Update from the Rappahannock MTM team

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CBP Modeling Workgroup Quarterly Review
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Update

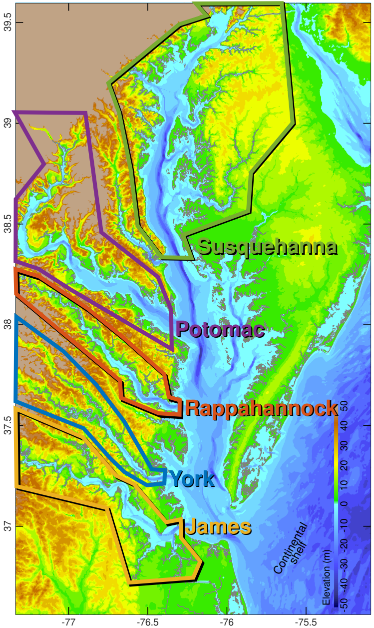
Over the past quarter, Zhengui and others have been heavily involved in the linkage between the MBM and the Phase 7 watershed model.

The work on the Rappahannock MTM was on pause during that time.

Next quarter, we will be in position to present a formal update on the Rappahannock MTM.

In the meantime, Jian suggested that I present unpublished work on the **Rappahannock's estuarine circulation**, while comparing it to other tributaries of the Bay.

Rappahannock vs. 4 other Bay tributaries

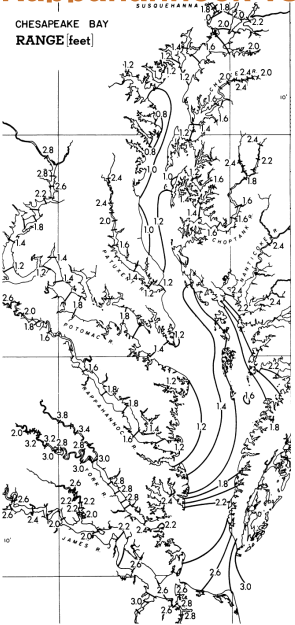


- 5 tributaries, together receiving 95% of the watershed's freshwater (cf. Phase 6).
- Upstream boundary: limit of salinity intrusion ($S = 0$) or farther inland.
  Downstream boundary: head (except Susquehanna).
- Similarities: ∼ partially-mixed, have a ∼ 20 m channel at their mouth.
- Differences: Tidal range, salinity at their mouth (S_{in}), freshwater input (Q_{riv}), area/length of the tributaries. . .

Questions:

1. Where does the Rappahannock rank among the 5 in *how vigorous its estuarine circulation is?*
2. What causes this ranking?
3. What is the primary driver of its temporal variability?

Rappahannock vs. 4 other Bay tributaries



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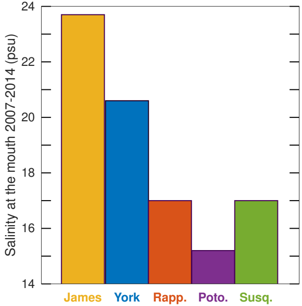

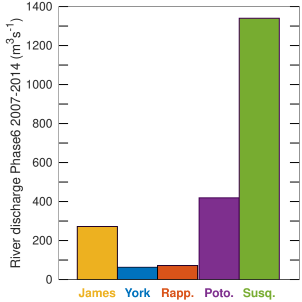

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Methods

Simplified representation of reality (MacCready *et al.* 2011,2018):

For cross-sections of the tributaries, sample the 3-D model every 30 min and compute:

$$Q(S) = \left\langle \int_{A(S)} u \, dA \right\rangle , \qquad \text{then decompose into } Q_{in}, Q_{out} \text{ and } S_{in}, S_{out} \ (\textbf{2 layers}) .$$

Q_{in} is how we define the “strength” of the estuarine circulation
(we are not focusing on the salt transport in this study).

