# Jet-like Lagrangian Coherent Structures in the Madagascar plankton bloom

**F. Huhn, A. von Kameke, V. Pérez-Muñuzuri**

University of Santiago de Compostela, Spain

**M.J. Olascoaga, and F.J. Beron-Vera**

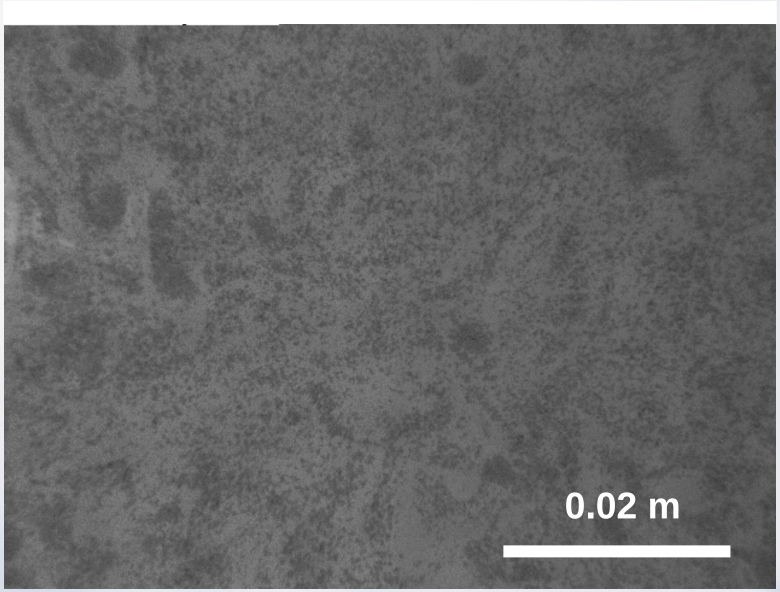
Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, USA

**2nd International Workshop NLOA - Madrid – 04/07/2012**

# Outline

- Madagascar plankton bloom
- Lagrangian methods
- Results
  - Jet-like LCS
  - Eastward propagation
- Summary & Outlook

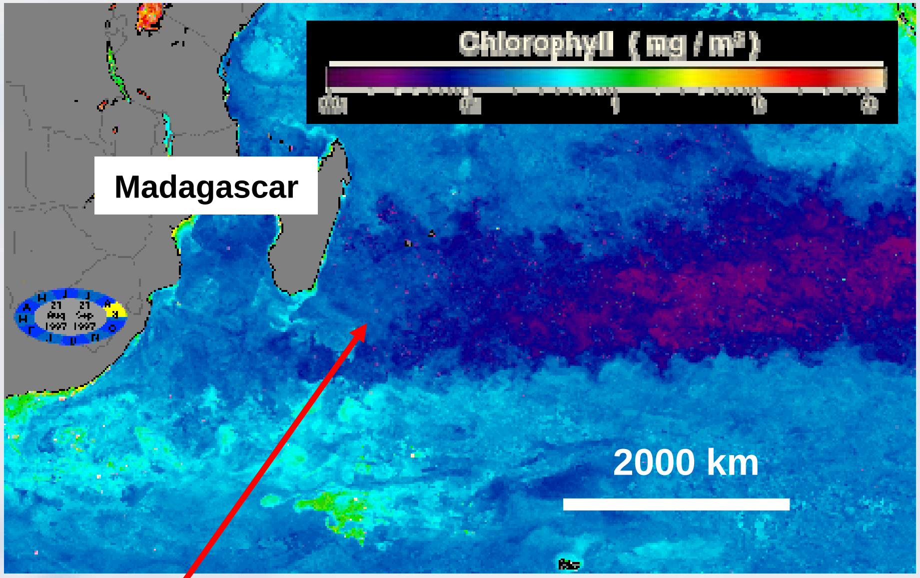
# Motivation




Laboratory reaction-advection-diffusion system
Excitable Belousov-Zhabotinsky reaction in turbulent 2D Faraday flow

*von Kameke et al. (2010), PRE*
*von Kameke et al. (2011), PRL*

Advection by chaotic flow decisive for pattern formation!



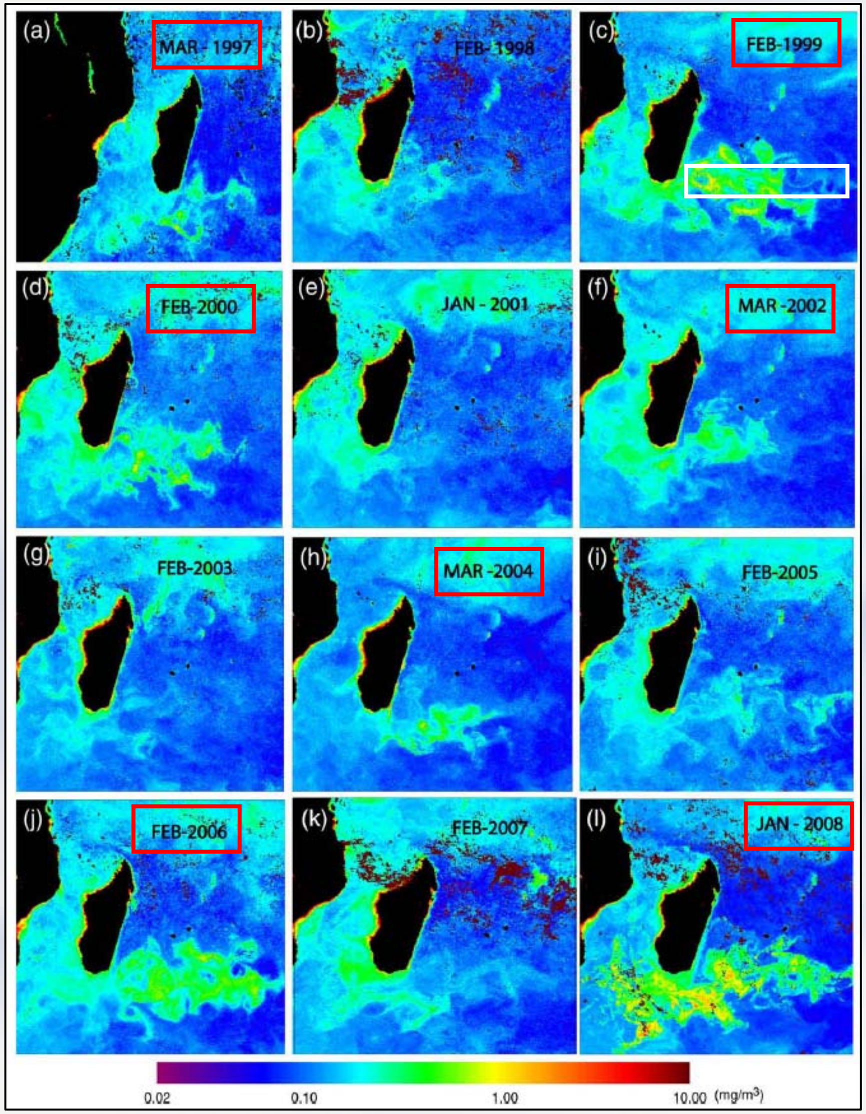

**Phytoplankton bloom**
SeaWiFS - http://oceancolor.gsfc.nasa.gov

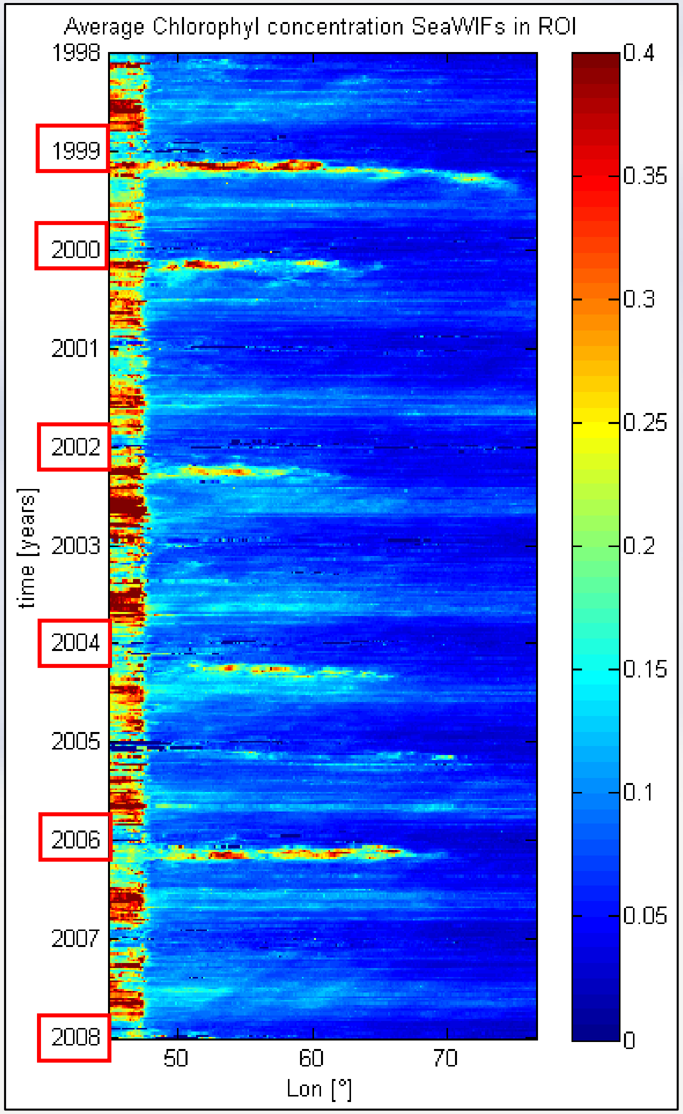
**Remarkable eastward propagation!**

**Reaction-Diffusion-Advection System?**

**Controlled by advection?**

# Madagascar plankton bloom - Intermittency




from: Raj et al.(2010)

