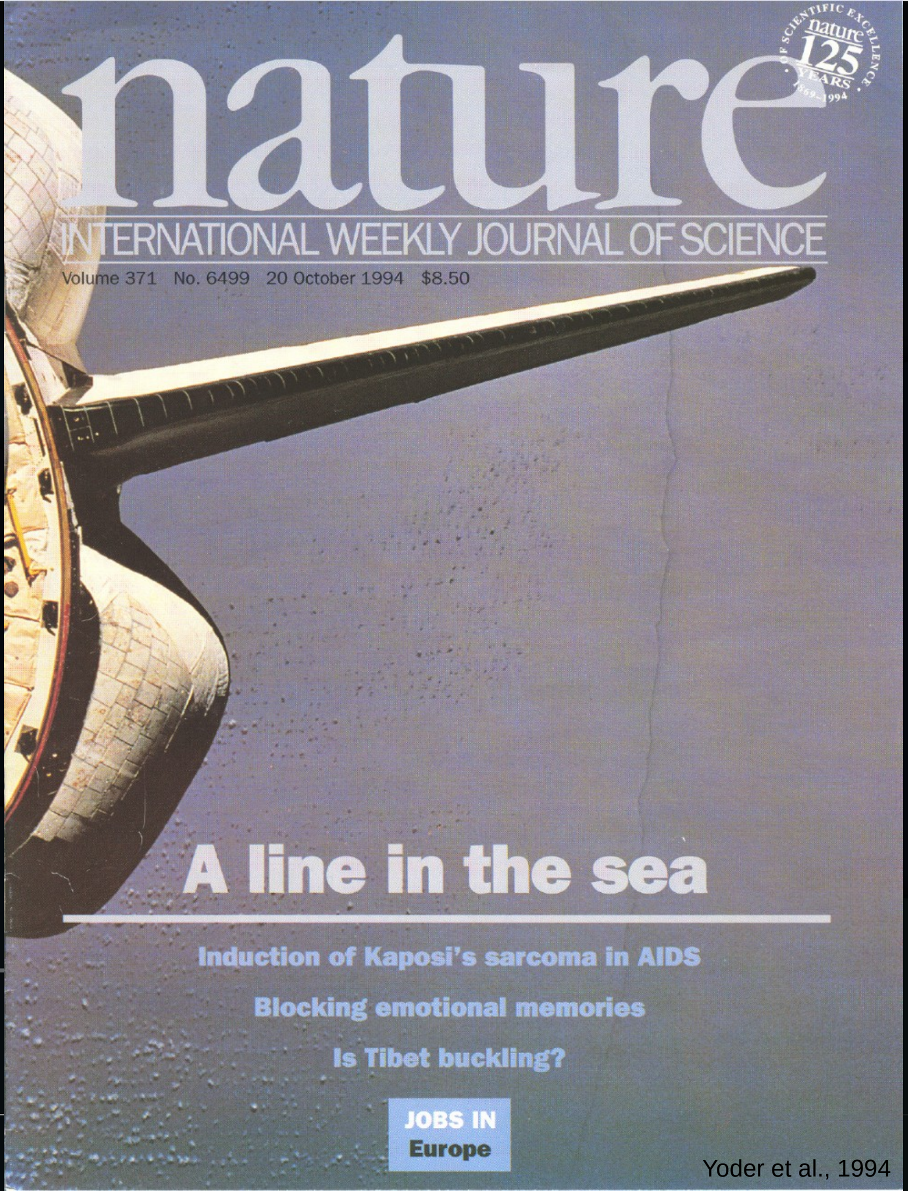
Radar observations of sub-mesoscale fronts in the equatorial Pacific

Lindsey Benjamin
17 May 2022

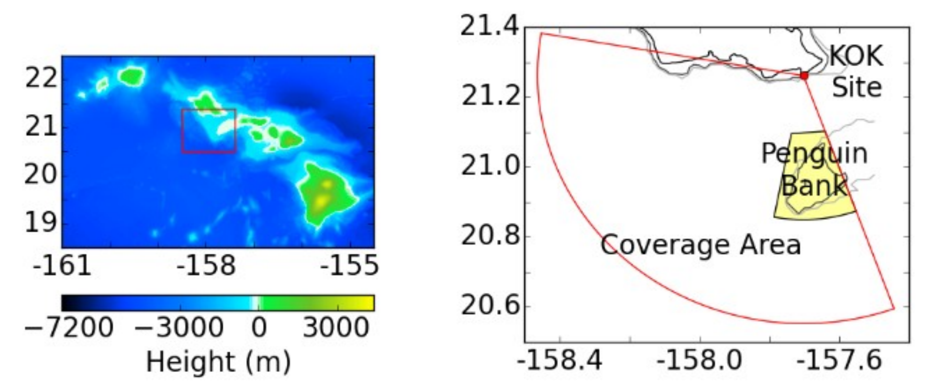


Yoder et al., 1994

Agenda

- Misadventures in meteotsunamis
- Radar obs of sub-mesoscale fronts
  - Tropical instability vortices
  - Sub-mesoscale fronts
  - Cross-front differences
  - Conclusions

