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Large-scale experiments on wave-induced shallow turbulent coherent structures

Experimental observations and interpretation

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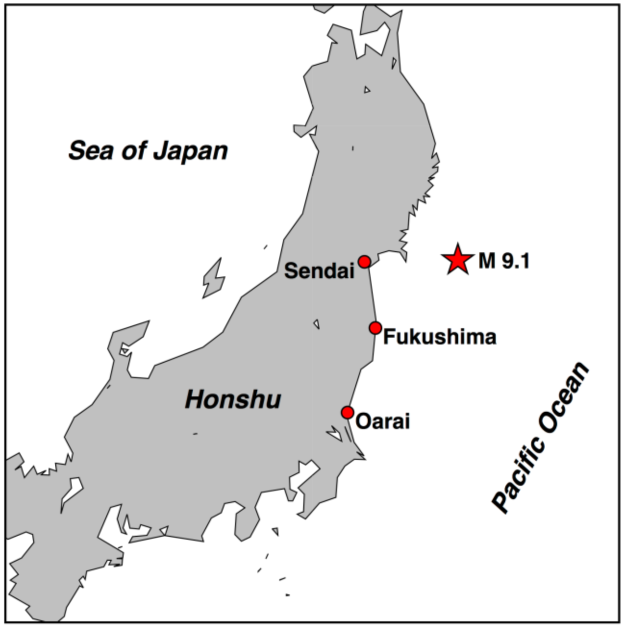
Observation of a tsunami-induced eddy

Port Oarai, Japan

- Interaction of the 2011 tsunami currents with the coastline created special effects.
- Formation of a gigantic rotational flow structure seen in a helicopter video.



The formation of a gigantic eddy inside the port basin

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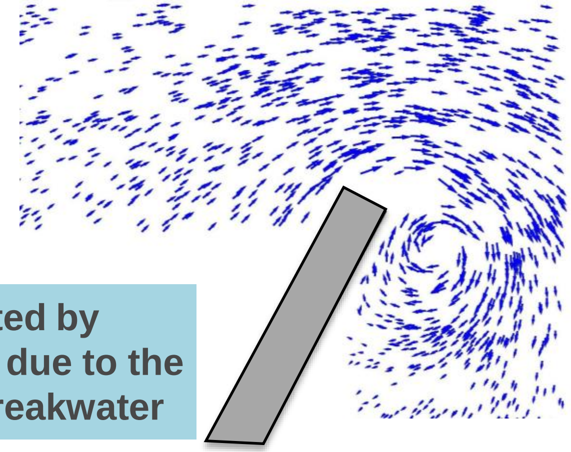
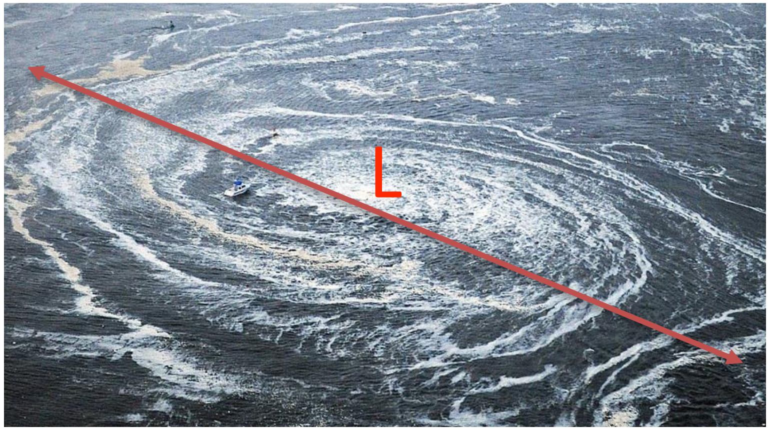
Turbulent Coherent Structures (TCS)

- 2D TCS definition:
  - "Two-dimensional, connected, large-scale turbulent fluid masses that extend uniformly over the full water depth and contain a phase-correlated vorticity, with the exception of a thin near-bottom boundary layer". (Hussain 1983; Jirka 2001)
- TCSs form in unidirectional and fully turbulent ($Re >> 10^3$) shallow flows ($L/H >>1$).
  - L is a characteristic length-scale, H is the flow depth.
- Kinetic energy decay is dominated by bottom friction.



TCS generated by transverse shear due to the presence of a breakwater



Large-scale experiments

- Lack on quantitative data on wave-induced TCS: setup a laboratory experiment.
- Re-create a shallow TCS in a well controlled environment.
- Study flow field during the TCS spatial growth and spin-down.
- Develop tools to estimate time-scales of TCS development and decay.

The wave basin used for the experiments.

