

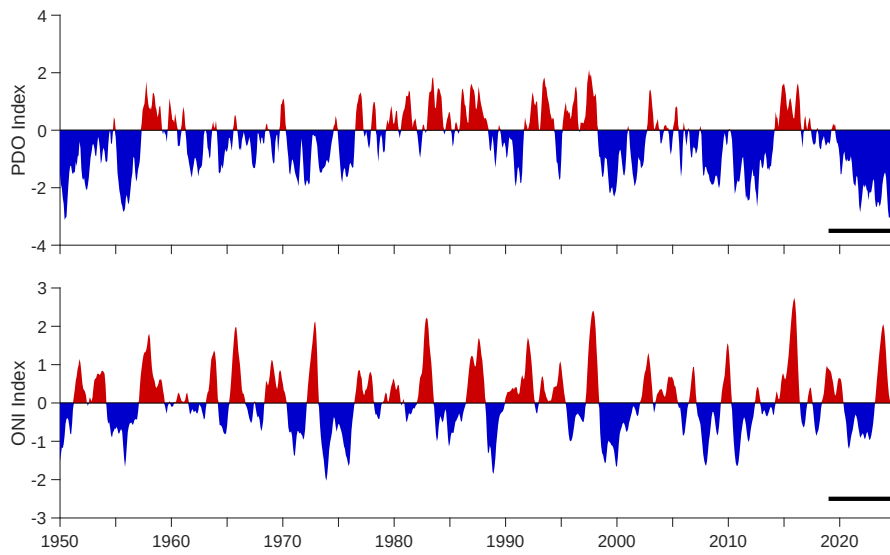
Supplementary Information

Columbia River plume intrusions drive episodic transport of larval Dungeness crab
into the Salish Sea

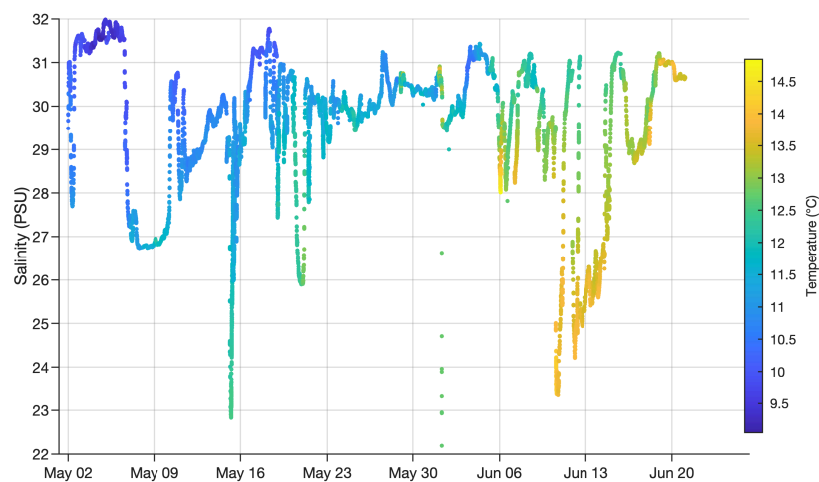
Heather J. Gordon, A. Mark Jellinek

This file contains Supplementary Figures 1-7, Supplementary Tables 1-3, and Supplementary Methods, which includes a complete development of the model solved numerically with a table (Supplementary Table 4) and references.

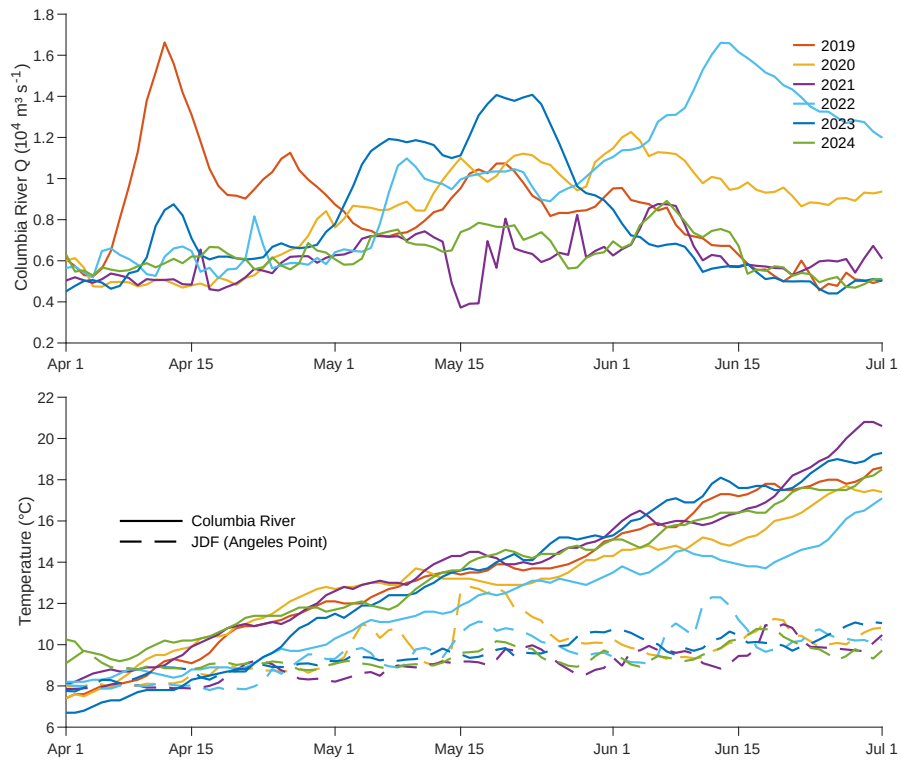
Supplementary Figures



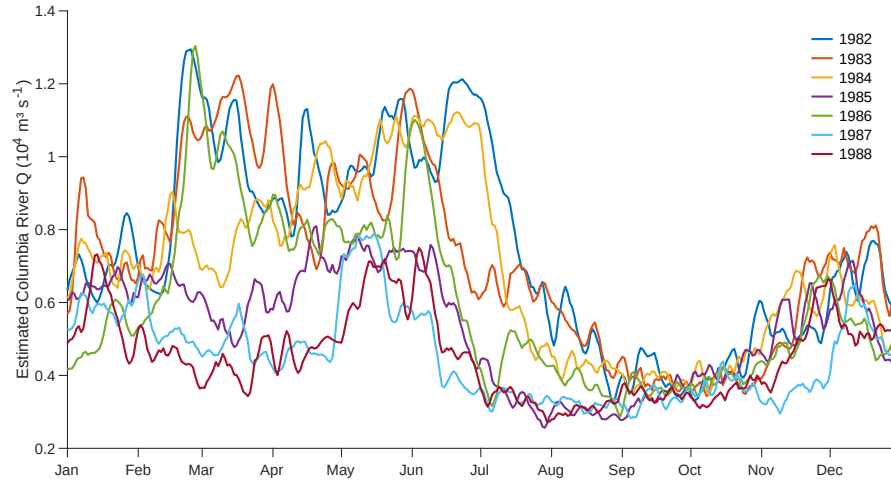
Supplementary Figure 1 Time series of the Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO) from 1950 to 2025. Horizontal black bars indicate the study period (2019–2024).