2011 Tōhoku tsunami

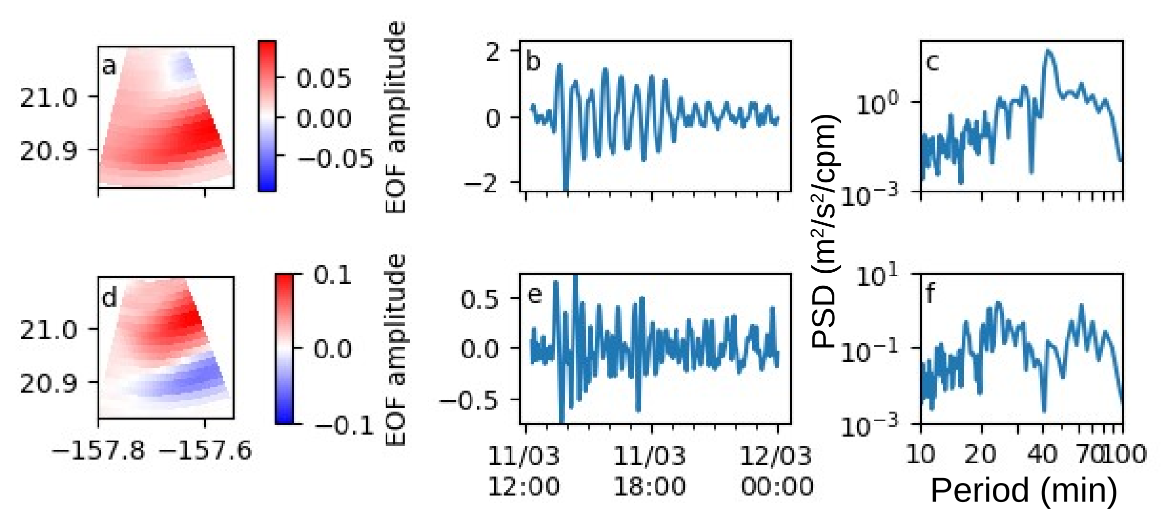


Moment magnitude 9.0

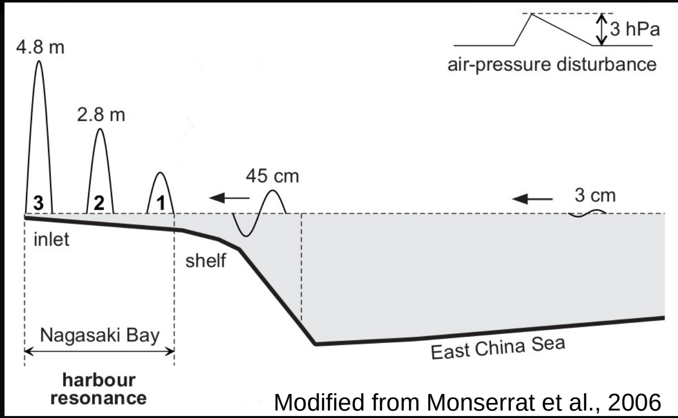
Arrived 1300 UTC on 11 March 2011

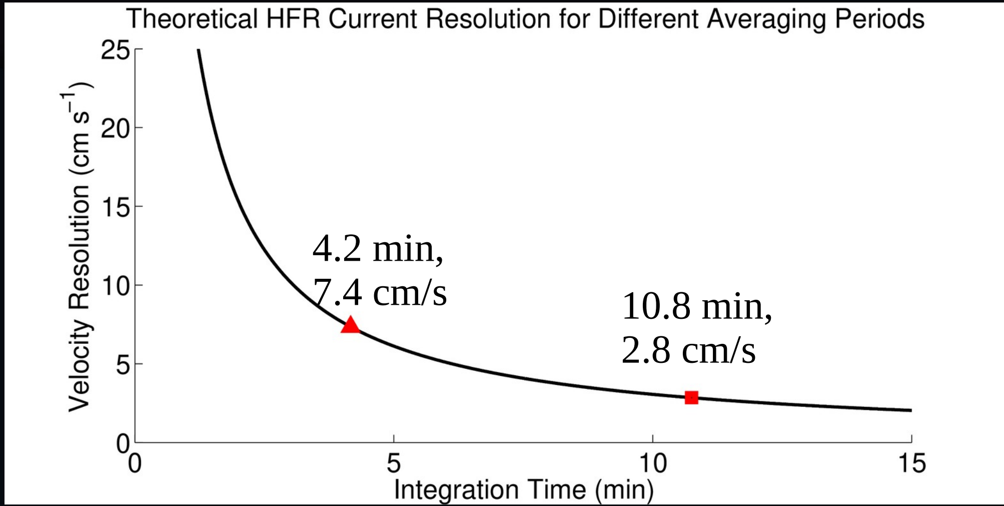
Asymmetrical expression on Penguin Bank

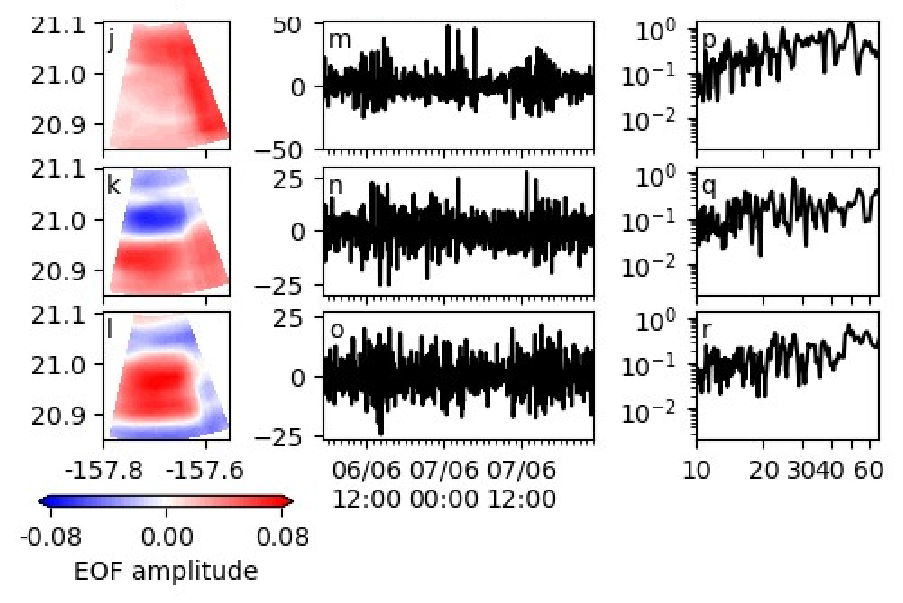
Well-defined arrival and subsequent oscillations



Meteotsunamis in Hawaii





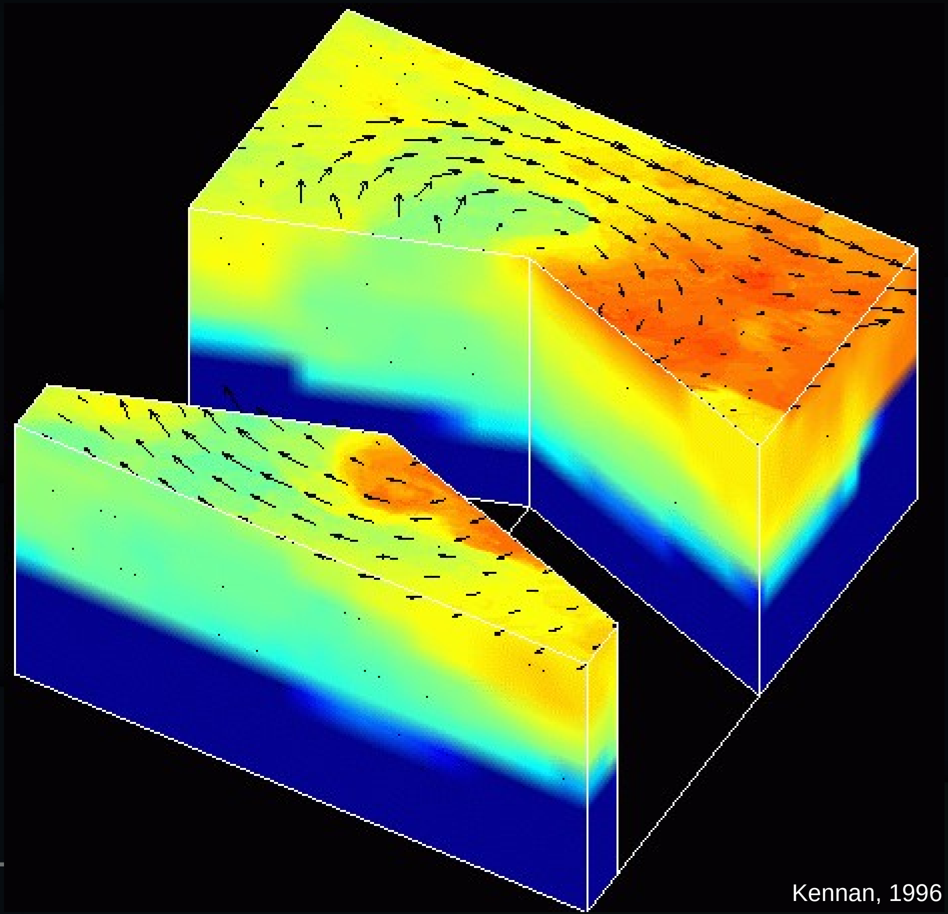


Some elements of resonance modes found, but not a complete suite of expected features

Conclusions

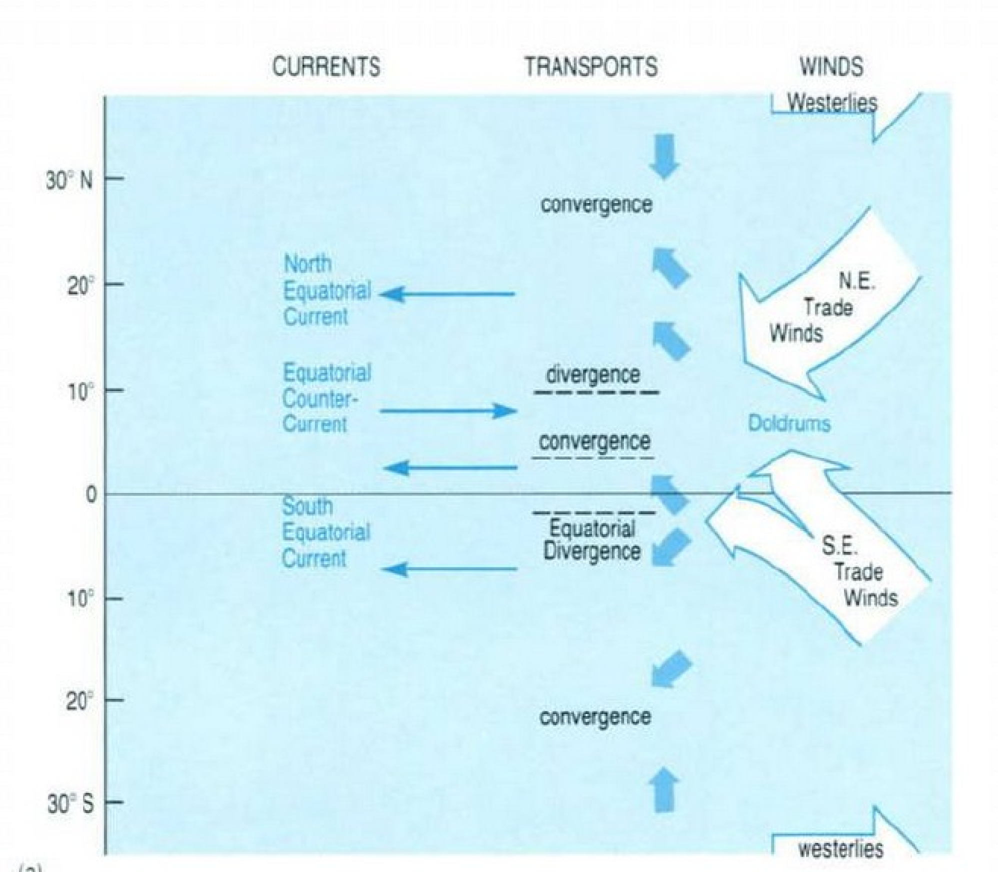
- Tsunamis arriving in Hawaii excite resonance modes that depend on local bathymetry and coastlines
- Meteotsunamis may occur in Hawaii, but they would be rare; if any occurred, resultant resonance excitation was too weak for HFDR detection
- In-situ instruments could detect resonance excitation from meteotsunamis