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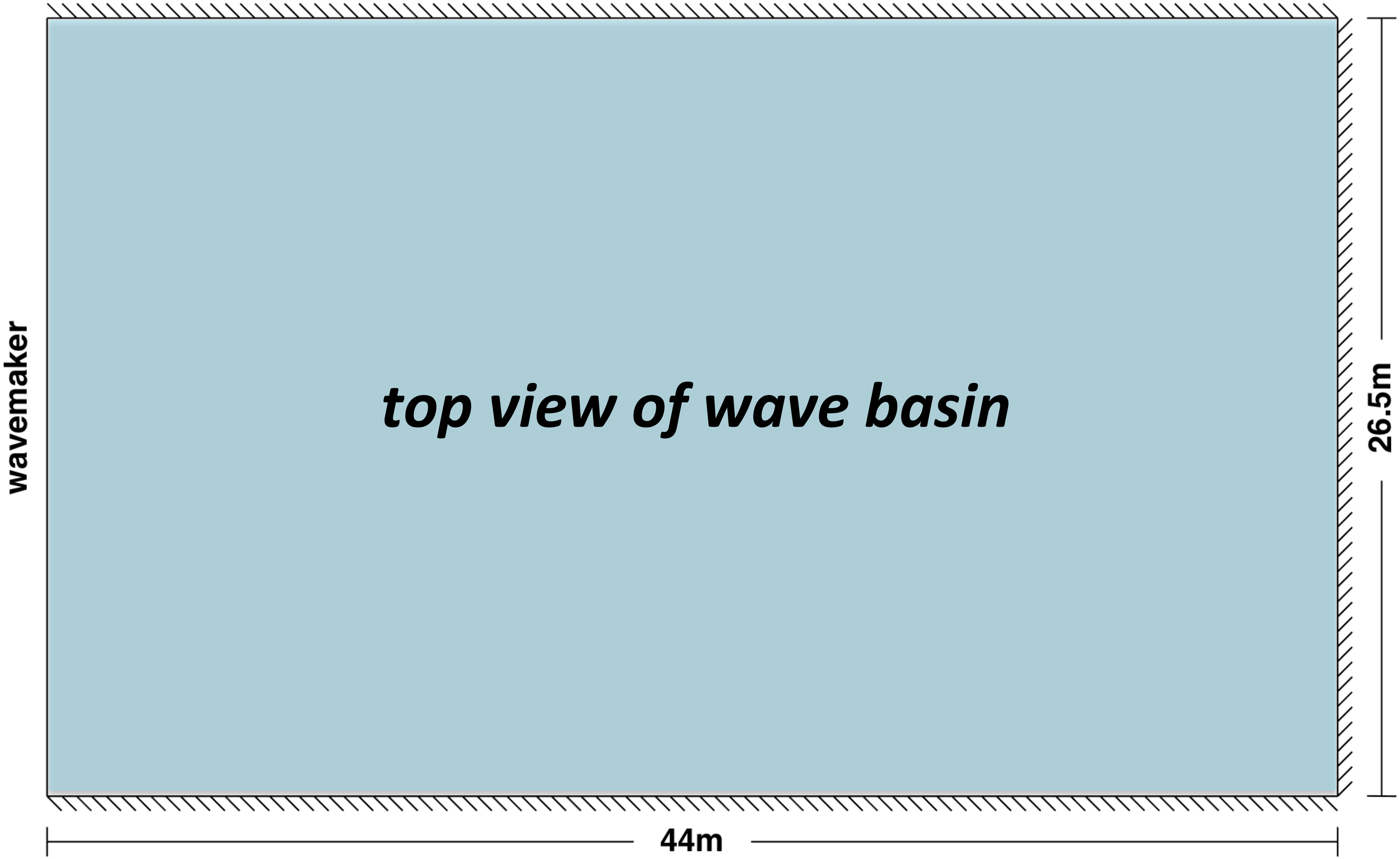
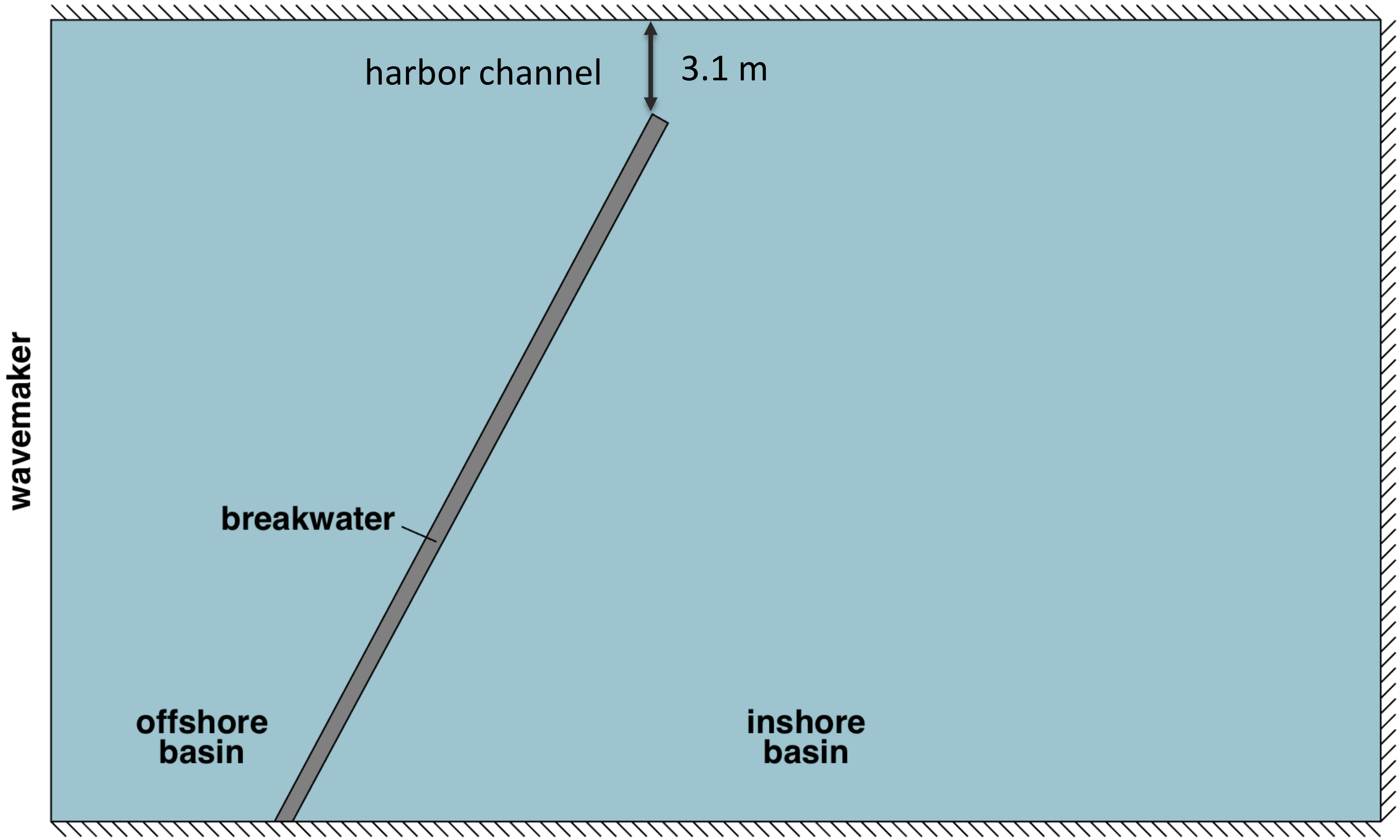
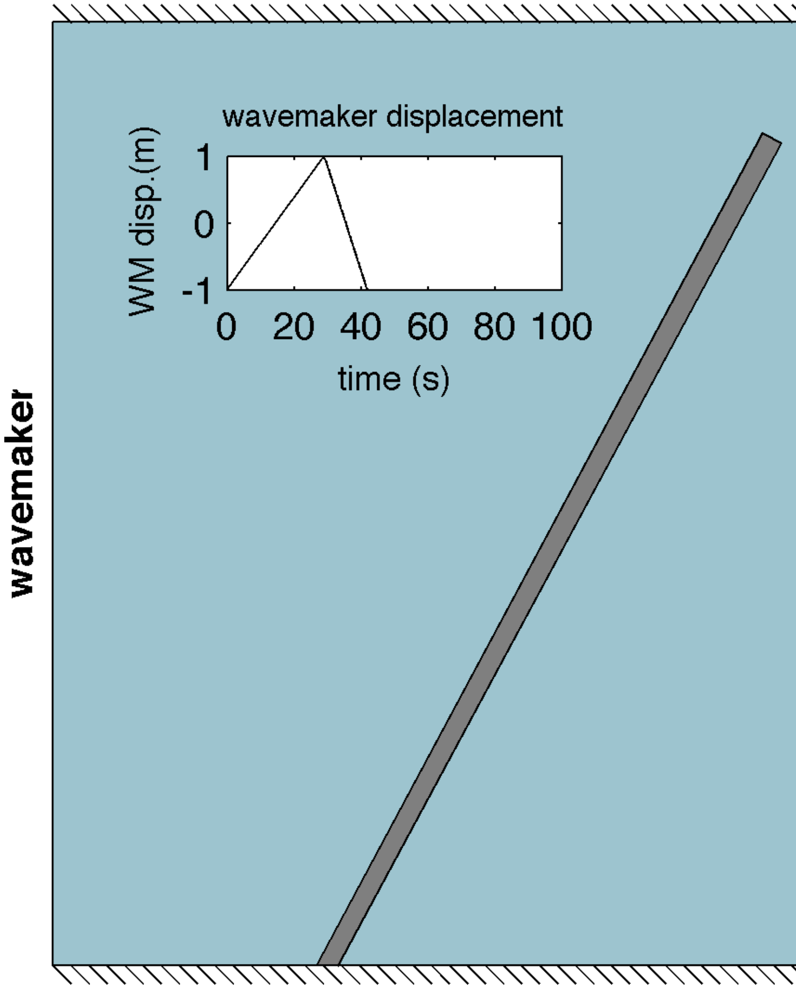
Experimental setup



Experimental setup



Experimental setup



Experimental scaling

- Experimental scale: ~ 1/27
- Prototype wave period : ~*4 min*
- Prototype wave amplitude: ~ *1 m*

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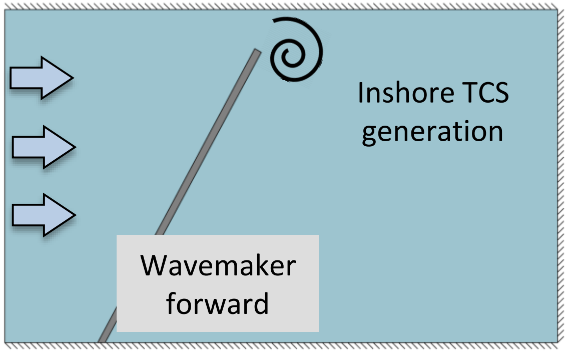
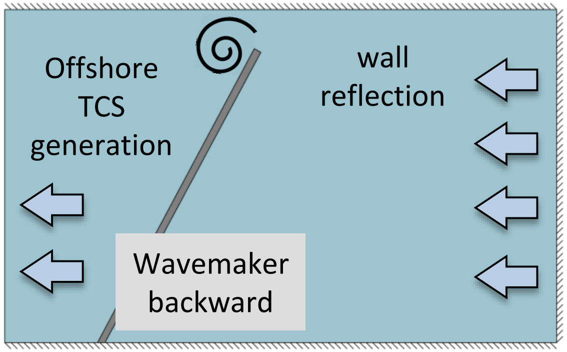
- Large Rossby number
- Fully-turbulent flow (Re = O(10^5))
- Sub-critical (F_r = 0.38)
- Laboratory results scale-independent for small-scale geophysical flows.