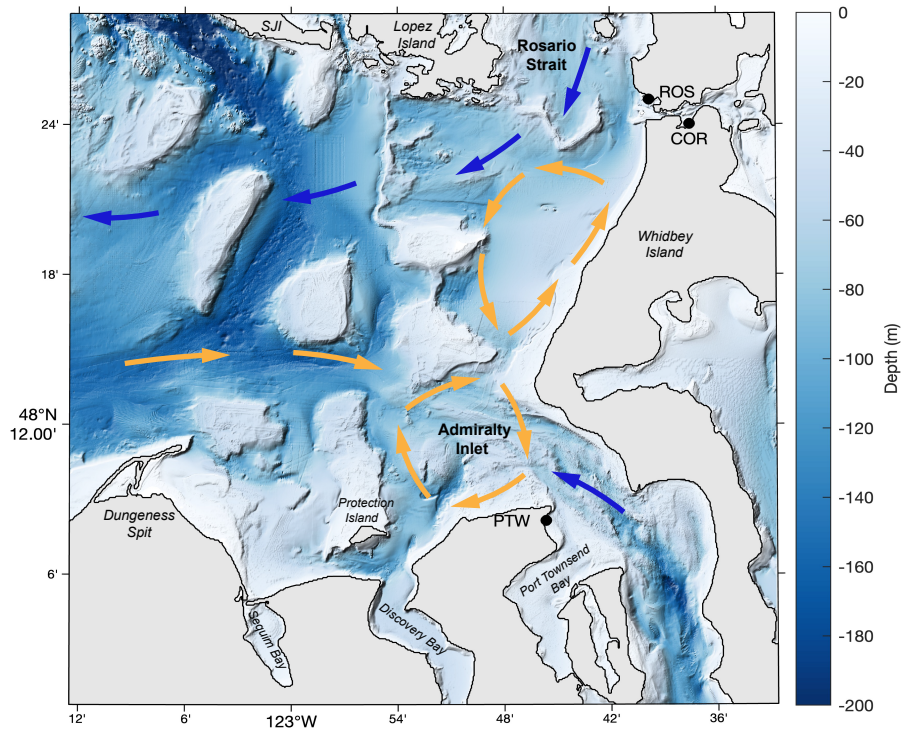
Supplementary Figure 2 Observations of Columbia River (CR) plume water on the northern Washington shelf. Temperature and salinity recorded at the surface (~ 1 m) in May-June 2022 at the NOAA PMEL $\acute{C}h\acute{a}\eta ba$ mooring located at $47^{\circ}57'59.8''$ N $124^{\circ}56'59.2''$ W, ~ 20 km offshore near LaPush, Washington and ~ 200 km north of the CR. CR plume water (23-29 PSU) is most evident at this site when upwelling-favorable winds push northward advected plume waters offshore.



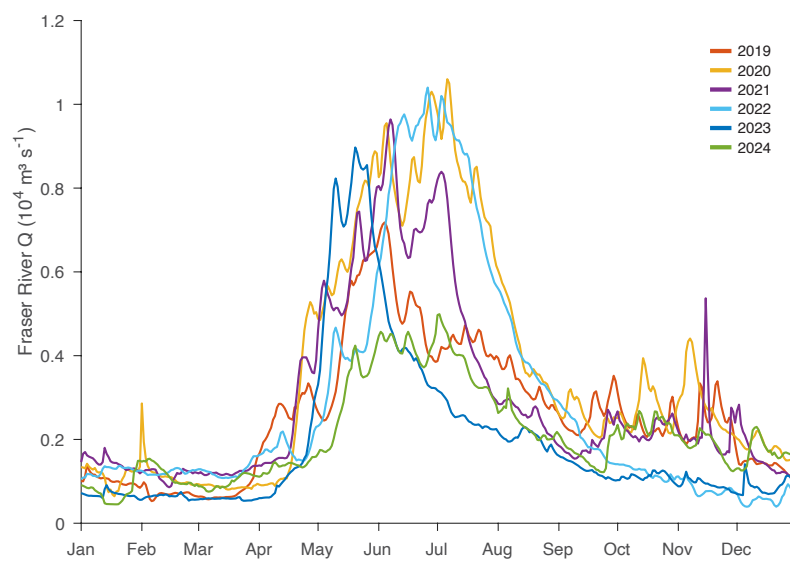
Supplementary Figure 3 Spring Columbia River (CR) discharge and temperature compared with temperature in Juan de Fuca Strait (JDF). CR discharge in April-June, 2019-2024 at Port Westward near Quincy, OR (top). Temperature in April-June, 2019-2024 for the CR near Dodson, OR and in JDF at Angeles Point (bottom). Temperature data for the CR were obtained for the USGS Left Bank station near Dodson, OR (45°36'29.4" N 122°02'18.3" W) and averaged to daily values.



