Complexity in marine ecosystems

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Marine ecosystems are complex systems

- Composed by many individuals
- Interactions: predators and preys
- External factors: turbulence, noise…
- Emergent properties: patchiness

An example: Plankton patchiness

- Biological factors act on the individual scale (1mm-10m): mating, predator avoidance, finding food, migration….
- Physical factors act on larger scales (10m-100km): turbulence, current, noise
- Method: Satellite imagery. Analysis of the spectrum of visible light due to the absorption and fluorescence of chlorophyll pigments gives information of phytoplankton biomass

Observations

- Patchiness is much greater for zooplankton than for phytoplankton
- Spatial patterns of phytoplankton and zooplankton are negatively correlated
- Short scales lose their correlations faster than long ones, as observed in satellite measurements

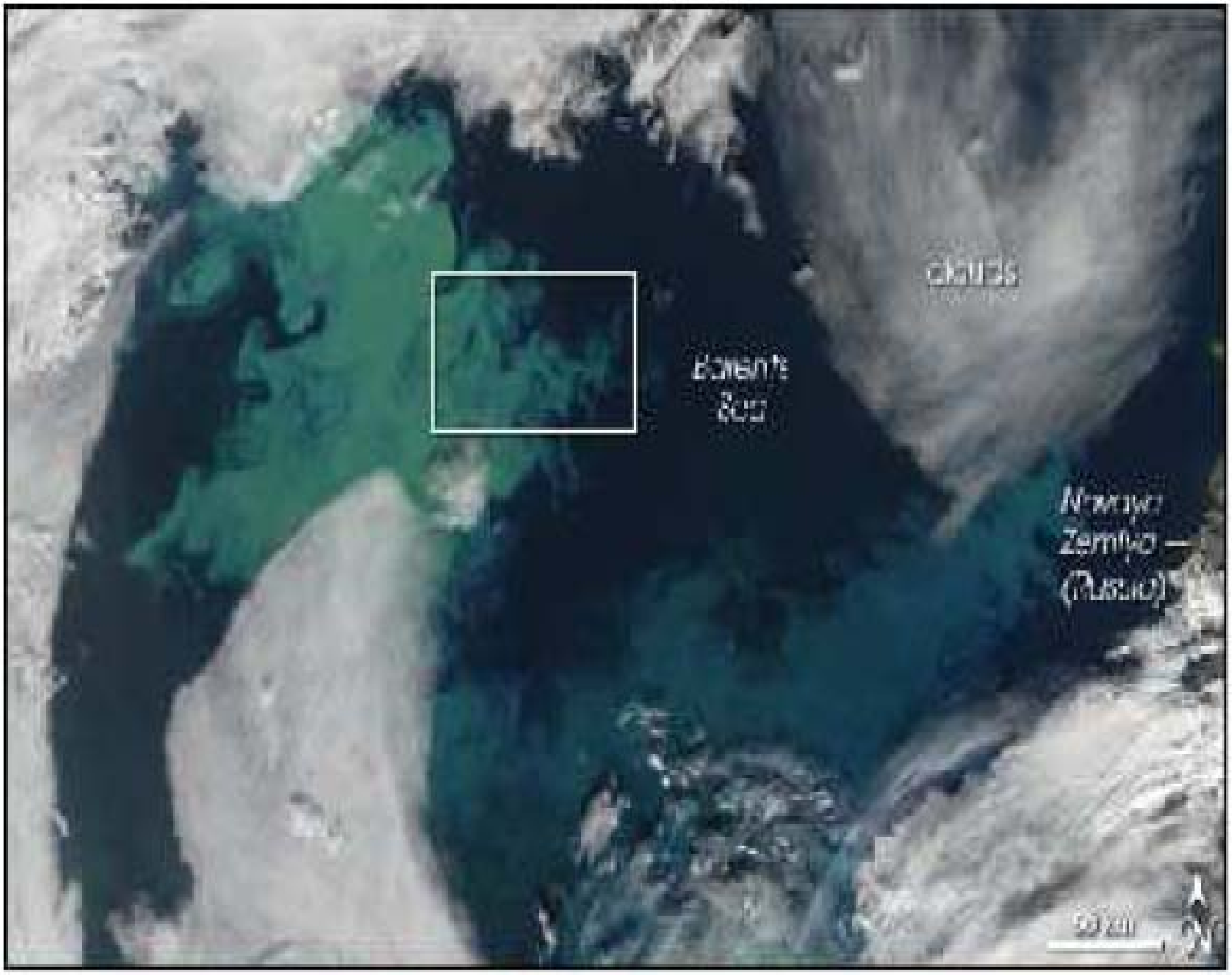
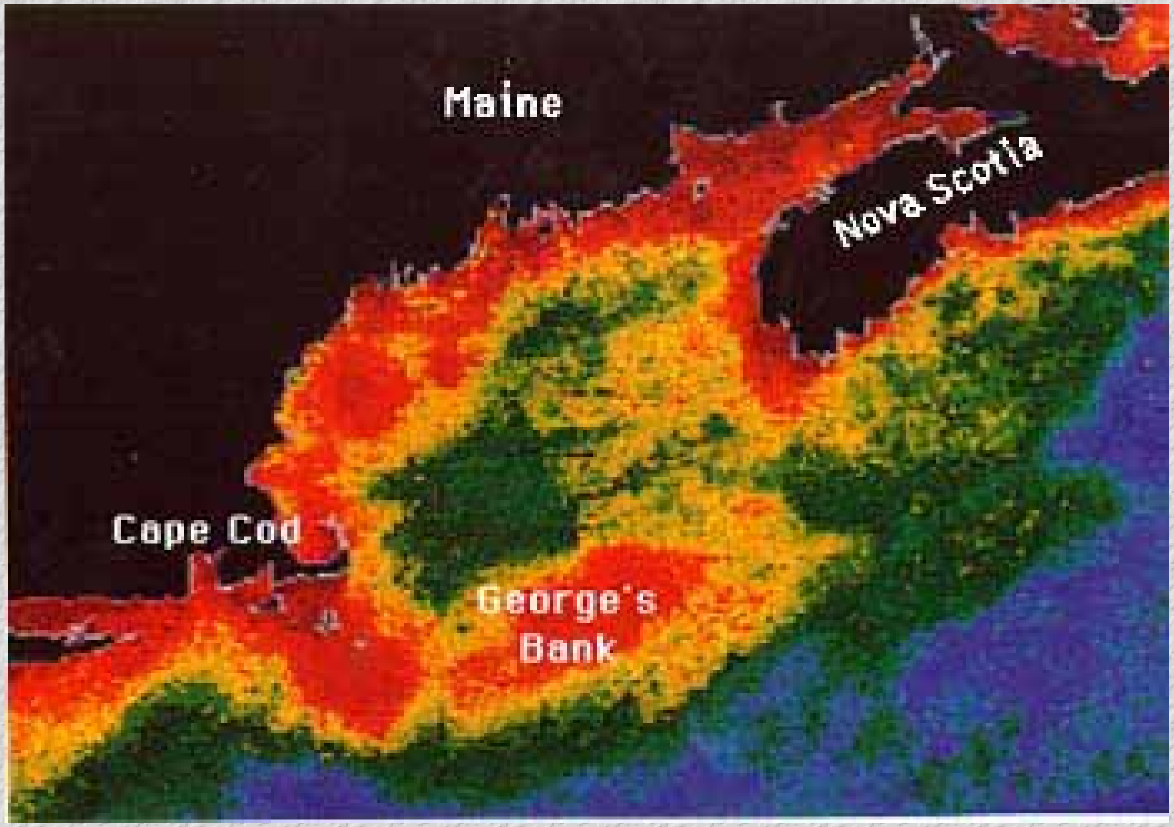