The three flow phases in the laboratory



Phase 1



Phase 2

Phase 3

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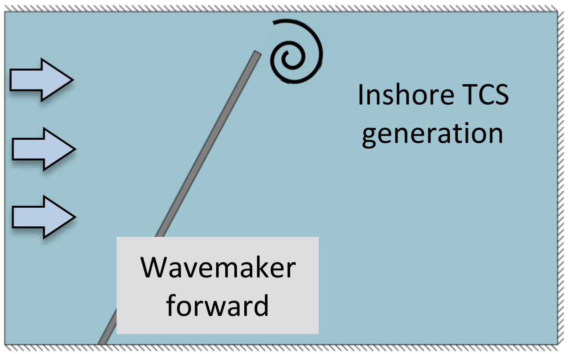
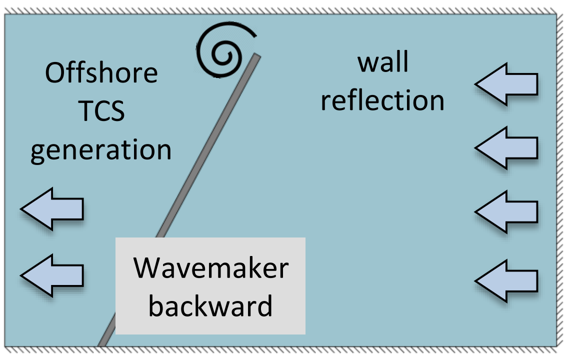
The three flow phases in the laboratory



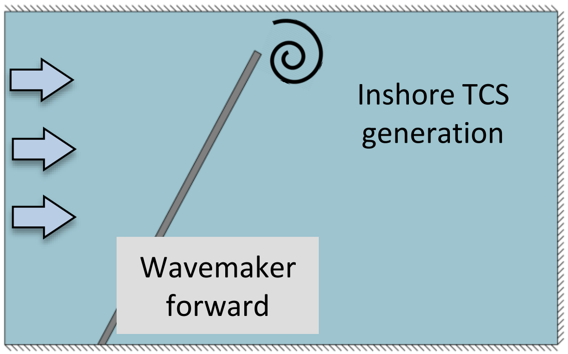
Phase 1



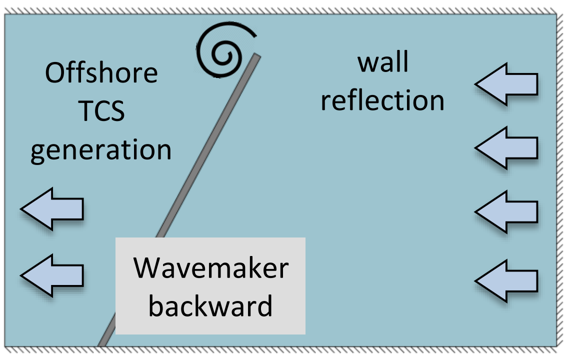
Phase 2

Phase 3

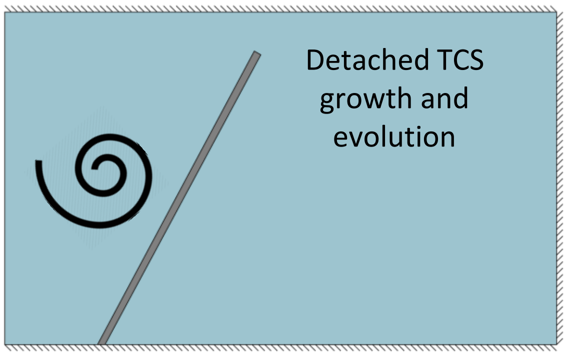
The three flow phases in the laboratory



Phase 1

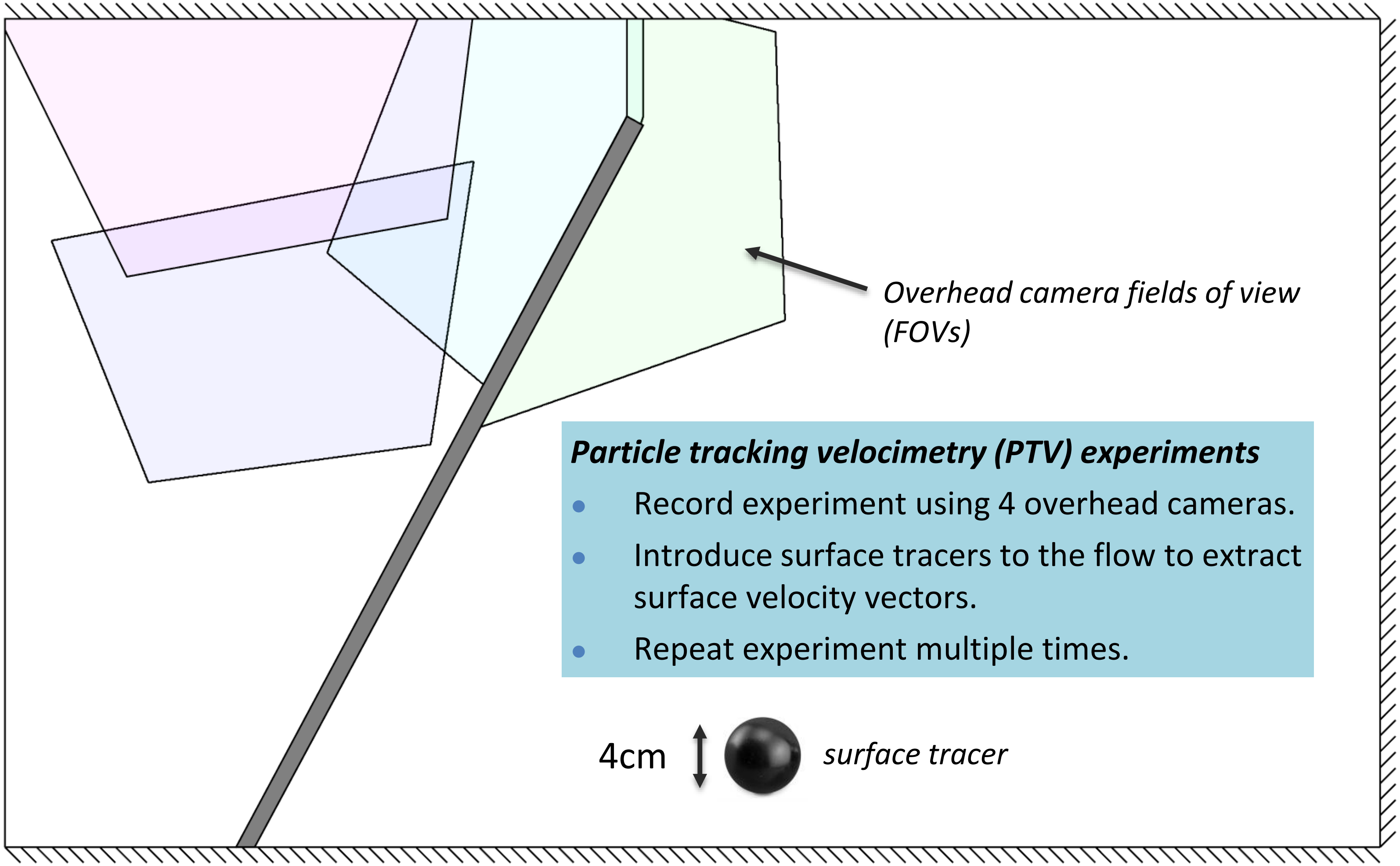


Phase 2



Phase 3

2D PTV experiments



Particle tracking velocimetry (PTV) experiments

- Record experiment using 4 overhead cameras.
- Introduce surface tracers to the flow to extract surface velocity vectors.
- Repeat experiment multiple times.