Tropical instability vortices



Kennan, 1996

Equatorial Pacific



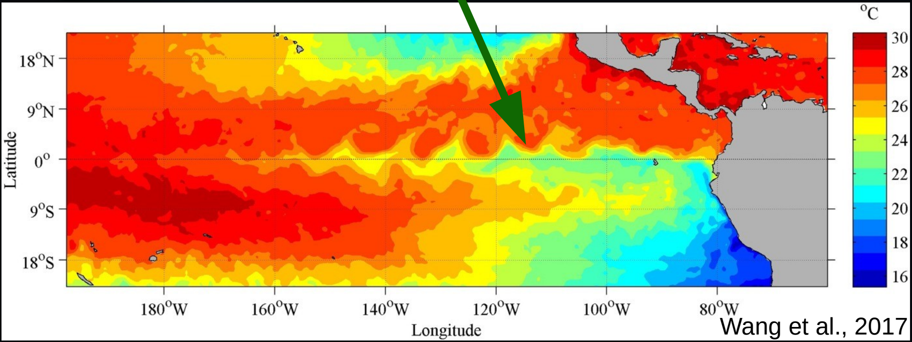
The Open University, 2001

Trade winds

Equatorial divergence

Upwelling of cold, salty water

North Equatorial Front



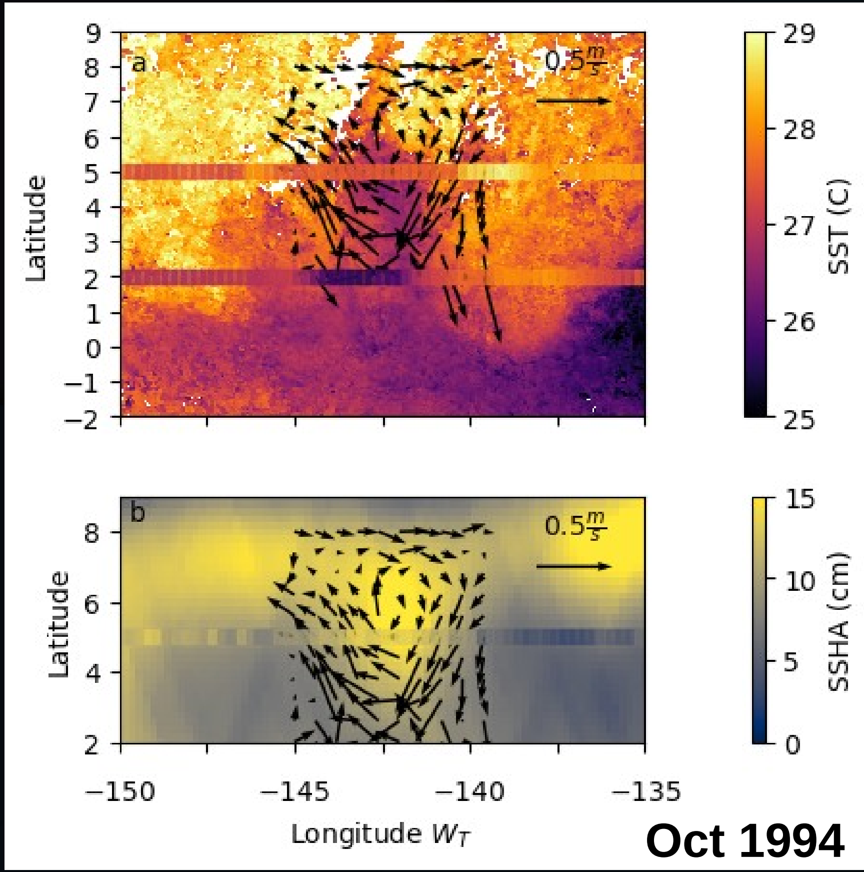
Wang et al., 2017

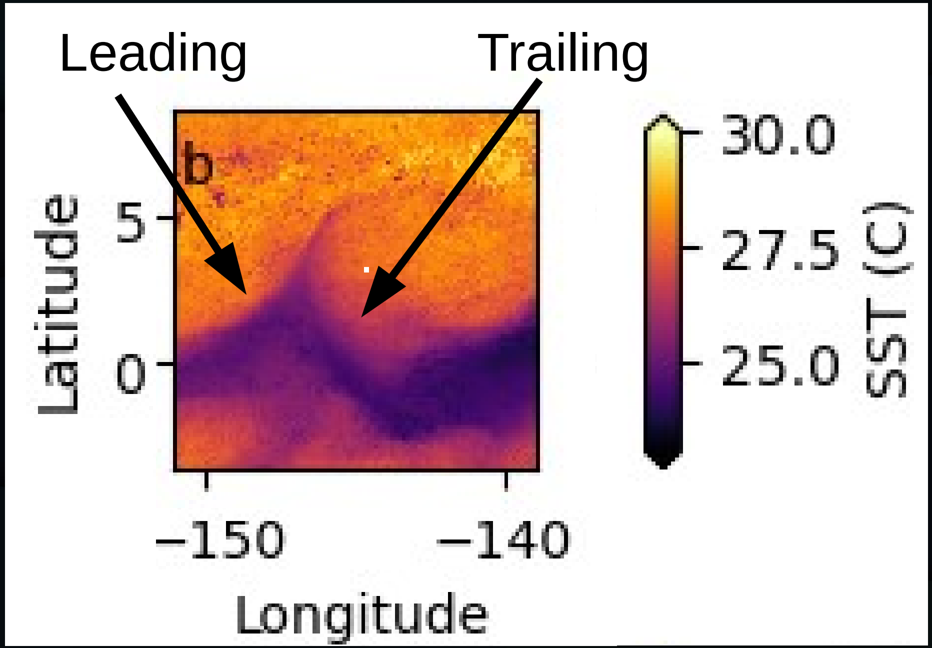
Zonal system of currents with shears

Tropical instability vortices

Tropical instability vortices

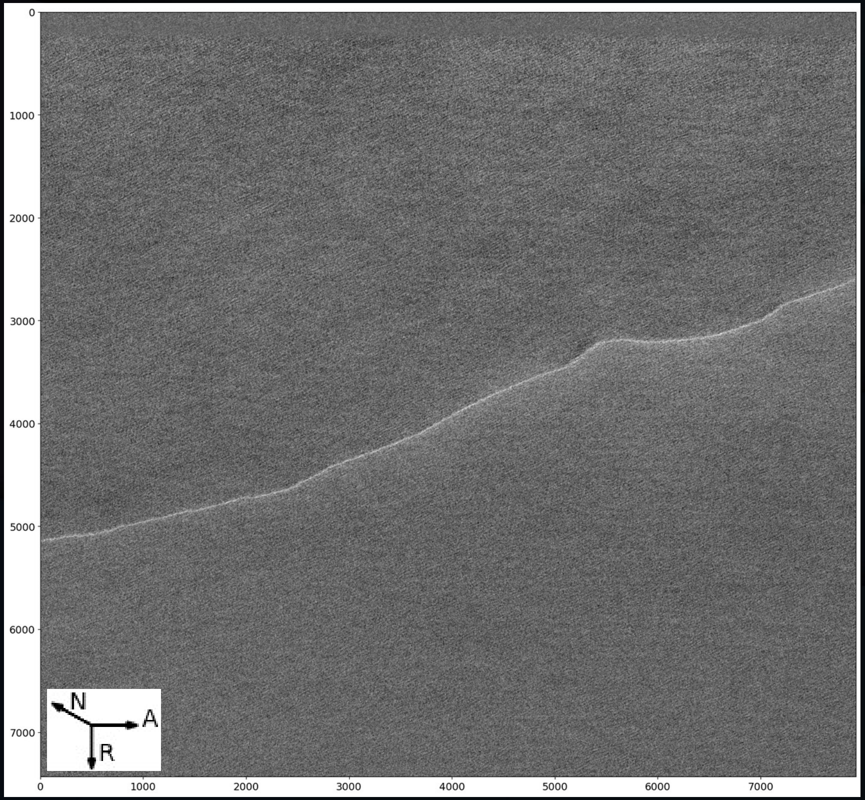
Translating frame of reference





2016 to 2019

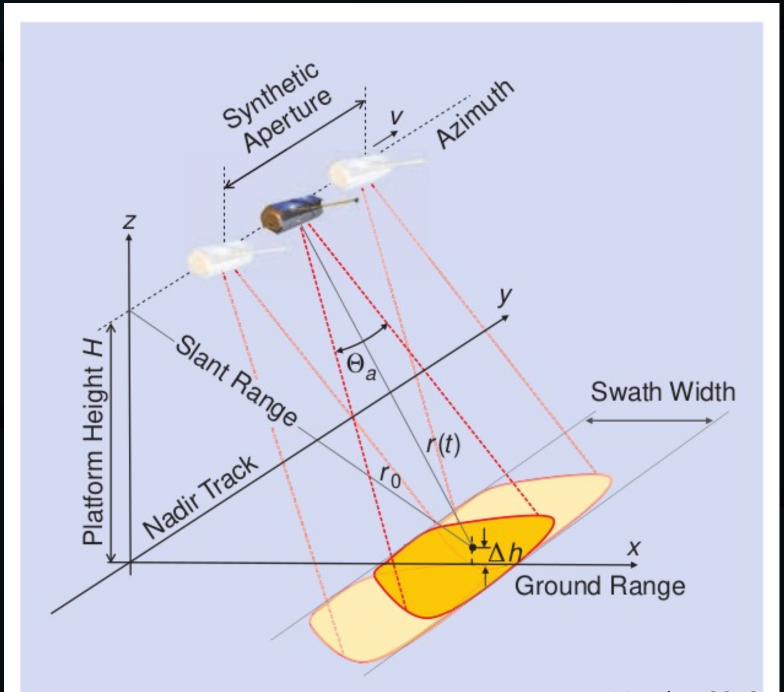
Synthetic aperture radar



Oct 1994

Surface roughness on 3-30 cm scales

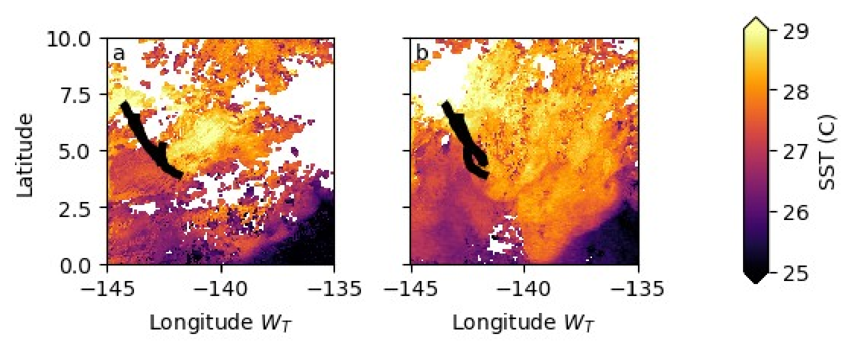