After averaging over 8 years (2007–2014), we get:

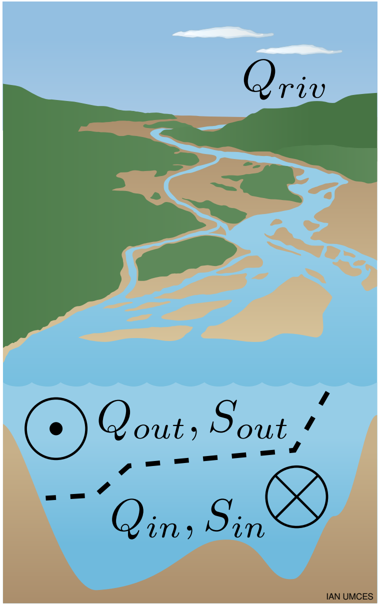
$$Q_{in} + Q_{out} \approx -Q_{riv} , \qquad (\text{here, } Q_{in}, Q_{riv} \text{ are } > 0 \text{ while } Q_{out} < 0),$$

$$Q_{in} S_{in} \approx -Q_{out} S_{out} ,$$

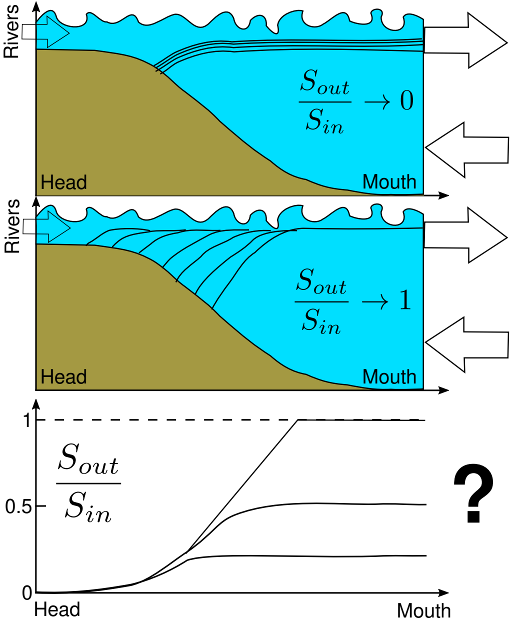
$$Q_{in} \approx Q_{riv} \frac{S_{out}}{S_{in} - S_{out}}$$

insight into what dictates the strength of circulation:

river discharge (Q_{riv}), and **mixing** (S_{in},S_{out}).



How complete is the mixing within the tributaries?

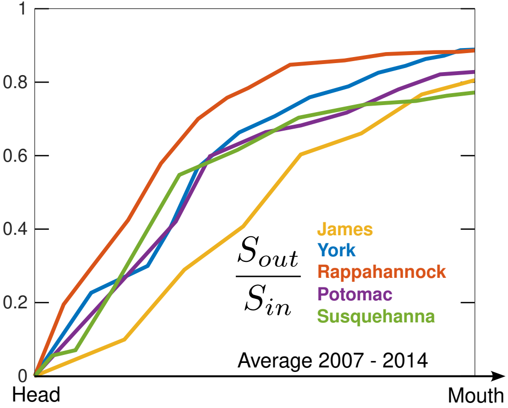


Extreme scenarios:

1. Nearly no mixing of the riverine freshwater,
2. Near-complete mixing of the riverine freshwater.

Where does the Rappahannock (and the other tributaries) stand within this continuum?

How complete is the mixing within the tributaries?



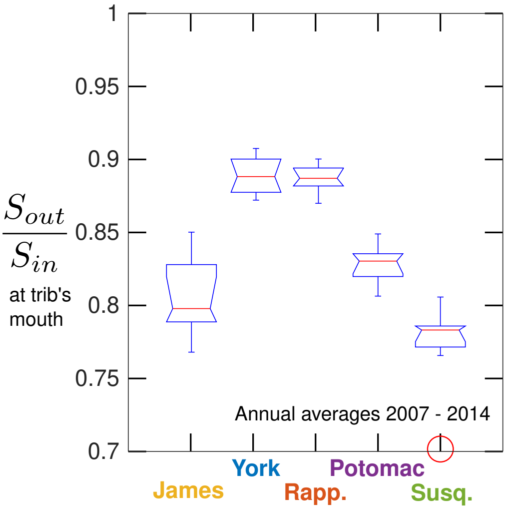
- After a rapid increase in the upstream portion of the tributary, **Rappahannock** exhibits an **asymptote** while approaching the mouth.
- Same is true for the other 4 tribs, **in spite** of their differences in size, tidal range, $Q_{riv}\ldots$
- Why is no tributary reaching beyond ~ 0.8?

  $$\text{“Mixing”} \equiv \sum_{i=1}^{3} \iiint 2K_i \left(\frac{\partial s'}{\partial x_i}\right)^2 dV.$$

  Gradients → 0 while moving downstream, so it's increasingly harder to mix additional freshwater as you move toward the mouth.