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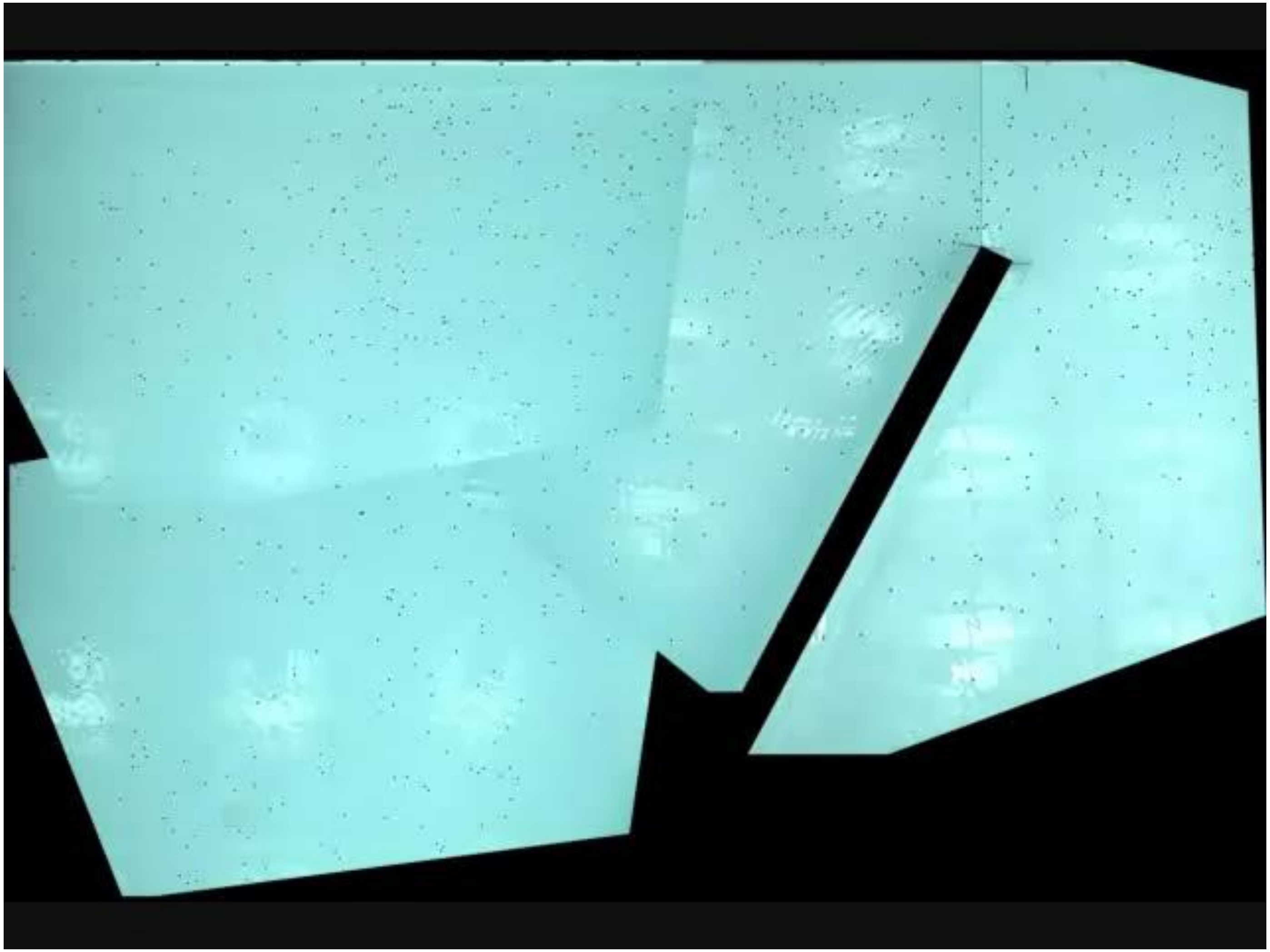
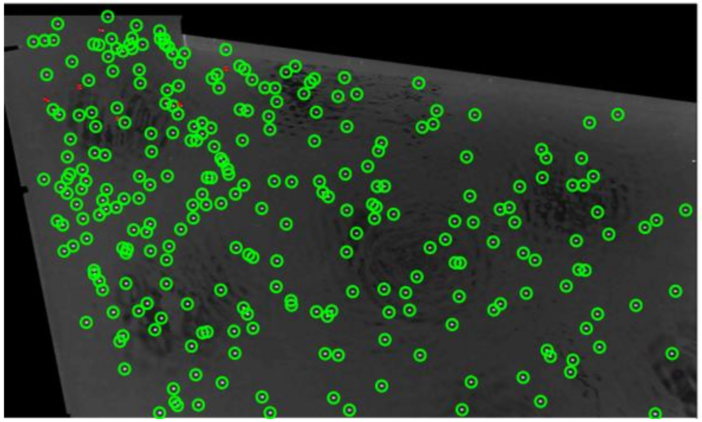
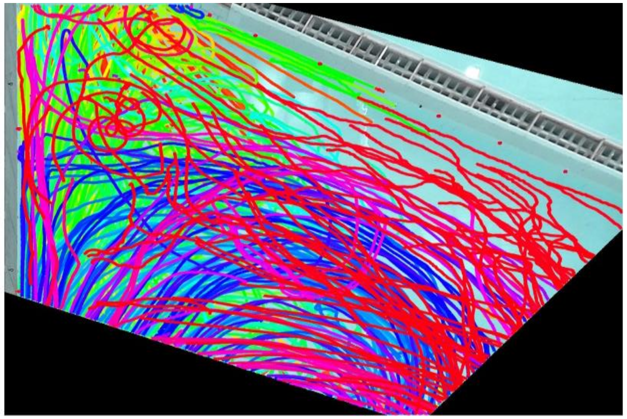
A single 2D PTV experiment



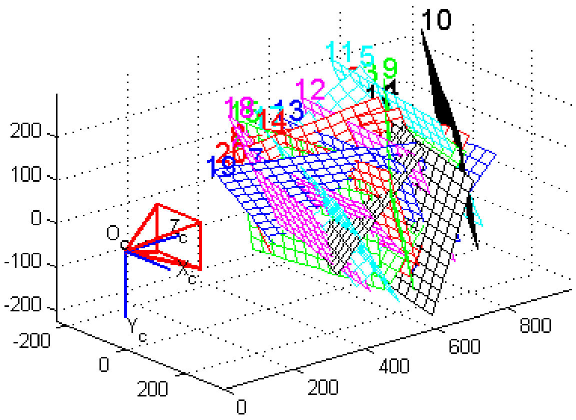
2D PTV steps to extract surface velocity vectors



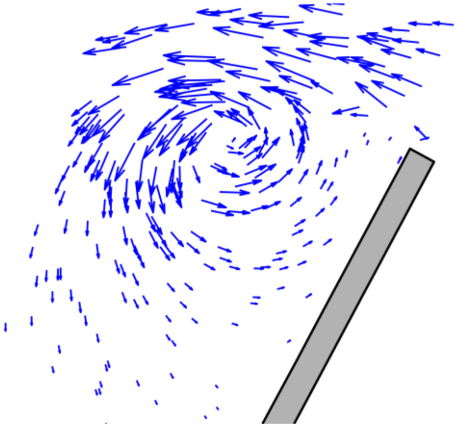
(1) Tracer center detection



(2) Particle tracking



(3) Image- to world-coordinate transformation



(4) Extraction of surface velocity vectors

Kalligeris and Lynett (2017), *Exp Fluids* (in preparation)