Convergence ➡ wave breaking

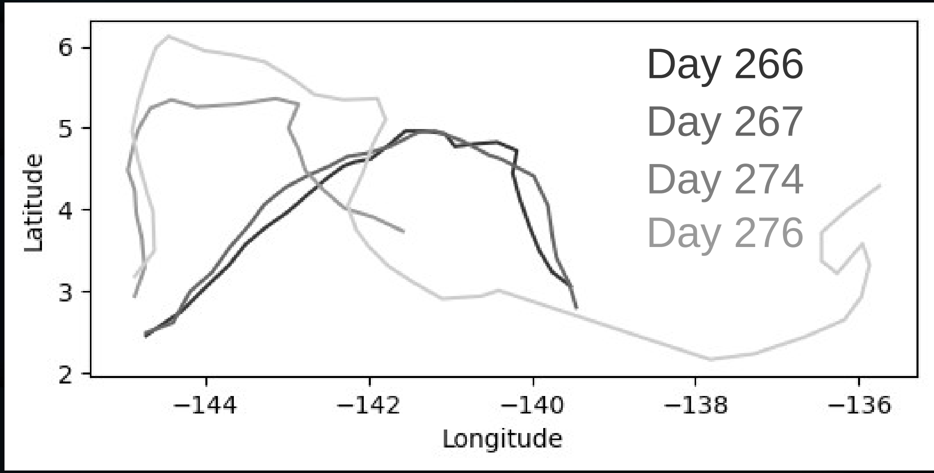


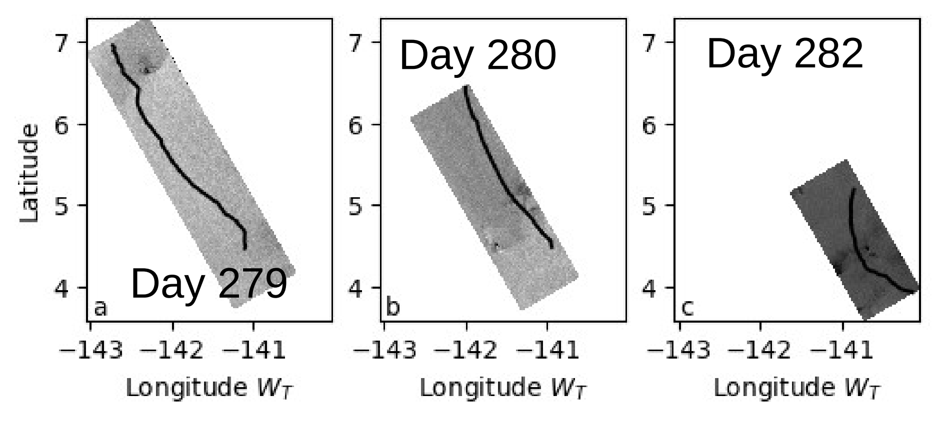
Moreira, 2013

Swirling currents

Oct 1994



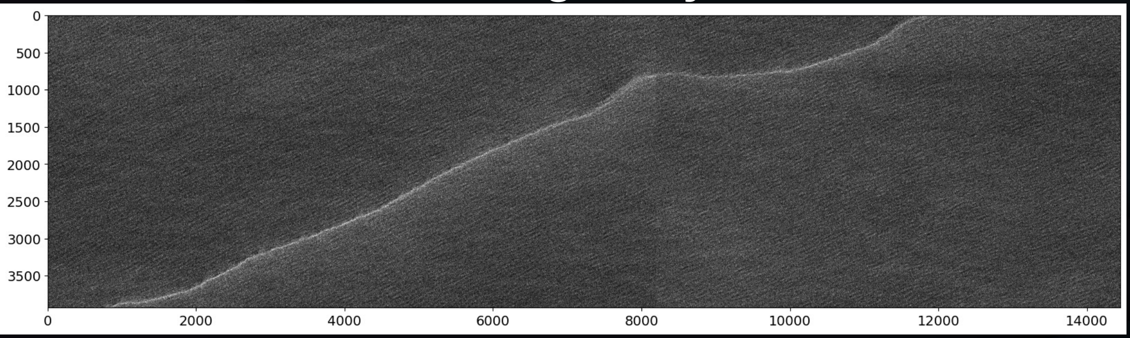




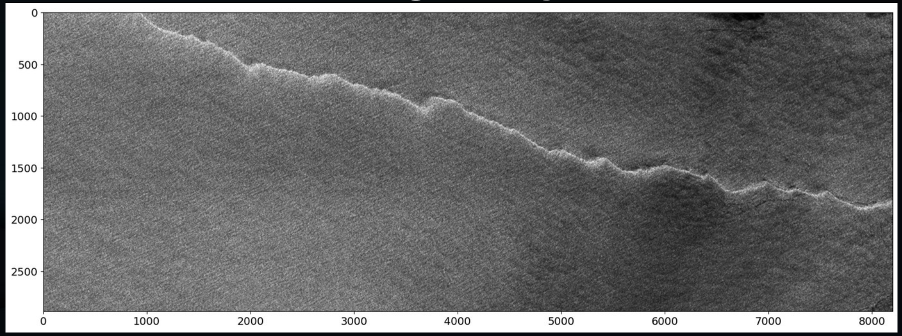
SAR instabilities

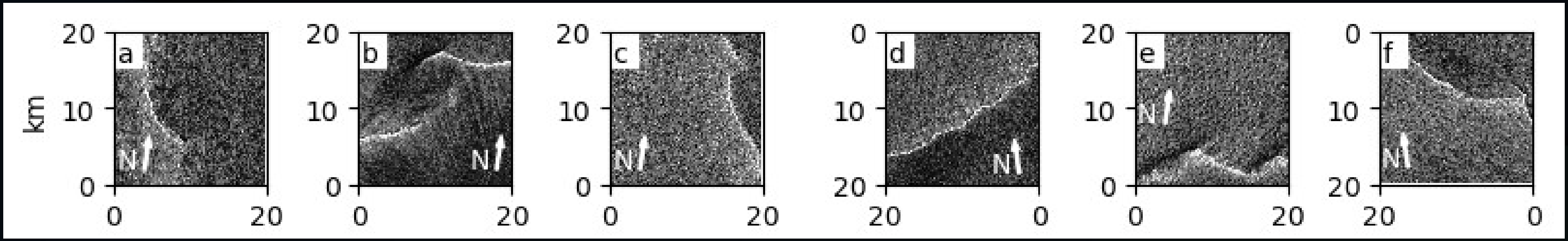
Oct 1994

Trailing – day 279



Trailing – day 282





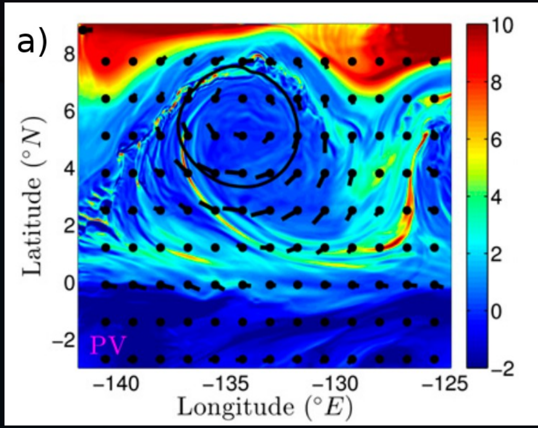
Trailing **Leading** **Trailing** **Leading** **Leading** **Trailing**

2016 to 2019

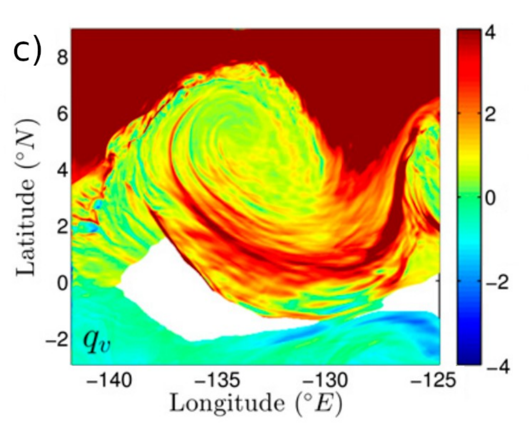
Potential vorticity

$$q = \vec{\omega} \cdot \nabla b = \underbrace{(f + \zeta)N^2}_{q_v} + \underbrace{\vec{\omega}_h \cdot \nabla_h b}_{q_h}$$

