Evolution of mesoscales in a countable configuration space

UNIVERSITY OF MIAMI
ROSENSTIEL SCHOOL of MARINE, ATMOSPHERIC & EARTH SCIENCE

Brian E. Mapes, University of Miami
mapes or bmapes @miami.edu

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1. Introduction

QUESTION: How do *unlikely but efficient* mesoscale organizations of convection evolve from more *likely but random* configurations of convective updrafts, in a newly convecting fluid?

Evolutionary reasoning principles:

- Consider an abstract space of possible configurations of convective cells (here, w=1 updrafts)
- Vast majority of these are un-special; nearly redundant functionally
- A few are 'fitter' at persistence and/or reproduction (propagating)
- Hypothesis: Some config. ***adjacency*** defines a ***gradient*** of 'fitness' for evolution to climb

- Numerical experiments: how fast can a system discover its 'fitter' = 'organized' configurations?

2. Simplest, *enumerable* convection-like configuration space:

* 4x4 lattice, with 4 w=1 "updrafts" at every time. Enforce mean [w]=0.

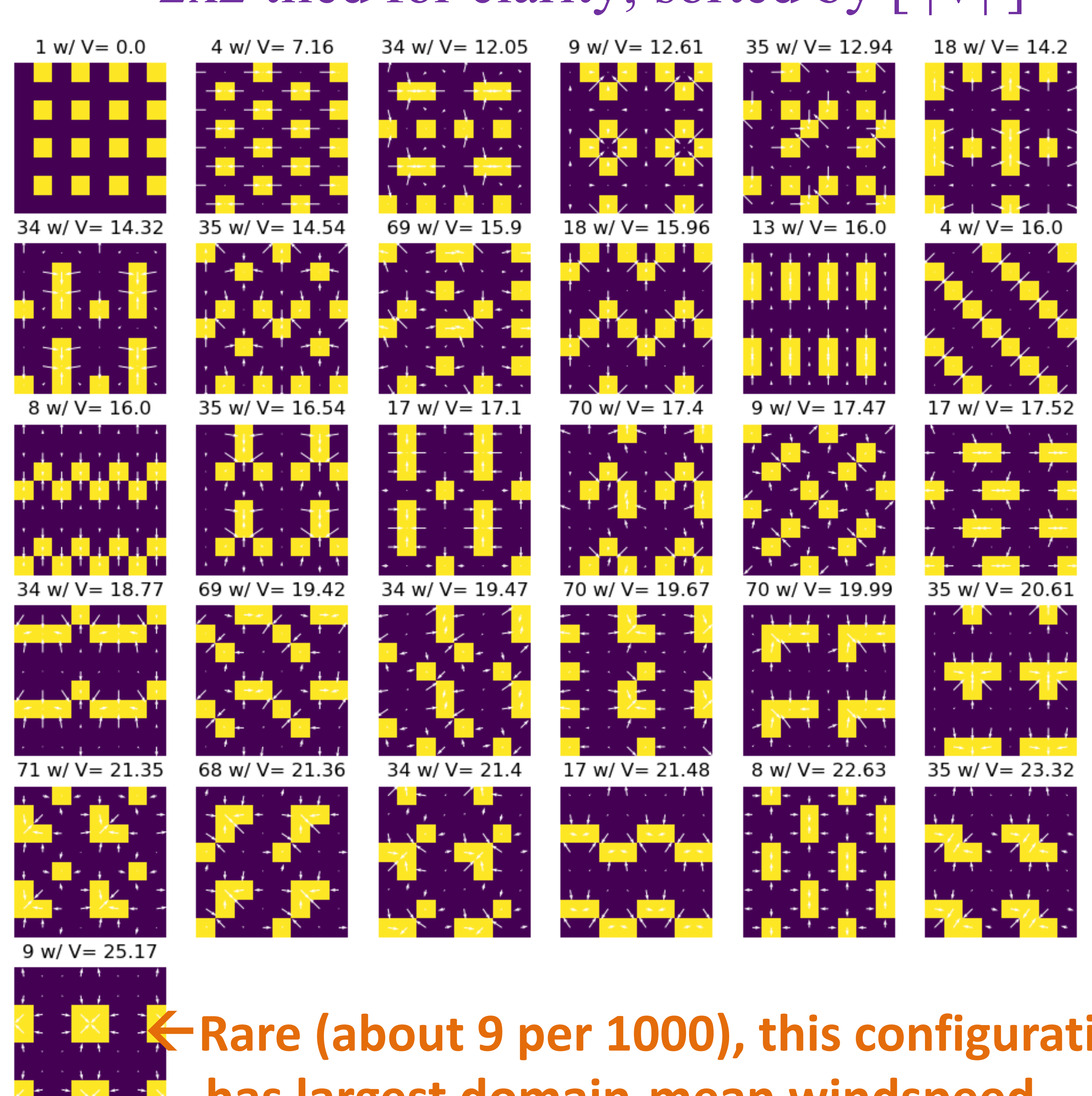
* Velocity potential χ = ifft(fft(w)/k^2) for total wavenumber k. **V** = grad(χ).