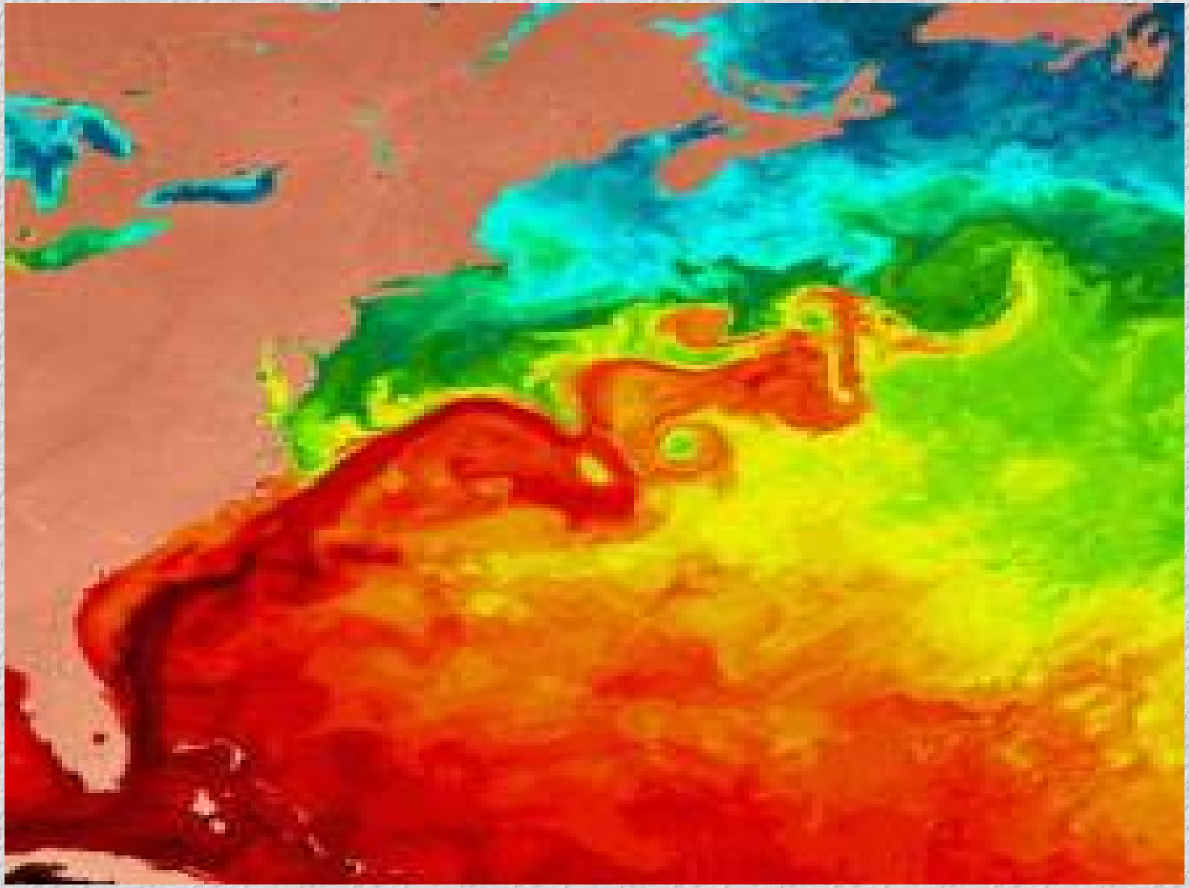
FIG. 1: Image of a phytoplankton bloom in the Barents Sea north of Russia, captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite on August 29, 2006. Source: NASA's Earth Observatory [5].


