# On the imaging of rip currents at X-band

Rebecca Kloster
Merrick Haller and David Lyzenga

Coastal & Ocean Engineering
Oregon State University

1) Rip current observations via marine radar

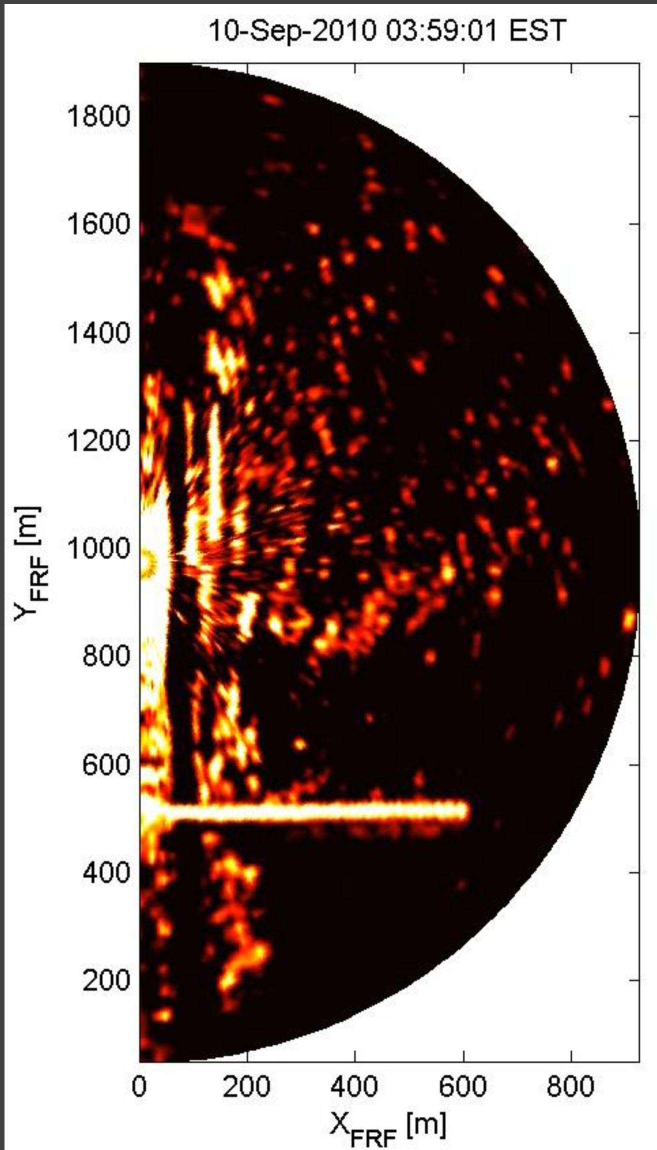
2) Rip current model

3) Implications for X-band scattering

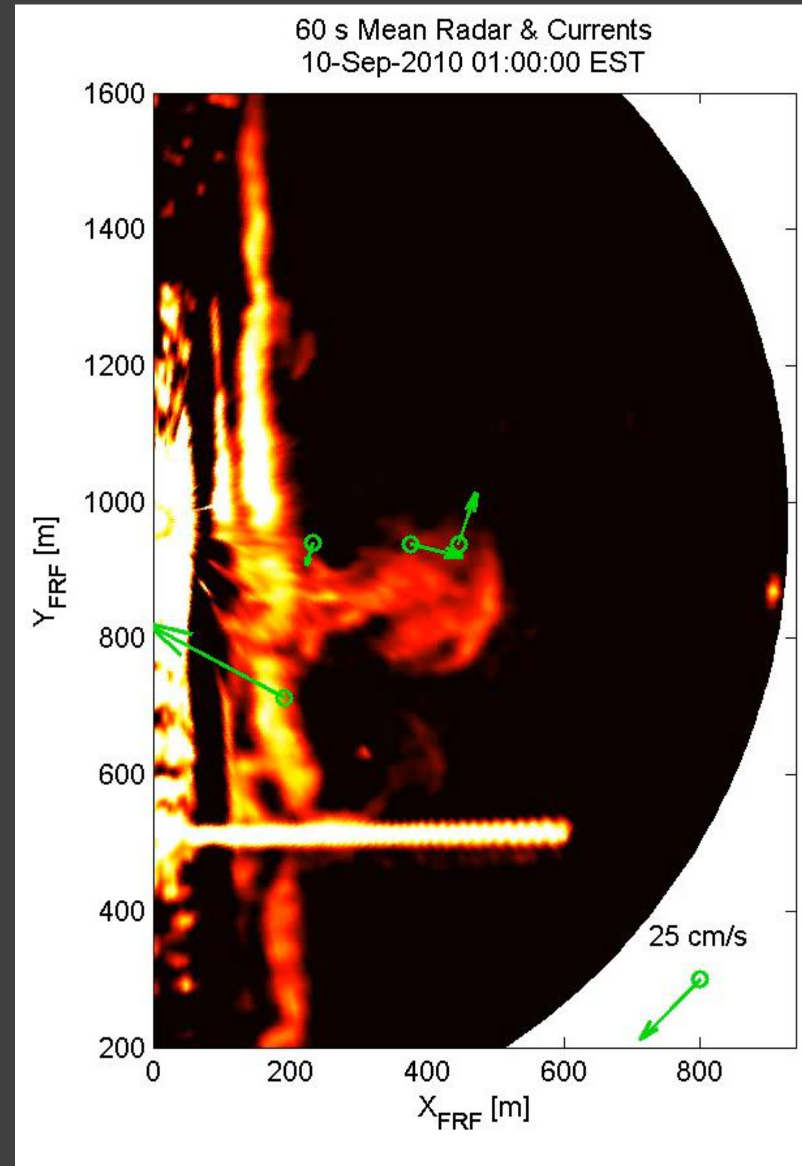
4) Summary

# Observations – Duck, NC

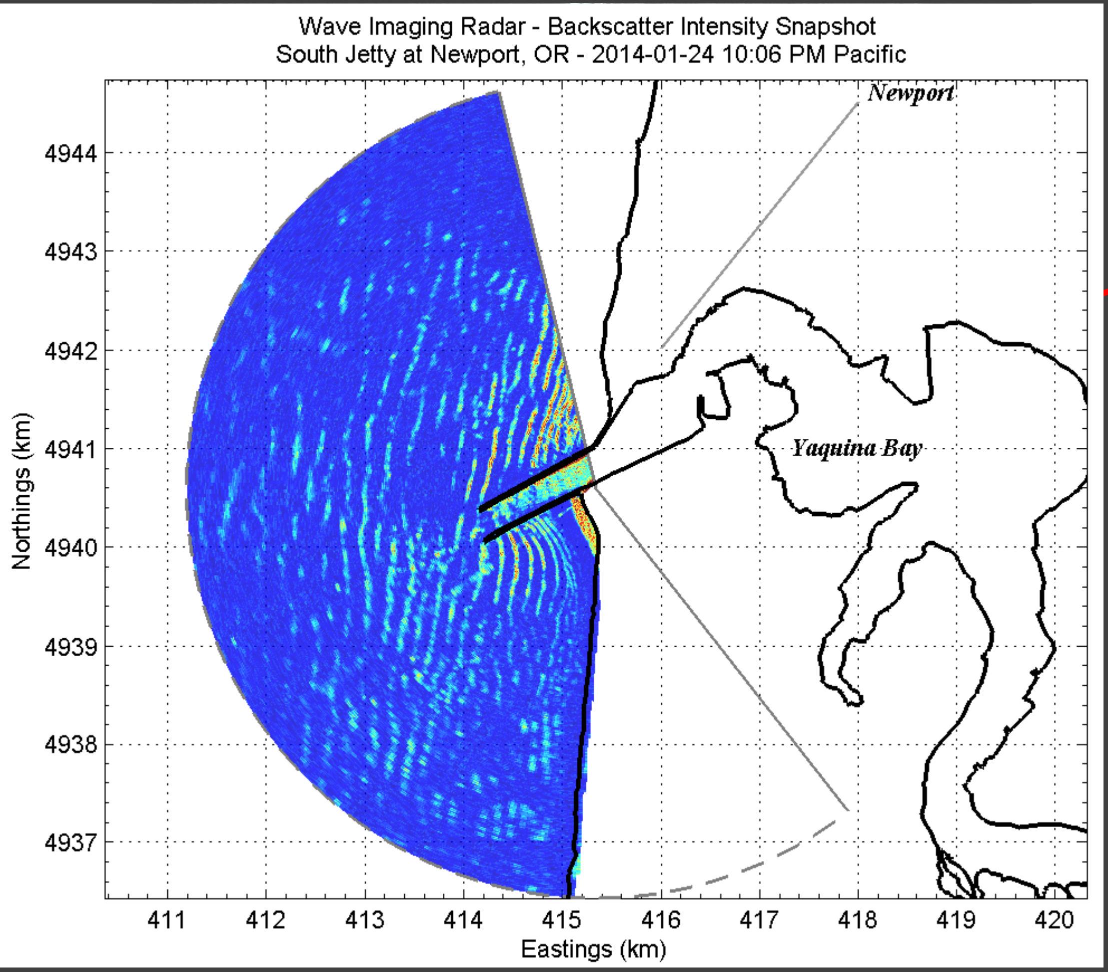

Raw image sequence (0.75Hz)