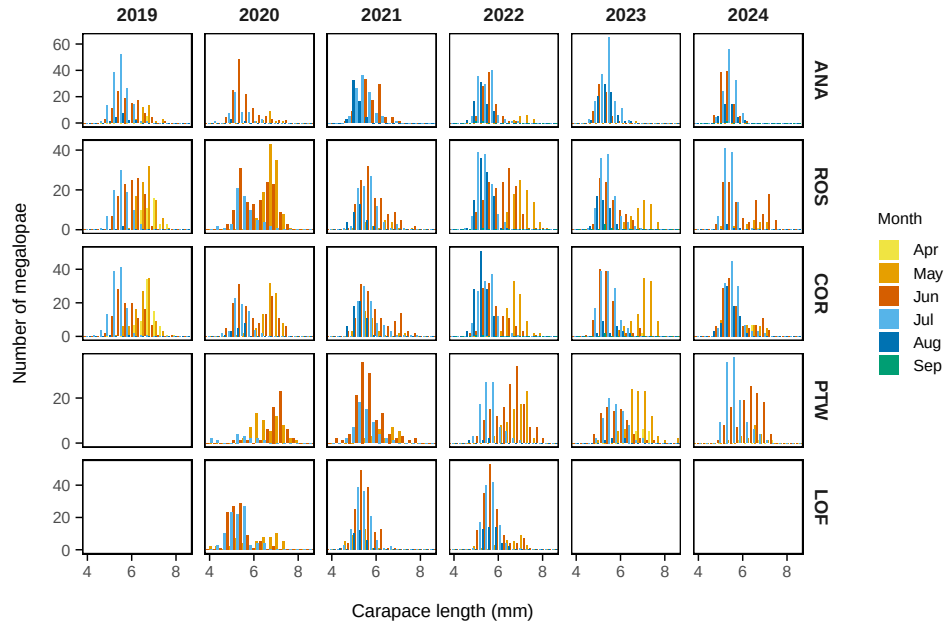
Supplementary Figure 4 Estimate of the major upstream freshwater contribution to lower Columbia discharge from combined daily discharge at the Bonneville Dam and Willamette River for the years 1982 – 1988. Daily mean discharge data were obtained from the Fish Passage Center (Army Corp of Engineers flow and spill data) for the Bonneville Dam site BO1 and from USGS Station 14191000 at Salem, OR. Discharge was smoothed using a 5-day moving average to reduce high-frequency variability associated with dam operations. This estimate does not account for all tributaries entering the lower Columbia downstream of Bonneville, and is therefore an underestimate of lower daily river discharge magnitudes.



Supplementary Figure 5 Conceptual drawing of hypothesized recirculation features in the eastern Juan de Fuca Strait (JDF) and inland waters of the Salish Sea during intrusions of the Columbia River plume, over a bathymetric map produced using NOAA’s National Centers for Environmental Information (NCEI) Strait of Juan de Fuca 1/3 arc-second NAVD 88 Coastal Digital Elevation Model. Shallow bathymetry at the Admiralty Inlet sill, combined with surface outflow from Puget Sound, generates a topographically-steered eddy or recirculation cell (~ 7 km radius) where inflowing (orange arrows) and outflowing (blue arrows) currents interact. The larger magnitude of the coastal larval recruitment signal at Point Wilson (PTW) compared to other sites may be due in part to retention within this recirculation feature. To the north, strong surface outflow through Rosario Strait driven by discharge from the Fraser River generates a larger recirculation cell (~ 14 km radius). At a current velocity of 20 cm s^{-1} , recirculation timescales are approximately two days near Admiralty Inlet and four days near Rosario. Multiple recruitment peaks in May 2020, separated by two days at PTW and five days at Rosario Head (ROS), are consistent with modulation by local circulation. Early recruitment events at ROS typically peak close to neap tide or during the neap–spring transition, when reduced tidal mixing enhances stratification, allowing low-salinity pulses from the Fraser River to reach eastern JDF. Discharge from the Fraser River in late May was approximately twofold higher in 2020 than in 2022 (see Supplementary Fig. 6) when recruitment showed a single peak at ROS. Retention in east JDF and southward flow through Rosario Strait probably limit larval transport beyond the San Juan Islands. Some larvae may be carried in the strong outflow along the northern boundary of the strait and observed on the southern shores of Vancouver Island. Topographically steered eddies may also promote larval retention and settlement at Dungeness Spit, Protection Island, and Discovery Bay. A weaker settlement signal is expected in nearby Sequim Bay, where sandbars create a narrow entrance that restricts exchange with adjacent waters.



Supplementary Figure 6 Seasonal Fraser River discharge for the years 2019-2024. Daily mean discharge data for the Fraser River were obtained from the National Hydrological Service of Canada for the station at Hope, BC (Station 08MF005) located at $49^{\circ}23'09'' \text{ N } 121^{\circ}27'15'' \text{ W}$.



Supplementary Figure 7 Histograms of *M. magister* megalopae carapace length measured between April and September (2019-2024). Each subplot corresponds to a site-year combination, with histogram bars coloured by month of collection. Carapace length distributions are shown using 0.3 mm bins. The average number of megalopae measured each week from May-July (the period when the majority of megalopae were caught each year) ranges from 23.1 ± 2.9 (mean $\pm$ SD) at Anacortes (ANA) to 26.4 ± 1.4 at Lofall (LOF).

Supplementary Tables

Supplementary Table. 1: Sources of observational data from moored instruments and their locations.

Source	Station	Variable(s)	Latitude	Longitude
NDBC	46041	Wind	47°21'9" N	124°44'22" W
NDBC	46029	Wind	46°9'48" N	124°29'12" W
NDBC	46267	Current, SST	48°10'21" N	123°36'26" W
CHS	07100	JDF tides	48°13'55" N	123°31'48" W
NOAA	9439040	CR tides	46°12'24" N	123°46'06" W
USGS	14246900	CR discharge	46°10'52" N	123°11'00" W
NDBC	46099	SST	46°59'17" N	124°34'1" W
NDBC	46100	SST	46°51'5" N	124°57'51" W

Supplementary Table. 2: Columbia River (CR) outflow at Astoria: physical constants, discharge, geometry, derived quantities, and mixing/entrainment controls used in the box model.