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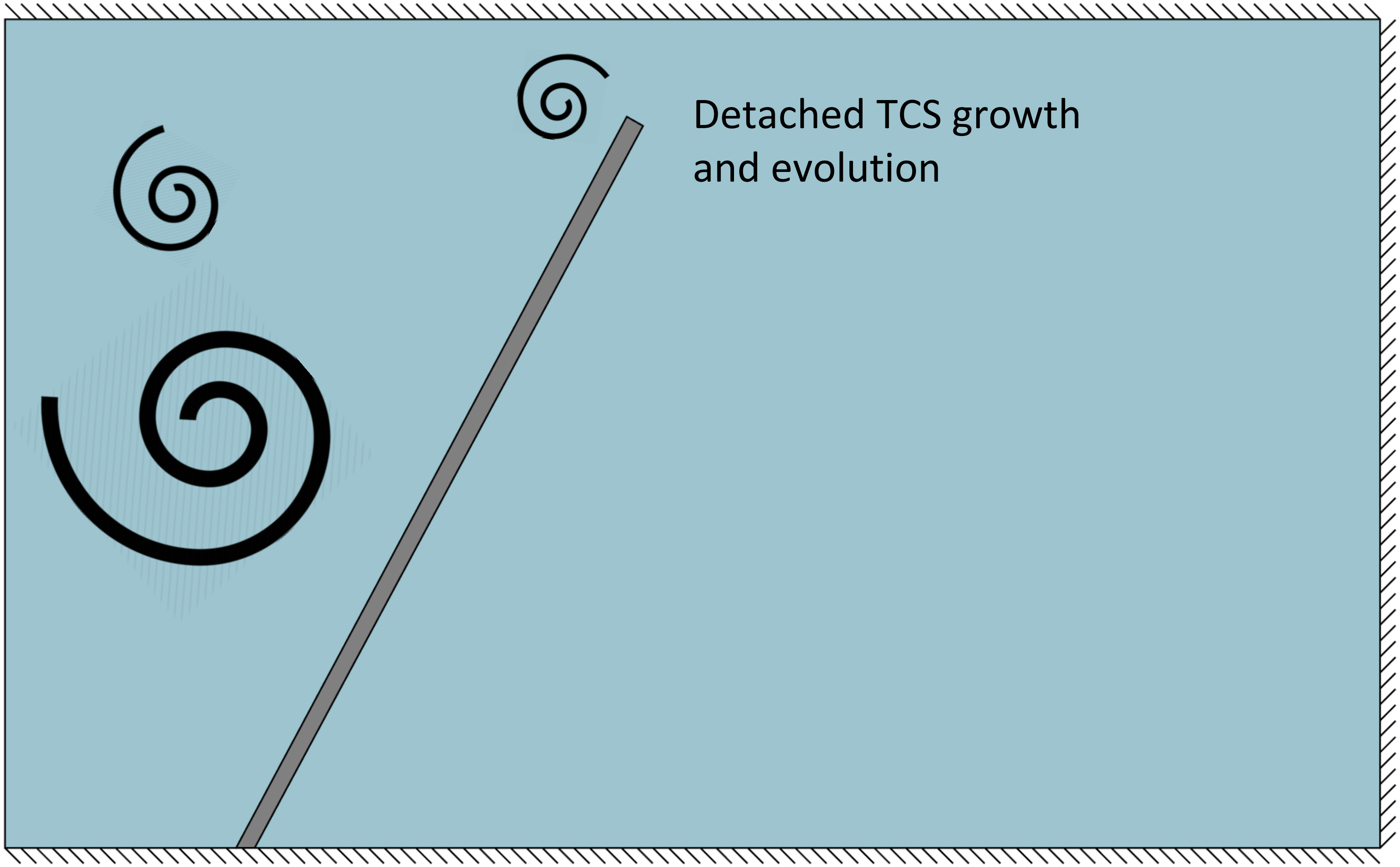
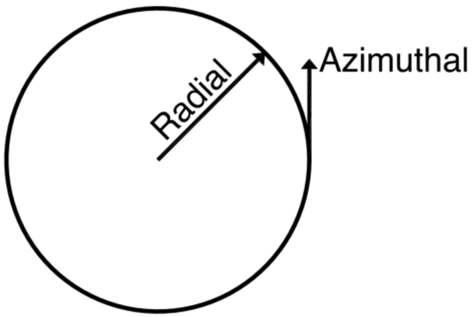
Experimental analysis – phase 3

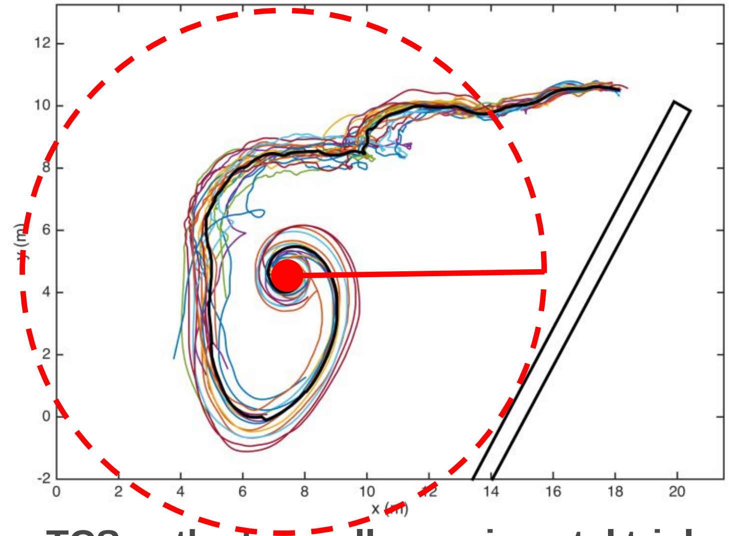


TCS-centered ensemble

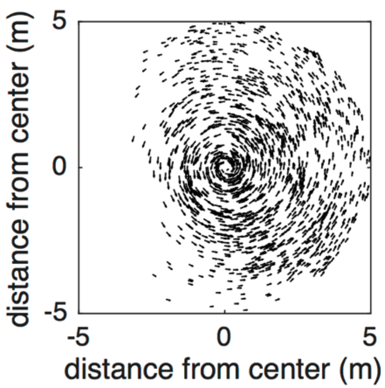
Obtain azimuthal-averaged TCS velocity profiles

- Construct a TCS-centered ensemble.
- Get azimuthal-averaged velocity profiles.

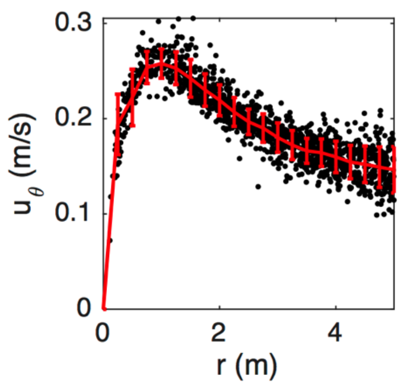




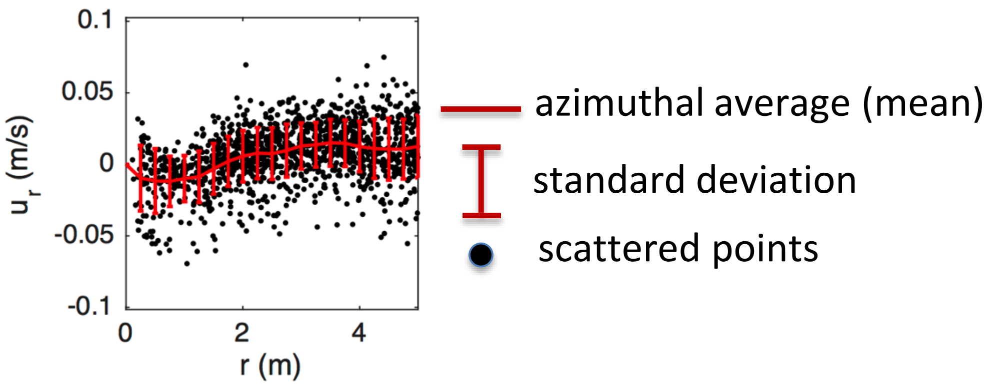
TCS paths from all experimental trials



Top view of TCS-centered vector ensemble



Azimuthal velocity



Radial velocity

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Governing equations of motion