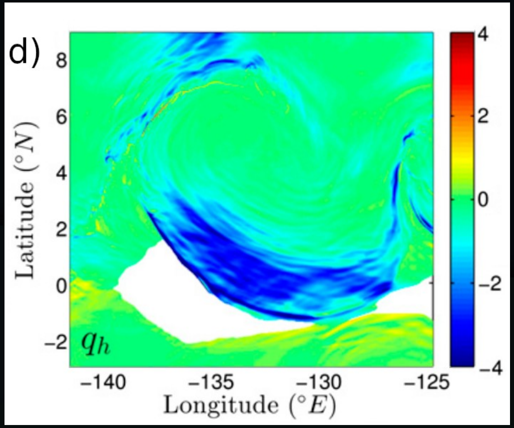
- Potential vorticity (q)
- Total vorticity ($\vec{\omega}$)
- Buoyancy gradient (∇b)
- Coriolis frequency (f)
- Vertical vorticity (ζ)
- Buoyancy frequency (N)
- Horizontal vorticity ($\vec{\omega}_h$)
- Horizontal buoyancy gradient ($\nabla_h b$)



q =



q_v +



q_h

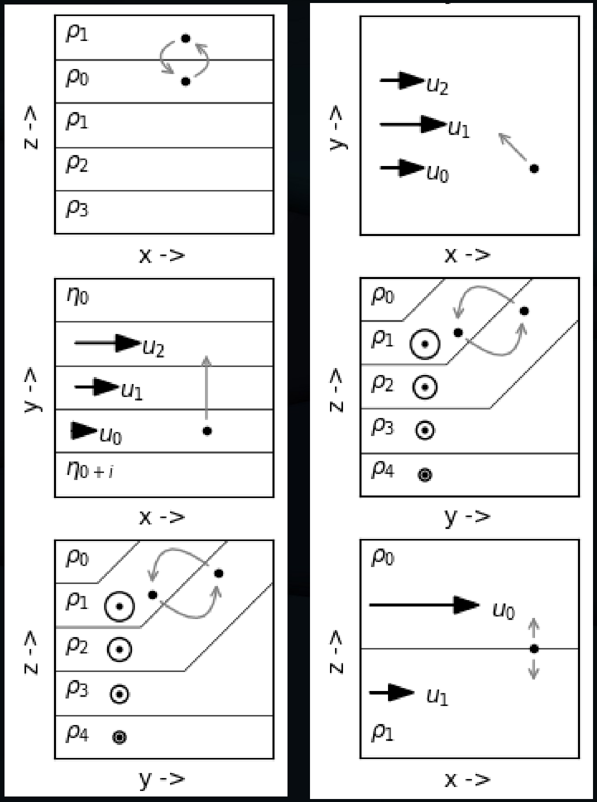
Holmes, 2014

Instability types

Gravitational instability:
Heavy over light
$N^2 < 0$
$q < 0$

Inertial instability:
Strong shear
$\partial u/\partial y > f$
$q < 0$

Symmetric instability:
Strong thermal wind
$N^2/|\partial u/\partial z|^2 < f/(\zeta + f)$
$q < 0$



Barotropic instability:
Specific shear
$\partial q_v/\partial y$ changes sign

ML baroclinic instability:
Specific horizontal or vertical shear
$\partial q/\partial y$ changes sign
$\partial q/\partial y$ & $\partial u/\partial z$ are:
same sign @ bottom
opposite sign @ top

Kelvin-Helmholtz instability:
Strong shear
$N^2/|\partial u/\partial z|^2 < 1/4$

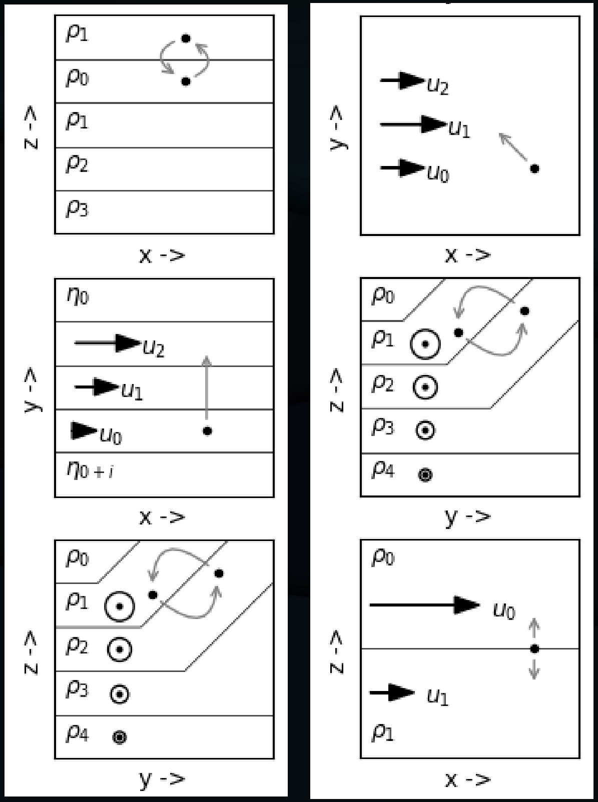
Instability types

Gravitational instability:
Heavy over light
$N^2 < 0$
$q < 0$

Inertial instability:
Strong shear
$\partial u / \partial y > f$
$q < 0$

FOR FRONTAL SCALES

Symmetric instability:
Strong thermal wind
$N^2 / |\partial u / \partial z|^2 < f/(\zeta + f)$
$q < 0$



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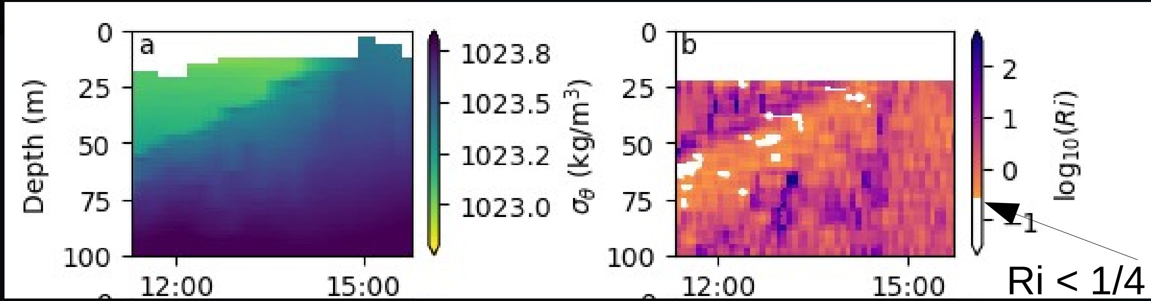
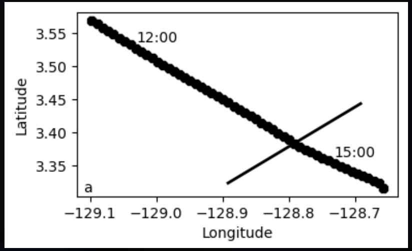
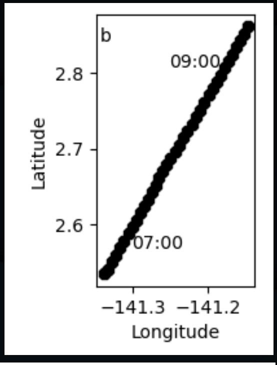
Richardson numbers