Parameter	Label	Value [unit]
g	Gravitational acceleration	9.81 m s^{-2}
$\Omega_{\oplus}$	Earth rotation rate	$7.2921 \times 10^{-5} \text{ rad s}^{-1}$
ϕ_{Ast}	Astoria latitude	46.25°
f_{Ast}	Coriolis parameter at Astoria	$2\Omega_{\oplus} \sin \phi_{\text{Ast}} \text{ [s}^{-1}\text{]}$
Q_{CR}	Instantaneous discharge	$\text{m}^3 \text{s}^{-1}$
w_{CR}	Active source channel width	300 m
h_{CR}	Initial plume thickness	6.5 m
A_{CR}	Active channel cross-sectional area	$w_{\text{CR}} h_{\text{CR}} = 1950 \text{ m}^2$
V_{CR}	Instantaneous outflow speed	$Q_{\text{CR}}/A_{\text{CR}} \text{ m s}^{-1}$
ρ_{CR}	Initial CR plume density	1013 kg m^{-3}
ρ_{ocean}	Ocean density	1024 kg m^{-3}
g'_{CR}	Reduced gravity	$g \Delta\rho/\rho_{\text{ocean}} \approx 0.105 \text{ m s}^{-2}$
c_g	Front collapse speed	$\sqrt{g'_{\text{CR}} h_{\text{CR}}} \text{ m s}^{-1}$
$L_{R,\text{CR}}$	Observation-adjusted Rossby radius at Astoria	$2c_g/f_{\text{Ast}} \approx 1.47 \times 10^4 \text{ m}$
$R_{0,\text{store}}$	Box-0 storage radius	$L_{R,\text{CR}} \approx 1.47 \times 10^4 \text{ m}$
$A_{0,\text{store}}$	Box-0 storage area	$\frac{1}{2}\pi R_{0,\text{store}}^2 \approx 3.39 \times 10^8 \text{ m}^2$
$V_{0,\text{init}}$	Initial box-0 storage volume	$A_{0,\text{store}} d_{\text{mix,max}} \approx 1.70 \times 10^9 \text{ m}^3$
τ_w	Alongshore wind stress	0.2 N m^{-2}
k_{eddy}	Eddy diffusivity	$0.01 \text{ m}^2 \text{s}^{-1}$
Ri_{crit}	Critical Richardson number	$0.5 \times (0.05 + 0.08) = 0.065$
$\Lambda_{\text{basal,CR}}$	Basal mixing efficiency coefficient	0.25

Parameter	Label	Value [unit]
$C_{D,\text{CR}}$	Basal drag coefficient	10^{-3}
α_{front}	Frontal entrainment coefficient	0.07
$V_{\text{wind,CR}}$	Local wind speed	m s^{-1}

Supplementary Table. 3: Juan de Fuca (JDF) inflow geometry, derived quantities, and mixing/entrainment controls used in the box model.

Parameter	Label	Value [unit]
ϕ_{JDF}	JDF inlet latitude	48.5°
f_{JDF}	Coriolis parameter	$2\Omega_{\oplus} \sin \phi_{\text{JDF}} [\text{s}^{-1}]$
H_{JDF}	Mean JDF depth	100 m
H_{sill}	Sill depth near Victoria	60 m
L_{sill}	Sill length	10^4 m
$h_{\text{JDF,in}}$	CR plume depth before sill	20 m
$h_{\text{JDF,out}}$	CR plume depth after sill	10 m
w_{JDF}	N-S width of inflowing plume	5×10^3 m
$A_{\text{JDF,in}}$	Inflow cross-sectional area	$1.0 \times 10^5 \text{ m}^2$
$A_{\text{JDF,out}}$	Outflow cross-sectional area	$1.0 \times 10^5 \text{ m}^2$
V_{JDF}	JDF box volume	$A_{\text{JDF,in}} \times L_{\text{sill}} = 1.0 \times 10^9 \text{ m}^3$
$h_{\text{VBL,JDF}}$	Ekman boundary-layer inflow depth	$\sqrt{2k_{\text{eddy}}/f_{\text{JDF}}} \approx 16.7 \text{ m}$
V_{Ek}	Ekman inflow speed	$\tau_w/(\rho_{\text{CR}} f_{\text{JDF}} h_{\text{VBL,JDF}}) \approx 0.154 \text{ m s}^{-1}$
$V_{g,\text{in}}$	Instantaneous gravity-current inflow speed in JDF	$\sqrt{2g'_1 f_g h_{\text{in}}} \text{ m s}^{-1}$
$V_{\text{JDF,avg}}$	Mean JDF inflow speed scale	$V_{\text{Ek}} + V_{g,\text{in}} \text{ m s}^{-1}$
α_{JDF}	Entrainment coefficient in JDF	0.05

Supplementary Methods

3-Box model Version 1 (V1) and explicit Euler algorithm scheme

This section develops in detail version 1 of the three-box model (V1) used to explore and understand larval pickup by spreading Columbia River (CR) plumes, preservation or loss of the resulting signal during northward transport, and delivery into the eastern Juan de Fuca Strait (JDF). The purpose is to state the model in a form that is both physically transparent, directly traceable to our numerical implementation and readily implemented by other researchers. The model is deliberately reduced: it does not resolve the three-dimensional plume circulation or larval locomotion, but instead represents the dominant exchange processes through time-dependent control volumes, entrainment velocities, and transport time scales. The data demand little more.

The three prognostic concentrations are normalized larval concentrations $C_0(t)$, $C_1(t)$, and $C_2(t)$. Box 0 is a finite near-surface larval reservoir underlying the CR plume source region. Box 1 is the spreading turbulent CR plume. Box 2 represents the JDF inflow and the part of the eastern strait over which the incoming signal is retained or diluted before passage beyond Victoria Sill. The transport between Boxes 1 and 2 is not represented by an additional along-coast storage box because entrainment and mixing is suppressed under downwelling conditions. Instead, the JDF inflow is parameterized directly from buoyancy, Ekman, tidal, and alongshore velocity scales. This is consistent with the conceptual model described in the main text. We note that the diluting effects of entrainment and mixing on larval concentration between box 1 and box 2 would be difficult to distinguish from parameterized losses to the north. Such effects would, however, reduce g' and the contribution of buoyancy forces to the speed of eastward flow into the JDF which have a velocity $\sim g'^{1/2}$. This effect would cause Π_{JDF} to increase.

The calculation proceeds at each explicit Euler time step in the following order:

1. Interpolate river discharge and tidal forcing at Astoria, Port Angeles, and Port Townsend.
2. Calculate the instantaneous CR source-layer thickness, discharge velocity, shear velocity, and Richardson numbers.
3. Calculate basal and frontal entrainment velocities and combine them using the evolving basal and frontal surface areas of a *semi-circular* spreading plume.
4. Advance the mixed-layer thickness, calculate the fraction of the source layer occupied by the mixed layer, and update the density and reduced gravity carried by Box 1.
5. Calculate the volumetric larval-pickup flux from the finite Box 0 reservoir into Box 1 and advance C_0 .
6. Advance C_1 using the Box-1 filling and loss time scales.
7. Calculate the JDF inflow and outflow time scales from buoyancy, Ekman, tidal, and alongshore motions and advance C_2 .
8. Advance the semi-circular plume radius and update its front thickness from a volume budget.