Bloom years

# Madagascar plankton bloom - Eastward propagation
# A review

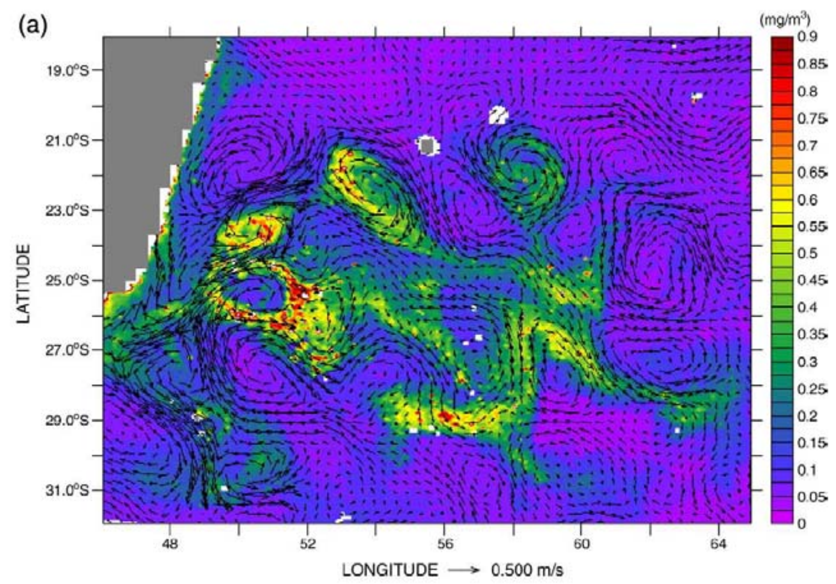
- Longhurst (2001): First description based on SeaWiFS data
  "...deepening of mixed layer within a strong mesoscale eddy field..."

- Srokosz et al. (2004): "A possible plankton wave...The chlorophyll feature travels from west to east, in the opposite direction to the mean flow..."

- Uz (2007): "...the intense eddy activity would allow it [high iron concentration] to be stirred eastward against the slow mean current."

- Lévy et al. (2007): "...upwelling along the coast of Madagascar, followed by transport by the retroflection of the South East Madagascar Current."

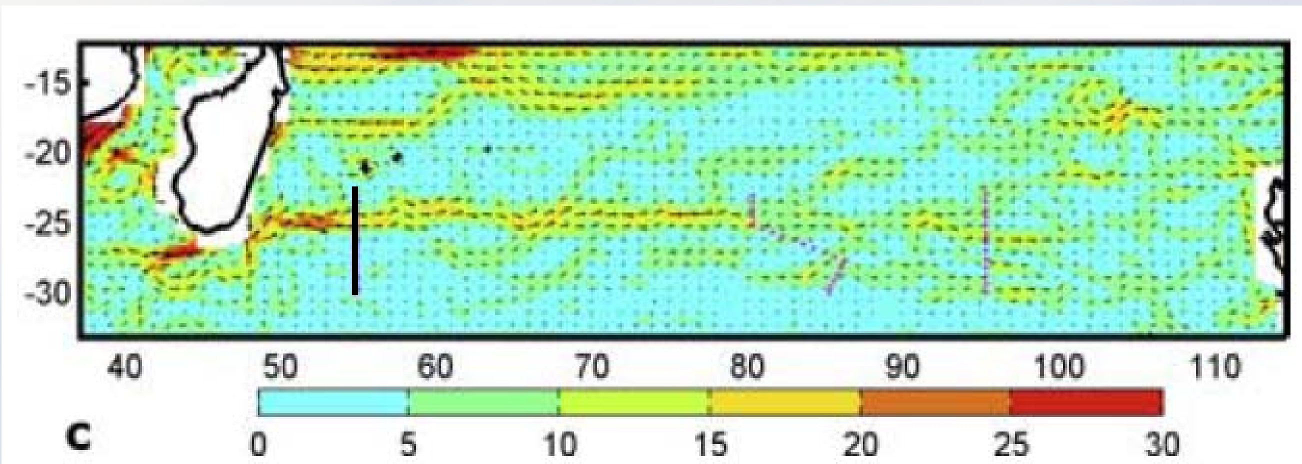
- Raj et al. (2010): "...associated with long chains of mesoscale eddies..."




from: Raj (2010)

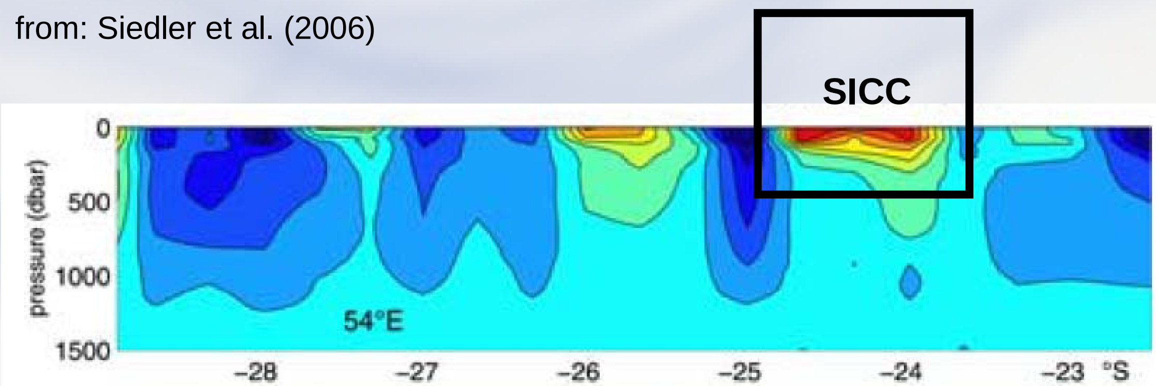
# South Indian Ocean Countercurrent (SICC)

- Palastanga et al. (2007): "...existence of a shallow eastward jet with its core around 25ºS..."
- Siedler et al. (2006): "...evidence for a narrow SICC being embedded in a planetary wave and eddy flow pattern."




Geostrophic currents
5 year mean

from: Siedler et al. (2006)

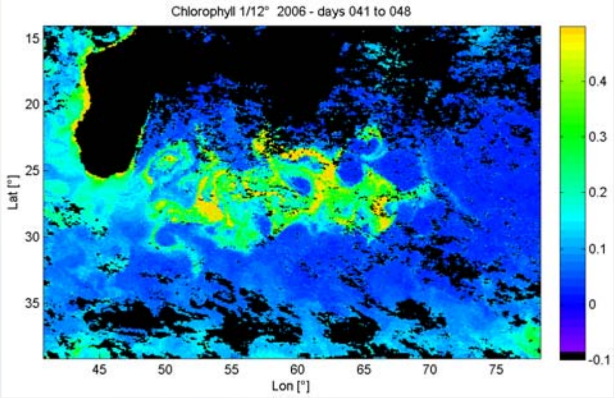



WOCE section
SICC ~25cm/s

from: Siedler et al. (2006)

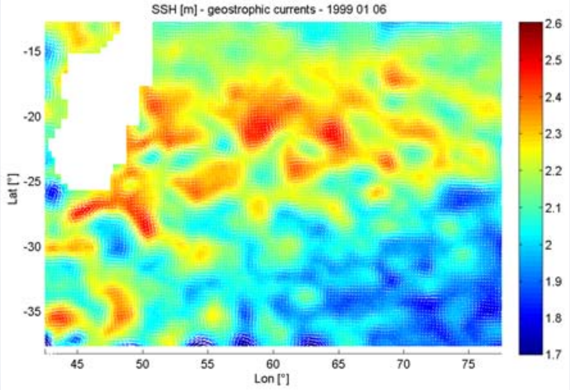
# Aim of study

1. Chlorophyll concentration




SeaWiFS – chlorophyll concentration

2. Mesoscale geostrophic currents




- What is the impact of advective transport on the Madagascar plankton bloom?
- Does the plankton bloom go with the flow?