- Depth-averaged, incompressible equations of motion: hydrostatic, axisymmetric

$$\frac{\partial \eta}{\partial t} + \frac{1}{r}\frac{\partial (r d \bar{u}_r)}{\partial r} = 0,$$ ***continuity equation***

$$\frac{\partial \bar{u}_r}{\partial t} + \bar{u}_r \frac{\partial \bar{u}_r}{\partial r} - \frac{\bar{u}_\theta^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \nu_{eff}\left[\frac{1}{d}\frac{\partial \eta}{\partial r}\frac{\partial \bar{u}_r}{\partial r} + \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r\bar{u}_r)}{\partial r}\right)\right] - \frac{\tau_{br}}{\rho d},$$

$$\frac{\partial \bar{u}_\theta}{\partial t} + \bar{u}_r \frac{\partial \bar{u}_\theta}{\partial r} + \frac{\bar{u}_\theta \bar{u}_r}{r} = \nu_{eff}\left[\frac{1}{d}\frac{\partial \eta}{\partial r}\frac{\partial \bar{u}_\theta}{\partial r} + \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r\bar{u}_\theta)}{\partial r}\right)\right] - \frac{\tau_{b\theta}}{\rho d}.$$

Momentum equations

convective terms — *turbulent diffusion terms* — *bottom shear stress term*

- *h* is the still water depth.
- *η* is the surface elevation.
- *d* is the total water depth (*d*=*h*+*η*).
- u_ϑ is the azimuthal velocity.
- u_r is the radial velocity.
- ν_{eff} is the added turbulent viscosity.

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Governing equations of motion

- Depth-averaged, incompressible equations of motion: hydrostatic, axisymmetric

$$\frac{\partial \eta}{\partial t} + \frac{1}{r}\frac{\partial (r d \bar{u}_r)}{\partial r} = 0,$$ ***continuity equation***

$$\left.\begin{aligned} \frac{\partial \bar{u}_r}{\partial t} + \bar{u}_r \frac{\partial \bar{u}_r}{\partial r} - \frac{\bar{u}_\theta^2}{r} &= -\frac{1}{\rho}\frac{\partial p}{\partial r} + \nu_{eff}\left[\frac{1}{d}\frac{\partial \eta}{\partial r}\frac{\partial \bar{u}_r}{\partial r} + \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r\bar{u}_r)}{\partial r}\right)\right] - \frac{\tau_{br}}{\rho d}, \\ \frac{\partial \bar{u}_\theta}{\partial t} + \bar{u}_r \frac{\partial \bar{u}_\theta}{\partial r} + \frac{\bar{u}_\theta \bar{u}_r}{r} &= \nu_{eff}\left[\frac{1}{d}\frac{\partial \eta}{\partial r}\frac{\partial \bar{u}_\theta}{\partial r} + \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r\bar{u}_\theta)}{\partial r}\right)\right] - \frac{\tau_{b\theta}}{\rho d}. \end{aligned}\right\}$$

Momentum equations

- Assume purely azimuthal flow (*$u_r = 0$*)

$$\frac{u_\theta^2}{r} = \frac{1}{\rho}\frac{\partial p}{\partial r}$$ ***cyclostrophic balance equation***

- Turbulent viscosity *$\nu_{eff} = Sqrt(c_f/2)Uh$*
- Bottom shear stress *$\tau_{b\vartheta} = c_f \rho u_\vartheta^2/2$*
  - *c_f* is the quadratic law friction coefficient

$$\frac{\partial u_\theta}{\partial t} = \sqrt{\frac{c_f}{2}} u_\theta h \left[\frac{1}{h}\frac{\partial \eta}{\partial r}\frac{\partial u_\theta}{\partial r} + \frac{1}{r}\frac{1}{\partial r}\left(r\frac{\partial u_\theta}{\partial r}\right) - \frac{u_\theta}{r^2}\right] - \frac{c_f u_\theta^2}{2h}$$ ***radial diffusion equation***

TCS kinetic energy decay

- Radial diffusion equation

bottom friction term

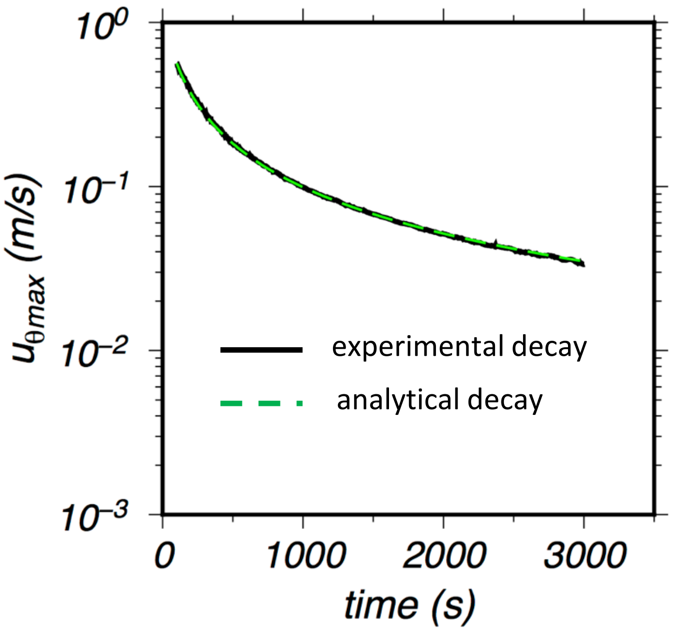
$$\frac{\partial u_\theta}{\partial t} = \sqrt{\frac{c_f}{2}} u_\theta h \left[\frac{1}{h}\frac{\partial \eta}{\partial r}\frac{\partial u_\theta}{\partial r} + \frac{1}{r}\frac{1}{\partial r}\left(r \frac{\partial u_\theta}{\partial r}\right) - \frac{u_\theta}{r^2}\right] - \frac{c_f u_\theta^2}{2h}$$

- Bottom friction dominates kinetic decay

$$\frac{\partial u_\theta}{\partial t} = -\frac{c_f u_\theta^2}{2h}$$

- Separation of variables provides temporal azimuthal-velocity dependence

$$u_{\theta,max}(t) = \frac{1}{\frac{1}{u_{\theta,max,0}} + \frac{c_f}{2h} t}$$



Decay of maximum u_θ *with time*

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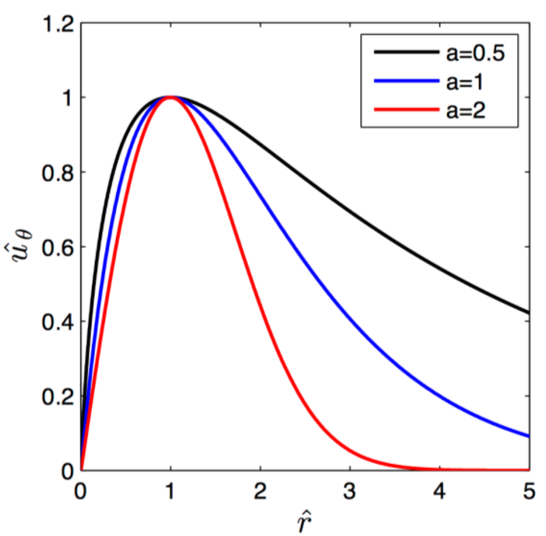
TCS primary flow radial profile