The main text and tables above express the box equations using characteristic time scales, and we retain that notation throughout this summary. The numerical implementation internally stores coefficients used to advance the equations, but the physical model is reported here entirely through the associated characteristic time scales, τ . The same volumetric exchange flux Q_{01} removes larvae from the finite Box 0 source reservoir and supplies the spreading plume represented by Box 1. We therefore formulate the Box 0 evolution as an inventory balance and define the characteristic Box 1 filling timescale from the ratio of its instantaneous control volume to Q_{01} .

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1 Forcing, geometry, and state variables

1.1 Time and external forcing

The model is advanced on a uniform time grid

$$t_n = n\Delta t, \quad (1)$$

with Δt prescribed. River discharge is either supplied through an interpolated discharge record or, when no record is supplied, replaced by a prescribed mean discharge $Q_{\text{CR,avg}}$.

At Astoria, the tidal elevation $\eta_A(t)$ modifies the instantaneous source-layer thickness,

$$h_t = \max(h_{\text{CR}} + \eta_A, h_{\text{min}}), \quad (2)$$

where h_{CR} is the nominal plume thickness after lift-off and $h_{\text{min}} = 0.5$ m is a numerical floor in the V1 implementation. The source discharge velocity is

$$V_t = s_V \frac{Q_{\text{CR}}(t)}{A_{\text{CR}}}, \quad A_{\text{CR}} = w_{\text{CR}} h_{\text{CR}}, \quad (3)$$

where s_V is an optional velocity scaling factor used in sensitivity calculations.

The tidal-velocity quantity used by the V1 implementation is a kinematic proxy obtained from the time derivative of a smoothed tide-height series,

$$u_T(t) \equiv \frac{d\eta}{dt}, \quad (4)$$

followed by interpolation to the model time. The sign is retained so that flood and ebb phases can enter the box-exchange terms with opposite signs. Separate tidal time series are used at Astoria and at Port Angeles.

1.2 Reduced gravity and rotation effects

The initial reduced gravity of the CR plume is

$$g'_{\text{CR}} = g \frac{\rho_o - \rho_{\text{CR}}}{\rho_o}, \quad (5)$$

where ρ_{CR} and ρ_o are the prescribed source-plume and ocean densities. The Coriolis parameter is

$$f = 2\Omega_{\oplus} \sin \phi. \quad (6)$$

A gravity-wave speed and Rossby-radius scale at Astoria are defined by

$$c_g = \sqrt{g'_{\text{CR}} h_{\text{CR}}}, \quad L_{R,\text{CR}} = a_R \frac{c_g}{f_A}, \quad (7)$$

where a_R is the empirical Rossby-radius adjustment used in the parameter file to ensure that plume spreading is consistent with observations.

2 Semi-circular plume spreading and mixing

2.1 Basal shear and Richardson-number control

Basal mixing is driven by shear between the spreading plume and the underlying seawater. The shear velocity is

$$u_* = \sqrt{C_D} |V_t + V_{\text{wind,CR}}|, \quad (8)$$

where C_D is the basal drag coefficient. The code records the shear-based Richardson number

$$\text{Ri}_* = \frac{g'_{\text{CR}} h_t}{u_*^2}, \quad (9)$$

but the suppression of entrainment in V1 is controlled by the bulk Richardson number

$$\text{Ri}_{\text{bulk}} = \frac{g'_{\text{CR}} h_t}{V_t^2}. \quad (10)$$

Consistent with the entrainment closure used in the manuscript, mixing is progressively suppressed as Ri_{bulk} approaches a critical value[1–6]:

$$f_{\text{Ri}} = \max \left(0, 1 - \frac{\text{Ri}_{\text{bulk}}}{\text{Ri}_{\text{crit}}} \right). \quad (11)$$

Balancing turbulent mechanical power, scaling as ρu_*^3 , against the work required to mix across a stabilizing density interface gives the basal entrainment velocity used in V1,

$$V_{\text{mix,base}} = f_{\text{Ri}} s_{\text{mix}} \frac{\Lambda_b u_*^3}{g'_{\text{CR}} h_t}, \quad (12)$$

where Λ_b is a basal mixing-efficiency coefficient and s_{mix} is the model tuning multiplier. This form follows the energetic scaling used in the main-text development and related stratified-mixing studies[6, 7].

2.2 Kinematic frontal spreading and frontal mixing

The plume is treated as a buoyant gravity current spreading away from the CR mouth as a semi-circular lens. Let $R_{\text{mix}}(t)$ be the radial extent and $h_{\text{front}}(t)$ the front thickness. The V1 implementation advances the front using

$$U_f \equiv \frac{dR_{\text{mix}}}{dt} = \sqrt{g'_{\text{CR}} h_{\text{front}}}. \quad (13)$$

This is a kinematic gravity-current closure for the largest-scale front motion rather than a resolved model of the lobe-and-cleft and overturning structures at a natural plume front[8–10].

Frontal entrainment is taken proportional to the front speed,

$$V_{\text{mix,front}} = f_{\text{Ri}} \alpha_f U_f, \quad (14)$$

where α_f is the frontal entrainment coefficient. The V1 code applies the same Richardson-number suppression factor f_{Ri} to basal and frontal entrainment.

For a semi-circular plume, the basal planform area and vertical frontal area are

$$A_{\text{base}} = \frac{1}{2} \pi R_{\text{mix}}^2, \quad A_{\text{front}} = \pi R_{\text{mix}} h_{\text{front}}. \quad (15)$$

Thus, when both mechanisms are active, the effective entrainment velocity is the area-weighted value

$$V_{\text{mix,eff}} = \frac{V_{\text{mix,base}} A_{\text{base}} + V_{\text{mix,front}} A_{\text{front}}}{A_{\text{base}} + A_{\text{front}}}. \quad (16)$$

The implementation can alternatively retain only the basal or only the frontal contribution.

The relative geometric importance of frontal and basal mixing follows directly from eq. (15):

$$\frac{A_{\text{front}}}{A_{\text{base}}} = \frac{2h_{\text{front}}}{R_{\text{mix}}}. \quad (17)$$

Frontal mixing is therefore most important early in plume spreading, when R_{mix} is small relative to the front thickness, whereas basal mixing increasingly dominates as the plume becomes a broad shallow lens.