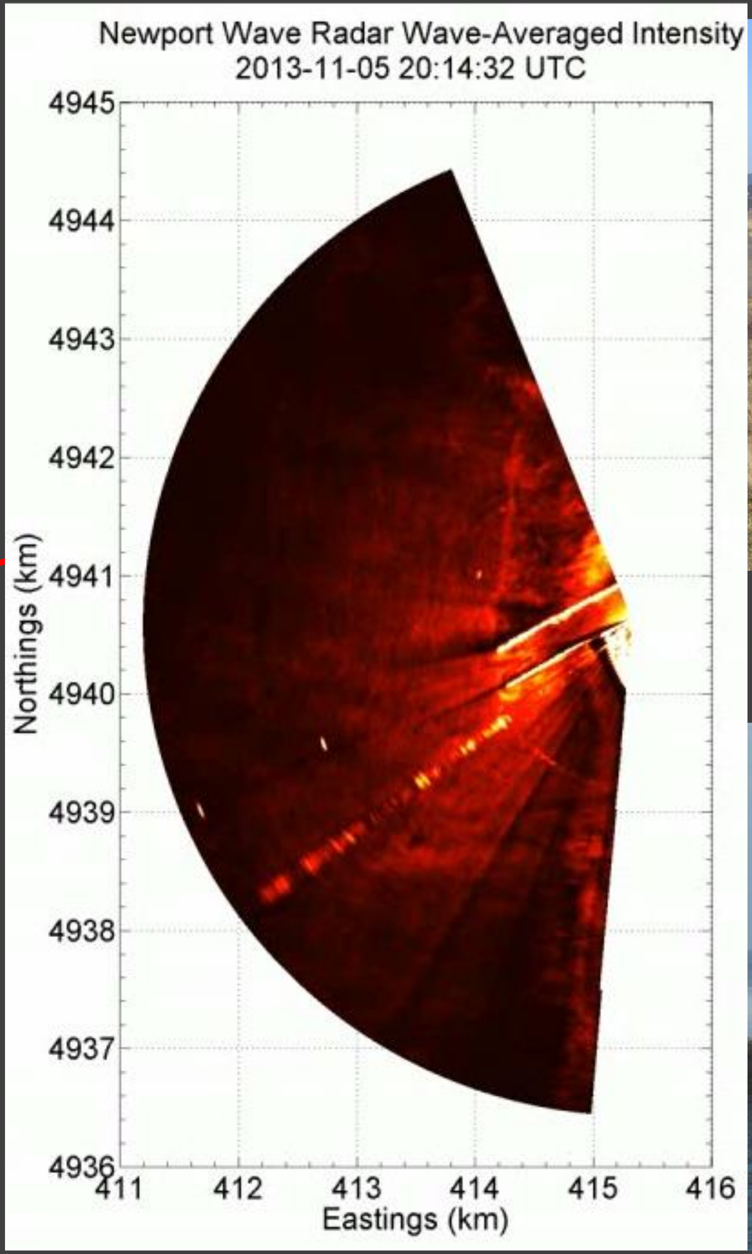



60 sec mean image (0.75 Hz)