10 km
N

Plankton distribution

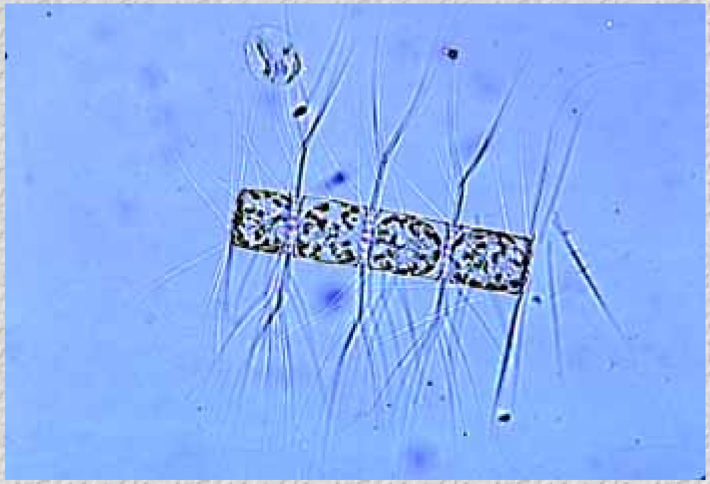


Satellite image of gulf of Maine: Chlorophyll



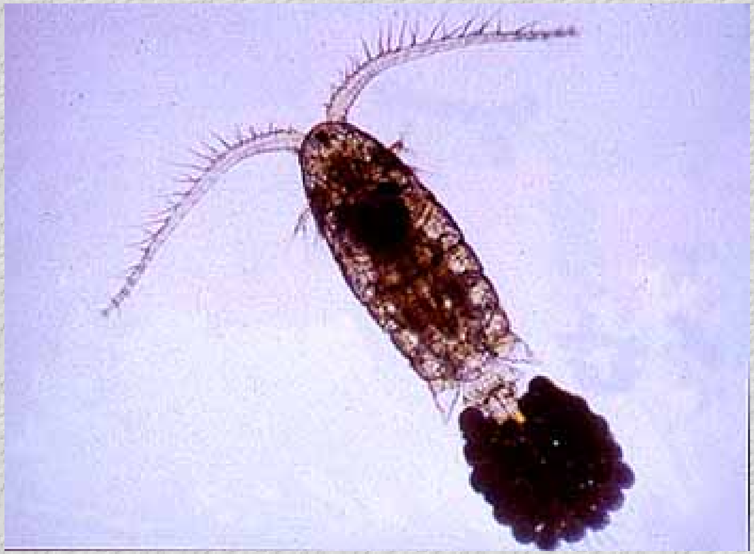
Meganyctiphanes norvegica

Paraeuchaeta elongata



Bacteriastrum hyalinum

Protoperidinium



Copepod *Eurytemora affinis*

Patchiness (observations)

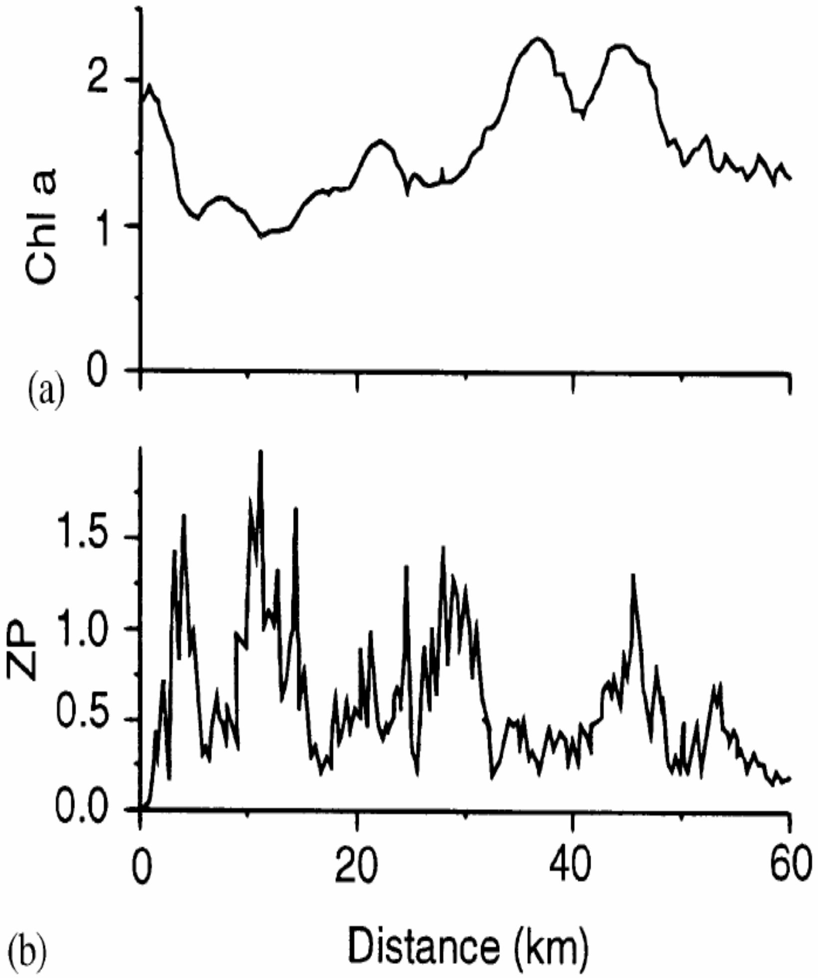


Fig. 1. Transects obtained from field observations for (a) phytoplankton and (b) zooplankton (redrawn from Ref. [5]). Here Chlorophyll *a* is a measure of phytoplankton activity.