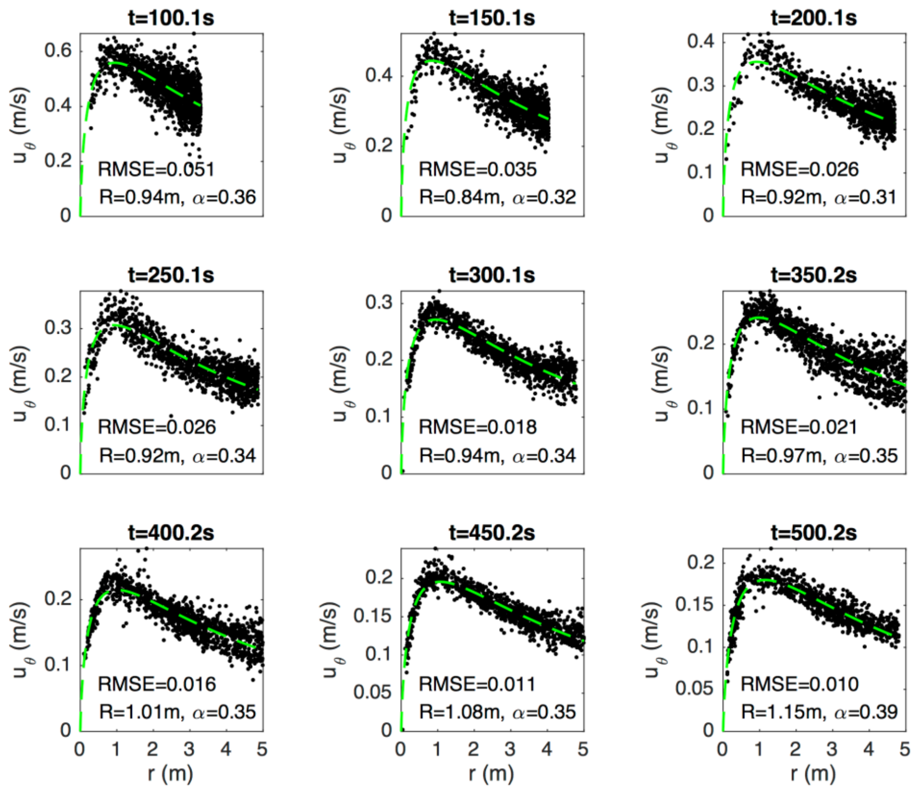
- Compare azimuthal velocity profiles with the stirring vortex profile (or α-profile)

$$\frac{r}{R}\exp\left(\frac{1-(r/R)^a}{a}\right)$$

- *R(t)* is the radius of $u_{\vartheta,max}(t)$
- *a* is a free parameter



Vortex α-profile



Fit u_θ scattered data to stirring vortex profile

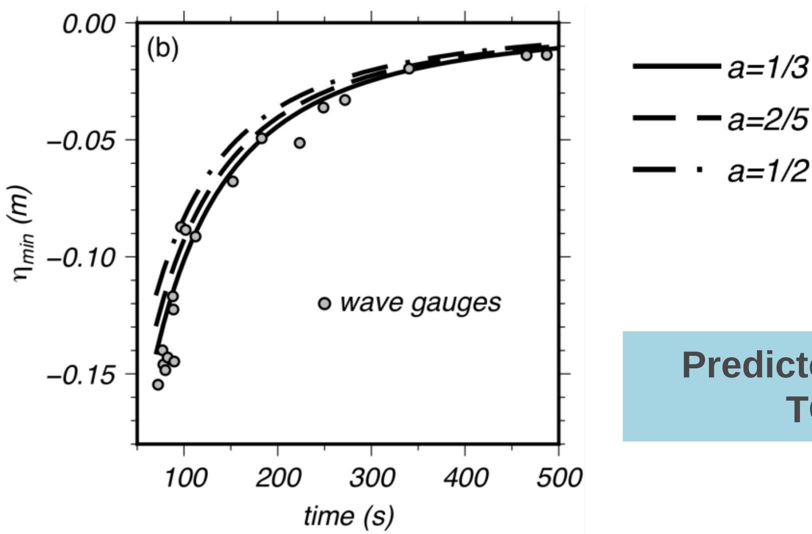
TCS free surface elevation (FSE) profile

- Full azimuthal-velocity profile (primary flow)

$$u_\theta(r,t) = u_{\theta,max}(t)\frac{r}{R}\exp\left(\frac{1-(r/R)^a}{a}\right), u_{\theta,max}(t) = \frac{1}{\frac{1}{u_{\theta,max,0}} + \frac{c_f}{2h}t}$$

- Use cyclostrophic balance equation to infer the experimental TCS FSE profile

$$\frac{\partial \eta}{\partial r} = \frac{1}{g}\frac{u_\theta^2}{r} \rightarrow \eta(r,t) = \frac{u_{\theta,max}^2(t)}{g}\int \frac{r}{R_{v_{max}}^2(t)}\exp\left(2\frac{1-(r/R_{v_{max}}(t))^a}{a}\right)dr$$



Predicted η_{min} decay at TCS center

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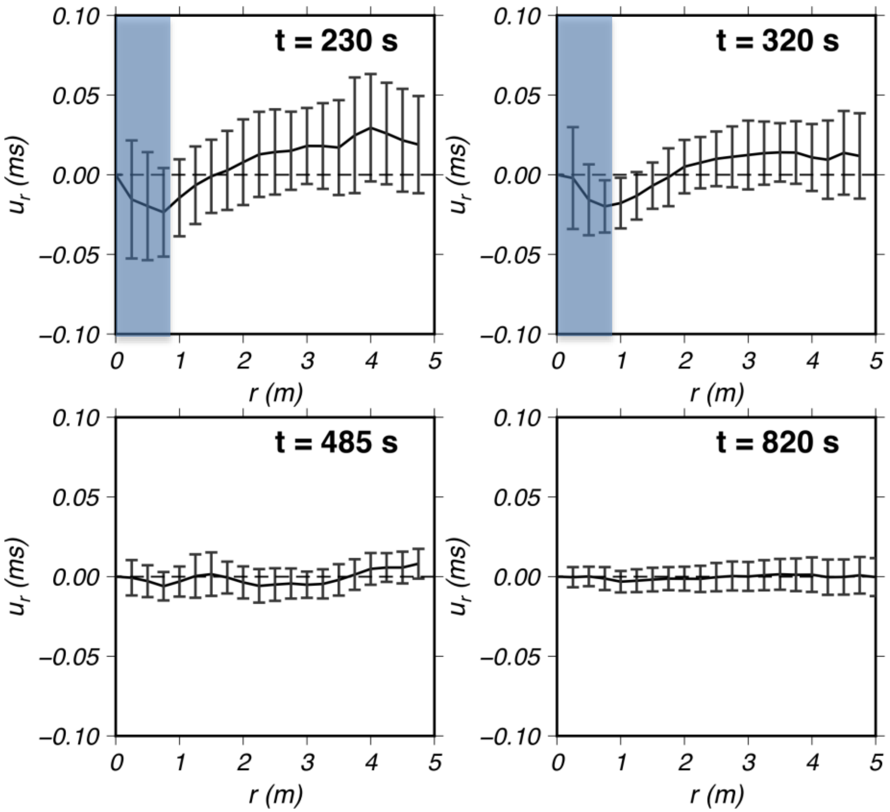
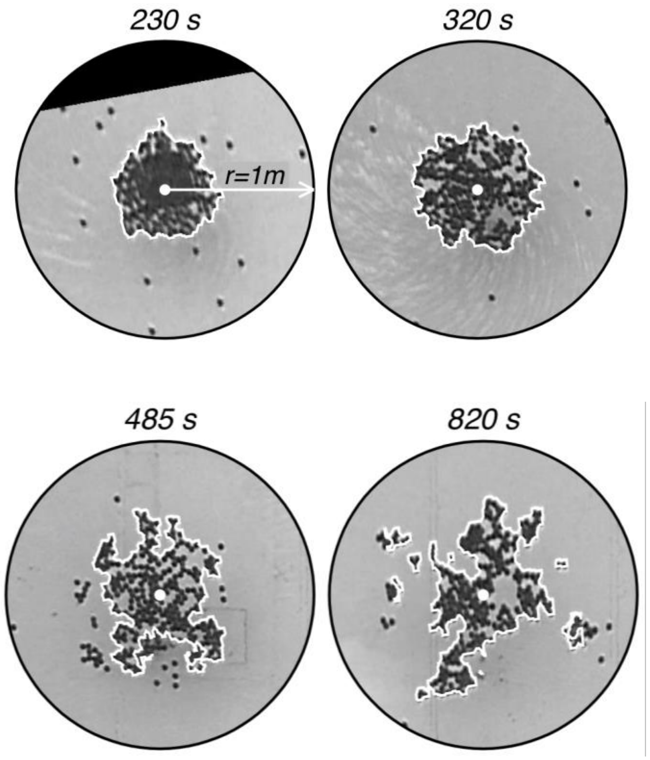
Secondary flow components - radial velocity



