The Impact of Structured Stirring on the Success of External Fertilisation by Broadcast-Spawning

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Motivation

The vast majority of sessile benthic invertebrates reproduce via external fertilisation by broadcast spawning. The worldwide demise of coral reefs and other sessile fauna highlights the need for better understanding of the physical-biological interactions which govern this little understood but important reproduction technique. Understanding the physical environment in which this takes place allows identification of adaptive strategies which increase fertilisation efficiency. [1]

External fertilisation by broadcast spawning

While fertilisation success by this method can be close to 100% many factors inhibit successful fertilisation [2]. Adaptations such as simultaneous spawning are key to avoiding sperm limitation by dilution. Conversely, polyspermy avoidance adaptations have been seen in all free-spawning marine invertebrates studied to date indicating that eggs can experience very high sperm concentrations. This is likely due to the role hydrodynamics plays in the mixing of gametes into concentrated thin filaments

Fig.1 *Coral spawning, Sangalaki, Indonesia. From [3]*

Historical modelling paradigms vastly underestimate observed fertilisation success

Fertilisation is modelled as a bimolecular reaction proportional to “virgin” sperm and egg concentrations. Gamete concentrations are historically modelled as an analytical time averaged Gaussian plume with spreading rates determined by an effective turbulent diffusivity and often modified by laminar flow.

These models predict fertilisation success rates of less than 1% whereas field measurements are rarely less than 5% and typically in the range of 50-90% success rates for initial separations of up to a meter. These methods do not include the instantaneous structure of gamete plumes.

A new modelling paradigm is required.

Analytical model of gamete stirring by a single point vortex

The single 2D vortex has an analytical solution which forms the basis for modelling more complex pseudo-turbulent flow fields. Gamete concentrations are included as a scalar field governed by a pair of reactive advection-diffusion equations coupled to the vector field of the flow. Coupling is determined by the product of the Reynolds number (R_e) and the Schmidt (S_c) number.