Reaction-diffusion models

$$\frac{\partial N}{\partial t} = F_N(N,P) + D_N \nabla^2 N$$

$$\frac{\partial P}{\partial t} = F_P(N,P) + D_P \nabla^2 P$$

N: phytoplankton
P: zooplankton

$$F_N(N,P) = rN(1 - N/K) - cf(N)$$

$$F_P(N,P) = P(gf(N) - \varepsilon)$$

-These models display spatial heterogeneity under homogeneous conditions

- They predict that zoo-p is less patchilly distributed than ph-p, in contradiction with the observed pattern

Features not taken into account by these models

- Diffusion in the sea is not quantitatively well modeled by usual Fickian diffusion

$$\frac{\partial f}{\partial t} = -\vec{v} \cdot \vec{\nabla} f$$

$$D_{eff} \sim k^{\beta-2}$$

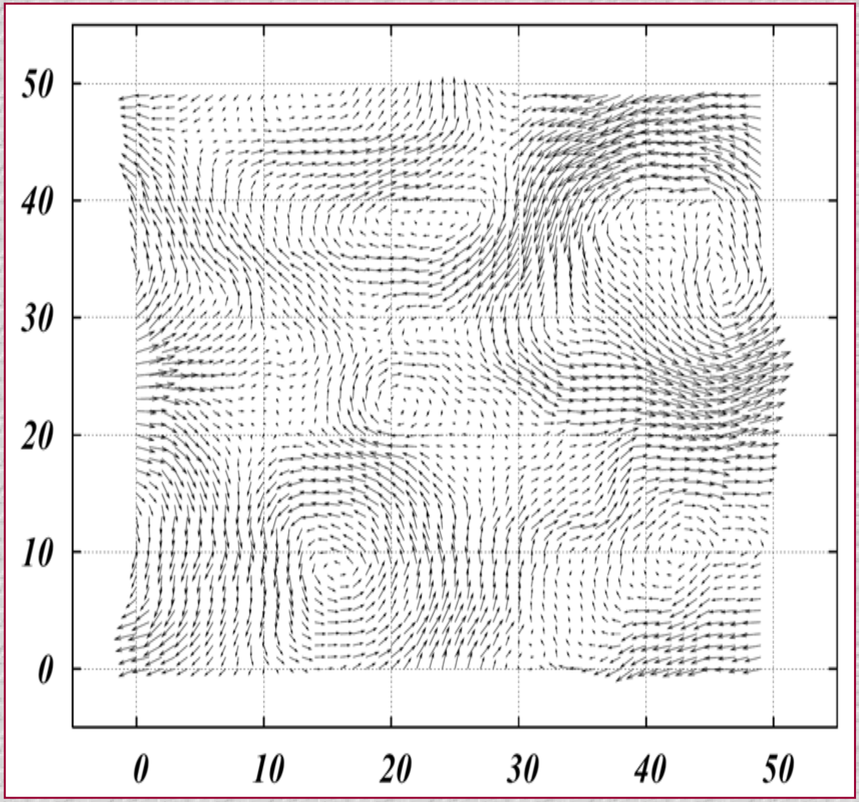
$$\frac{\mathrm{d} f_k}{\mathrm{d} t} = -D|k|^{\beta} f_k$$