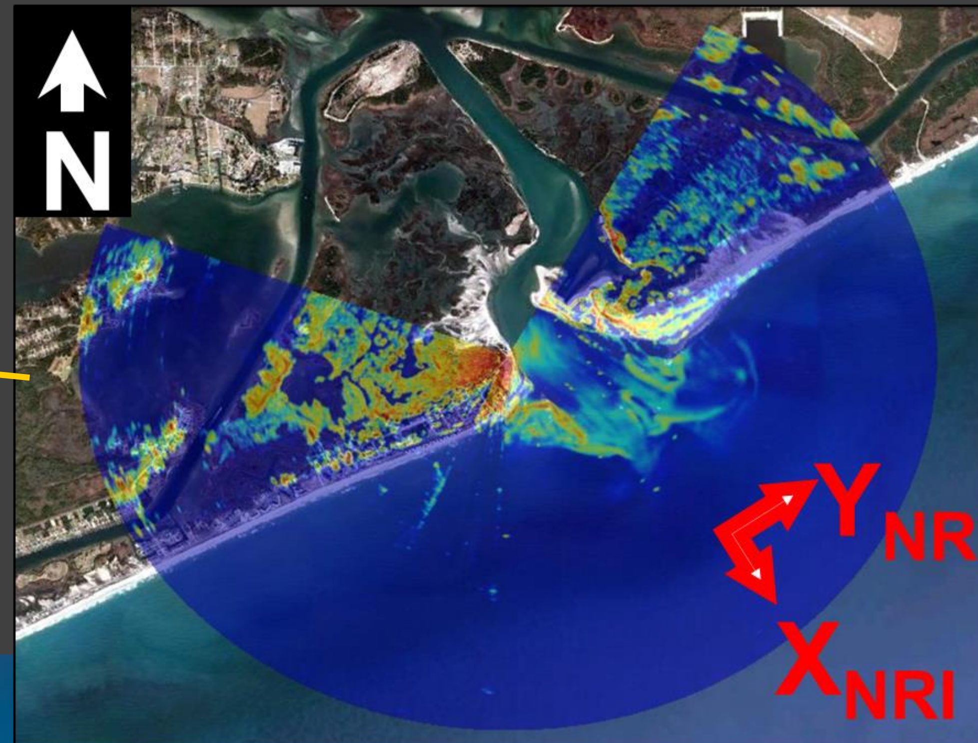


# South Jetty, Newport, Oregon



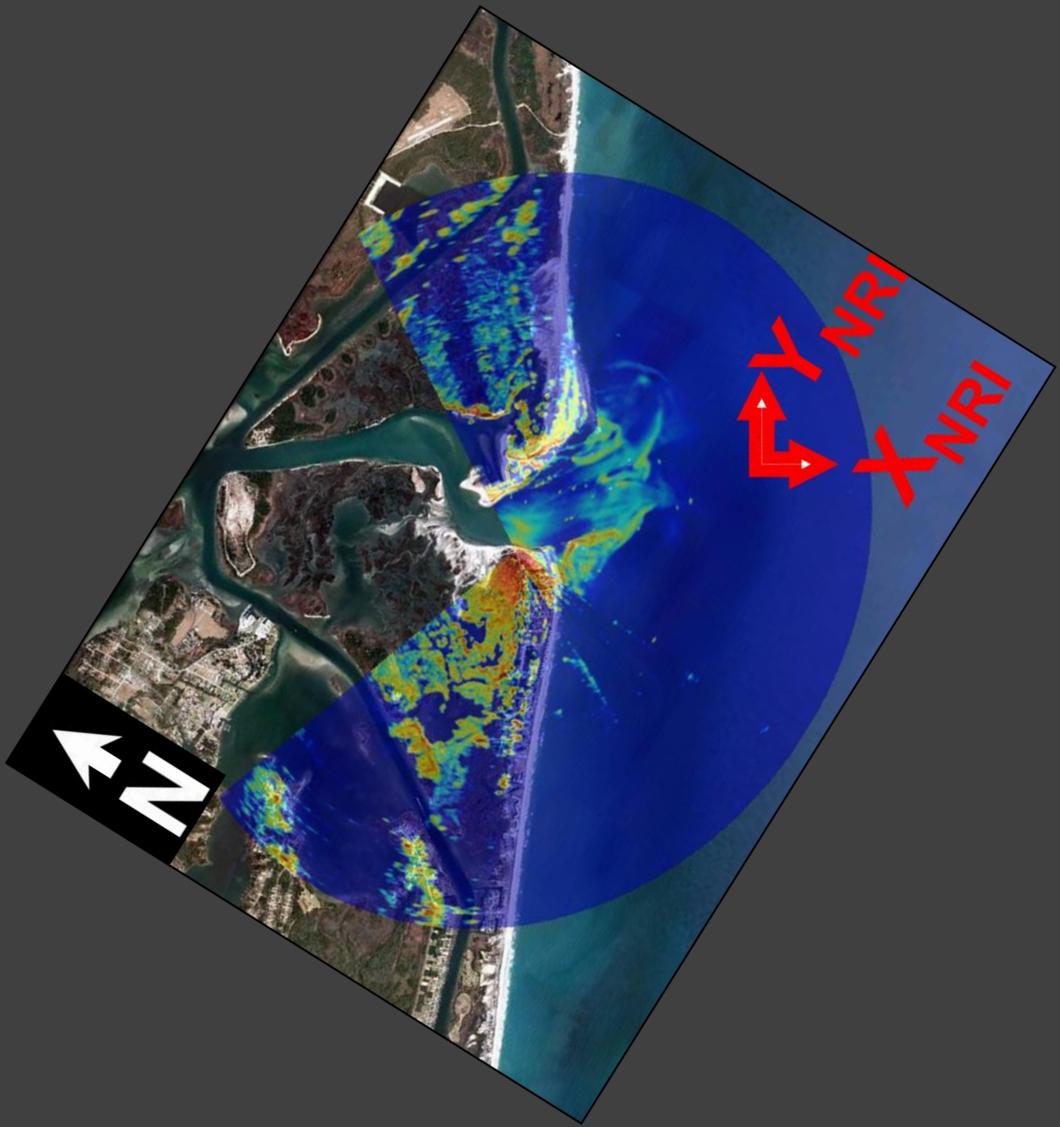



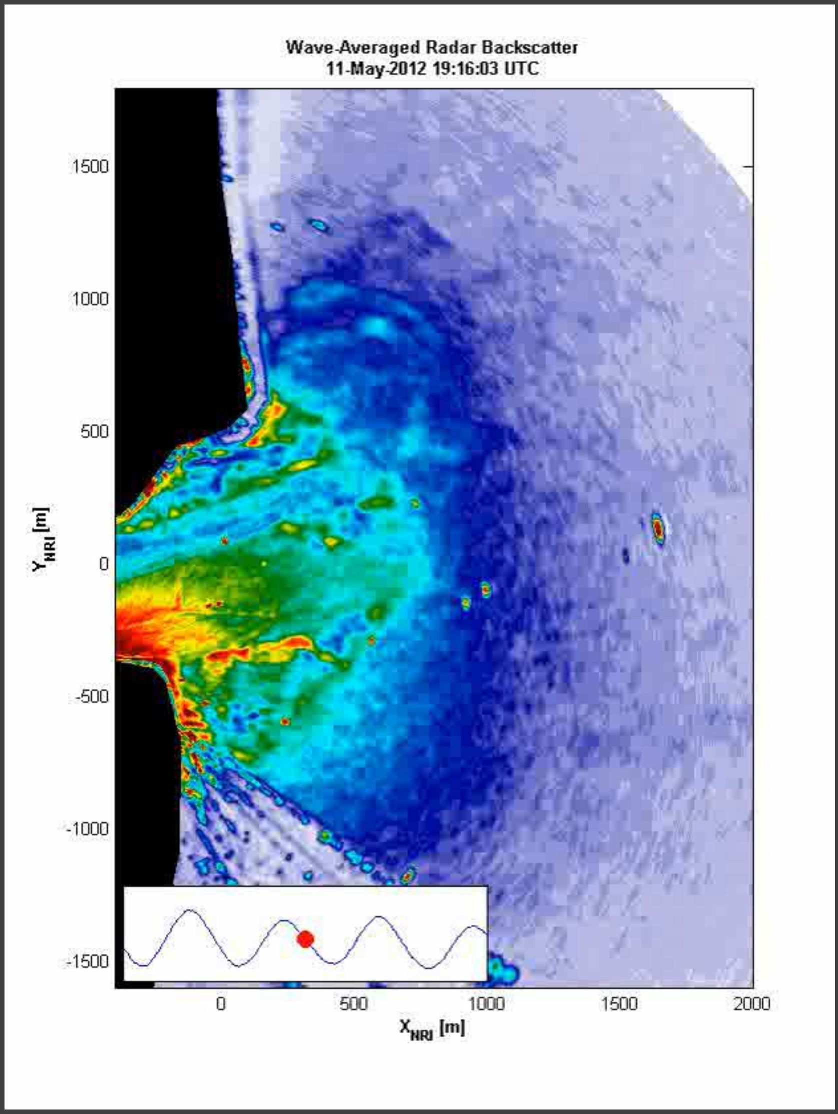
# Observation Stations


Data Assimilation and Remote-sensing for Littoral Applications
(DARLA - MURI #N00014-10-1-0932)