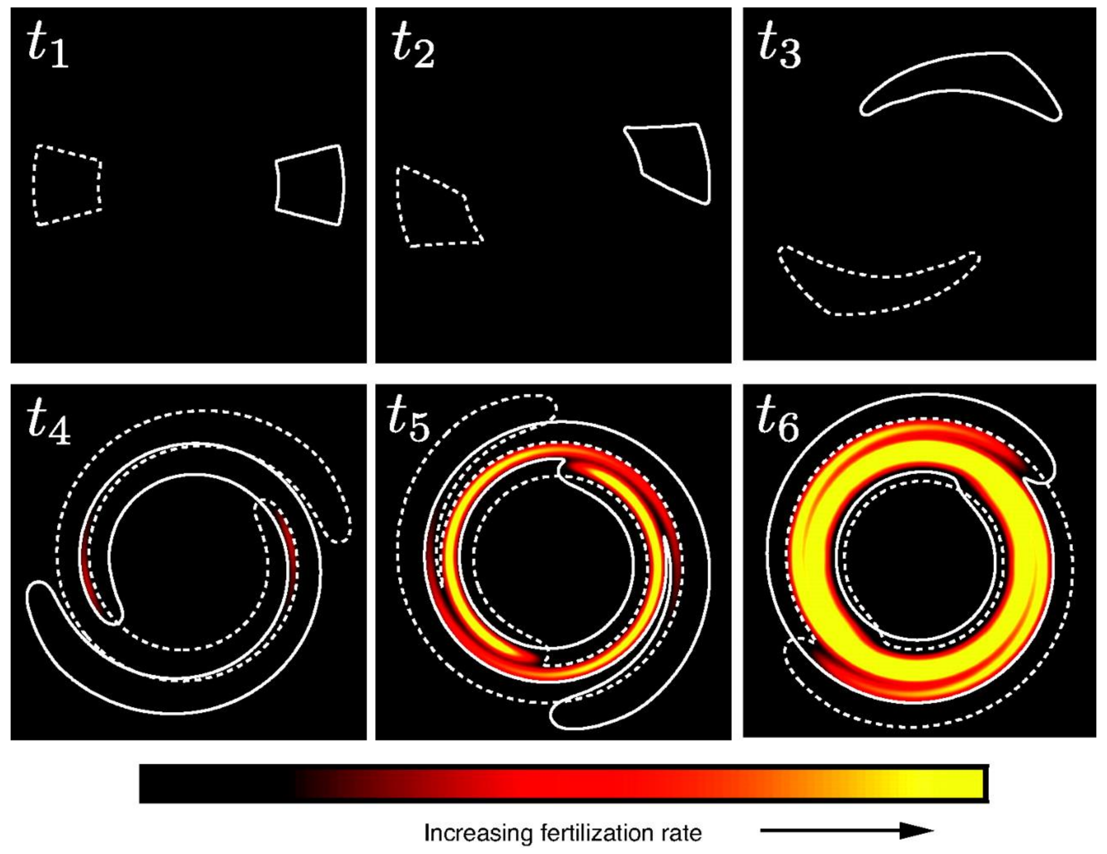


Fig.2 *Initially separate sperm and egg populations at t_1 in a single point vortex. At subsequent time points egg and sperm particles assume a circularly symmetric concentration distribution with high fertilisation success rates indicated in yellow. From [1]*

Coalescence in a 2D pseudo-turbulent flow field

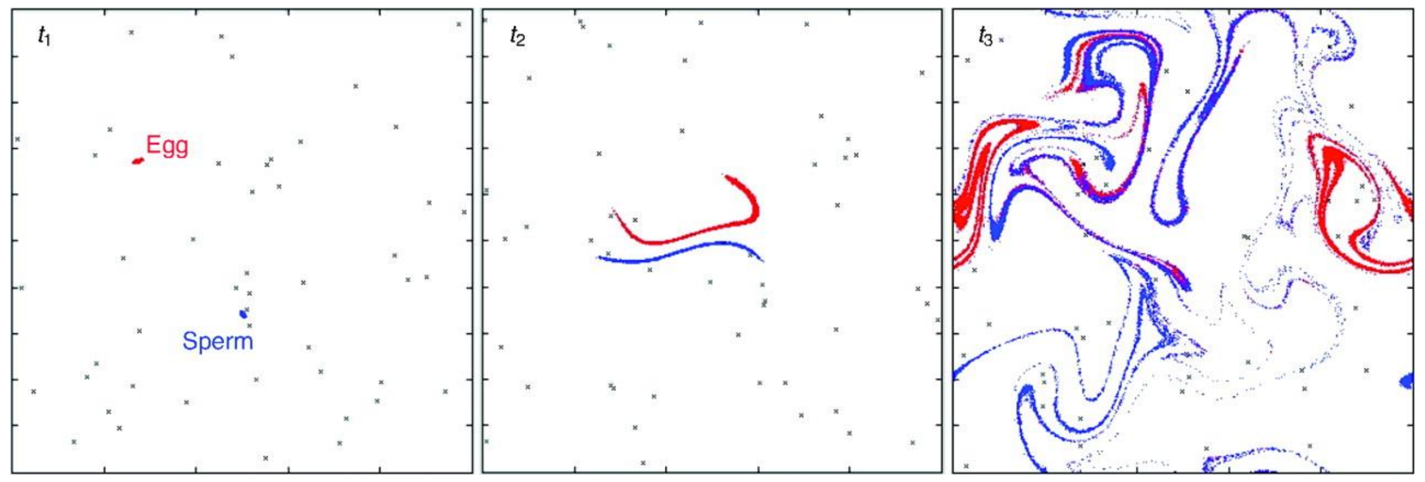
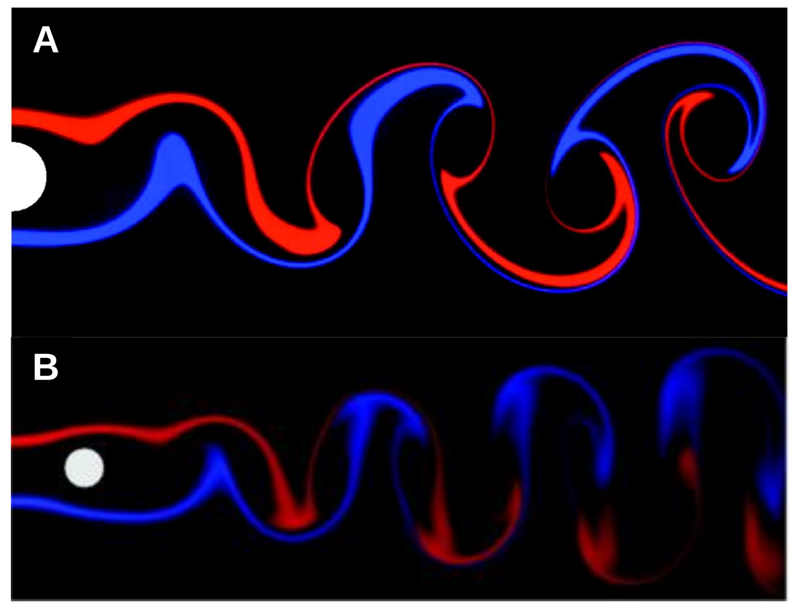