Experiments: 2,3

$$< r^2 > \sim t^{2/\beta}$$

$$\beta \sim 0,87$$

Advection

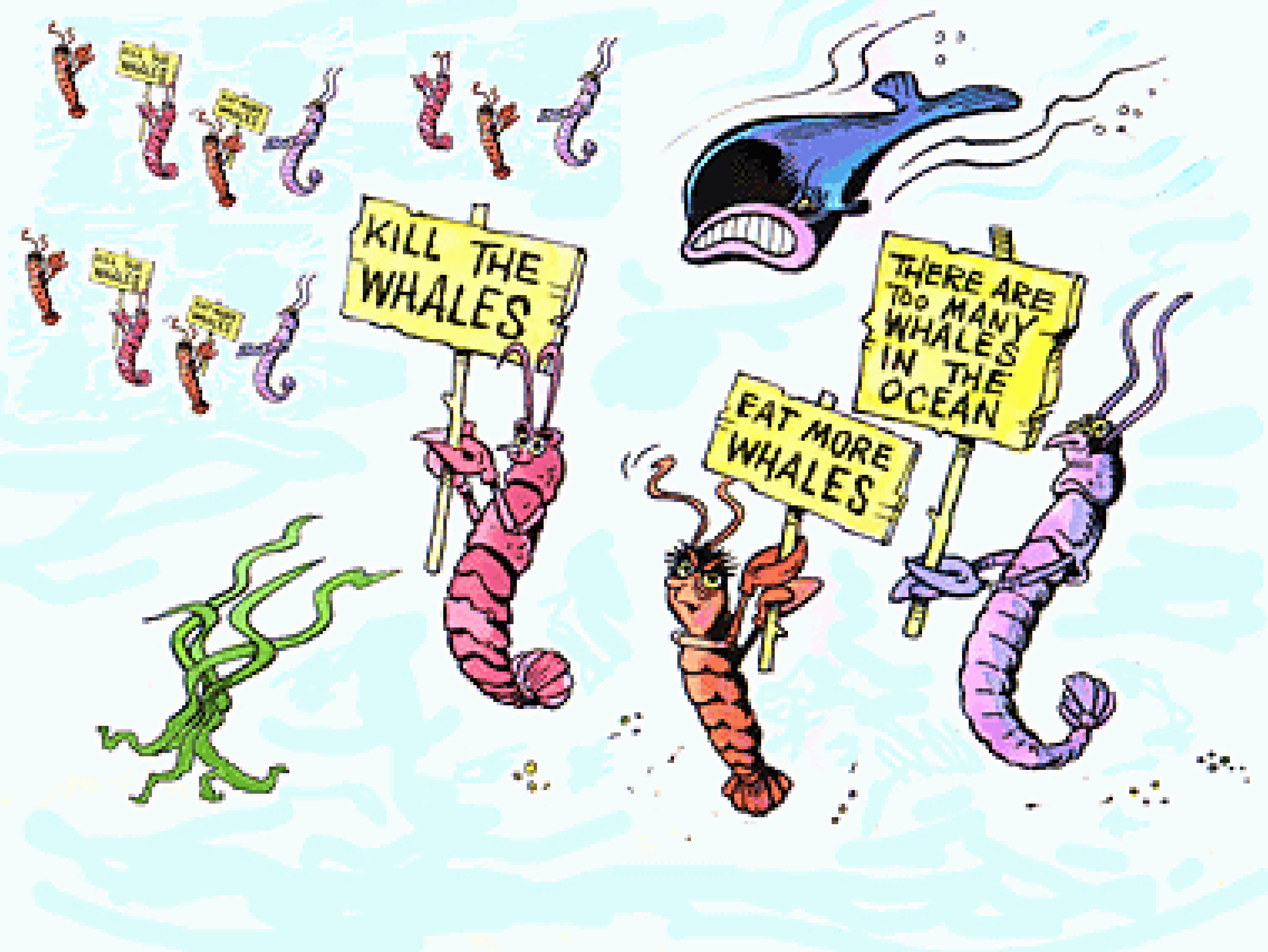


$$\psi(\mathbf{r}) = a \sum_{i=1}^{n} (\pm)_i R_i^2 e^{-(\mathbf{r}-\mathbf{r}_i)^2/2R_i^2}$$

$$\mathbf{v} \equiv \mathbf{v}(x,y) = \left(-\frac{\partial \psi}{\partial y}, \frac{\partial \psi}{\partial x} \right)$$

The role of noise

- Intrinsic stochasticity associated to the dynamics of the population. From birth to death all processes share some degree of chance. Random distribution of fishes and whales.
- The way randomness manifests in the dynamics of individuals depends on the scale we are looking at
- Deterministic eqs. are expected to be valid for high numbers of individuals (ph-p)


KILL THE WHALES
THERE ARE TOO MANY WHALES IN THE OCEAN
EAT MORE WHALES

Model

$$\frac{\partial N}{\partial t} = F_N(N,P) - \vec{v} \cdot \vec{\nabla} N \ ,$$

$$\frac{\partial P}{\partial t} = F_P(N,P) - \vec{v} \cdot \vec{\nabla} P + \xi(t)$$

noise

advection

$$F_N(N,P) = rN(1 - N/K) - cf(N)$$

$$F_P(N,P) = P(gf(N) - \varepsilon)$$

Linear model

$$F_N(N,P) = c_N - a_{11}N - a_{12}P$$

$$\langle \xi(\vec{r},t)\xi(\vec{r}',t')\rangle = 2\sigma^2\delta(\vec{r}' - \vec{r})\delta(t' - t)]$$

$$F_P(N,P) = c_P + a_{21}N - a_{22}P + \xi$$

$$S_N(k) = \frac{a_{12}^2\sigma^2}{(\tilde{D}_N + \tilde{D}_P)\tilde{D}_N\tilde{D}_P}$$

$$\tilde{D}_N \equiv D|k|^\beta + a_{11}$$

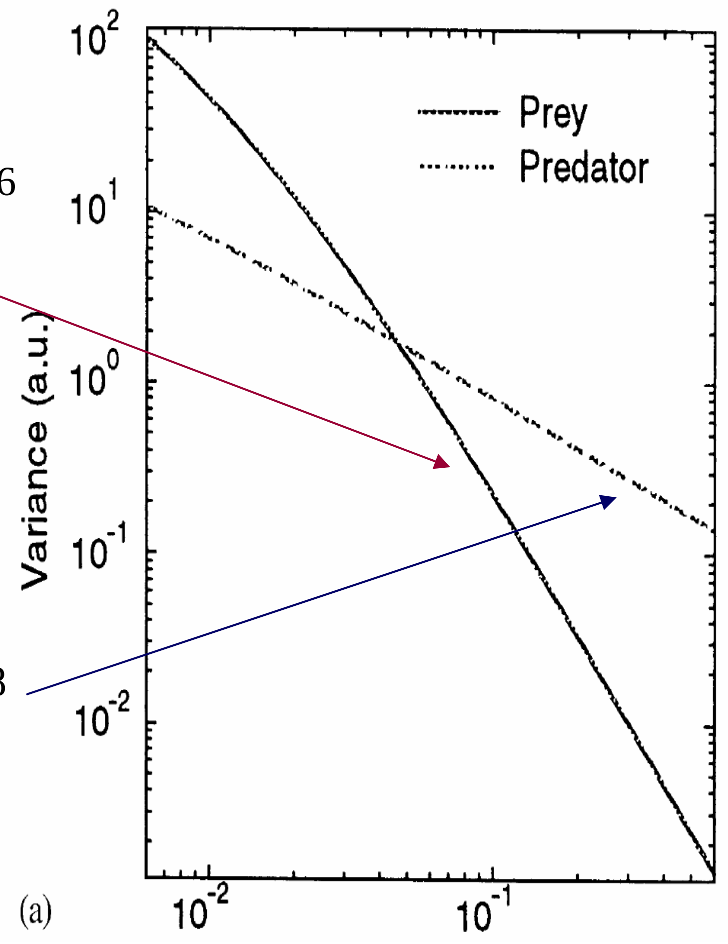
$$S_P(k) = \frac{\sigma^2}{\tilde{D}_P}$$