- **Compare 2D chlorophyll patterns with Lagrangian patterns of passive transport in the horizontal mesoscale flow**

## Do take into account...

- Plankton
  - Measured chlorophyl concentration, spatio-temporal patterns
- Flow
  - Geostrophic mesoscale flow (2D), Lagrangian patterns

## Do not take into account...

- Plankton
  - Biological reaction
  - Chemical cycles
  - Different species
  - Different nutrients
  - Light limitation
  - Temperature
  - Local upwelling
  - Mixed layer depth
  - Atmospheric events
  - ...
- Flow
  - Vertical flow (3D)
  - Non-geostrophic flow
  - ...

**Coupling**

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# Lagrangian view – detect coherent structures

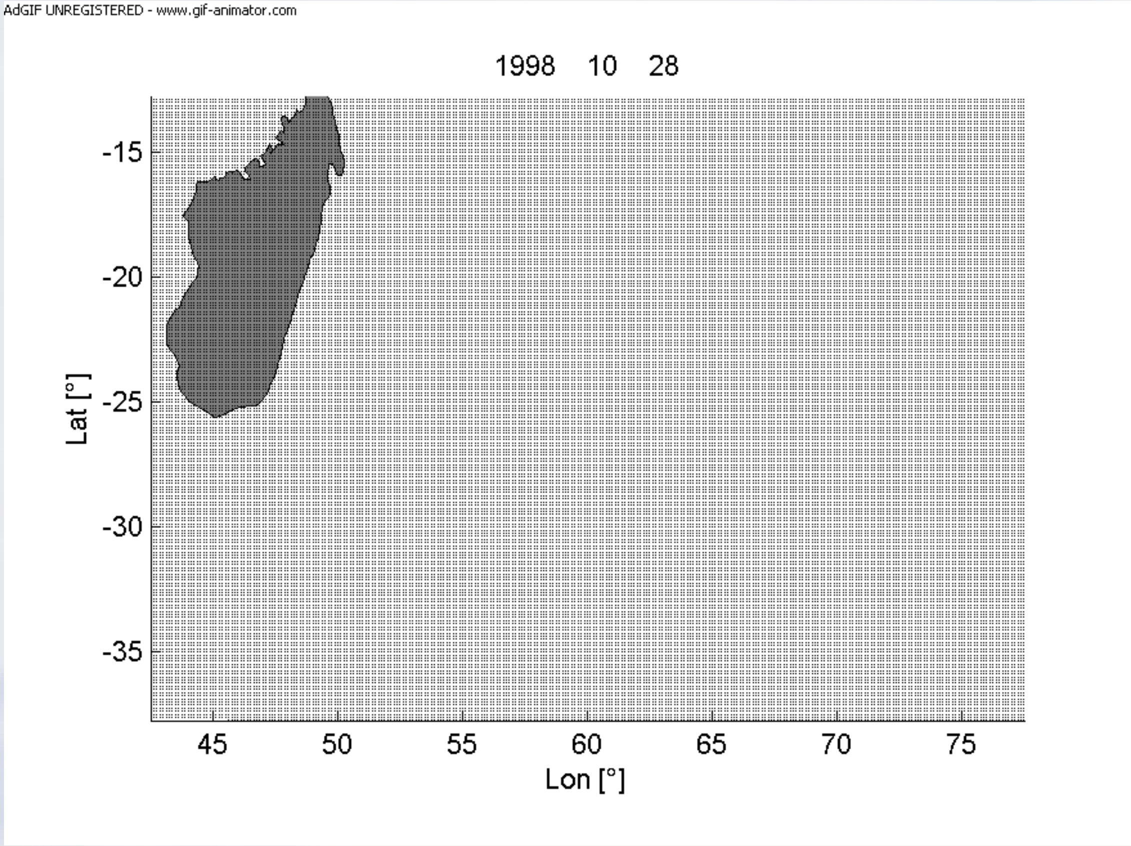
- Given geostrophic velocity field – integrate trajectories

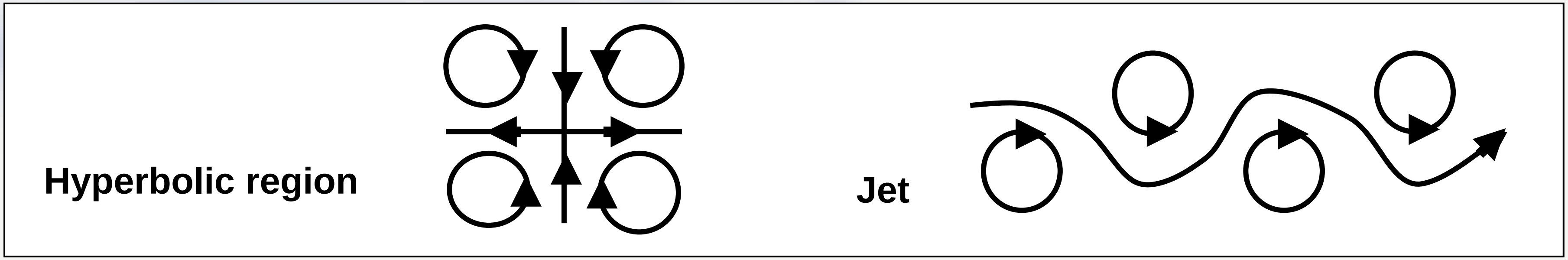
$$\dot{\lambda} = -\frac{g}{R^2 f(\theta)\cos\theta}\partial_\theta \eta(\lambda,\theta,t),$$
$$\dot{\theta} = +\frac{g}{R^2 f(\theta)\cos\theta}\partial_\lambda \eta(\lambda,\theta,t).$$

- Time dependent flow – chaotic transport

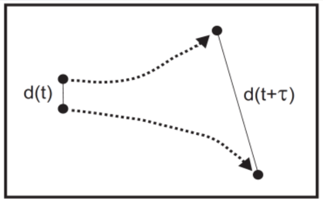
- Streamlines not closed

- Adjust duration of advection to typical time scale of the problem. Here: several weeks (plankton growth)



# Finite-Time Lyapunov Exponents (FTLE)




- Exponential growth rate of infinitesimal perturbations for finite time

$$\mathrm{FTLE}\,(t,\tau) \;=\; \frac{1}{\tau}\,\ln\left(\frac{d(t+\tau)}{d(t)}\right)$$

- Compute FTLE from Cauchy-Green deformation matrix [Haller, Beron-Vera (2010)]

$$\mathbf{x}(t+\tau) = \varphi_t^{t+\tau}(\mathbf{x}(t))$$

$$\nabla\varphi_t^{t+\tau}(\mathbf{x_0}) = \begin{pmatrix} \frac{\partial x}{\partial x_0} & \frac{\partial x}{\partial y_0} \\ \frac{\partial y}{\partial x_0} & \frac{\partial y}{\partial y_0} \end{pmatrix}$$

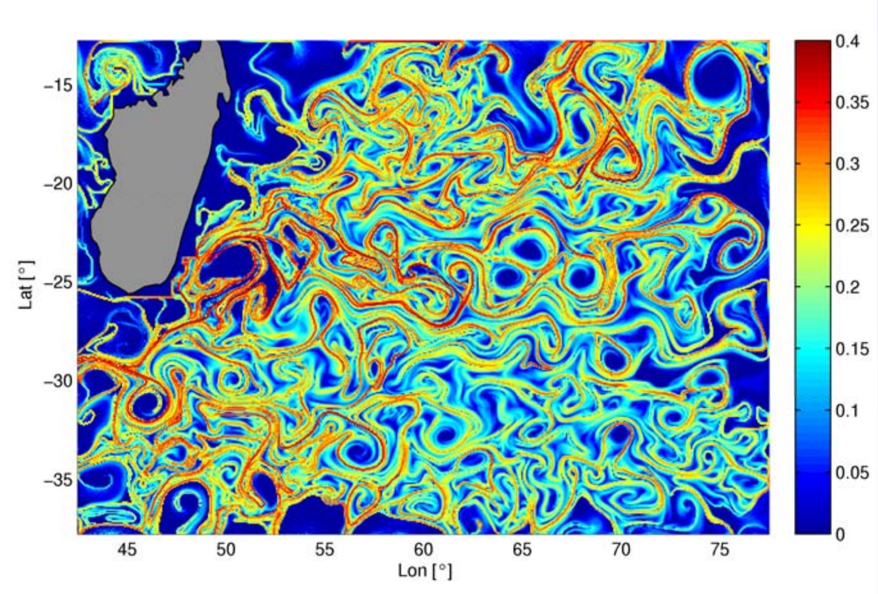
$$\Delta = \nabla\varphi_t^{t+\tau}(\mathbf{x_0})^T\,\nabla\varphi_t^{t+\tau}(\mathbf{x_0})$$