2.3 Mixed-layer thickness and density evolution

The mixed-layer thickness grows at the effective mixing velocity,

$$\frac{dd_{\text{mix}}}{dt} = V_{\text{mix,eff}}, \quad 0 \leq d_{\text{mix}} \leq d_{\text{mix,max}}. \quad (18)$$

The fraction of the instantaneous source layer occupied by the mixed layer is

$$\Gamma_b = \min \left[1, \max \left(0, \frac{d_{\text{mix}}}{h_t} \right) \right]. \quad (19)$$

This factor is used explicitly in the V1 larval-pickup flux, so exchange from Box 0 is small while the mixed layer is shallow and approaches the full kinematic entrainment flux as the mixed layer occupies the source layer.

For the density update, the model uses the newly advanced mixed-layer fraction

$$F_m = \min \left[1, \max \left(0, \frac{d_{\text{mix}}(t + \Delta t)}{h_t} \right) \right], \quad (20)$$

and linearly mixes river-plume and ocean density,

$$\rho_1 = (1 - F_m)\rho_{\text{CR}} + F_m\rho_o. \quad (21)$$

The reduced gravity exported from Box 1 toward JDF is then

$$g'_1 = g \frac{\rho_o - \rho_1}{\rho_o}. \quad (22)$$

The source-region mixing and radial-spreading closures themselves continue to use the prescribed source value g'_{CR} ; the evolving g'_1 enters the JDF transport calculation.

3 Box 0: finite larval source reservoir

Box 0 represents the finite near-surface reservoir of larvae available for entrainment beneath the spreading plume. Its concentration is normalized so that

$$C_0(0) = 1. \quad (23)$$

The source region is also represented as a semi-circle extending seaward from the CR mouth, with prescribed storage radius $R_{0,\text{store}}$,

$$A_{0,\text{store}} = \frac{1}{2}\pi R_{0,\text{store}}^2. \quad (24)$$

The source volume is fixed during a run,

$$V_0 = A_{0,\text{store}} d_{\text{mix,max}}, \quad (25)$$

and the larval inventory is

$$M_0 = V_0 C_0. \quad (26)$$

The storage radius is prescribed independently of the instantaneous plume radius, so the semi-circular Box 0 reservoir can be larger than the plume footprint at any instant while retaining the same river-mouth origin and geometry.

The exchange area between Box 0 and Box 1 is, however, explicitly tied to the instantaneous semi-circular plume footprint,

$$A_{\text{ent}}(t) = \frac{1}{2}\pi R_{\text{mix}}(t)^2. \quad (27)$$

The volumetric pickup flux implemented in V1 is

$$Q_{01} = \Gamma_b V_{\text{mix,eff}} A_{\text{ent}}. \quad (28)$$

Thus plume spreading affects pickup both by changing the mixed-layer growth through $V_{\text{mix,eff}}$ and by enlarging the footprint over which exchange occurs.

Conservation of larval inventory in Box 0 gives

$$\frac{dM_0}{dt} = -Q_{01}C_0. \quad (29)$$

Because V_0 is fixed,

$$\frac{dC_0}{dt} = -\frac{Q_{01}}{V_0}C_0, \quad (30)$$

This finite-volume form is the Box-0 source-depletion equation used in the model; no separate named pickup time scale is introduced for Box 0.

4 Box 1: the spreading CR plume

4.1 Evolving Box-1 volume and pickup time scale

The effective Box-1 control volume is the semi-circular footprint multiplied by the front thickness,

$$V_1(t) = \left(\frac{1}{2} \pi R_{\text{mix}}^2 \right) h_{\text{front}}. \quad (31)$$

The same physical flux Q_{01} that removes larvae from Box 0 supplies Box 1. Therefore the Box-1 filling time scale is

$$\boxed{\tau_{01} = \frac{V_1}{Q_{01}}}. \quad (32)$$

The named time scale τ_{01} is reserved for filling of the evolving Box-1 control volume.

Box-0 depletion is represented directly by the inventory balance above.

4.2 Loss from Box 1 and the CR time-scale ratio

The full Columbia River outflow calculation determines the time-dependent pickup flux $Q_{01}(t)$ and therefore the Box-1 filling time scale $\tau_{01}(t)$. All variability associated with the CR forcing and plume evolution is retained in this quantity. Rather than introducing separate controls for individual contributions to Box-1 export, the model defines a single dimensionless ratio

$$\Pi_{\text{CR}} = \frac{\tau_{01}}{\tau_{1,\text{out}}} \quad (33)$$

that compares the instantaneous Box-1 filling and export time scales. Hence

$$\tau_{1,\text{out}}(t) = \frac{\tau_{01}(t)}{\Pi_{\text{CR}}}. \quad (34)$$

For a given calculation, Π_{CR} is prescribed, while $\tau_{01}(t)$ evolves with $Q_{01}(t)$ and the spreading-plume control volume. The Box-1 concentration therefore obeys

$$\frac{dC_1}{dt} = \frac{1}{\tau_{01}(t)} (C_0 - \Pi_{\text{CR}} C_1). \quad (35)$$

This is the form used to interpret the Π_{CR} sweeps in the paper. Small Π_{CR} corresponds to export that is slow compared with filling and therefore preserves the time-dependent pickup signal. Large Π_{CR} corresponds to export that is rapid compared with filling and progressively damps that signal. Because the same evolving $\tau_{01}(t)$ multiplies both terms, changing Π_{CR} alters the relative export strength without removing the event-scale time dependence inherited from the calculated CR outflow.

The V1 numerical update additionally enforces non-negative concentration and caps the new Box-1 concentration at the updated source concentration,

$$0 \leq C_1^{n+1} \leq C_0^{n+1}. \quad (36)$$

5 Plume radius and front-thickness evolution

The plume radius is advanced explicitly using the gravity-current speed from eq. (13).

In the principal V1 branch,

$$R_{\text{mix}}^{n+1} = \min \left(R_{\text{mix}}^n + \Delta t \sqrt{g'_{\text{CR}} h_{\text{front}}^n}, L_{R, \text{CR}} \right). \quad (37)$$

The model contains an alternate wind-comparison branch used when the prescribed CR wind-speed parameter exceeds the frontal spreading speed; under the parameter choices used for the calculations described in the manuscript, $V_{\text{wind, CR}} = 0$ and eq. (37) is the active branch.