Evolution of TCS radial velocity profile



Tracer-conglomerate compactness at TCS center

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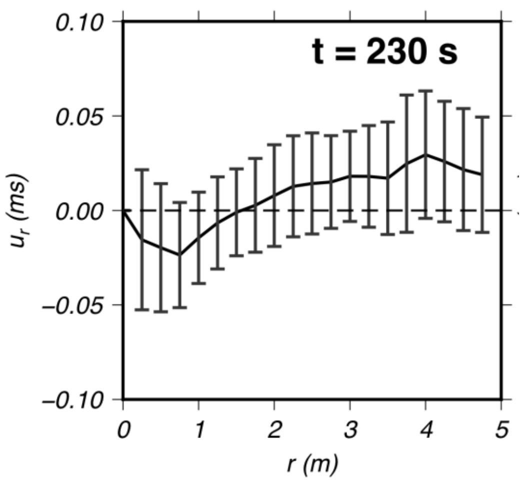
Secondary flow components - vertical velocity

- Use kinematic free surface boundary condition for axisymmetric flow

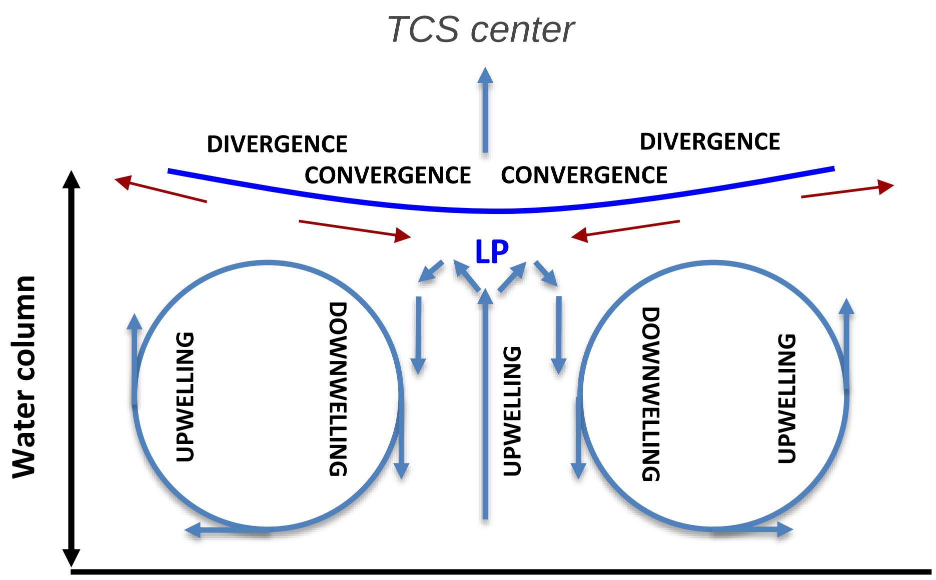
$$w(r,\eta) = \frac{\partial \eta}{\partial t} + \frac{u_r u_\theta^2}{gr}$$

, where *w(r,η)* is the vertical velocity at the free surface (+ upwards)

positive quantity



Radial velocity profile



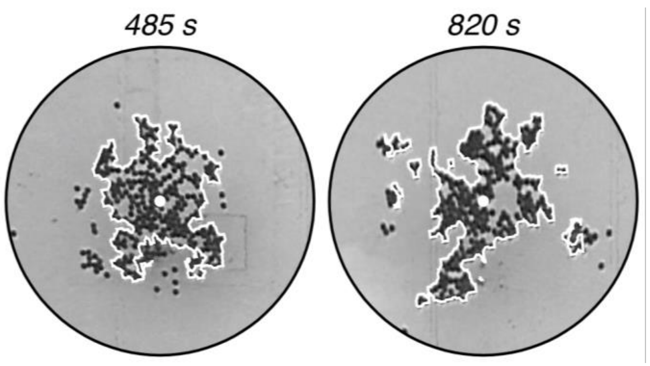
TCS re-circulation pattern around center

Flow transition to Q-2D

- Study the decay of the kinetic energy of the radial and azimuthal flow components

- The kinetic energy of velocity components *(ur, u*$_\vartheta$*)* in the free surface are evaluated from

$$E_{k,i} = \pi\rho \int_0^R u_i^2(r) r dr,$$



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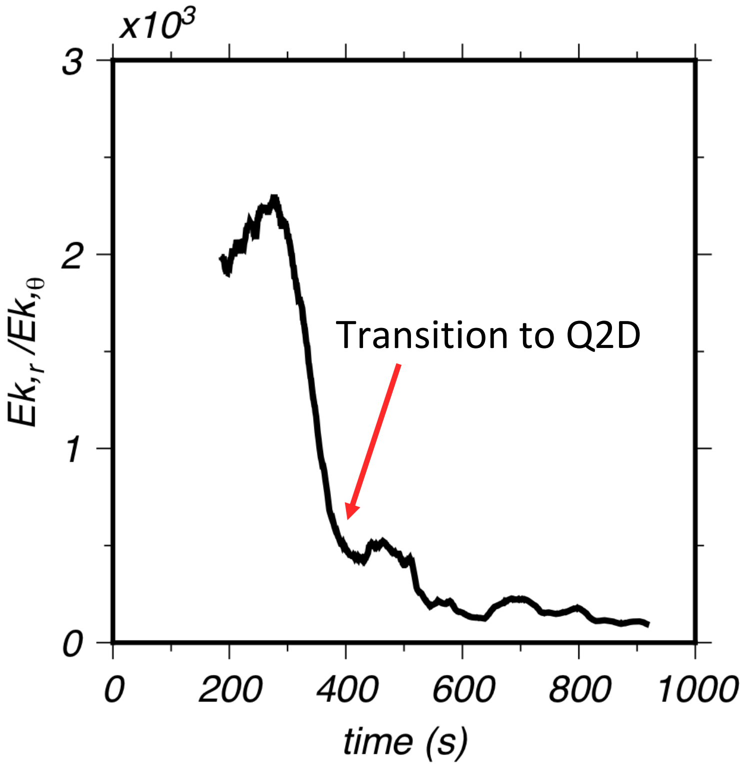

Ratio of radial and azimuthal kinetic energy

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Summary

- The flow structure of a wave-induced TCS was studied through a series of large-scale experiments in a wave basin
- First-order models were derived to describe TCS flow field, spatial growth, kinetic decay, and the FSE around the TCS-center
- The secondary flow components suggest a flow recirculation pattern along the water depth
- The secondary flow components decay faster than the primary flow component, leading to a more Q-2D flow at later stages.

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- Myronis Foundation fellowship.

Acknowledgements

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- Many thanks to Aykut Ayca (USC) and Adam Ryan (OSU) for their help during the experiments at OSU.