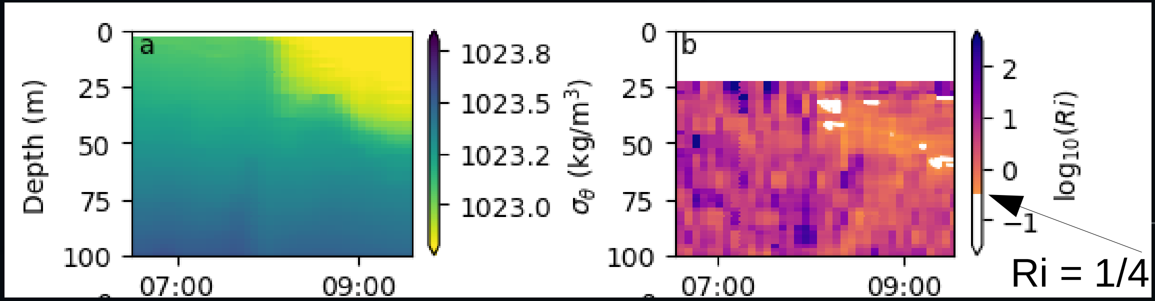




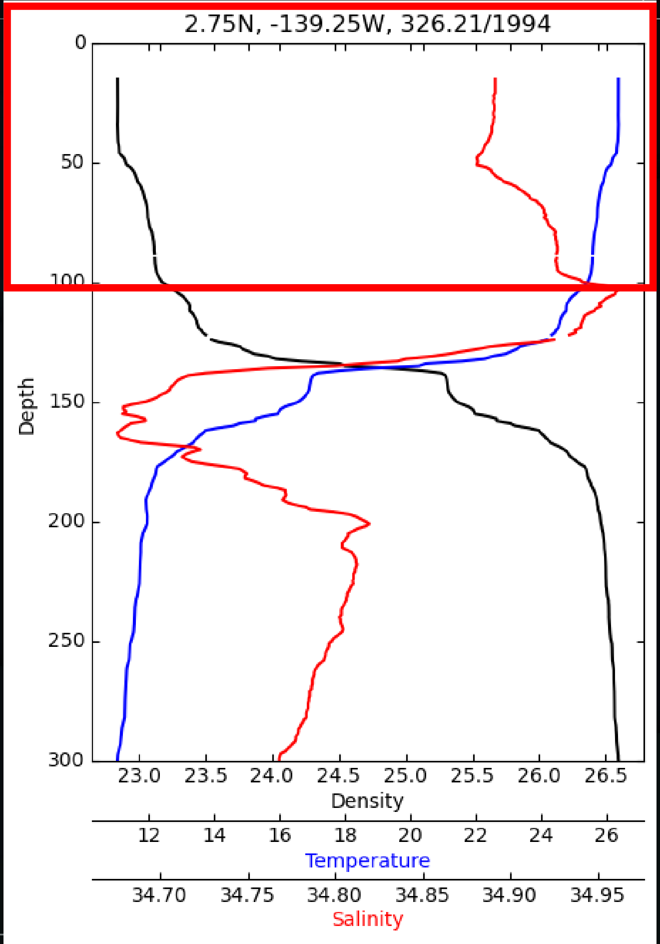
Leading front
Aug 1990



Trailing front
Nov 1990



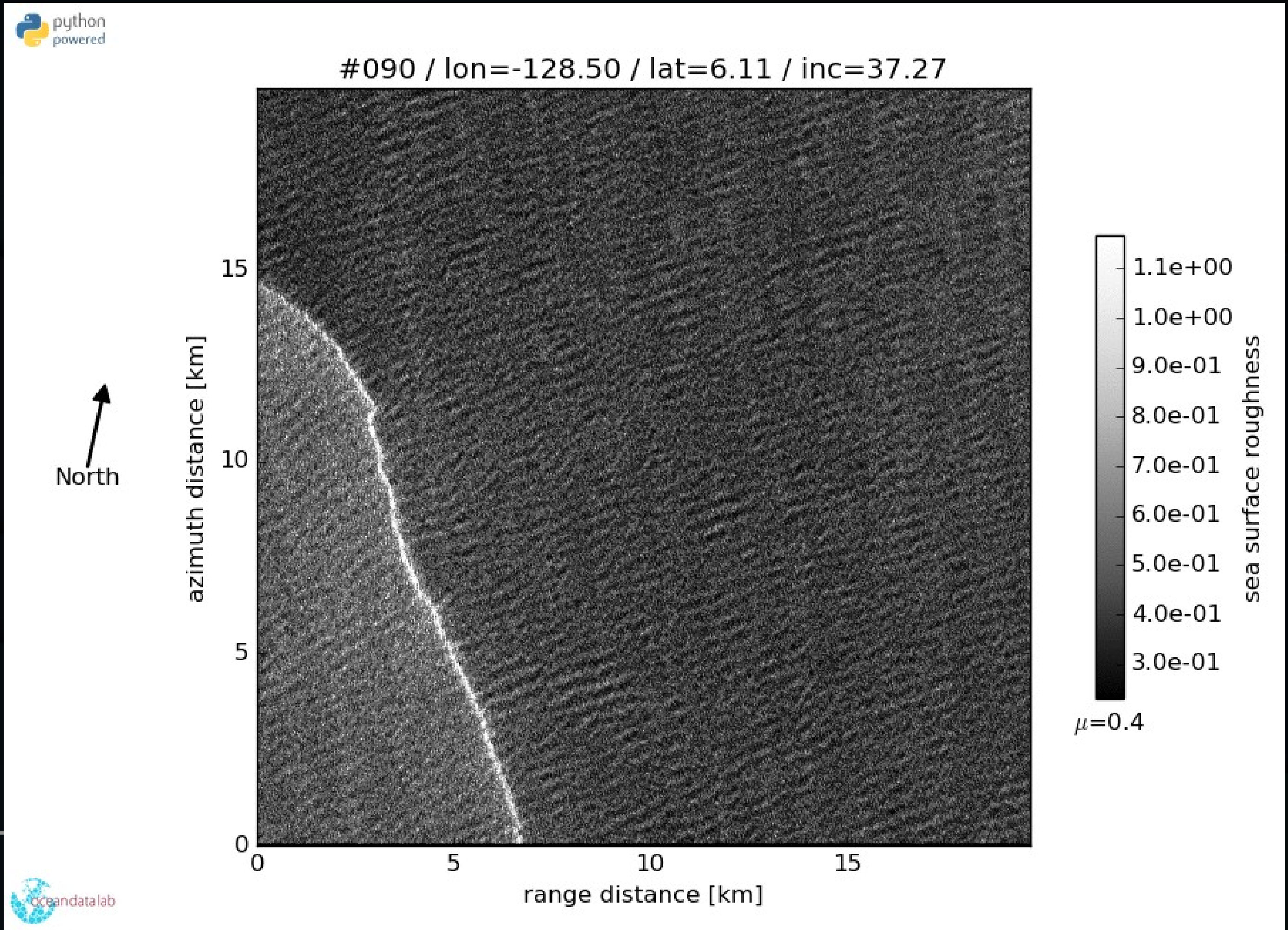
Only this
in panels



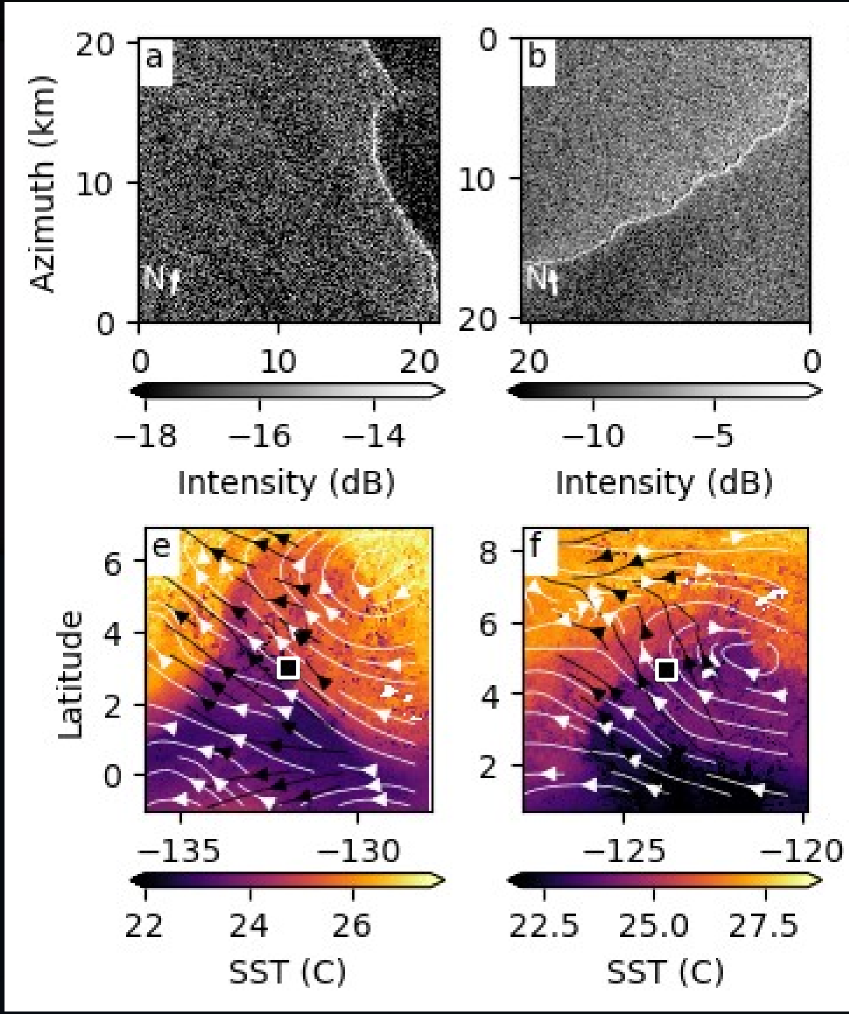
Conclusions

- Swirling currents advect, rotate, and deform SST fronts and trigger small-scale waves, cusps, and breaks
- Leading and trailing fronts are not subject to negative-PV instabilities, but instead to barotropic and mixed layer baroclinic instabilities
- Kelvin-Helmholtz instability may play a role in frontal dynamics

Cross-front differences



Back-scatter intensity



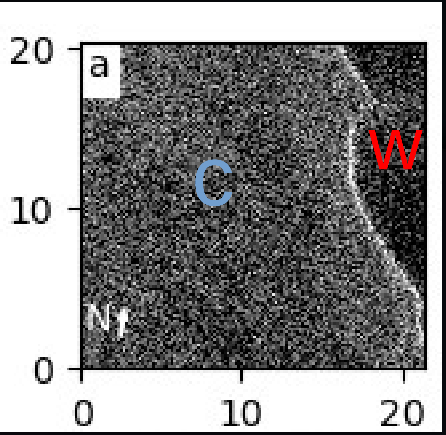
2016 to 2019

Back-scatter used in model to derive winds, much like scatterometer

LARGE SCALES
Color – SST
(Modis - NASA)
Black – winds
(MetOp scatterometer - Eumetsat)
White – currents
(altimetry assimilated
into Mercator model)