The plume volume accumulator is increased by the instantaneous river input,

$$V_{\text{lens}}^{n+1} = V_{\text{lens}}^n + Q_{\text{CR}}^n \Delta t. \quad (38)$$

For a semi-circular lens, the geometric thickness implied by this volume is

$$h_{\text{geom}}^{n+1} = \frac{V_{\text{lens}}^{n+1}}{\frac{1}{2} \pi \left(R_{\text{mix}}^{n+1} \right)^2}. \quad (39)$$

The updated front thickness is

$$h_{\text{front}}^{n+1} = \min \left[h_t^n, \max \left(0, h_{\text{geom}}^{n+1} + d_{\text{mix}}^n \right) \right]. \quad (40)$$

This construction couples river discharge, radial spreading, and mixing-layer growth to the evolving front geometry.

6 Box 2: JDF inflow, retention, and loss

Box 2 represents delivery of the Box-1 signal into JDF and its retention or loss near the eastern strait. The incoming and outgoing layer thicknesses are modulated by the local tide heights,

$$h_{\text{in}} = h_{\text{JDF},0}^{\text{in}} + \eta_{PA}, \quad h_{\text{out}} = h_{\text{JDF},0}^{\text{out}} + \eta_{PT}. \quad (41)$$

6.1 Ekman and gravity-current velocity scales

The model defines an Ekman/viscous boundary-layer thickness

$$h_E = \sqrt{\frac{2K_e}{f_{\text{JDF}}}}, \quad (42)$$

where K_e is the prescribed eddy diffusivity. The onshore Ekman velocity scale is

$$V_E = \frac{\tau_w}{\rho_{\text{CR}} f_{\text{JDF}} h_E}. \quad (43)$$

The instantaneous buoyancy-driven inflow speed used in the Euler solver is

$$V_{g,\text{in}} = \sqrt{2g'_1 f_{g'} h_{\text{in}}}, \quad (44)$$

where g'_1 is the reduced gravity carried out of Box 1 into JDF and $f_{g'}$ is an optional scaling applied within the JDF calculation. The outgoing buoyancy speed is

$$V_{g,\text{out}} = \sqrt{2g'_2 h_{\text{out}}}. \quad (45)$$

The reduced gravity passed into Box 2 is updated as

$$g'_2 = f_{g'} g'_1. \quad (46)$$

6.2 JDF inflow and outflow time scales

Let $u_{T,PA}(t)$ and $u_{T,PT}(t)$ denote the signed tidal-velocity proxies at Port Angeles and Port Townsend. As at Astoria, these explicitly time-dependent advective velocities enter directly with their measured sign. The net Box-1 to Box-2 transport coefficient represented in the numerical model is therefore written as

$$\mathcal{T}_{12}(t) = \frac{V_E + V_{g,\text{in}} + u_{T,PA}(t)}{h_{\text{in}}} - \frac{V_{\text{along}}}{h_{\text{out}}}, \quad (47)$$

where V_{along} represents northward loss past the mouth of JDF. When $\mathcal{T}_{12} > 0$, the corresponding effective delivery time scale is

$$\boxed{\tau_{12} = \frac{1}{\mathcal{T}_{12}}}. \quad (48)$$

Stronger northward transport reduces $\mathcal{T}_{12}$, lengthens τ_{12} , and can eliminate net delivery if the balance becomes non-positive.

At the eastern end of JDF, the signed Port Townsend tidal velocity likewise enters the advective export directly. When the net eastward export velocity is positive, the characteristic export time scale is

$$\boxed{\tau_{2,\text{out}} = \frac{h_{\text{out}}}{V_E + u_{T,PT}(t) + V_{g,\text{out}}}}. \quad (49)$$

Define

$$\Pi_{\text{JDF}} = \frac{\tau_{12}}{\tau_{2,\text{out}}}. \quad (50)$$

The Box-2 equation is therefore

$$\boxed{\frac{dC_2}{dt} = \frac{1}{\tau_{12}} (C_1 - \Pi_{\text{JDF}} C_2)} \quad (51)$$

which is the same time-scale form used in the manuscript. The numerical update enforces $C_2 \geq 0$.

7 Unified three-box system

At any instant, the concentration part of the model can be summarized as

$$\frac{dC_0}{dt} = -\frac{Q_{01}}{V_0} C_0, \quad (52)$$

$$\frac{dC_1}{dt} = \frac{1}{\tau_{01}} (C_0 - \Pi_{\text{CR}} C_1), \quad (53)$$

$$\frac{dC_2}{dt} = \frac{1}{\tau_{12}} (C_1 - \Pi_{\text{JDF}} C_2). \quad (54)$$

The physical time scales evolve with discharge, tides, plume geometry, stratification, mixing-layer thickness, and wind-related velocity scales. The CR control parameter Π_{CR} is prescribed, while both the Box-1 filling and export time scales vary together:

$$\tau_{01} = \frac{V_1}{\Gamma_b V_{\text{mix,eff}} A_{\text{ent}}}, \quad (55)$$

$$\tau_{1,\text{out}} = \frac{\tau_{01}}{\Pi_{\text{CR}}}, \quad (56)$$

$$\mathcal{T}_{12}(t) = \frac{V_E + V_{g,\text{in}} + u_{T,PA}(t)}{h_{\text{in}}} - \frac{V_{\text{along}}}{h_{\text{out}}}, \quad (57)$$

$$\tau_{12} = \mathcal{T}_{12}^{-1} \quad \text{for } \mathcal{T}_{12} > 0, \quad (58)$$

$$\tau_{2,\text{out}} = \frac{h_{\text{out}}}{V_E + u_{T,PT}(t) + V_{g,\text{out}}}. \quad (59)$$

Thus the observed pickup “fingerprint” arises from a cascade of time-dependent filters: source depletion, plume filling and loss, and JDF delivery and retention.

