United By Noise:
Randomness Helps Swarms Stay Together

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Outline

- Introduction to locust swarms
- Experimental findings
- A self-propelled particle model
- Comparing the model to the data
- Revising the model
- Inferences of revised model on individual locust behaviour
- Possible explanations

Biblical Proportions

An old problem

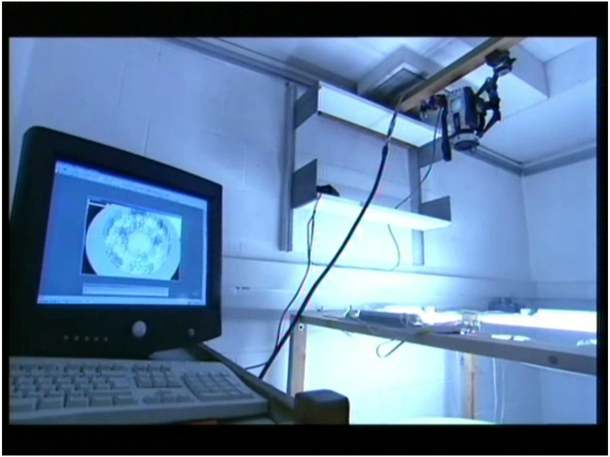
"The locusts came up over all the land of Egypt and settled in all the territory of Egypt; they were very numerous. There had never been so many locusts, nor would there be so many again. For they covered the face of the whole earth, so that the land was darkened; and they did eat every herb of the land, and all the fruit of the trees which the hail had left: and there remained not any green thing in the trees, or in the herbs of the field, through all the land of Egypt."
Exodus(10:14-15)

Facts

Why do we care?

- Affect:
  - 60 countries
  - 10% of the world's population
- Cover:
  - 29 million square kilometres
  - 20% of the total land surface of the world
- Traffic accidents
- House Eating!!

The Experiments



Buhl et al. *Science.* From Disorder to Order in Marching Locusts. **312(5778)**:1402-1406, 2006.

Movie

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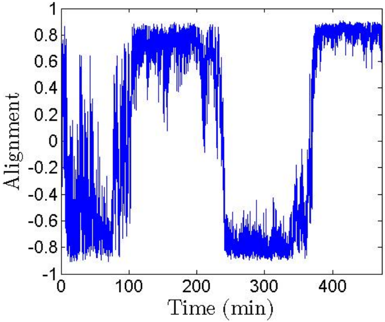
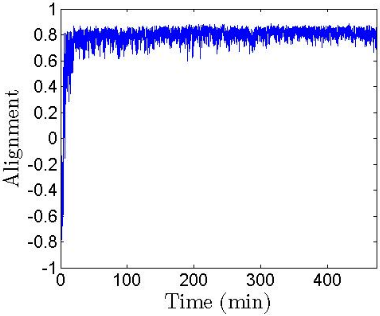
One minute of experimental collective locust motion.

Experimental Findings

1. Collective motion
2. Switching between two steady states: Clockwise and Anticlockwise
3. Stochastic process



Average velocity (or aligment) of 20 locusts over a period of 8 hours



Average velocity (or aligment) of 60 locusts over a period of 8 hours

Cziròk Model

Self-propelled paticle model

Position update equation:

$$\Delta x_i = u_i \Delta t,$$

Velocity update equation:

$$\Delta u_i = \left\{ G\left(\bar{u}_i^{loc}\right) - u_i(t) \right\} \Delta t + \Delta Q \eta \left(\bar{u}_i^{loc}\right), \qquad (*)$$

where

$$\bar{u}_i^{loc} = \frac{1}{n_i(t)} \sum_{j \in \mathcal{J}_i^R} u_j(t),$$

$\mathcal{J}_i^R$ is the set of locusts inside the interaction radius of locust i,
$\eta\left(\bar{u}_i^{loc}\right) \equiv 1$, and

$$G(z) = \frac{1}{1+\beta}\{z + \beta \text{sign}(z)\}.$$

SDE Coefficient Estimation Approach I

Assume the average velocity can be modelled by an SDE:

$$U(t+dt) = U(t) + F(U(t))dt + \sqrt{2D(U(t))}dW.$$

dW is the standard Wiener process or standard Brownian motion.
In the above SDE the formula for the potential is

$$\phi(U) = -\int_0^U \frac{F(s)}{D(s)}ds + \ln(D(U)); \qquad (1)$$

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SDE Coefficient Estimation Approach II

Rewrite the SDE:

$$U(t+dt) - U(t) = F(U(t))dt + \sqrt{2D(U(t))}dW.$$

We want to find the drift and diffusion coefficeints.