Temperature impact on wind

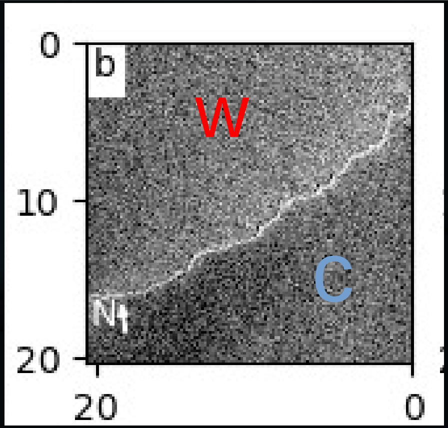
7.7 m/s



6.7 m/s

Wind row direction

5.8 m/s

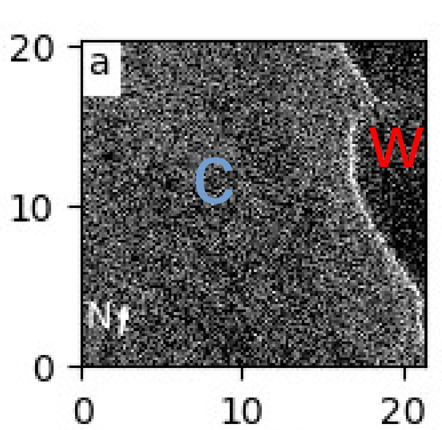


4.7 m/s

Wind row direction

Temperature impact on wind

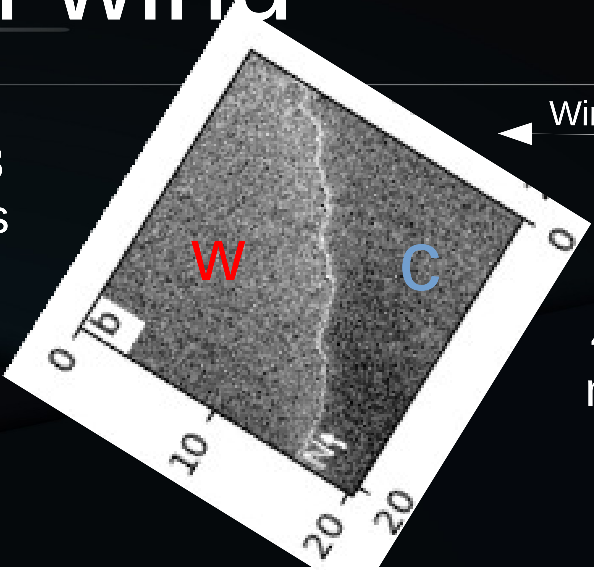
7.7 m/s



6.7 m/s

Wind row direction

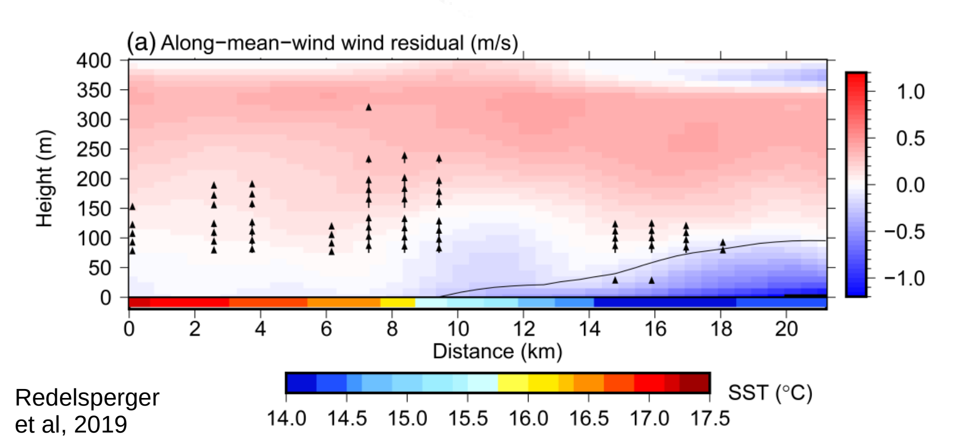
5.8 m/s



Wind row direction

4.7 m/s

Cross-front winds
Leading front



Temperature impact on wind

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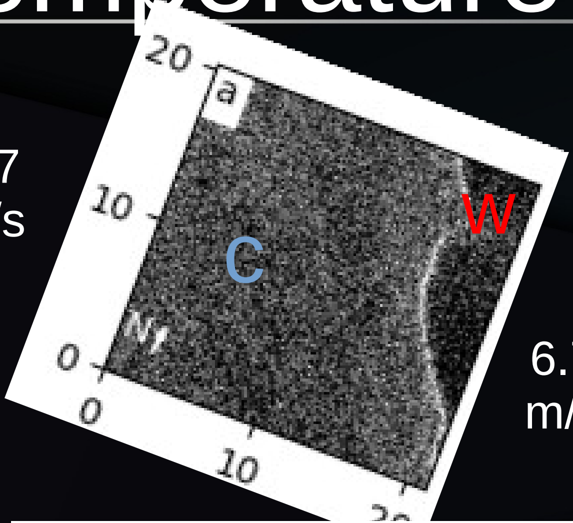

6.7 m/s

Wind row direction

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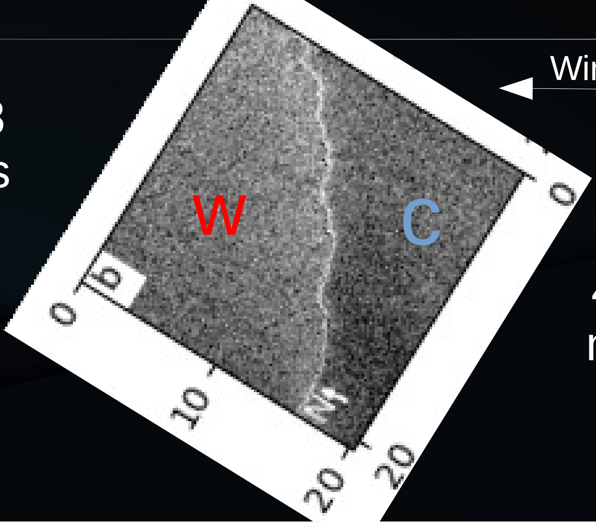
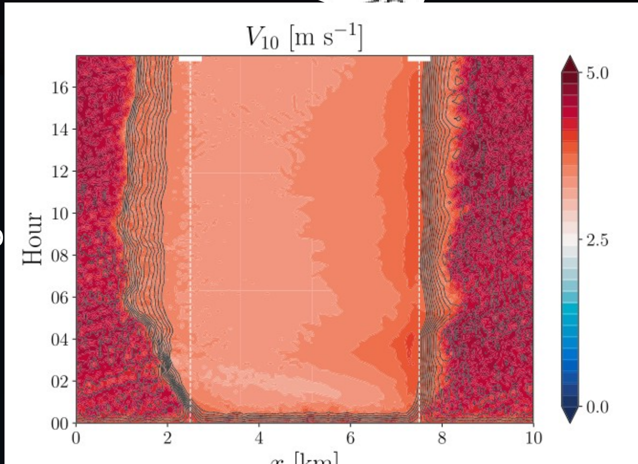


Wind row direction

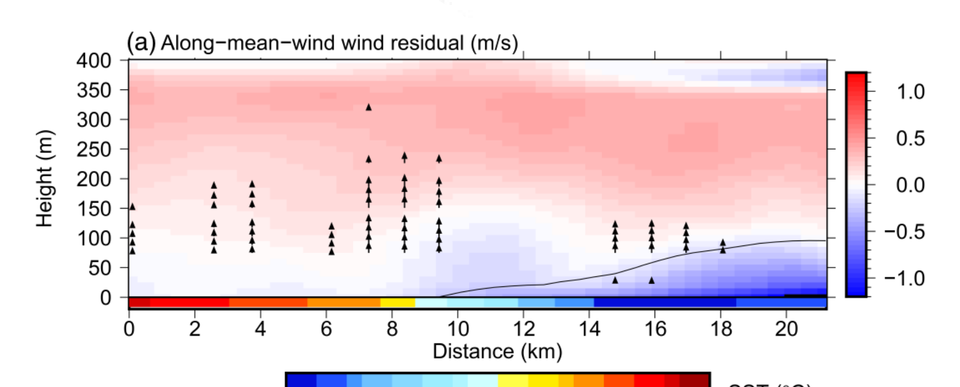
4.7 m/s

Along-front winds
Trailing front



Wenegrat and Arthur, 2018

Cross-front winds
Leading front



Redelsperger et al, 2019

Wind relative to ocean surface instead of absolute wind affects backscatter!