8 Explicit Euler implementation

The V1 solver uses forward Euler integration. For a generic equation $dX/dt = F(X, t)$,

$$X^{n+1} = X^n + \Delta t F(X^n, t_n). \quad (60)$$

The Box-0 inventory is advanced directly,

$$M_0^{n+1} = \max[0, M_0^n - \Delta t Q_{01}^n C_0^n], \quad (61)$$

followed by

$$C_0^{n+1} = \frac{M_0^{n+1}}{V_0}. \quad (62)$$

Box 1 is advanced as

$$C_1^{n+1} = C_1^n + \Delta t \left(\frac{C_0^n}{\tau_{01}^n} - \frac{C_1^n}{\tau_{1,\text{out}}^n} \right), \quad (63)$$

when the combined Box-1 exchange represents net removal, followed by the limiter in eq. (36). Box 2 is advanced as

$$C_2^{n+1} = \max \left\{ 0, C_2^n + \Delta t \left(\frac{C_1^n}{\tau_{12}^n} - \frac{C_2^n}{\tau_{2,\text{out}}^n} \right) \right\}. \quad (64)$$

The mixed-layer thickness, plume radius, front height, density, and reduced gravity are advanced in the same loop. Because several coefficients depend on variables updated during the current step, the implementation is semi-sequential within each Euler step: forcing and mixing are evaluated first, followed by Box 0, Box 1, Box 2, and

then the plume-radius/front-thickness update. This ordering is part of the numerical model definition.

9 Initial conditions, bounds, and model switches

The principal initial conditions are

$$C_0(0) = 1, \quad C_1(0) = 0, \quad C_2(0) = 0, \quad (65)$$

$$R_{\text{mix}}(0) = 1 \text{ m}, \quad d_{\text{mix}}(0) = 0, \quad h_{\text{front}}(0) = h_{\text{CR}}. \quad (66)$$

The finite nonzero initial radius prevents singular geometric factors at startup. The model also applies small positive floors to selected depths and volumes to avoid division by zero. The principal physically motivated bounds are the cap $d_{\text{mix}} \leq d_{\text{mix,max}}$ and the Rossby-radius cap on R_{mix} .

Three mixing configurations are supported:

<i>Basal</i>	$V_{\text{mix,eff}} = V_{\text{mix,base}}.$
<i>Frontal</i>	$V_{\text{mix,eff}} = V_{\text{mix,front}}.$
<i>Both</i>	$V_{\text{mix,eff}}$ is the area-weighted combination in eq. (16).

These switches are useful for diagnosing which entrainment mechanism controls the shape and magnitude of the larval pickup signal.

10 Model variables and time-scale definitions

Supplementary Table. 4: Principal dynamic quantities and time-scale definitions.

Symbol	Meaning	Definition or unit
C_0	Normalized larval concentration in finite source reservoir	dimensionless
C_1	Normalized larval concentration in spreading CR plume	dimensionless
C_2	Normalized larval concentration in JDF delivery box	dimensionless
M_0	Box-0 larval inventory	$V_0 C_0$
R_{mix}	Radius of semi-circular spreading plume	m
h_{front}	Plume-front thickness	m
d_{mix}	Mixed-layer thickness	m
Γ_b	Fraction of source thickness occupied by mixed layer	d_{mix}/h_t
A_{base}	Semi-circular basal plume area	$\frac{1}{2}\pi R_{\text{mix}}^2$
A_{front}	Vertical area of semi-circular plume front	$\pi R_{\text{mix}} h_{\text{front}}$
Q_{01}	Volumetric pickup flux from Box 0 to Box 1	$\text{m}^3 \text{s}^{-1}$
τ_{01}	Box-1 filling time	V_1/Q_{01}
$\tau_{1,\text{out}}$	Effective Box-1 loss time	defined by eq. (34) when net removal is positive
Π_{CR}	CR pickup-to-loss control ratio	$\tau_{01}/\tau_{1,\text{out}}$

Symbol	Meaning	Definition or unit
τ_{12}	Effective JDF delivery time	defined by eq. (48) for net eastward delivery
$\tau_{2,\text{out}}$	JDF outflow/retention time	defined by eq. (49)
Π_{JDF}	JDF delivery-to-loss control ratio	$\tau_{12}/\tau_{2,\text{out}}$

11 Implementation notes relevant to reproduction

The appendix equations above follow the operative V1 Euler solver. A few implementation details are worth stating explicitly for reproducibility.

First, both the fixed Box 0 source reservoir and the spreading plume are semi-circular with their origin at the CR mouth. The Box 0 storage radius is prescribed, whereas the plume radius evolves in time. The basal exchange area, Box-1 planform area, frontal area, source-storage area, and lens-volume inversion therefore use the semi-circular factors in eqs. (15), (24), (27), (31) and (39).

Second, the Richardson-number limiter in the V1 code is based on $\text{Ri}_{\text{bulk}} = g'h_t/V_t^2$, while a shear-based Richardson number using u_* is retained as a diagnostic. Both basal and frontal entrainment are multiplied by the same f_{Ri} .

Third, the source-region front propagation and entrainment closures use the initial CR reduced gravity g'_{CR} . The density dilution calculated from mixed-layer growth produces an evolving g'_1 that is passed forward to the JDF gravity-current calculation.

Fourth, the coastal transit between the CR plume and JDF is not represented by an additional prognostic concentration box. The main driver selects or aligns forcing records for the relevant event windows, while the Euler solver directly couples C_1 to the JDF delivery equation through τ_{12} .

Finally, the tidal velocity entering the present implementation is calculated from the derivative of tide height rather than from an independently observed horizontal current record. It should therefore be interpreted as a signed tidal-exchange proxy within this reduced model.

12 Interpretation of the two control ratios

The two dimensionless ratios used in the main paper provide a compact interpretation of model behavior. At the CR mouth,

$$\Pi_{\text{CR}} = \frac{\tau_{01}}{\tau_{1,\text{out}}} \quad (67)$$

compares the time required to fill the spreading plume by entrainment with the time over which Box 1 loses its larval signal. For $\Pi_{\text{CR}} \ll 1$, pickup is rapid relative to loss and the temporal structure imposed by discharge, tides, and plume mixing is preserved. For $\Pi_{\text{CR}} \gtrsim 1$, Box-1 loss competes strongly with pickup and the signal is damped.

At JDF,

$$\Pi_{\text{JDF}} = \frac{\tau_{12}}{\tau_{2,\text{out}}} \quad (68)$$

compares the delivery time into the eastern strait with the time for loss past the sill/out of the receiving control volume. Small Π_{JDF} favors retention of the incoming pickup signal, whereas increasing Π_{JDF} reduces its amplitude and can flatten its temporal structure. Together, Π_{CR} and Π_{JDF} separate the mechanics of larval pickup at the river mouth from the mechanics of signal preservation during delivery.

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