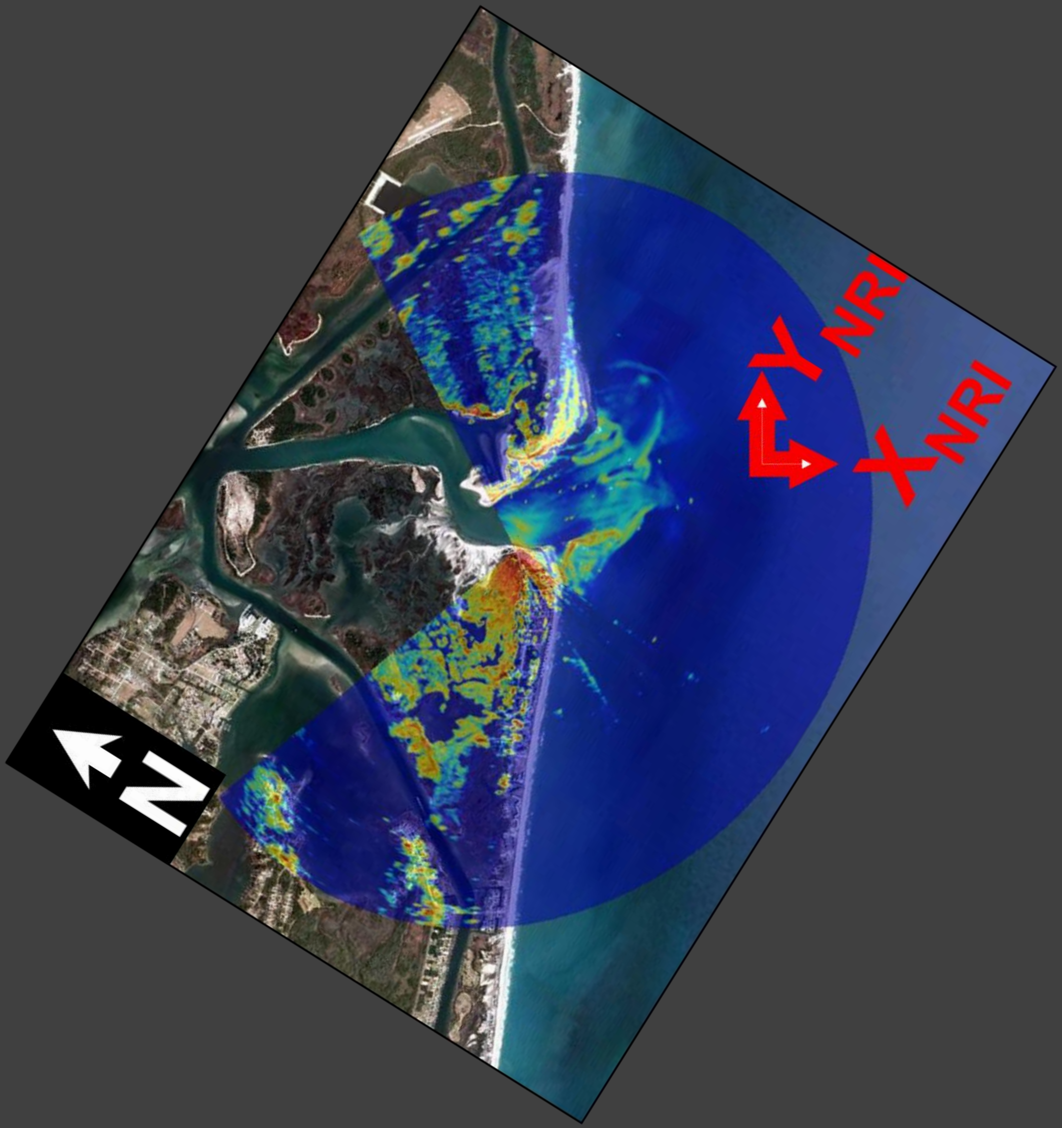
# Tidal flows – New River Inlet, NC

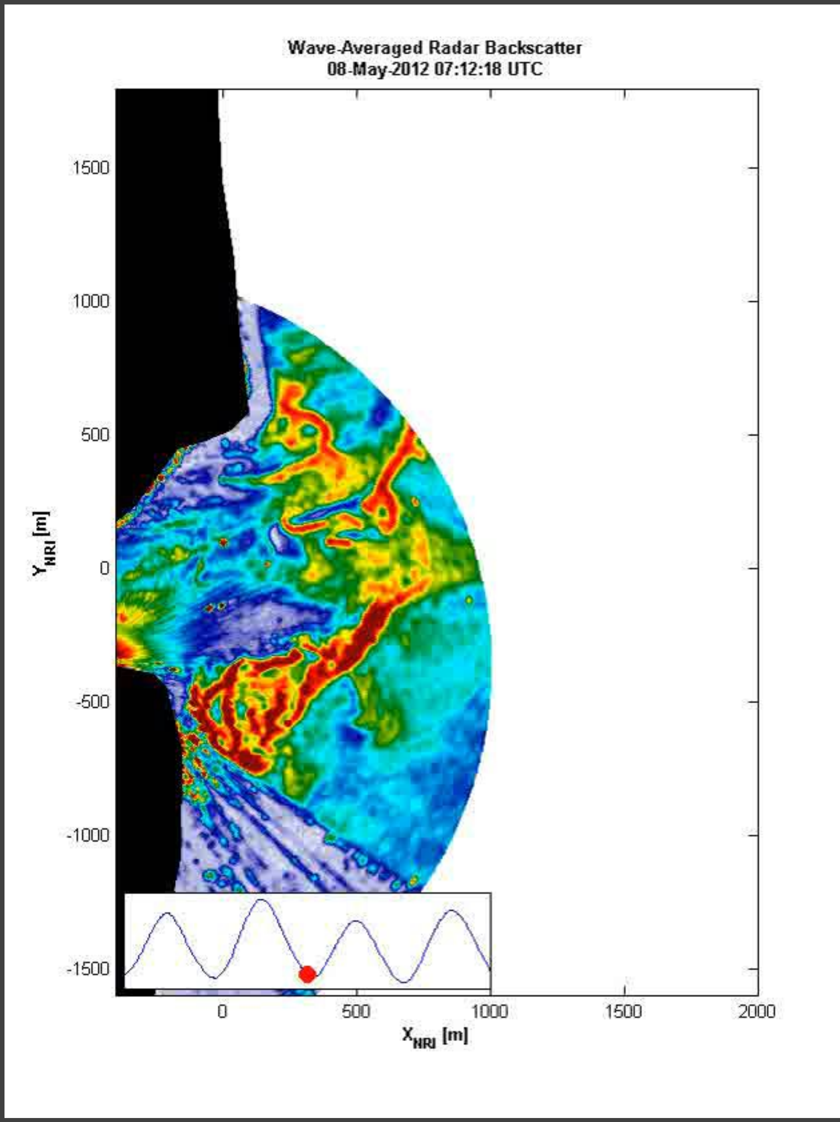


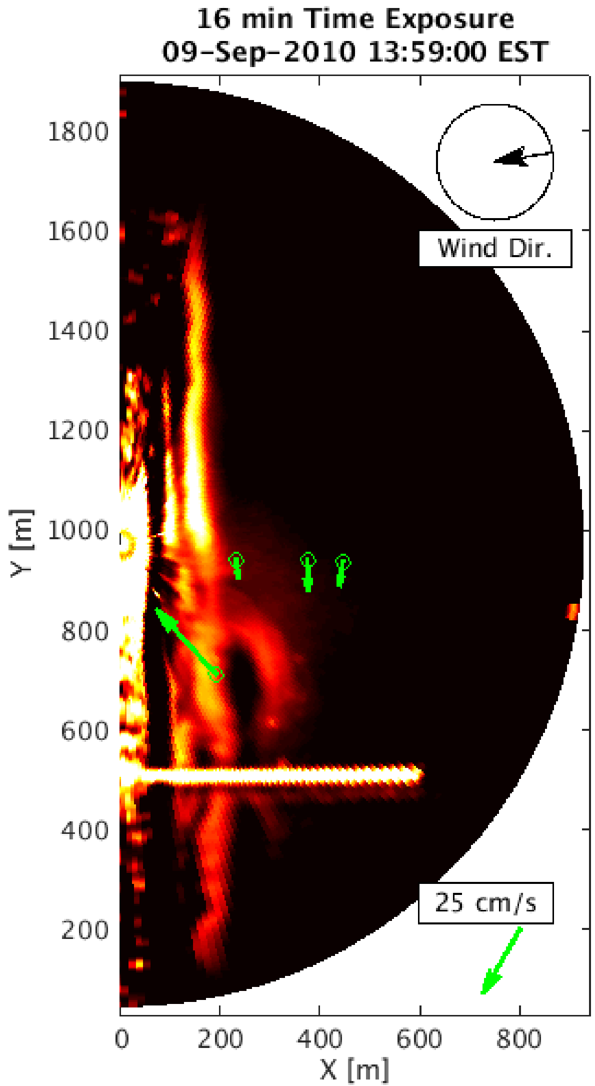

Ebb Jets

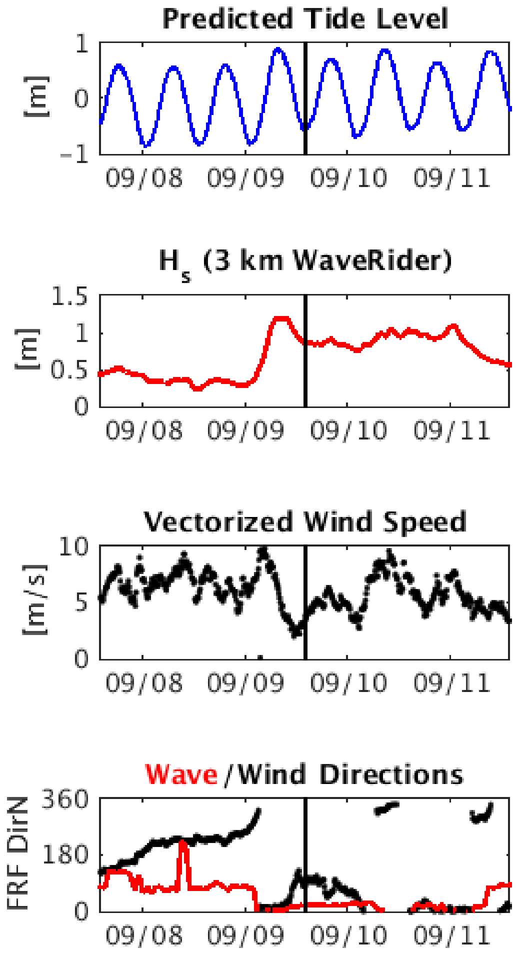
# Tidal flows – New River Inlet, NC

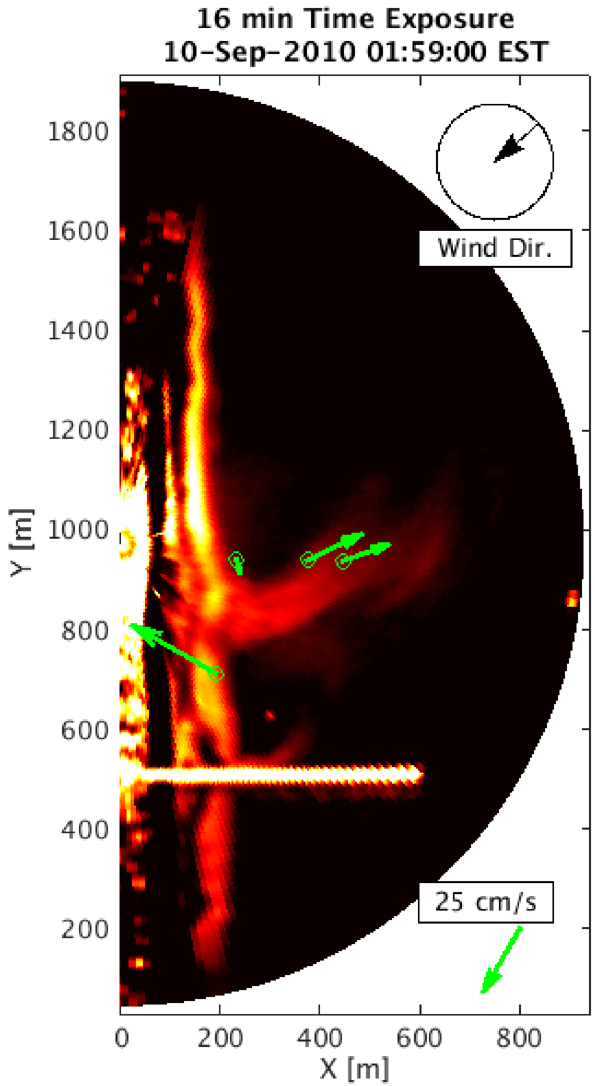


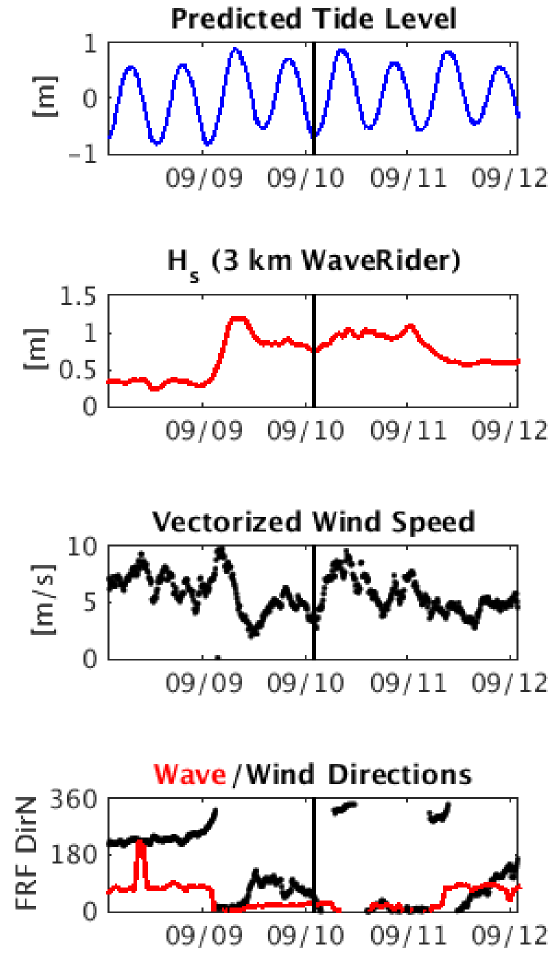

Ebb Jet-lets


16 min Time Exposure
09-Sep-2010 13:59:00 EST
Wind Dir.
25 cm/s
1800
1600
1400
1200
1000
800
600
400
200
Y [m]
0
200
400
600
800
X [m]