$$\tilde{D}_P \equiv D|k|^\beta + a_{22}$$

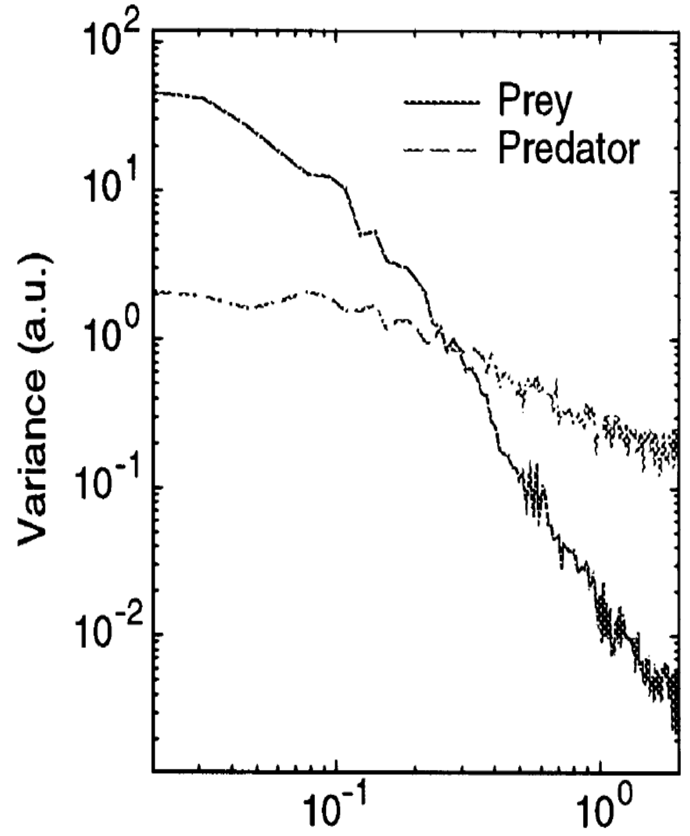
Spectral Analysis

$$k^{-3\beta} \sim k^{-2,6}$$

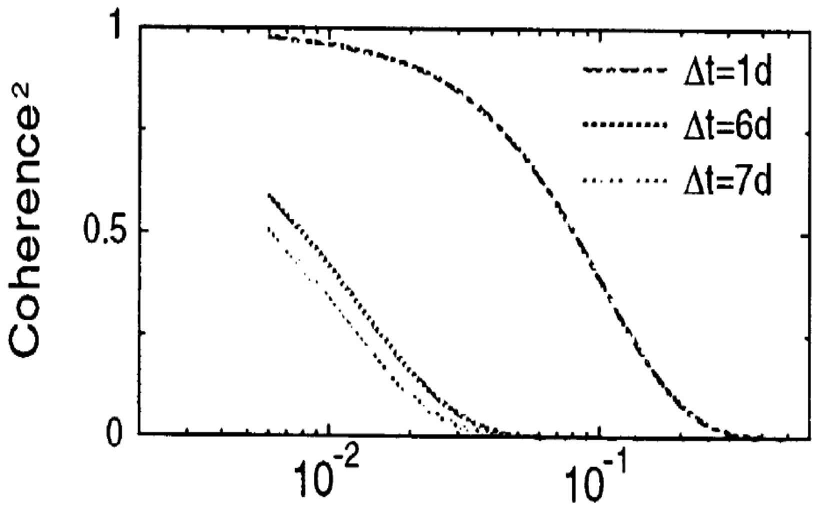
$$k^{-\beta} \sim k^{-0,8}$$



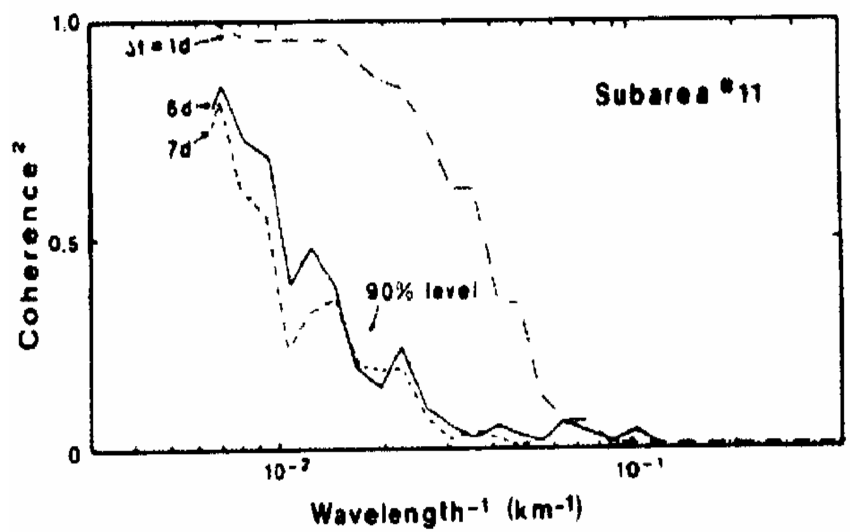
(a)