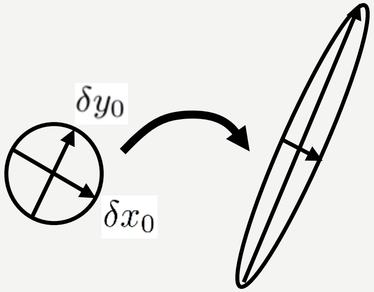
$$\sigma(\mathbf{x};t,\tau) = \frac{1}{2\,|\tau|}\ln\lambda_{max}(\Delta)$$

- Finite time $\tau$ = 12 weeks

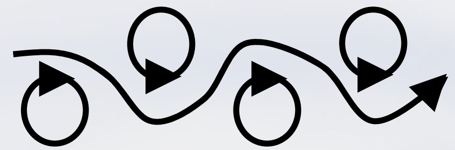
- Ridges in FTLE field as estimates of Lagrangian Coherent Structures (LCS) – material lines – transport barriers

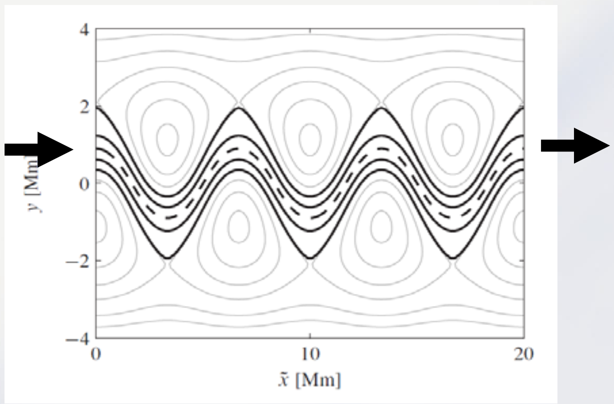
Forward FTLE field – repelling LCS



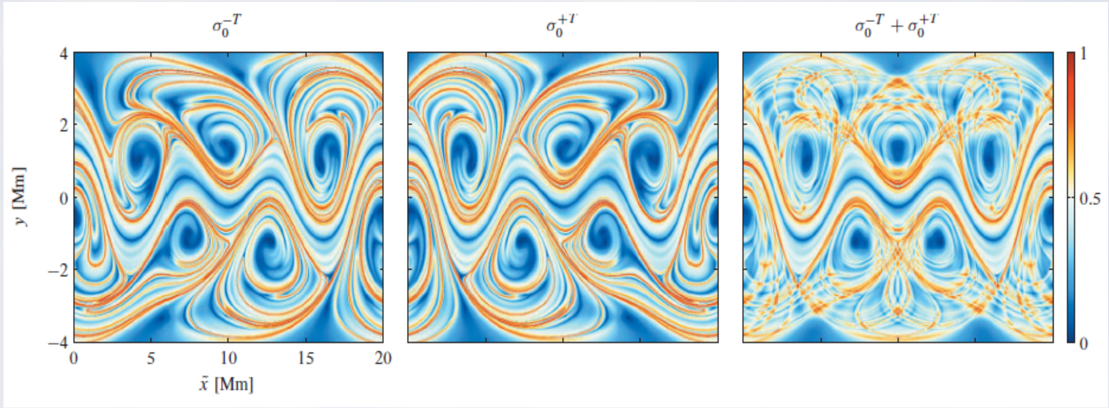



# Zonal jets as transport barriers





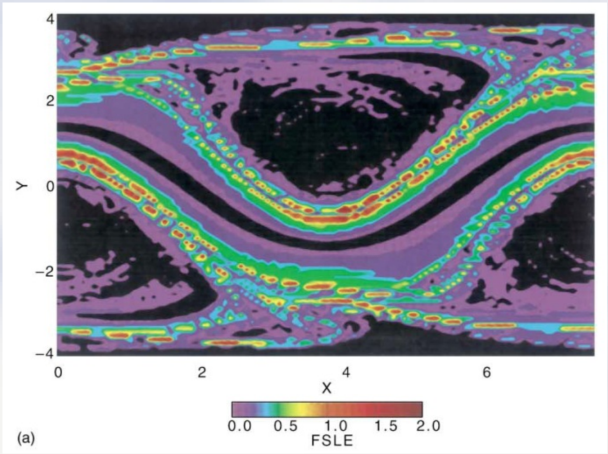

Bickley jet model



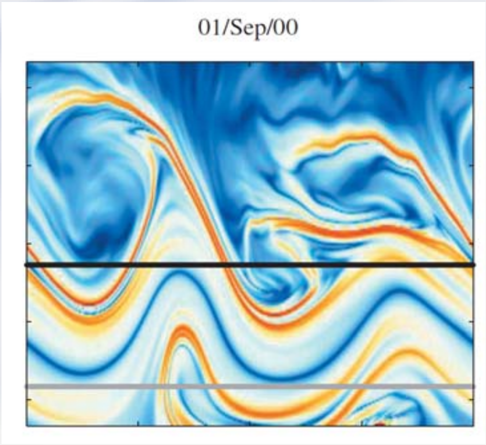

Forward and backward FTLE fields of perturbed Bickley jet

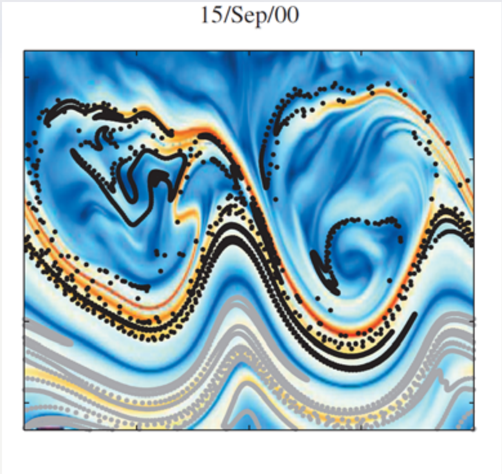
from: Beron-Vera et al. (2010)

Forward FSLE




from: Boffetta et al. (2001)




