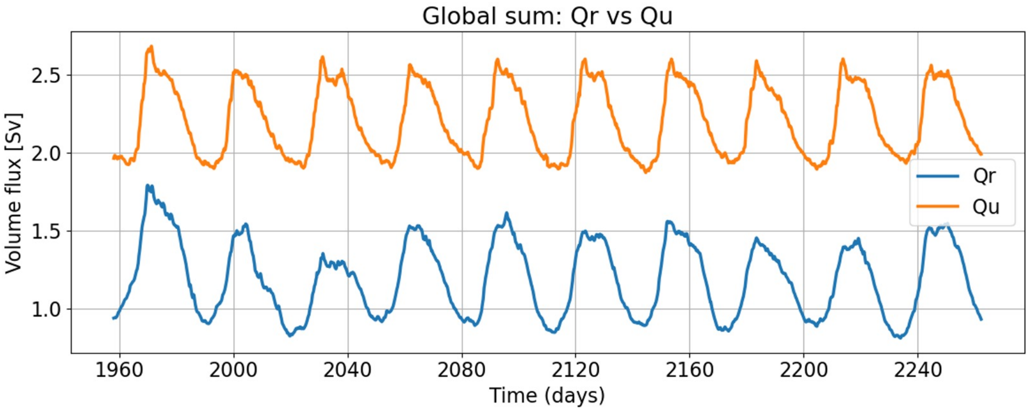
Activate EBM (exchange flow)

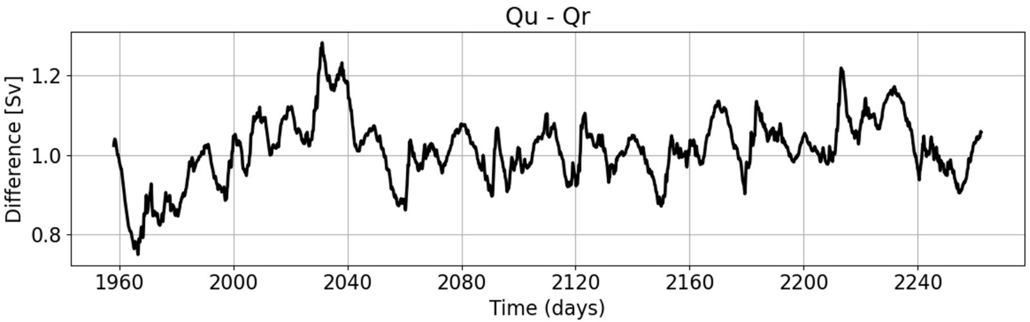
Exp	EBM (xchange)	Vertical Spreading	Aggregate FW	Isolate Runoff
Exp #4	No	Yes	No	Yes
Exp #5	Yes	Yes	No	Yes

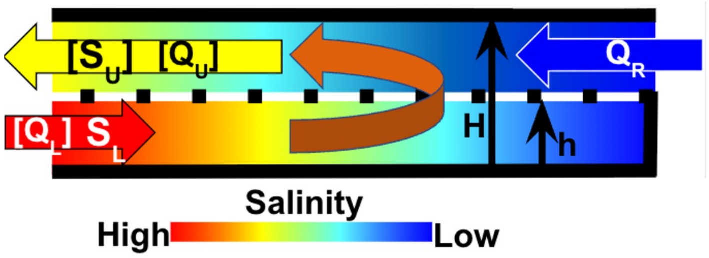


Exchange-flow effects are more pronounced away from the river input.

The effect of the exchange flow







Upper-layer volume flux is ~1.5–2× the river input.

Summary

- Rivers are a key but poorly represented in ocean models;

- Current models oversimplify river inputs → *ad hoc* treatment neglects estuarine mixing and transport;

- We implemented an existing estuary box model (EBM) in MOM6, leveraging its remapping infrastructure to define weighting functions for the upper and lower layes and ensure conservation.

Next Steps

- Develop a simplified test case and evaluate/tune the EBM in additional configurations (NWA12, CARIB12, CESM3 high resolution);
- Account for tidal pumping and extend the scheme to passive tracers;
- Allow river contributions to buoyancy fluxes to be excluded from surface boundary layer schemes (KPP, ePBL);
- Ensure compatibility with both Boussinesq and non-Boussinesq formulations.

Thank you!

Extra slide: tidal pumping effects

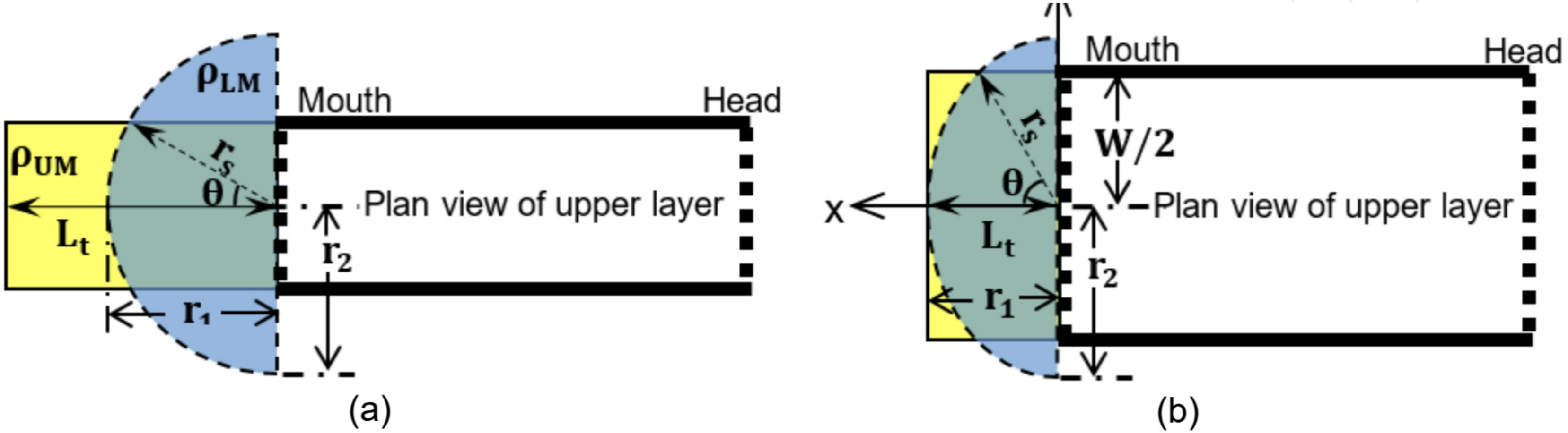


Figure A1 Schematic representation of tidal pumping effects in EBM upper layer for estuaries with (a) a narrow mouth and/or strong tides and (b) a wide mouth and/or weak tides. The yellow shade indicates the water released during ebbs and the blue shade shows the oceanic inflow water during floods (the green shade indicates the overlap region). The ebb and flood regions have the same water volume. The parameters marked with arrows are described in the appendix.

From Qiang Sun's PhD Dissertation, Appendix A