  Contributes to the plateauing of S_{out}/S_{in}.
- Can we explain the small variations in S_{out}/S_{in} between Rappahannock and 4 other tributaries?

How complete is the mixing within the tributaries?



- Zooming in over S_{out}/S_{in} at the mouth, do we see a pattern?
- **Rappahannock** is being paired with the York.
- Tributaries with higher Q_{riv} exhibit less complete mixing.
- Can we express this as an equation?

How complete is the mixing within the tributaries?

- We try regressing S_{out}/S_{sin} against known characteristics of the tributaries.

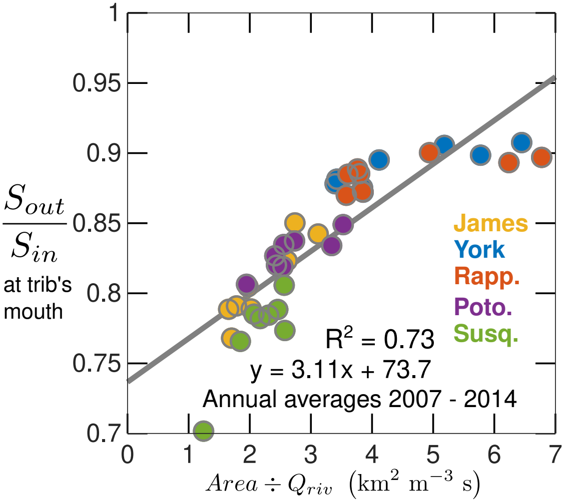
- $\sim$ Inversely proportional to Q_{riv},
  $\sim$ proportional to area (km^2) of the tributary.

- Interpretation:

  (1) The more freshwater is coming in, the harder it is to reach a given S_{out}/S_{in};

  (2) The larger (or longer) the tributary is, the easier it is to reach a given S_{out}/S_{in};

  I.e, **Rappahannock** has $S_{out}/S_{sin} \sim 0.9$ because of its lower Q_{riv} and its smaller area.



Circling back to Q_{in} (the estuarine circulation)

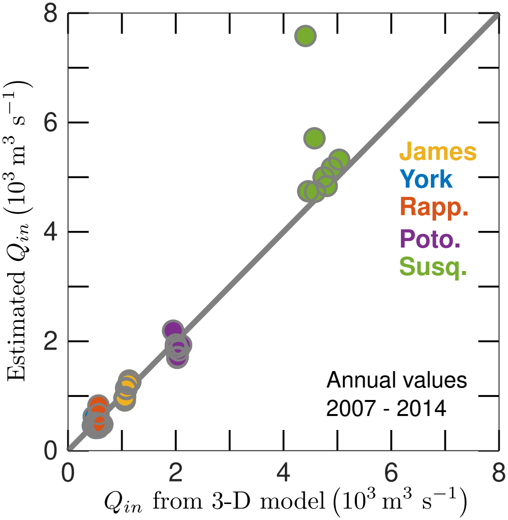
$$Q_{in} \approx Q_{riv} \frac{S_{out}}{S_{in} - S_{out}} \quad \text{(on timescales} \geq 1 \text{ year; ‘steady state’)},$$

. . . and we know:

- ✓ Q_{riv} (from watershed model),
- ✓ S_{in} (predictable from distance to continental shelf),
- ✓ S_{out} (from $Area$, Q_{riv}, S_{in}),

We can predict the 5 estuarine circulations
based on those characteristics of the tributaries (MAE = 14%).
Rappahannock ranks 4th, just ahead of York,
primarily because of its low Q_{riv}.

Outlier corresponds to year 2011 of the Susq. (Tropical storm Lee).

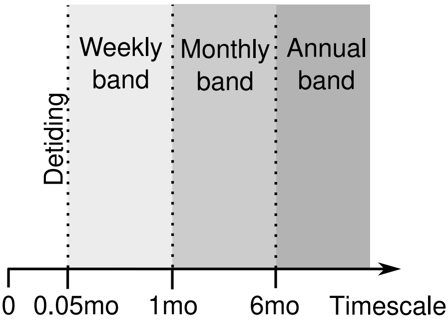


Partial summary

1. There are large differences between the 5 tributaries: tidal range, salinity at mouth, freshwater input, area. . .
2. In steady state, river discharge, and mixing completeness (S_{out} versus S_{in}), determine the ‘vigor’ of the estuarine circulation (Q_{in}).
3. Model indicates variations in S_{out}/S_{in} at mouth are **small** (~ 0.8). Increasingly weak salinity gradients prevent values > 0.9 from arising.