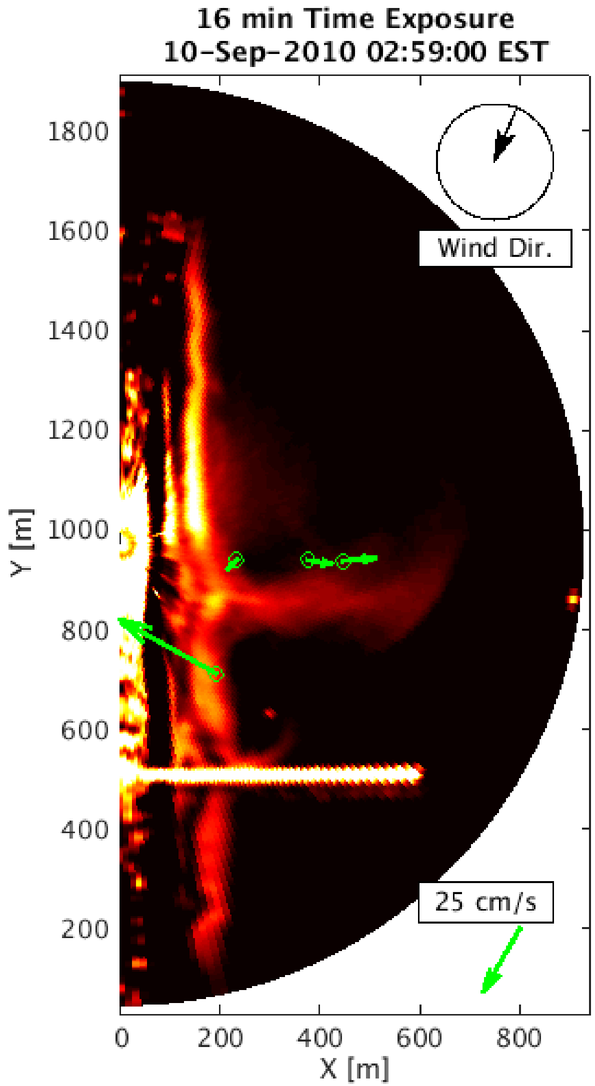

Predicted Tide Level
[m]
1
0
-1
09/08
09/09
09/10
09/11
$H_s$ (3 km WaveRider)
1.5
1
0.5
0
Vectorized Wind Speed
[m/s]
10
5
Wave/Wind Directions
FRF DirN
360
180

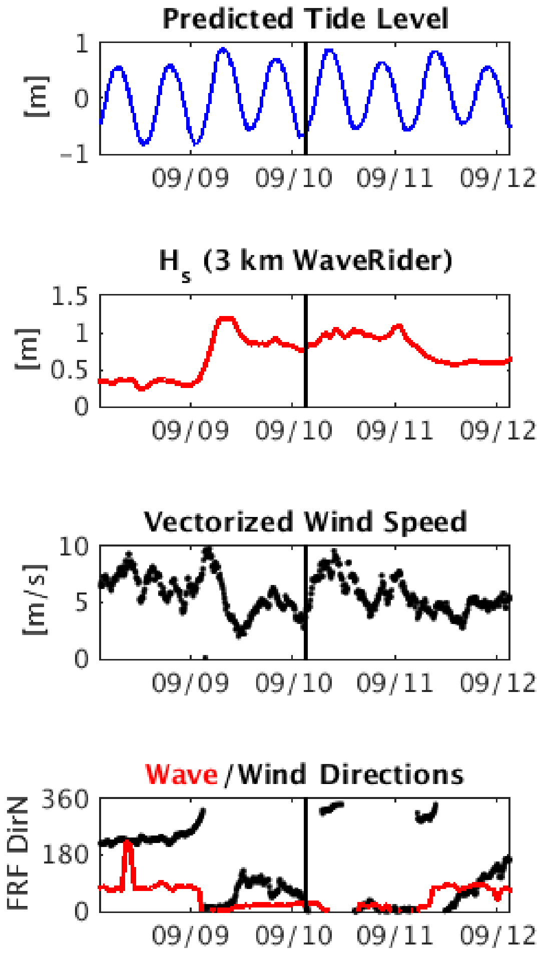


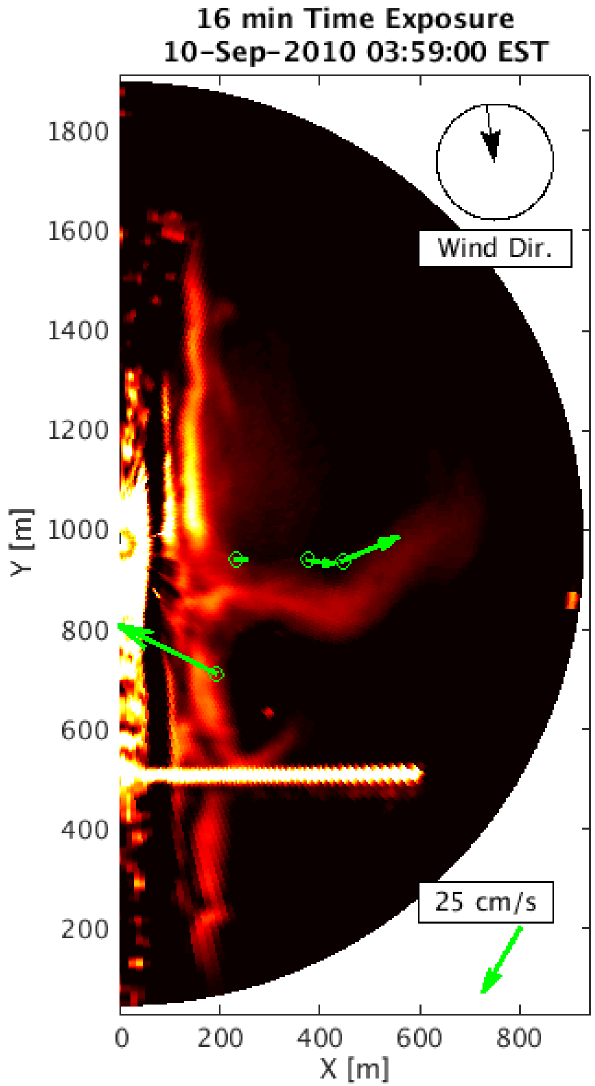
16 min Time Exposure
10-Sep-2010 01:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]

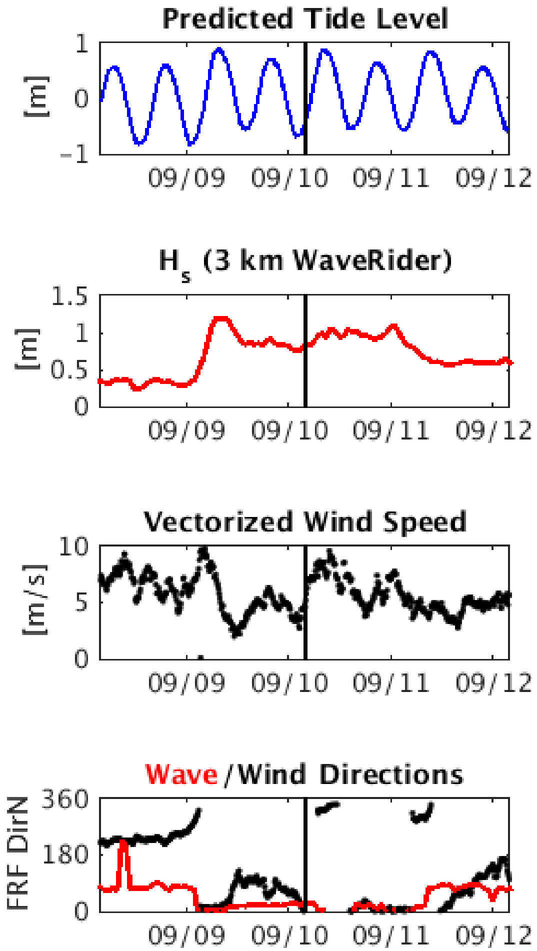
Predicted Tide Level
[m]
$H_s$ (3 km WaveRider)
[m]
Vectorized Wind Speed
[m/s]
Wave / Wind Directions
FRF DirN
09/09
09/10
09/11
09/12


16 min Time Exposure
10-Sep-2010 02:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
1800
1600
1400
1200
1000
800
600
400
200
0
200
400
600
800