Coherence between two patterns



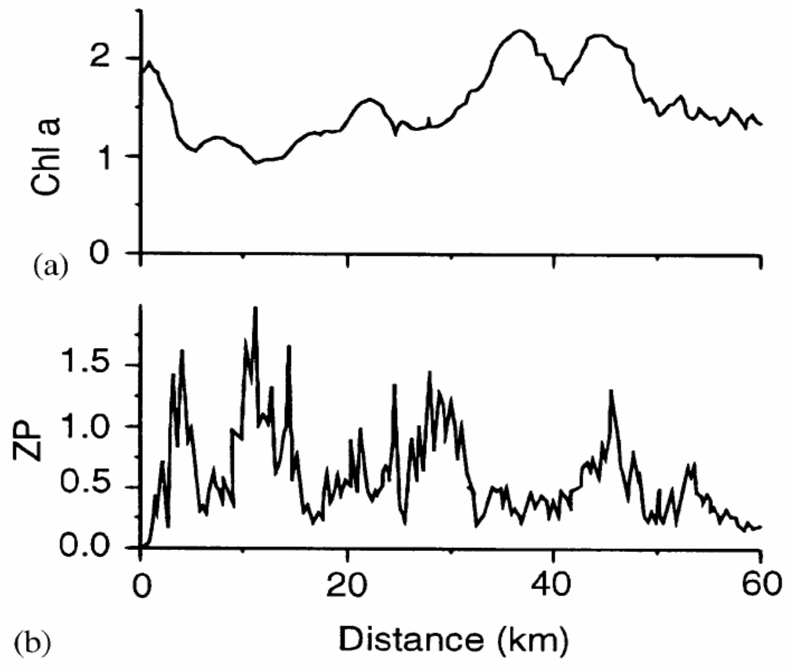
$$\frac{N(k,\Delta t)}{N(k,0)} = \frac{\tilde{D}_P e^{\tilde{D}_N \Delta t} - \tilde{D}_N e^{\tilde{D}_P \Delta t}}{\tilde{D}_P - \tilde{D}_N}$$

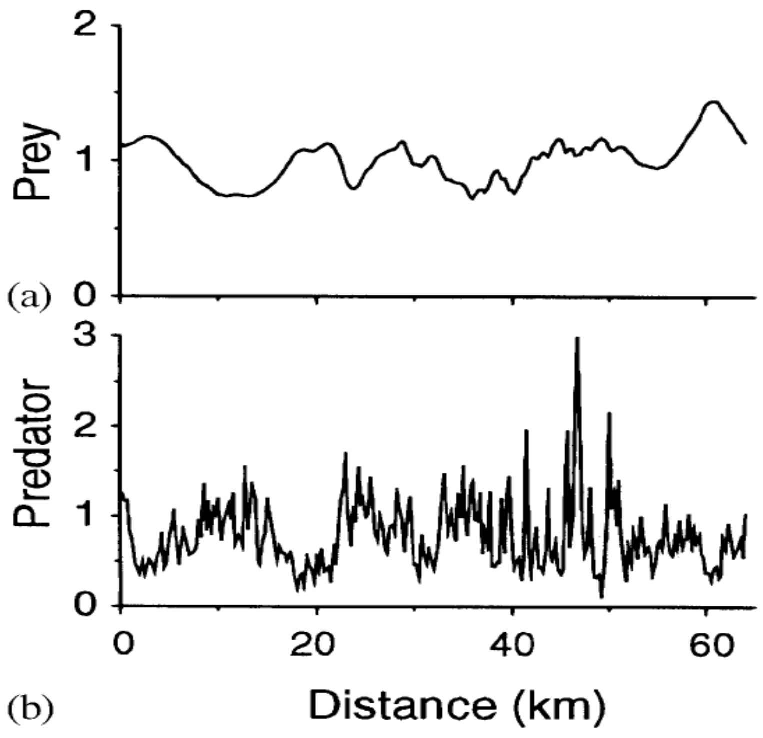


Short scales lose their correlations faster than long ones, as observed In satellite measurements