$$U_r(u_r, \theta_r) = U_w(u_w, \theta_w) - U_c(u_c, \theta_c)$$

Set by back-scatter

Angle

Radius

Set by wind rows

Color

Contour

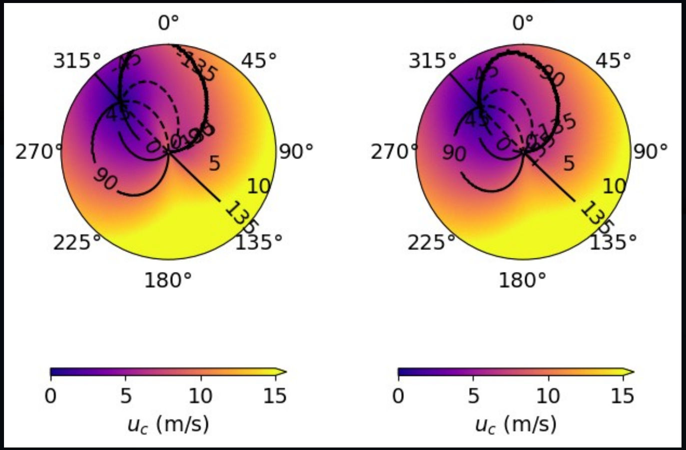
Bright, cold side:

u_w = 7.5 m/s

u_c = 0.8 m/s

θ_c = -110°

θ_r = -38°



Dark, warm side:

u_w = 8 m/s

u_c = 1.3 m/s

θ_c = -165°

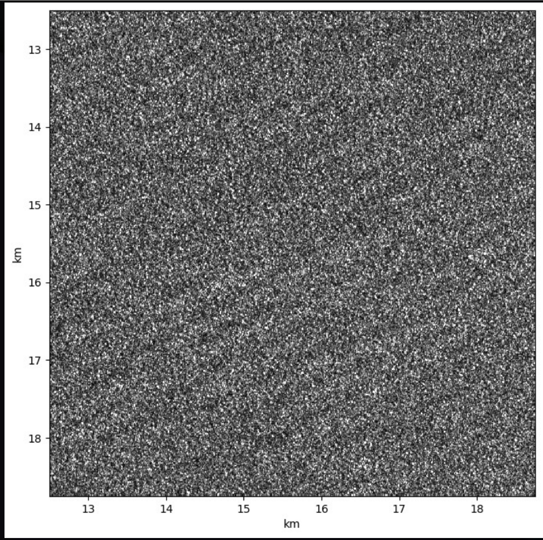
θ_r = -33°

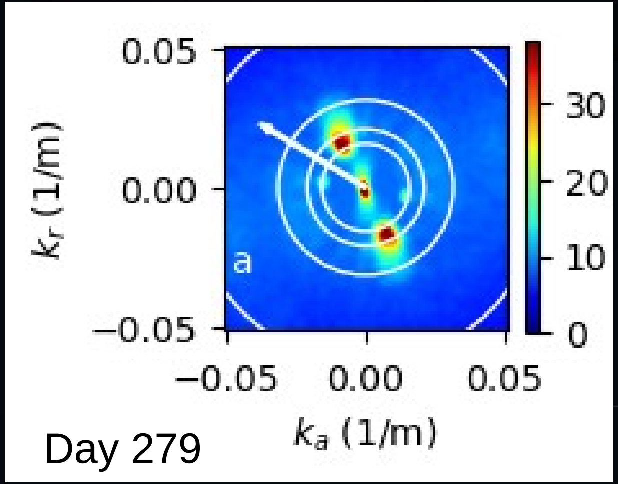
Different current magnitudes and directions across the front could account for back-scatter intensity difference

But can that happen?

Current inversion

Oct 1994





$$\omega_{obs} = \omega + \vec{k} \cdot \vec{u}$$

Observed frequency

Stationary frequency

Wave-number vector

Surface current

$$\frac{\partial \vec{k}}{\partial t} + \nabla \omega_{obs} = 0$$

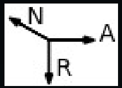
Conservation of crests

$$\omega_{obs} = constant = \sqrt{kg} + k_a u_a + k_r u_r$$

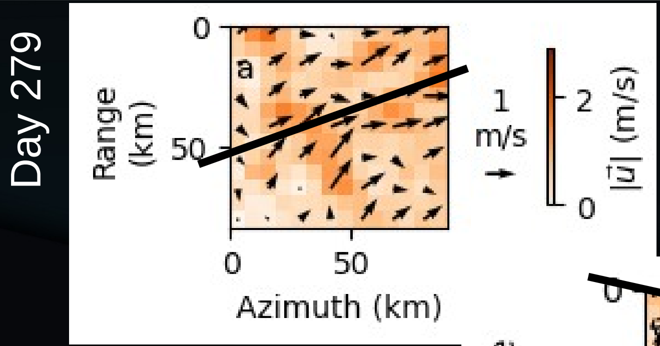
$$\mathbf{Ax} = \mathbf{b}$$

Surface currents

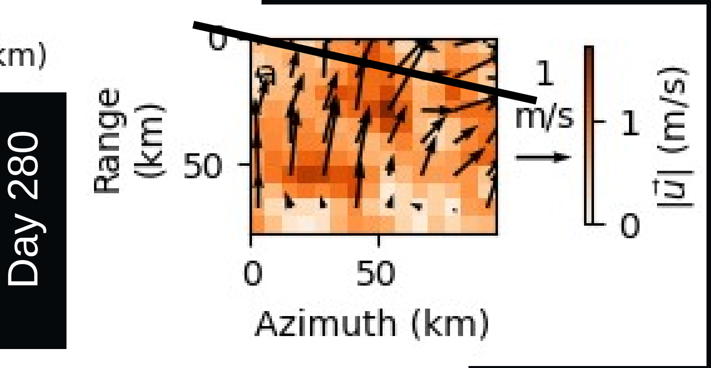
Oct 1994



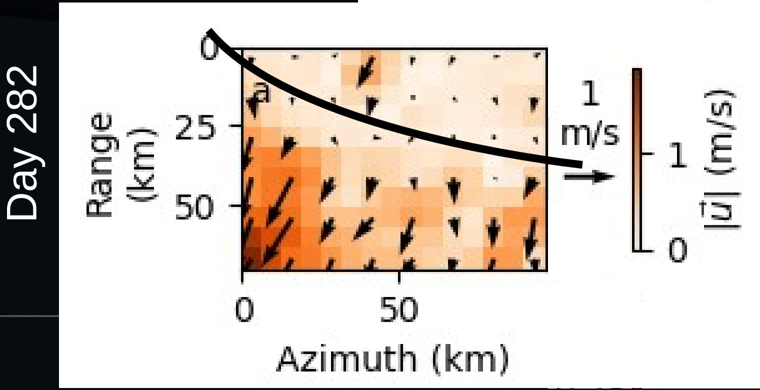
Along-front currents



Across-front in N and along-front in S



Across-front currents with strong cross-front divergent current

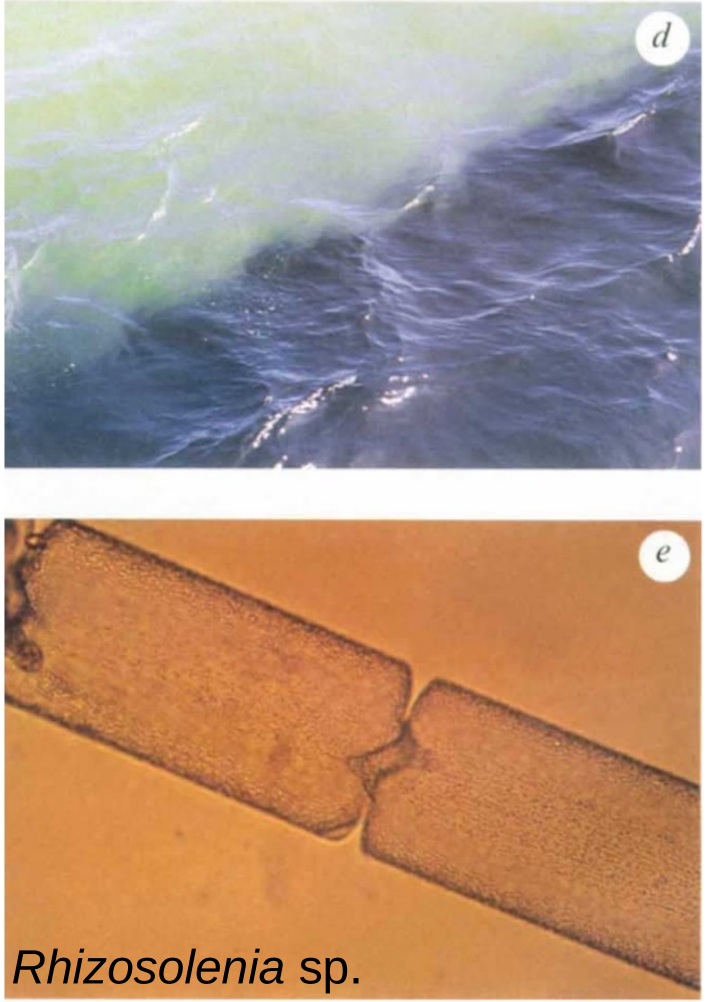


Conclusions

- Wind differences caused by SST differences across the front can explain back-scatter intensity differences across leading fronts
- On the trailing front, small variations in current magnitude and direction on the two sides of the front are important
- Surface currents can be any direction and strength around the front, but SAR data can determine what really happens

Implications

- Heat and energy analyses of TIVs can be incomplete
- Winds from scatterometer can be in error in regions of strong currents
- SAR offers opportunity to determine convergence and divergence from satellite



Rhizosolenia sp.

Questions?

Yoder et al., 1994

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Alma, Angeles, Gabi, Sherry, Victoria; Kate

Bénédicte Dousset

My family

Thank you