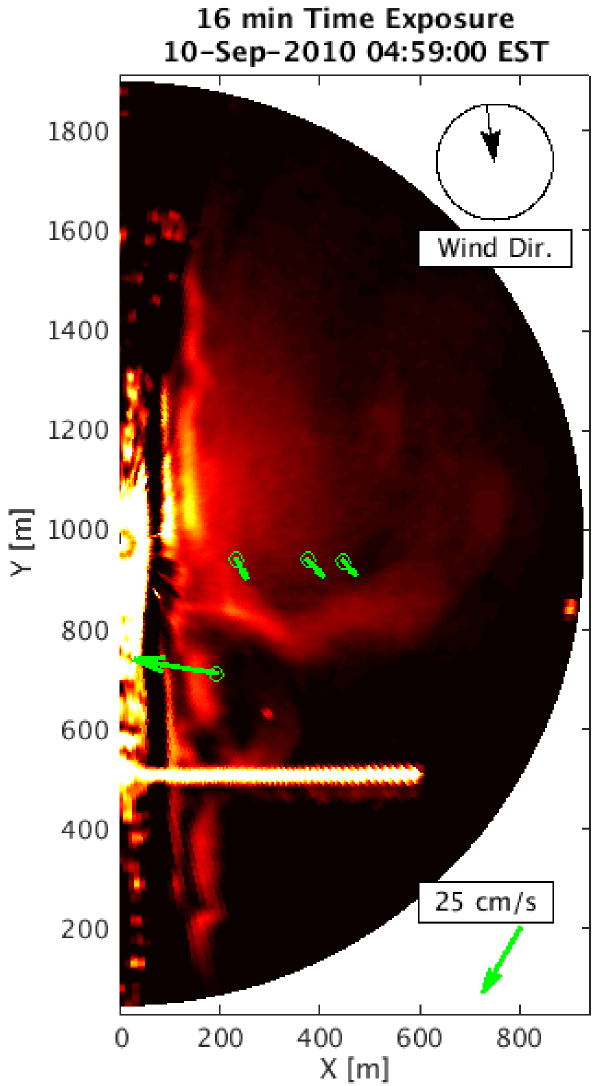

Predicted Tide Level
[m]
H s (3 km WaveRider)
[m]
Vectorized Wind Speed
[m/s]
Wave / Wind Directions
FRF DirN
09/09
09/10
09/11
09/12



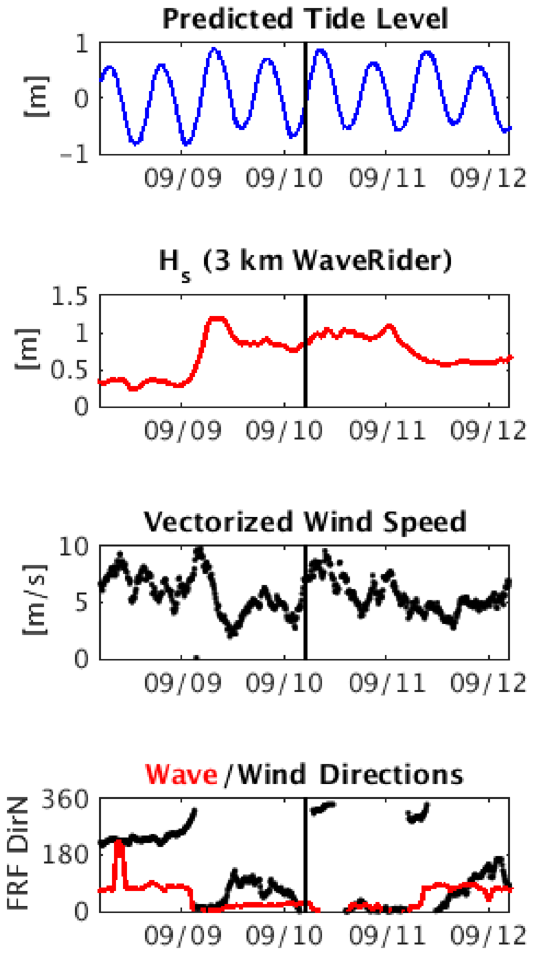
16 min Time Exposure
10-Sep-2010 03:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
1800
1600
1400
1200
1000
800
600
400
200
0
200
400
600
800

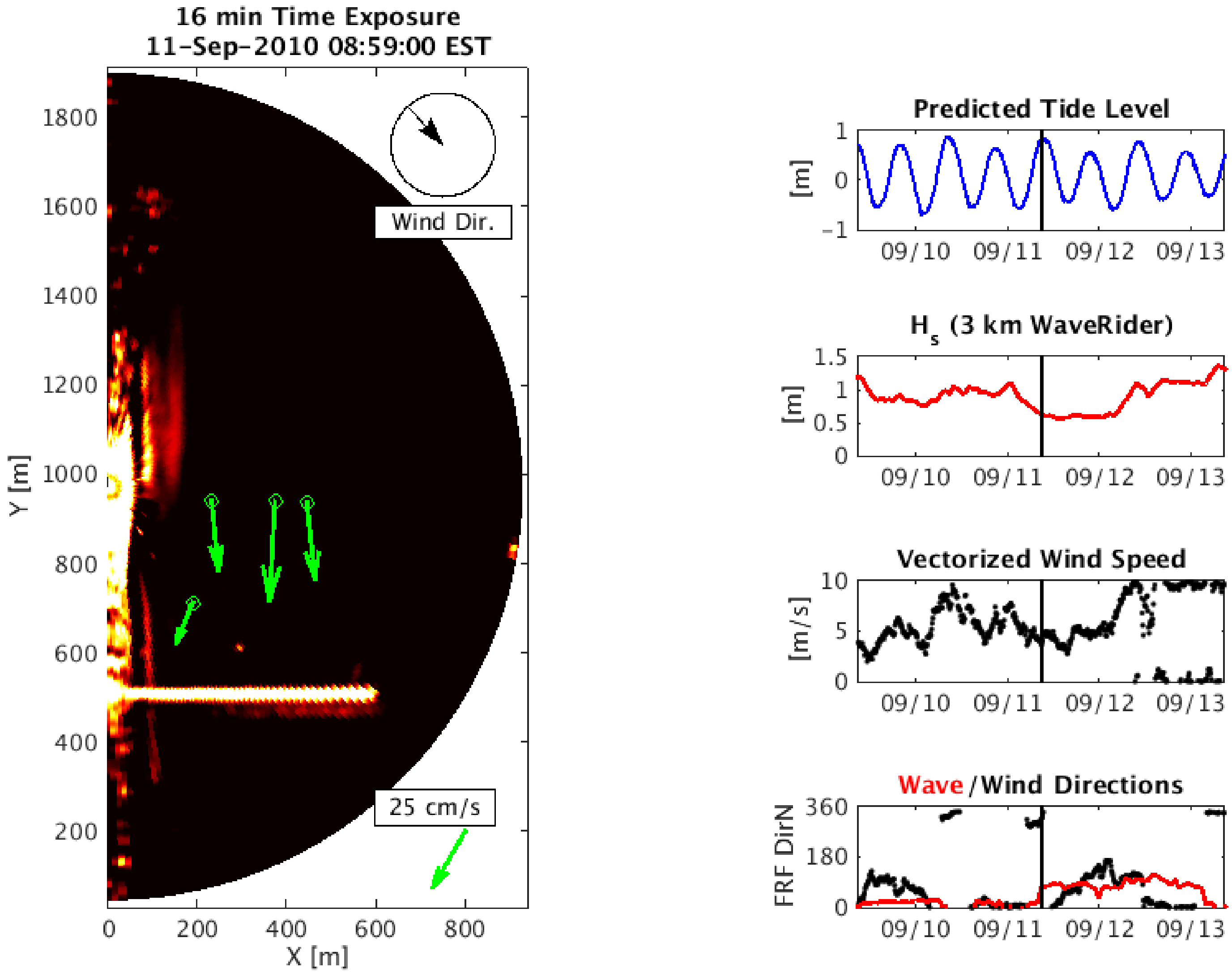
Predicted Tide Level
[m]
1
0
-1
H s (3 km WaveRider)
[m]
1.5
1
0.5
0
Vectorized Wind Speed
[m/s]
10
5
0
Wave/Wind Directions
FRF DirN
360
180
0
09/09
09/10
09/11
09/12



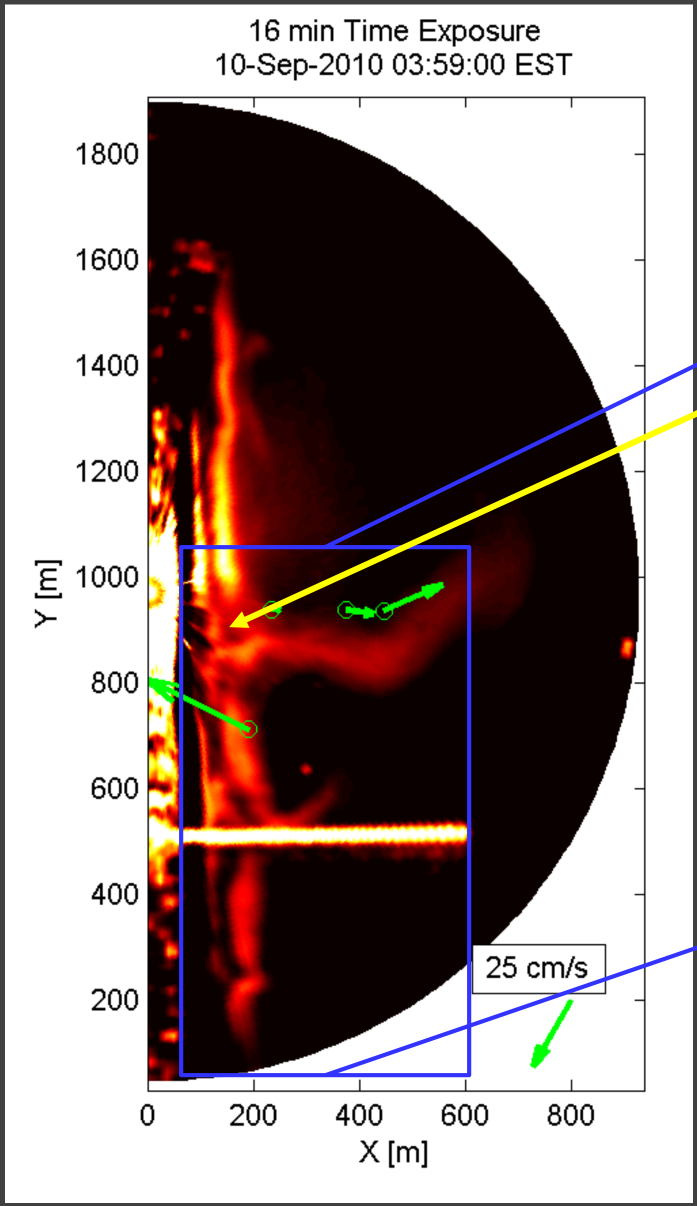
16 min Time Exposure
10-Sep-2010 04:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]