   Q_{riv} becomes the primary determinant of Q_{in}.
4. The small variations in S_{out}/S_{in} can be linked to the tributaries’ area and Q_{riv}.
5. The annual estuarine circulation is then predicted with a MAE = 14%.

Part 2: Temporal variability of the Rappahannock's circulation



- Everything presented so far assumed a steady state.

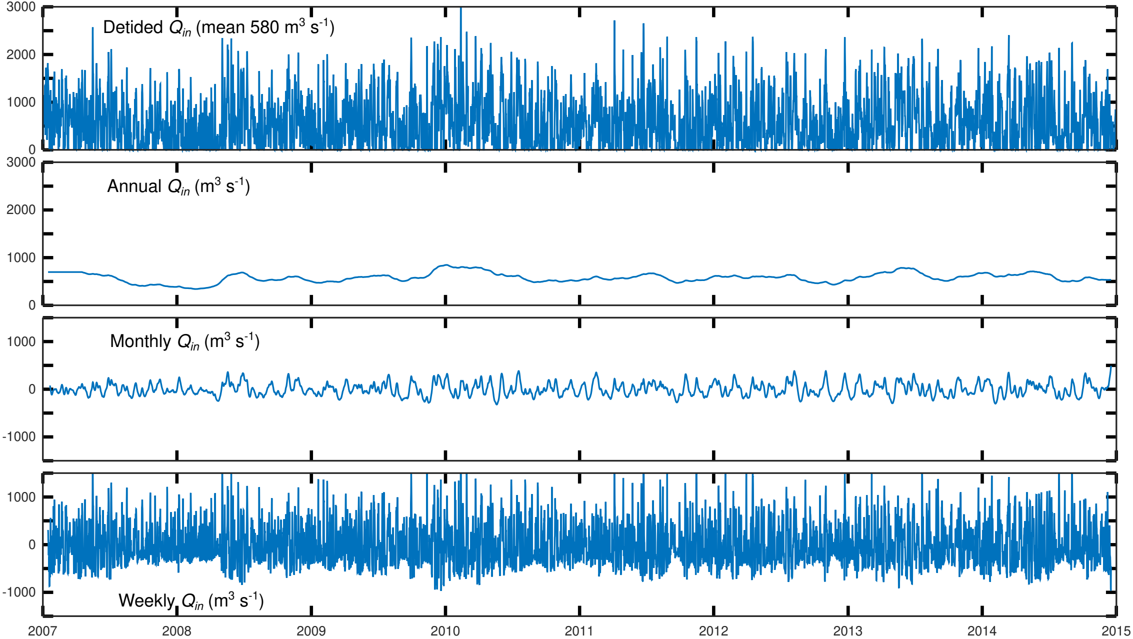
- Band-pass filtering is used to focus on 3 different timescales:

  (1) "Weekly", 35 hours to 1 month: Meteorological and hydrological events;

  (2) "Monthly", 1–6 months: Persistent weather/river conditions, *e.g.* droughts or El Nino;

  (3) "Annual", > 6 months: Wet vs. dry years, hurricane vs. no hurricane. . .

- Model results cover a period of 8 years (2007–2014).



Max/Mean detided $Q_{in} \approx 6$, falling to 1.1 for annual Q_{in}. 'Weekly' band dominates variability.

What drives the variability at each timescale?

Correlation analysis between Q_{in} and plausible drivers, allowing for lags up to 15 days.

Attempt #1: Turbulent diffusivity (K) comes into play in mixing, and in Hansen & Rattray 1965's solution:

$$\textit{estuarine circulation} \propto S_x \, H^3 \, K^{-1} \, .$$

We use the rate of work of tidal currents/winds as a proxy for their contribution to diffusivity:

$$\left\langle \iint \left| \boldsymbol{\tau} \cdot \mathbf{u}_{water} \right|_{bottom}^{surface} dx\, dy \right\rangle$$

No substantial correlation at any timescale.