simple numpy on unstaggered grid; V=0 for checkerboard w !

- **Randomly generate** configurations: thousands 16*15*14*13 = 43680
- Distinguish equivalencies by domain-mean [|**V**|], and [N_4_neighbors^2]

2 things that shape Prob(w @t+1) pattern: F_{sfc} α |**V**|; Entrainment α (4-N_4)

\# per random 1000 of **31 distinct** 4x4 4-cell configs
2x2 tiled for clarity; sorted by [|V|]



←Rare (about 9 per 1000), this configuration has largest domain-mean windspeed

Simple combinatorics so far.

Interest begins with a temporal evolution law!

Define probability P_w(x,y, t+1). Top 4 P_w locations get w=1.

Iterate.

Do "winners" emerge? How fast? By what pathways?

3. Time evolution: a game with rules + randomness

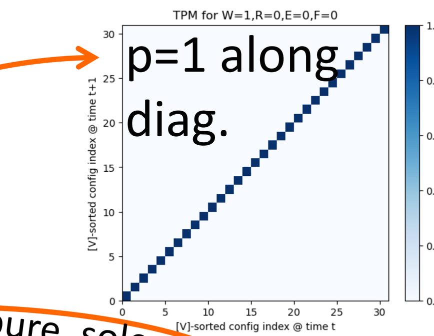
1-timestep jumps → 31x31 *transition probability matrix TPM*

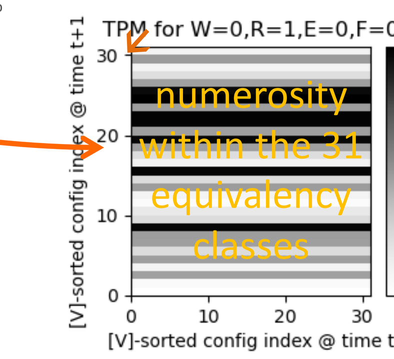
Probability for time t+1, based on configuration at time t:

$$P_w(x,y,t+1) = W\,w(x,y,t) + R\,\text{Noise} + E\,N_{4neigh}(x,y,t) + F\,|\mathbf{V}(x,y,t)|$$

Parameter space: W,R,E,F

- W governs persistence,
- R governs random noise strength
- E governs *entrainment protection by neighbors*
- F governs |*V*|*-dependent surface flux*