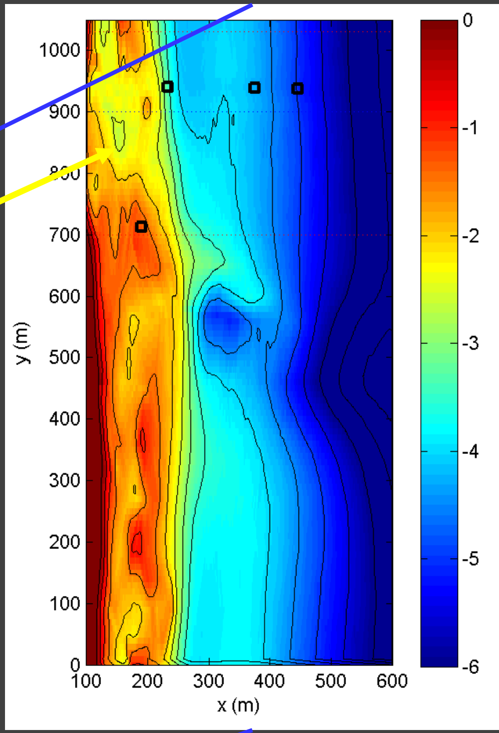
Predicted Tide Level
[m]
Hs (3 km WaveRider)
[m]
Vectorized Wind Speed
[m/s]
Wave/Wind Directions
FRF DirN
09/09 09/10 09/11 09/12

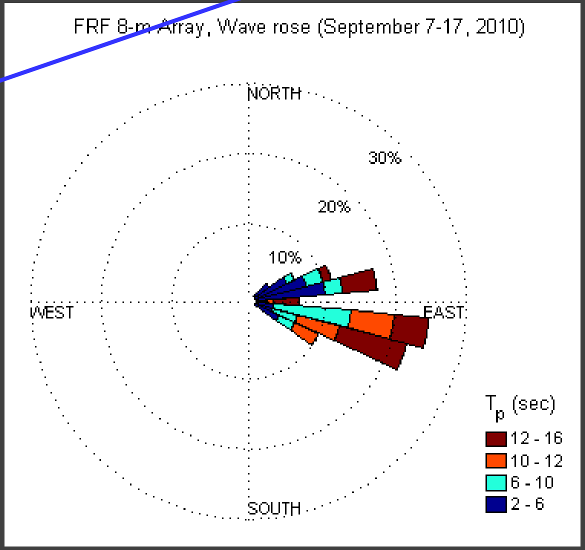


16 min Time Exposure
11-Sep-2010 08:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
Predicted Tide Level
$H_s$ (3 km WaveRider)
Vectorized Wind Speed
Wave/Wind Directions
[m]
[m/s]
FRF DirN
09/10
09/11
09/12
09/13