Stratospheric winds at 20km – 2D, CMAM model, Austral polar night jet

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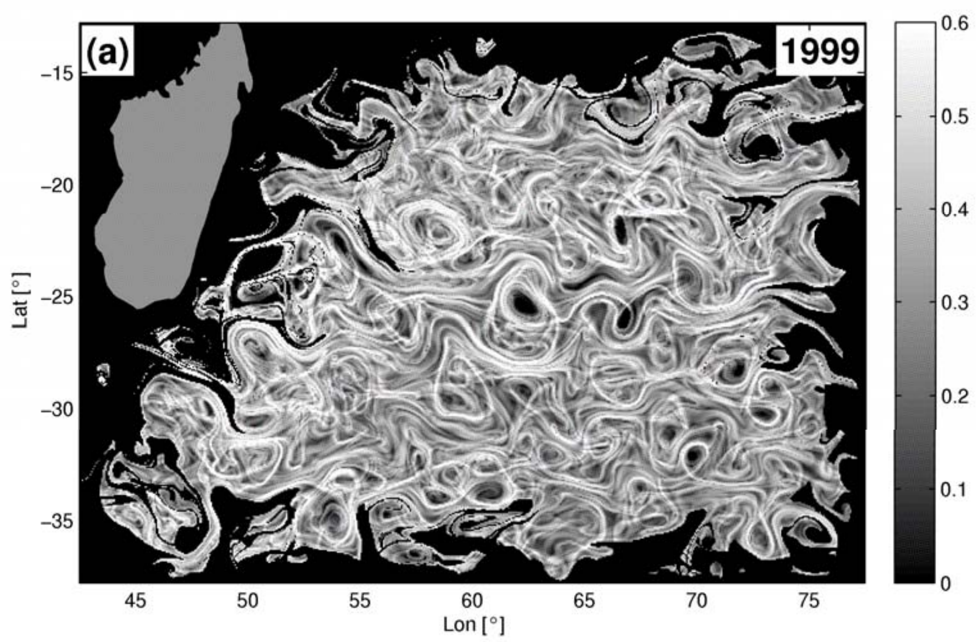
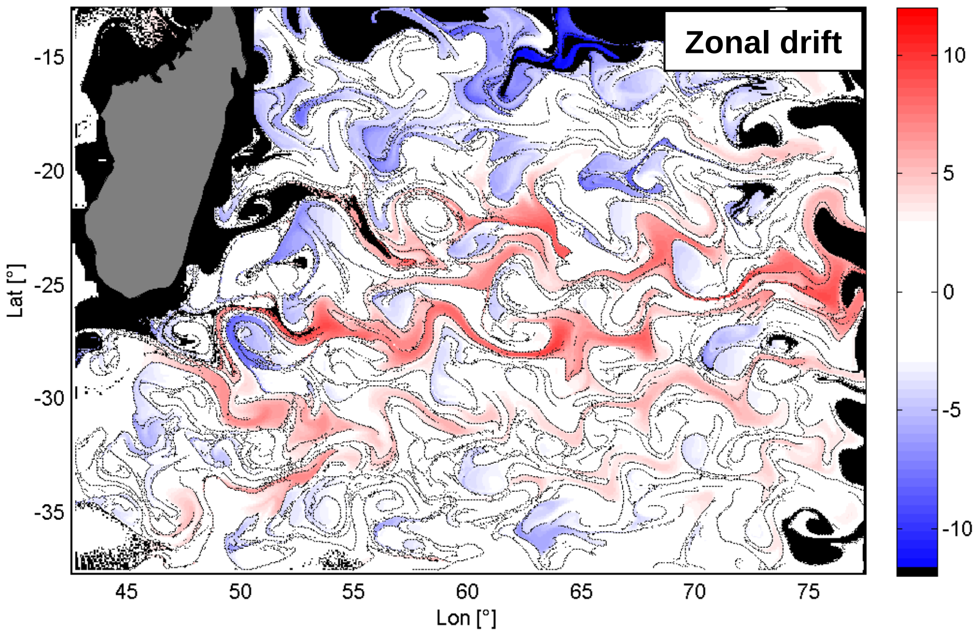
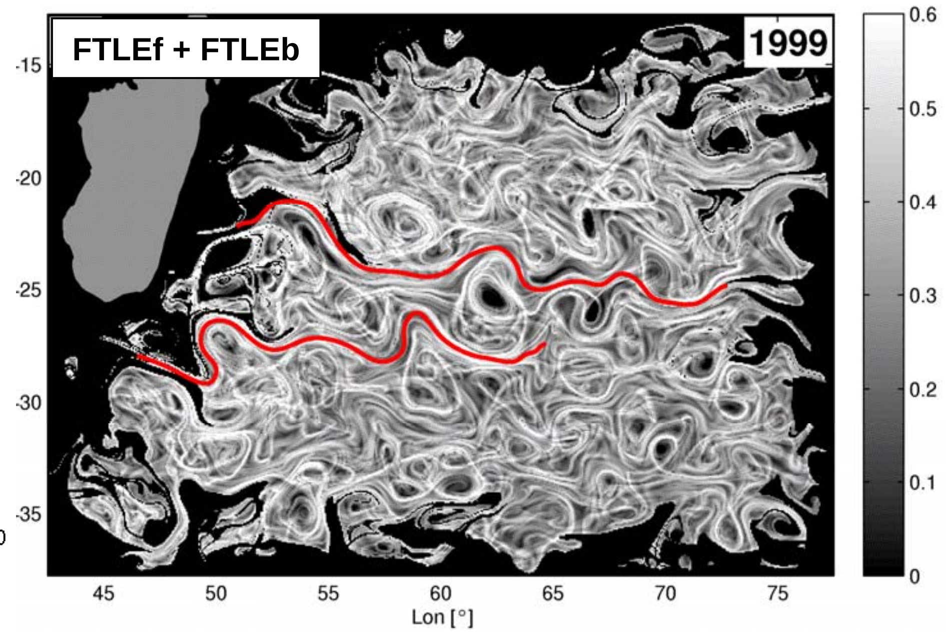
# Zonal jets and associated jet-like LCS

- Bands of parallel fwd and bwd FTLE structures identified as zonal jets [Beron-Vera et al. (2010)]
- Zonal jets as barriers to meridional transport
- Bands of strong zonal eastward drift (~14cm/s)