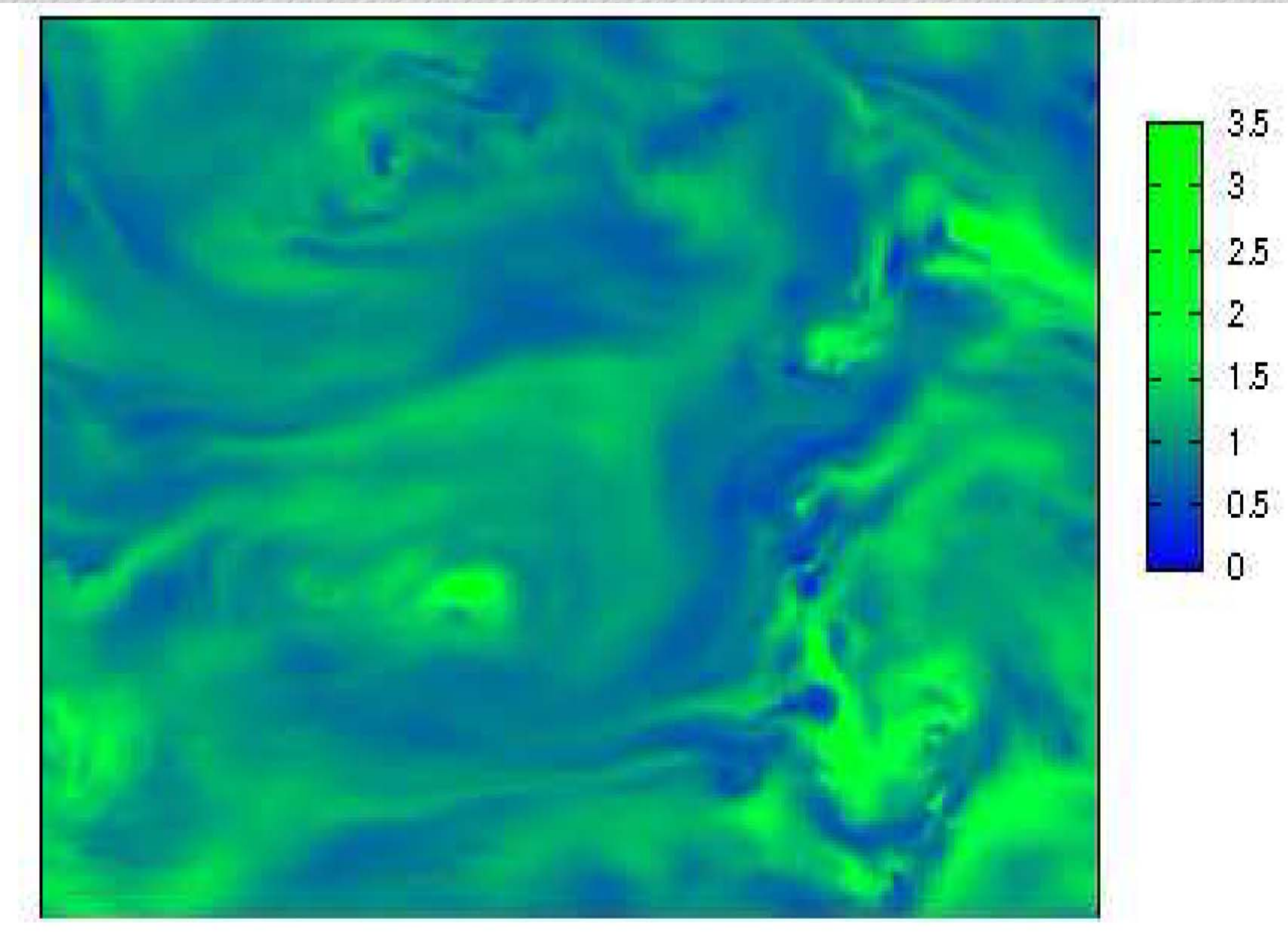
Experiments

Model

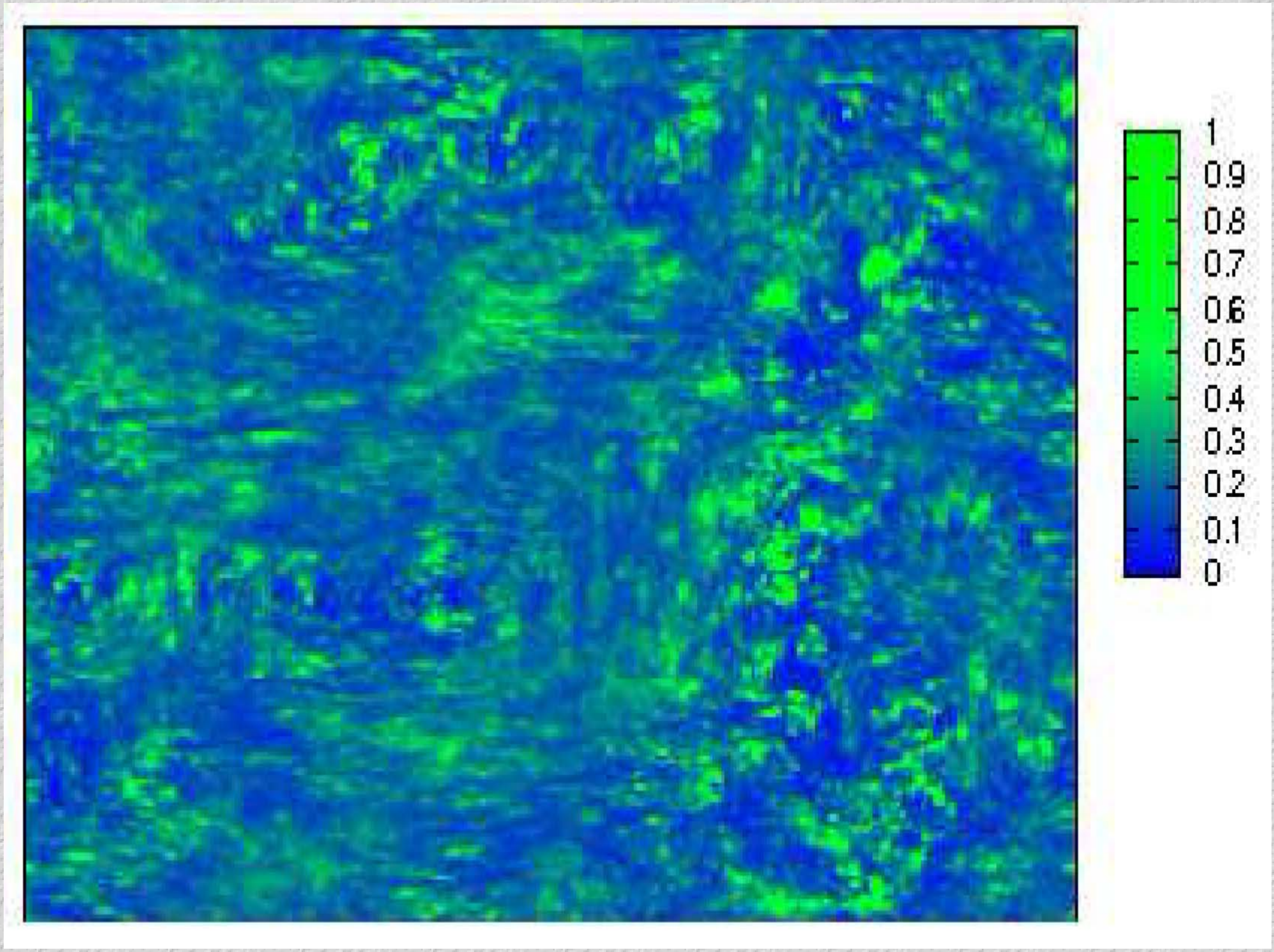




Ph-p



Zoo-p



Conclusions

- Plankton collonies are complex systems
- There exists an interplay between biological and physical factors, suggesting that the form in which small-scale biotic fluctuations are transferred to large scales may constitute a key element in determining the spatial distribution of plankton in the sea

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