Fig.3 *A numerical simulation with 50 interacting vortices can produce a chaotic flow field in which spatial correlations, resulting in coalescence along the unstable manifolds of the vector field, are rapidly formed resulting in enhanced fertilisation rates. From [1].*

Comparison of numerical and experimental simulations for 2D flow around an obstacle

Simple experimental simulations of external fertilisation in turbulent flows have shown increases in fertilisation rates relative to laminar flows.



Two colour fluorescence system
$R_e = 100$
$S_c = 1000$

Numerical Simulation
$R_e = 100$
$S_c = 10$

Fig.4. *Two colour laser induced fluorescence to allow visualisation and quantification of concentrations of egg (red) and sperm (blue) in a non laminar flow field (panel A). Comparison to numerical simulations (panel B). From [1].*

These experiments demonstrate the possibility that measurements could be made of coalescence in complex 3D turbulent flows far more complex than what is currently feasible using in-silico numerical simulations. [1][4]

Conclusions

Simulations demonstrate that the vector field of a simple vortex flow induces structural correlation on initially distant gamete parcels. **This enhances fertilisation rates.**

These results are replicated in simulations of more realistic turbulent flows.

Laboratory experiments allowing quantification of this fertilisation enhancement in real 3D turbulent flows are being developed.

Future Work

The selective benefit of biological adaptations is yet to be successfully integrated into modelling paradigms. These include:

- Gamete buoyancy expected to result in more efficient coalescence in free-surface flows.
- Sperm motility and taxis expected to result in short length-scale directed diffusion.
- Viscous non-Newtonian gamete secretion matrices expected to reduce the scalar dilution and prolong the structured stirring of gamete filaments.

[1] J.P. Crimaldi, The role of structured stirring and mixing on gamete dispersal and aggregation in broadcast spawning, *Journal of Experimental Biology*, 2012, 251, 1031-1039
[2] E.A. Serrão, J.N. Havenhand, Marine Hard Bottom Communities: Fertilization Strategies, *Springer*, Heidelberg, 149-164
[3] M. Oldfield, Corals Spawning, *The Epoch Times*, http://www.theepochtimes.com/n2/science/science-in-pics-corals-spawning-59372.html, accessed 21/05/2014
[4] M.A. Soltys, J.P. Crimaldi, Scalar interactions between parallel jets measured using a two-channel PLIF technique, *Experimental Fluids*, 2011, 50, 1625-1632

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