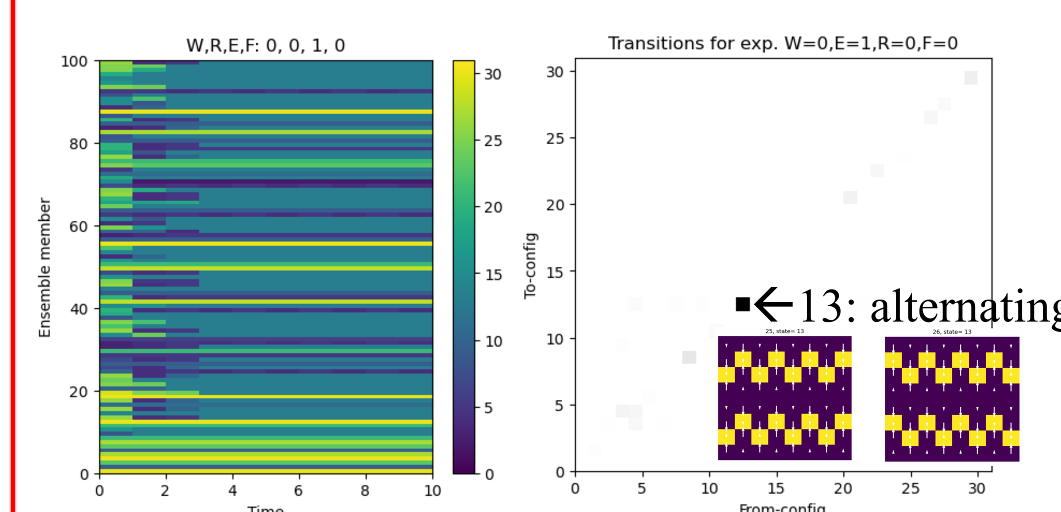




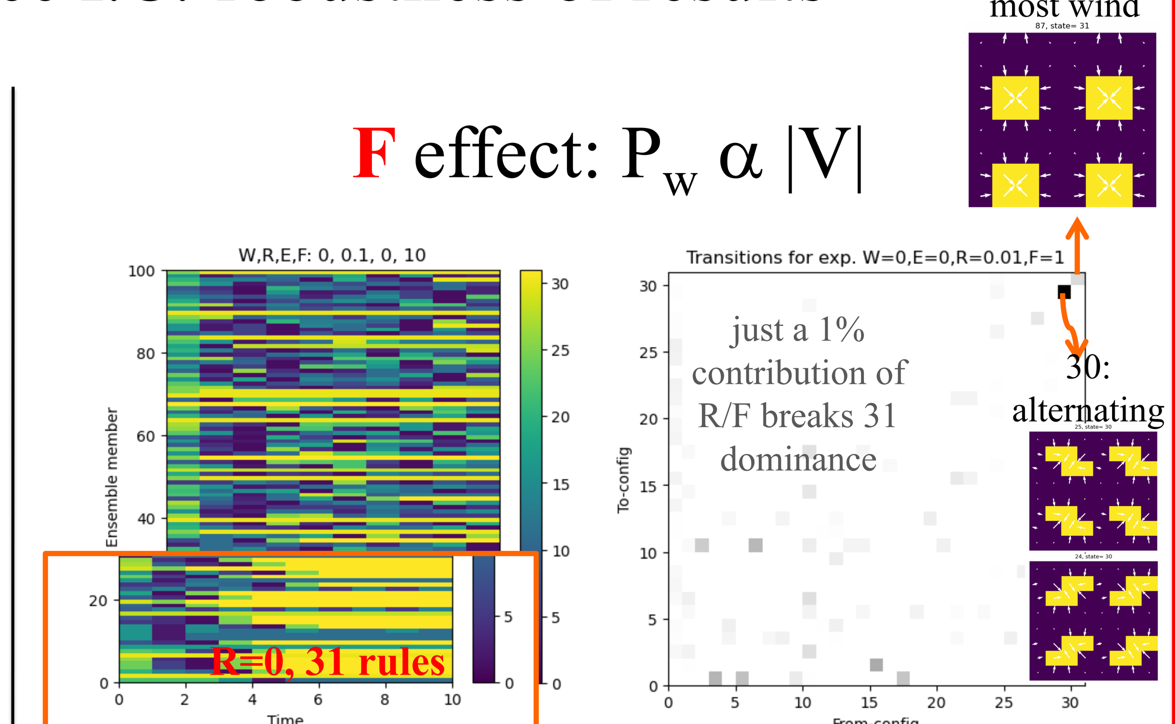
E,F (nonlocal) most interesting for *contingent* evolution...

1. Construct P_w(x,y, t+1; W,R,E,F)
2. Initialize 4 w=1 cells randomly, iterate for NT time steps
3. Repeat step 2. NENS times to see I.C.-robustness of results

E effect: P_w α N_{4neigh}



F effect: P_w α |V|



4. The evolutionary conceptual project

- Even for 4 cells in a 4x4 periodic grid, configuration space is size 31. For 5 in 5x5, > 300, and on from there.
- Welcome to combinatorics, and life! ***Pleiotropy.*** **How can back-propagation of evo. selection work??**
- Absurdly many *configurations* (e.g., DNA) → several *traits* → binary fitness *selection* (survival, reproduction)

- Unlikely but efficient configs can only discover themselves by *pathways* in vast config space. *Can we map it?*
  - In biology, key is meso GRNs (Gene Regulatory Networks).
  - In convection, meso state networks?

References:

Mapes (2025, ArXiv & JAS in press): Evolutionary theory of convective organization (but this work is not there!)