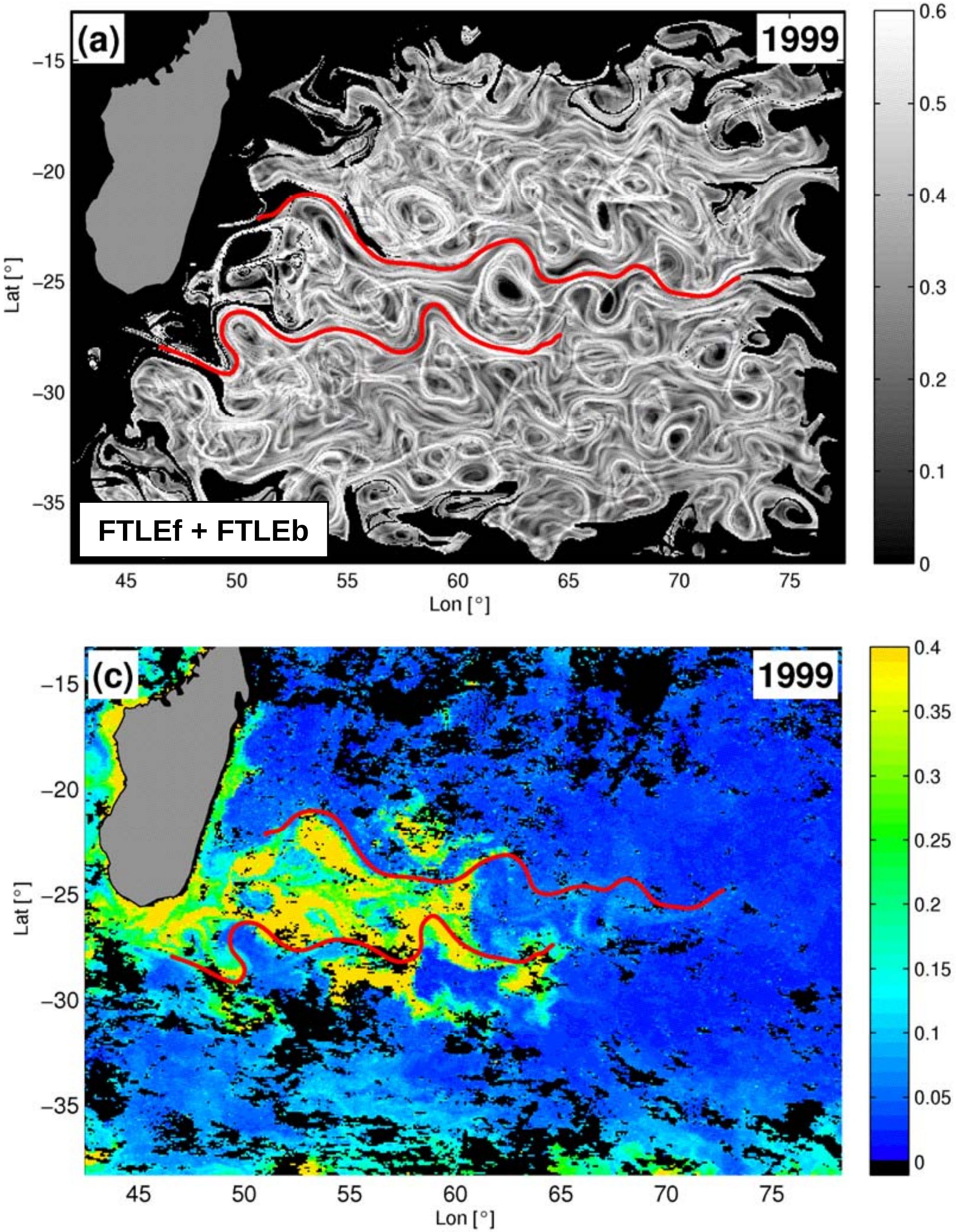



# Jet-like LCS confine plankton bloom

- Jet-like LCS as transport barriers

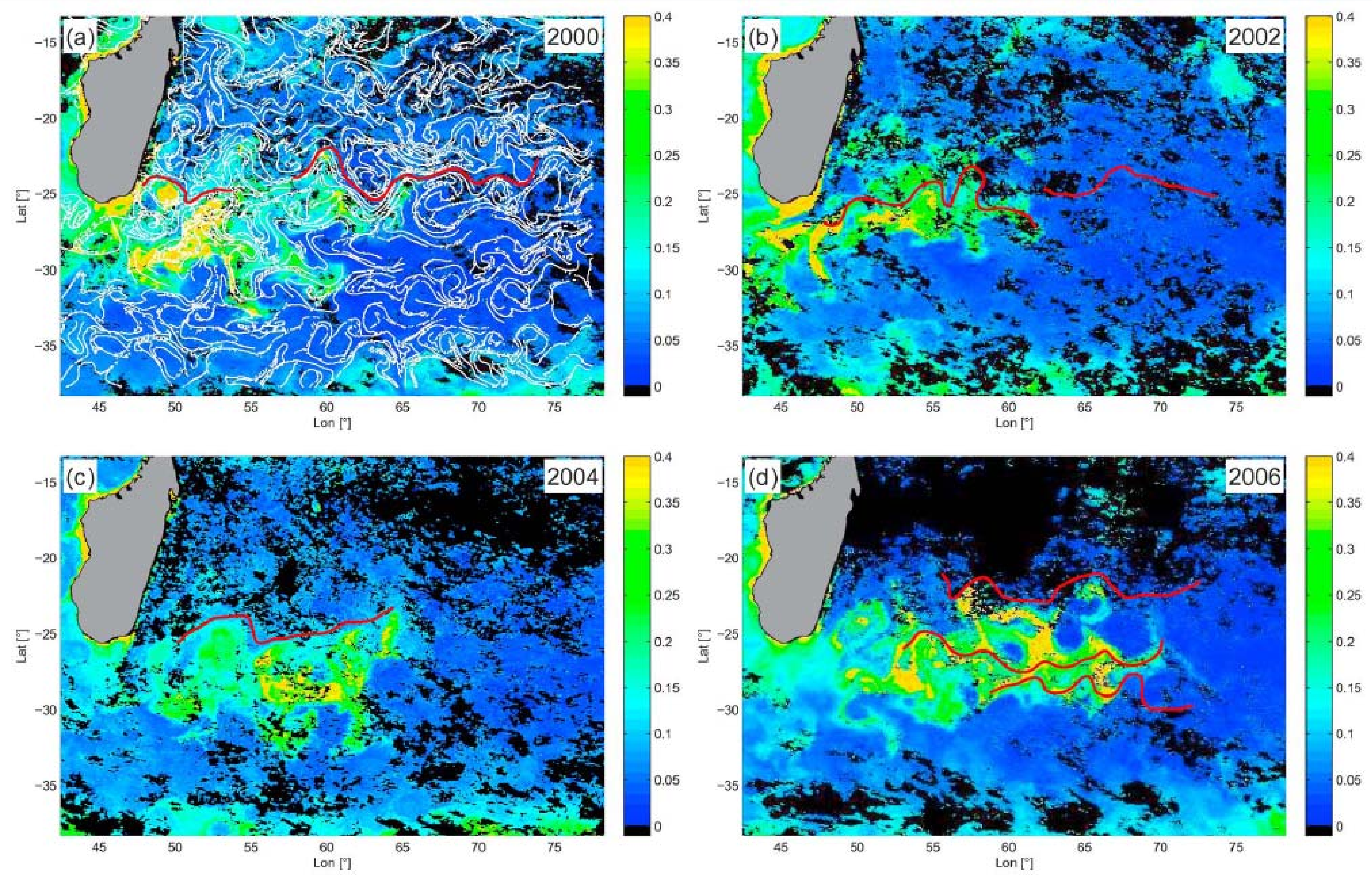
- Two jets mark the southern and northern boundary and confine the plankton bloom

- Leakage due to strong perturbation of jet




SeaWiFS chlorophyll concentration

# Jet-like LCS confine plankton bloom



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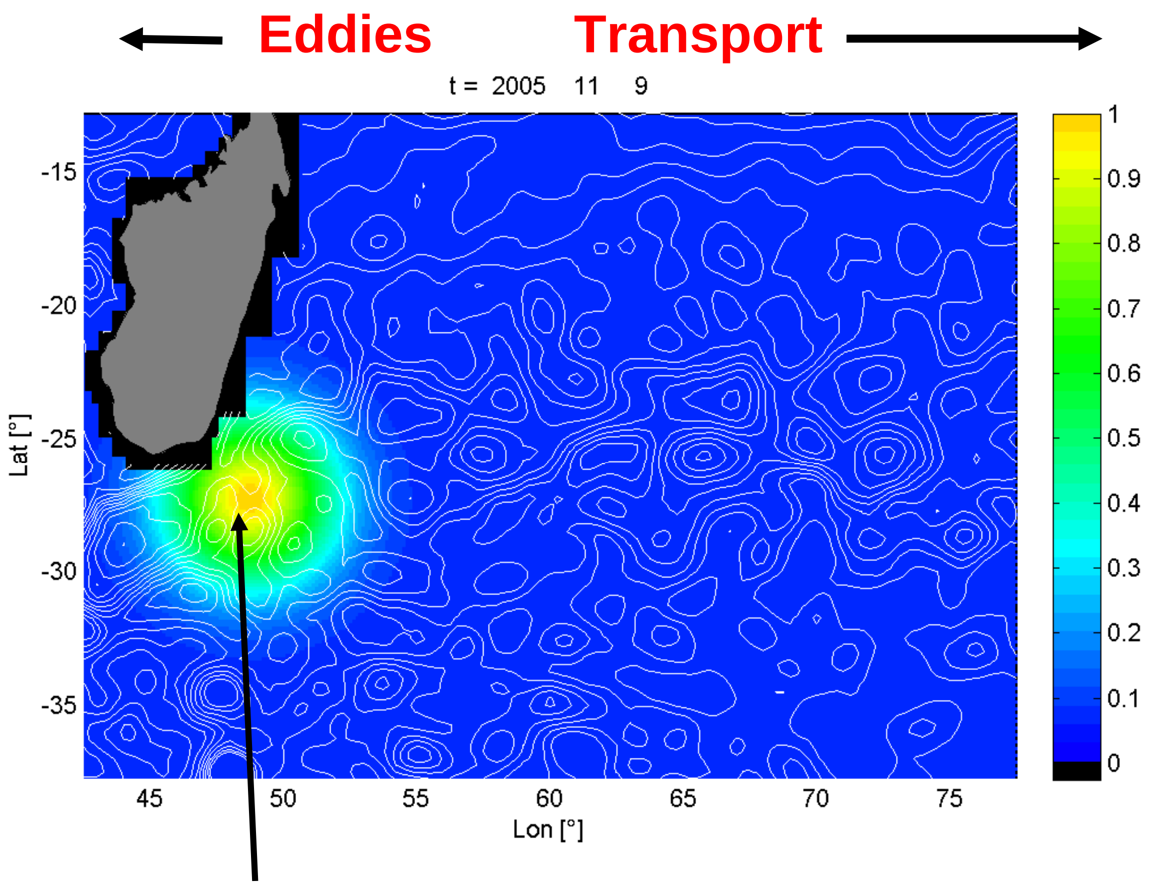
# Eastward transport - Passive tracer