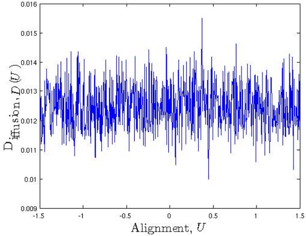
Drift:

$$F(U) \approx \left\langle \frac{U(t+dt) - U(t)}{dt} \right\rangle,$$

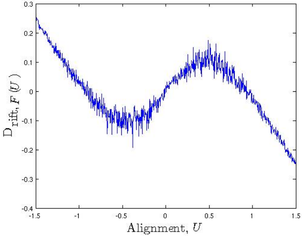
and diffusion:

$$D(U) \approx \frac{1}{2} \left\langle \frac{[U(t+dt) - U(t)]^2}{dt} \right\rangle.$$

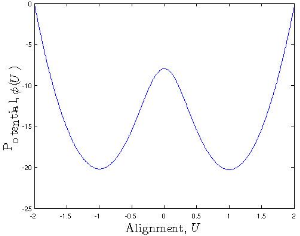
Model Results - 30 Particles



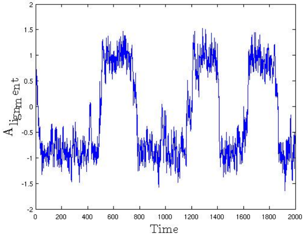
Diffusion, $D(U)$



Drift, $F(U)$

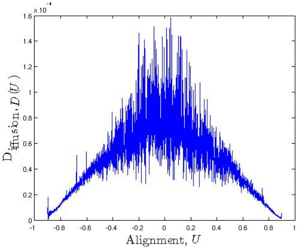


Potential, $\phi(U)$

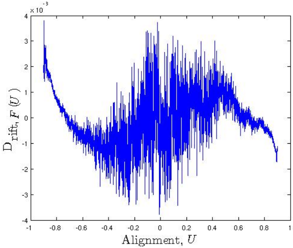


Alignment time series

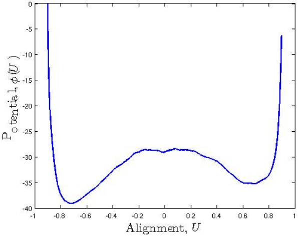
Experimental Data Analysis - 30 Locusts



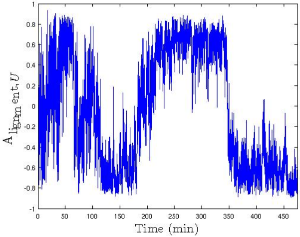
Diffusion, $D(U)$



Drift, $F(U)$



Potential, $\phi(U)$



Alignment time series

Model Revision

Recall the velocity update equation (*):

$$\Delta u_i = \left\{ G\left(\bar{u}_i^{loc}\right) - u_i(t) \right\} \Delta t + \Delta Q \eta\left(\bar{u}_i^{loc}\right),$$

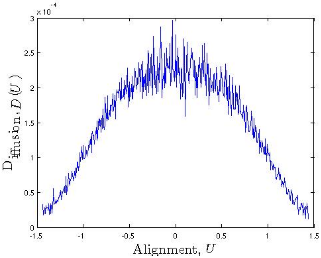
Previously $\eta\left(\bar{u}_i^{loc}\right) \equiv 1$.

We now take $\eta\left(\bar{u}_i^{loc}\right) = \frac{3}{2}\left\{1 - \left(\frac{\bar{u}_i^{loc}}{|\bar{u}_i^{loc}|_{max}}\right)^2\right\}$,

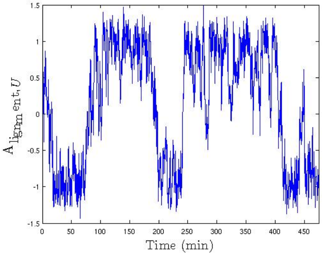
in an attempt to replicate the quadratic-like diffusion.

Here $|\bar{u}_i^{loc}|_{max}$ is the maximum of the absolute value of the mean local velocity.

Revised Model Results



Revised Diffusion, $D(U)$



Alignment time series

- From local alterations to the individual-based model we have replicated a group level propety.
- We infer that when the group becomes unaligned individuals increase the randomness of their motion in order to become realigned.

Possible Explanations

- Confusion - Disorientated locusts find it harder to gauge the velocities of their neighbours accurately.
- Evolution - Alignment increase harvesting efficiency and reduce predation.
- Cannibalism - Dangerous to fall out of line as sides are more vulnerable.

Cannibalistic behaviour of locusts and crickets

Conclusions

- Switching time between steady states is exponential in locust number.
- At high densities it becomes increasingly difficult to influence a group's motion.
- Agent-based approach allows speculation about the behaviour of individual locusts from group level information.
- Effect of individual alterations can be tested using the coarse variable U.
- Increased individual randomness when unaligned helps the swarm to stay together.

For more details see: Yates et al. *Proc. Natl. Acad. Sci. USA* Inherent noise facilitates cohesive behaviour in swarms. **106(14)**:5464-5469, 2009.

Extensions

- Adding stationary locusts into the model (i.e. a two-state model).
- Considering individual leader behaviour.
- Allowing evolution of parameters.
- Modelling in two dimensions and comparing to field data.

Locusts in the field/dessert!

Acknowledgements

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"Pharaoh says he doesn't want any locust insurance."