	Timescale	$\text{Work}_{\text{tides}}$	$\text{Work}_{\text{wind}}$
Q_{in}^{Rapp}	annual	-0.04	0.22
	monthly	-0.06	0.29
	weekly	0.08	0.16

What drives the variability at each timescale?

Attempt #2: Riverine freshwater discharge Q_{riv}; contributes to term S_x in Hansen & Rattray's solution.

Q_{riv} explains a large fraction of the variance at **annual timescale**.

Reflects spring freshet (peak discharge ~March)
but also large rain events (tropical storms).

However, correlation drops rapidly at shorter timescales.

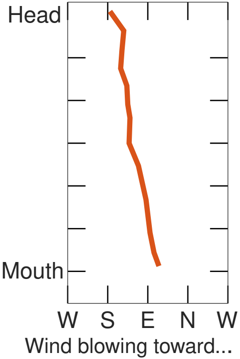
Timescale		Q_{riv}
Q_{in}^{Rapp}	annual	0.63
	monthly	0.11
	weekly	0.08

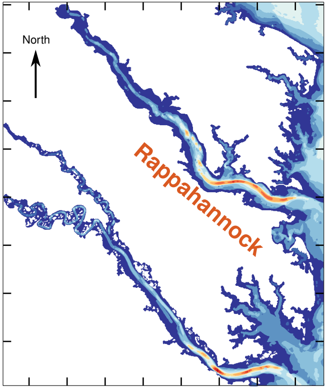
What drives the variability at each timescale?

Attempt #3: Wind stress components τ_x, τ_y.

At monthly/weekly timescales, we see higher correlations than with other predictors.

	Timescale	τ_x	τ_y
Q_{in}^{Rapp}	annual	0.04	0.01
	monthly	0.56	0.43
	weekly	0.42	0.26



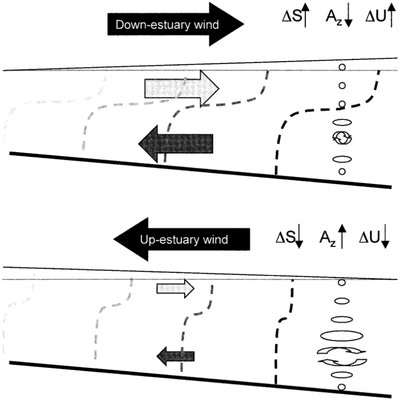


Wind direction that maximizes the correlation is south-eastward, i.e. **down-estuary**.

Why down-estuary winds? A possible interpretation

Scully *et al.* 2005 (based on fieldwork in the York):

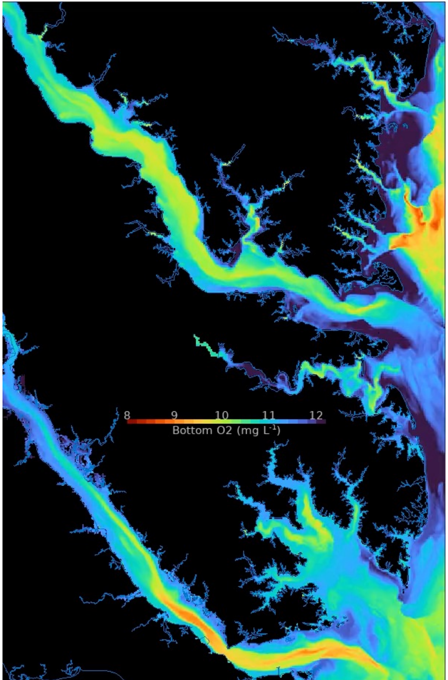
- Down-estuary winds strain the salinity field and increase vertical stratification;
- this leads to a reduction in the vertical turbulent viscosity,
- and the circulation ($\propto S_x \, H^3 \, K^{-1}$) increases in response.
- (vice versa for up-estuary winds.)



More analyses would be necessary to confirm this interpretation.

Thank you for your attention.

Appendix



3-D model

- SCHISM’s implementations of the MBM / MTM were not available at the time of the study.
- 3-D model was an implementation of ROMS,
  600 m resolution for the Bay,
  and a 120 m “MTM” for the Rappahannock + York.
- Realistic forcings from CBPWSM (Phase 6), ERA5,
  NOAA water levels on shelf.