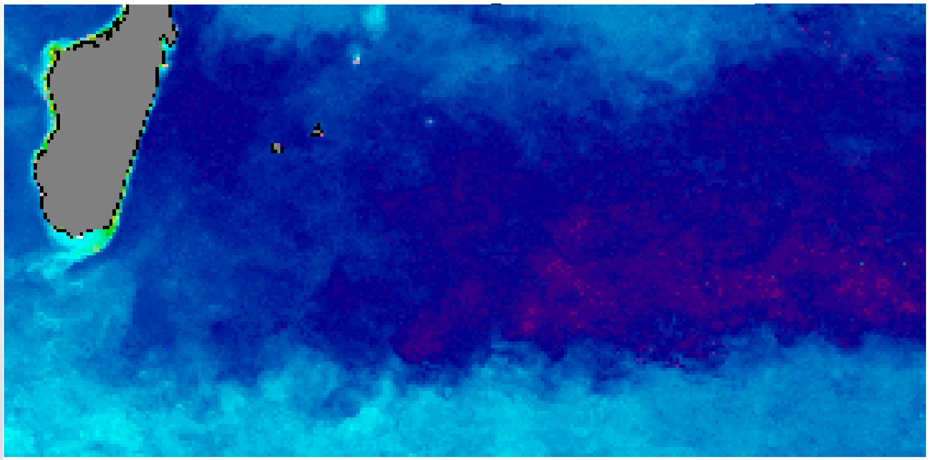

Upwelling region – Possible nutrient source

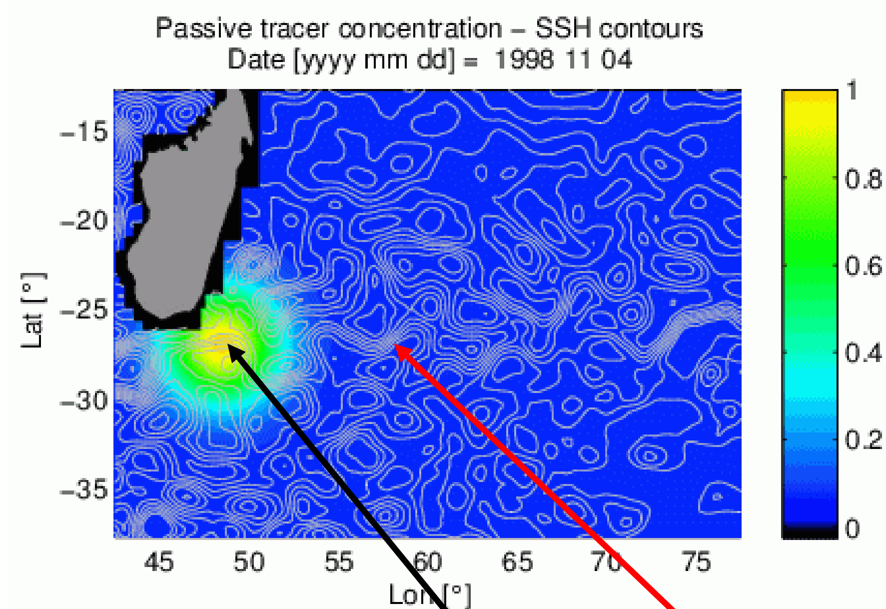
- Hypothesis of origin of bloom south of Madagascar [Uz (2007), Lévy et al.(2007), Raj et al.(2012)]
- Known upwelling region
- Clear eastward transport enhanced by SICC jets

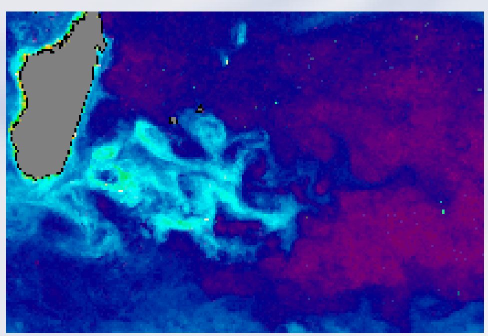
# Front propagation

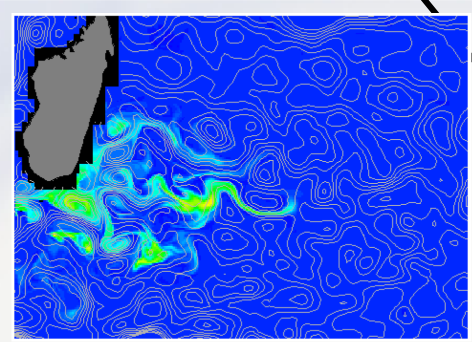
Chlorophyll

Passive tracer







Zonal jet
SICC

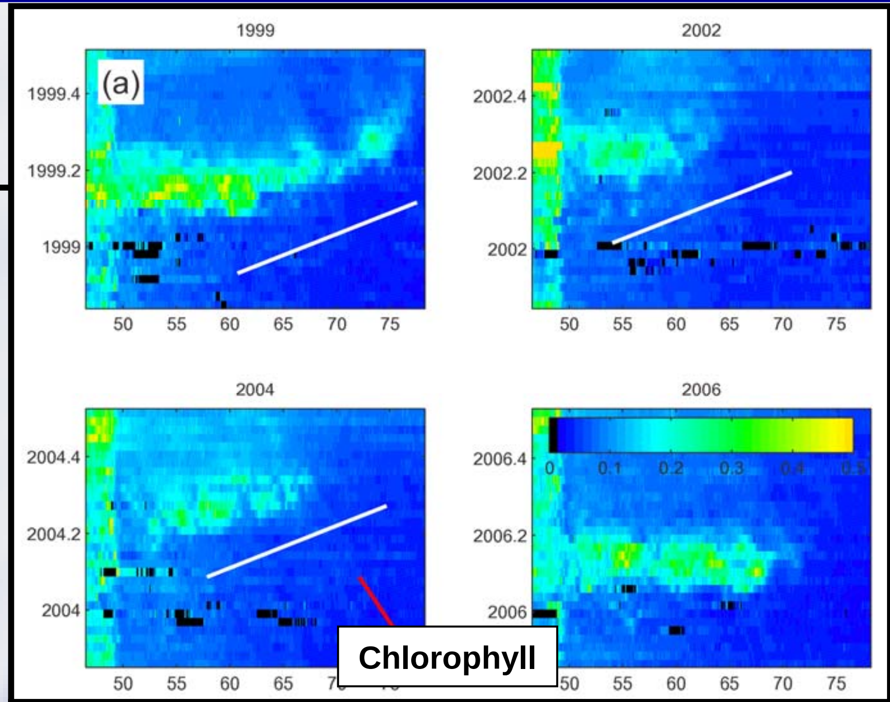
Upwelling region –
Possible nutrient
source

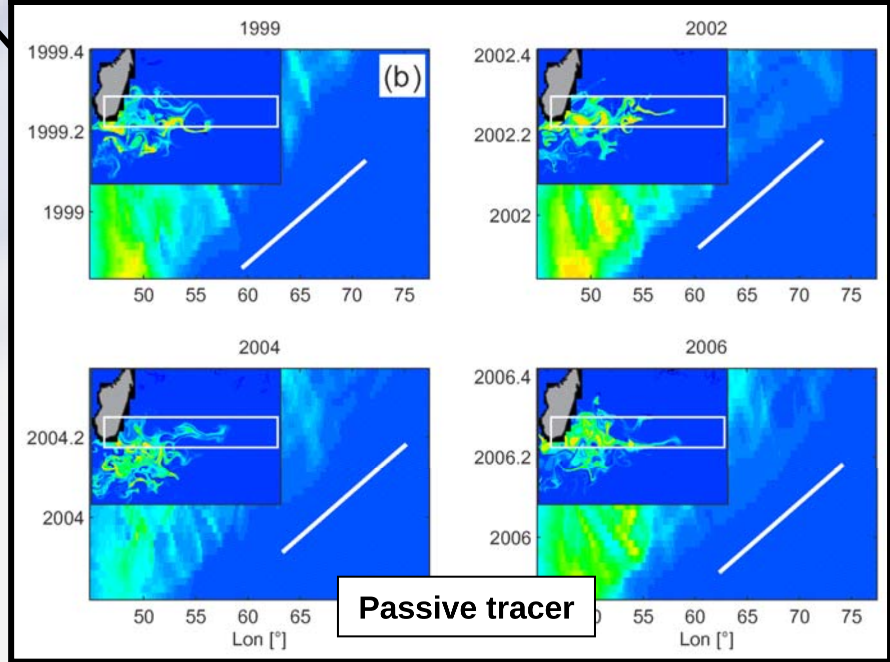
**BUT**: Tracer must be released very early to resemble extension of plankton bloom (~2 months before first rising of chlorophyll concentration)

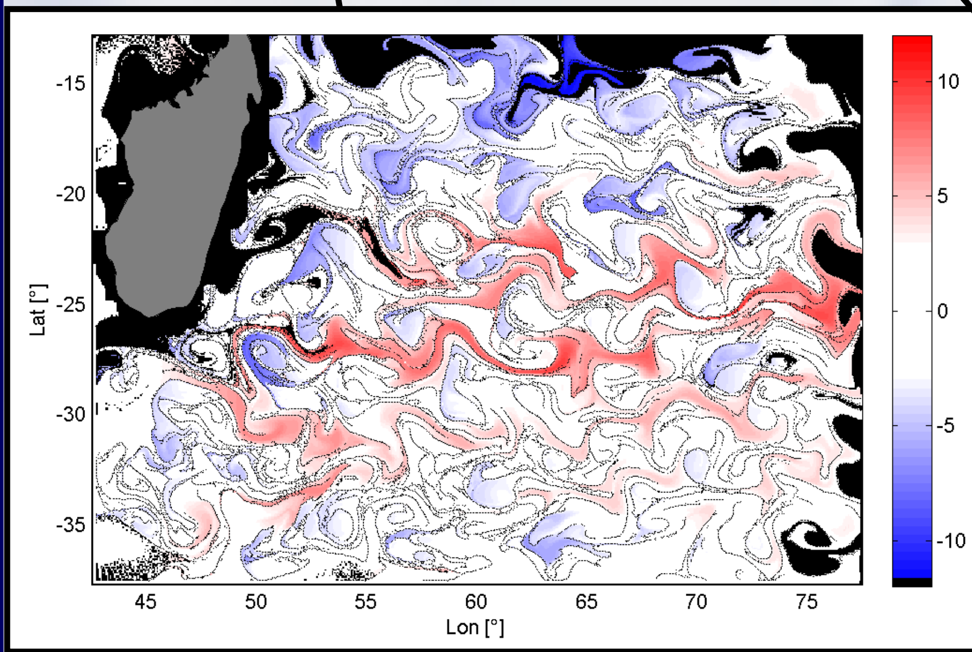
# Zonal front velocity

- Plankton front: v ~ 0.25m/s
- Tracer front: v ~ 0.14m/s
- Particles: v ~ 0.14m/s

**Plankton front significantly faster than mean advective velocity!**



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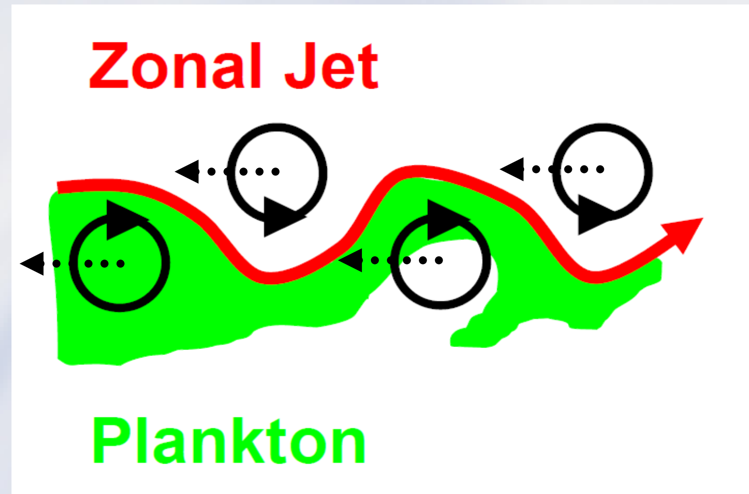
# Summary & Outlook

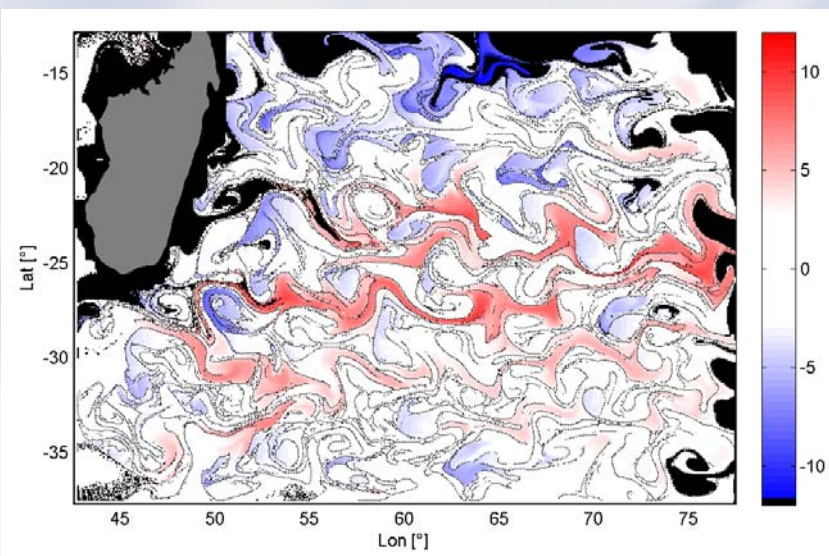
- Plankton bloom shaped by advection. Jets partly act as transport barriers
- Jet provides persistent eastward transport for plankton bloom
- Advection by SICC is key process for large extent of Madagascar plankton bloom
- Hypothesis of origin near the coast supported
- There are more ingredients:
  What triggers the bloom?
  Where does nutrient come from?

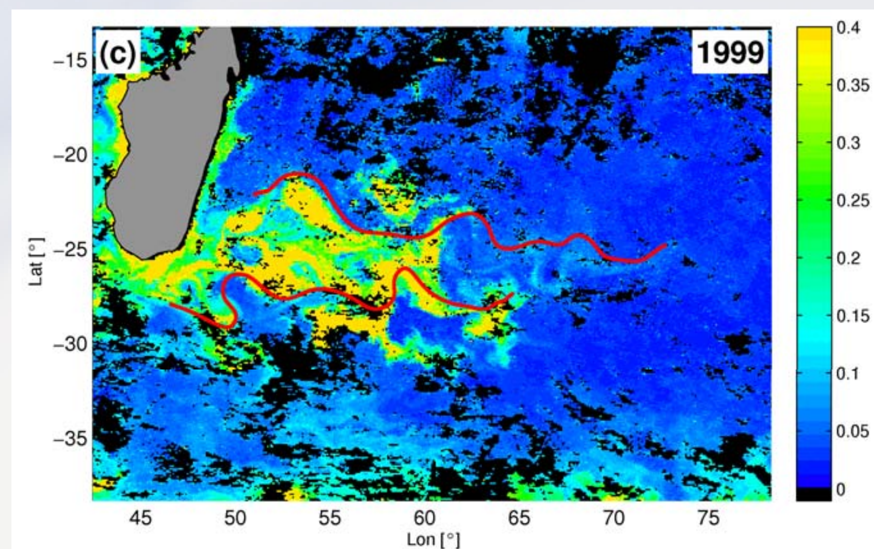
GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L06602, doi:10.1029/2012GL051246, 2012

**The impact of advective transport by the South Indian Ocean Countercurrent on the Madagascar plankton bloom**

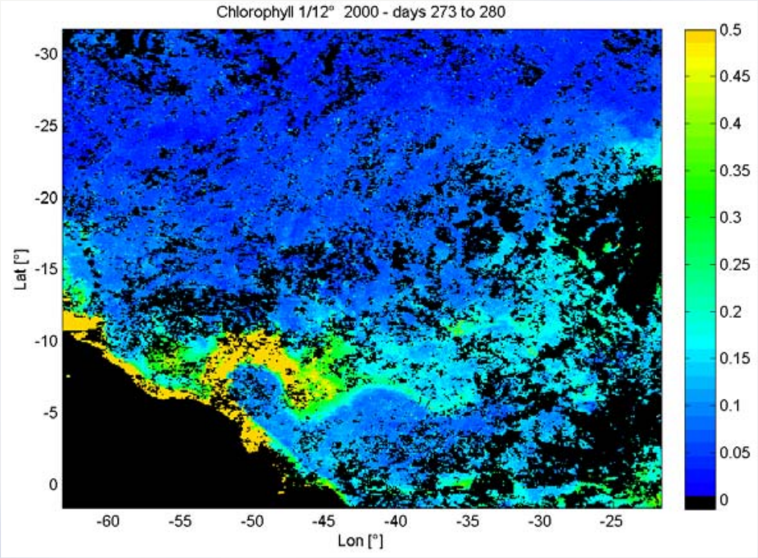
F. Huhn,[1,2] A. von Kameke,[1,3] V. Pérez-Muñuzuri,[1,4] M. J. Olascoaga,[2] and F. J. Beron-Vera[2]



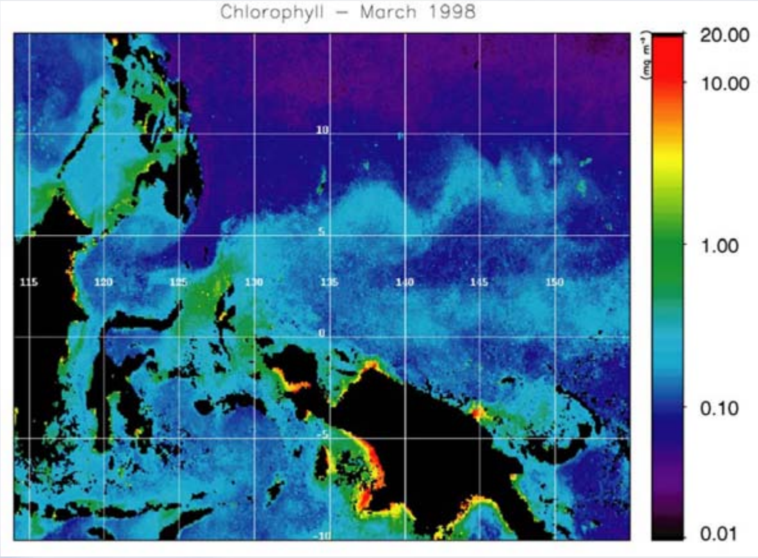



# Other regions




SeaWiFS - http://oceancolor.gsfc.nasa.gov




from: Christian et al. (2004)

Atlantic North Equatorial Countercurrent (Off Brazil, Amazon plume)

Pacific North Equatorial Countercurrent (Indonesia)


Thank you for your attention!
RSMAS, Miami