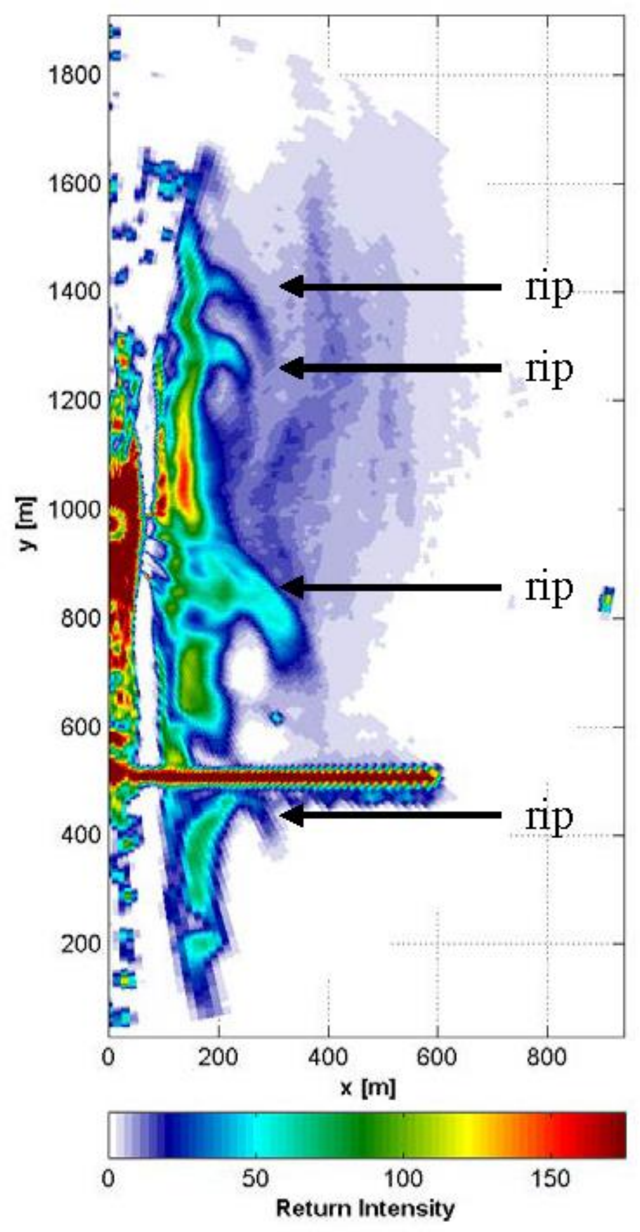

bathymetry



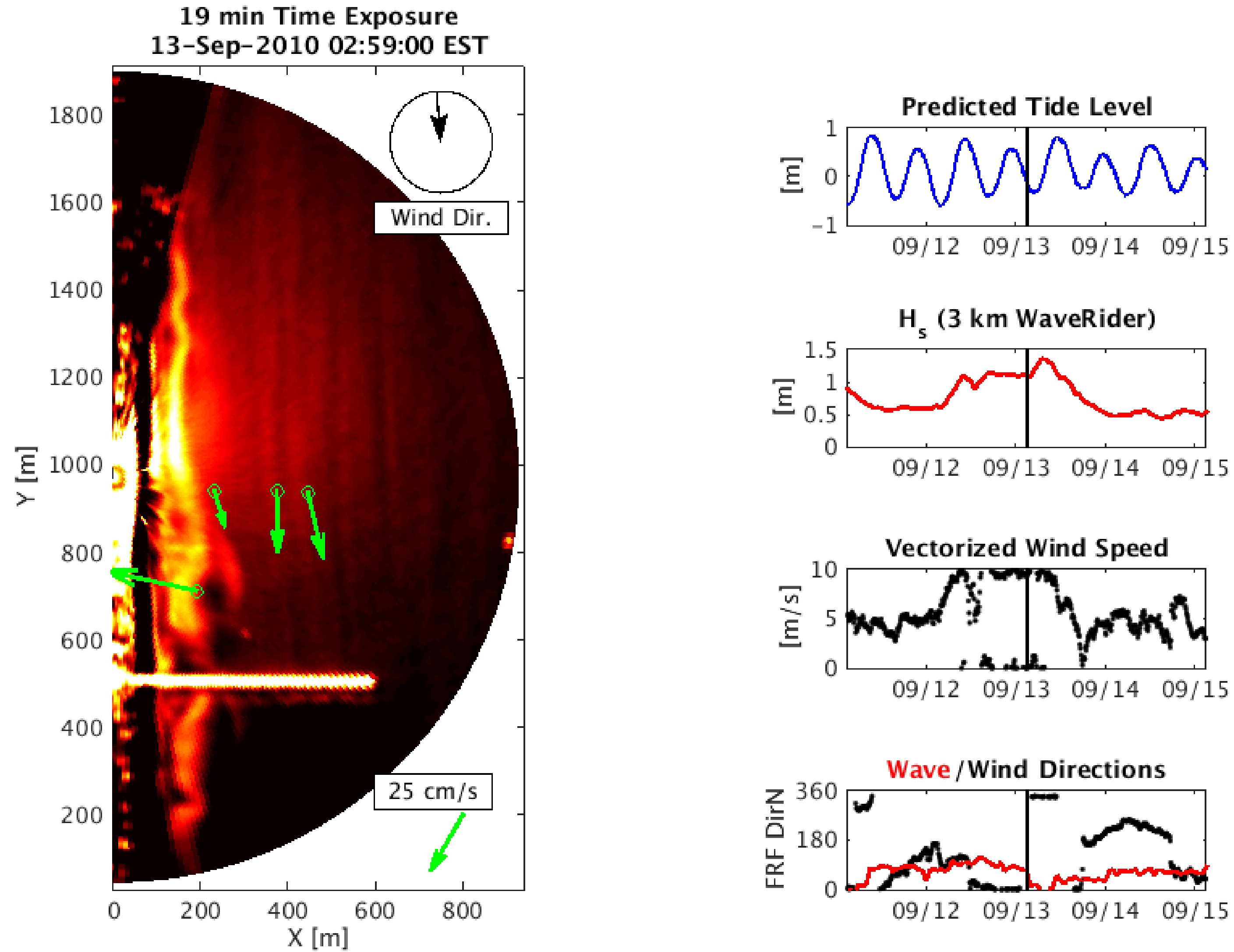

wave rose

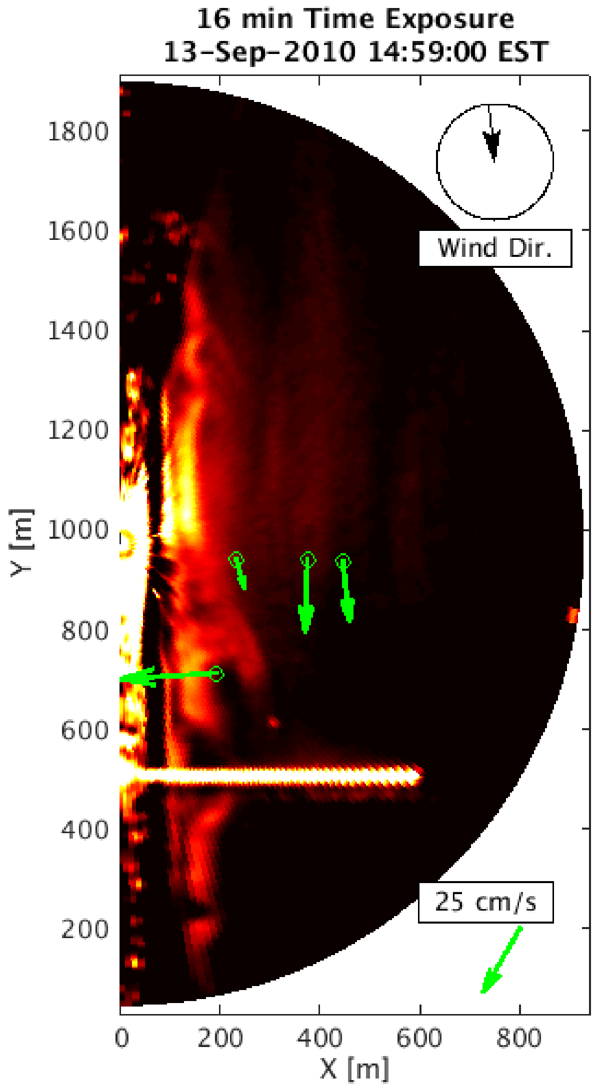
# Rip currents – summary results

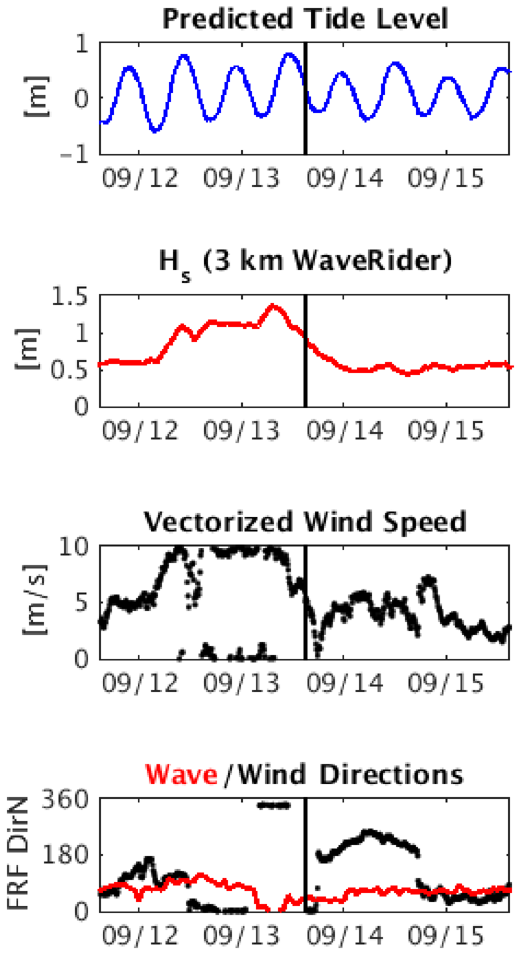


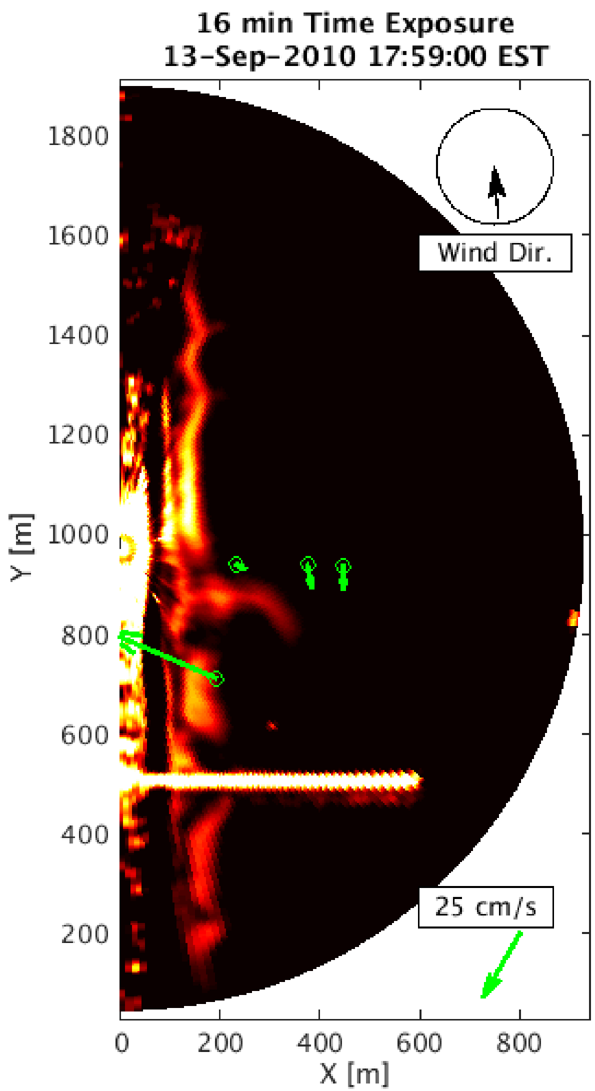

- Rip currents were persistent during low tides and extended several surf zone widths offshore
- Rip current obliquity was primarily driven by alongshore wind stress
- Rip current imaging is dependent on cross-shore wind stress

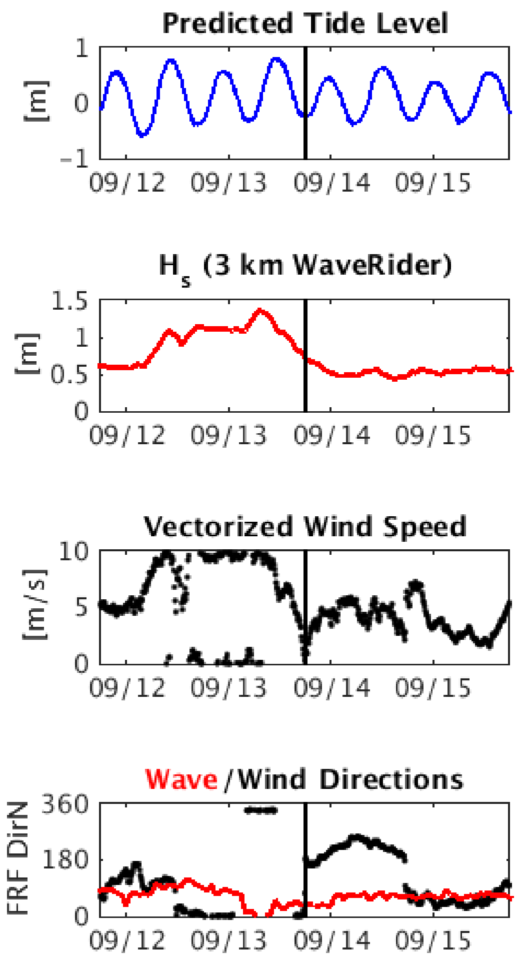
Haller et al., "Rip current observations via marine radar", Invited Technical Paper: *J. Waterway, Port, Coastal, and Ocean Engineering*, 140(2), 115-124, 2014.

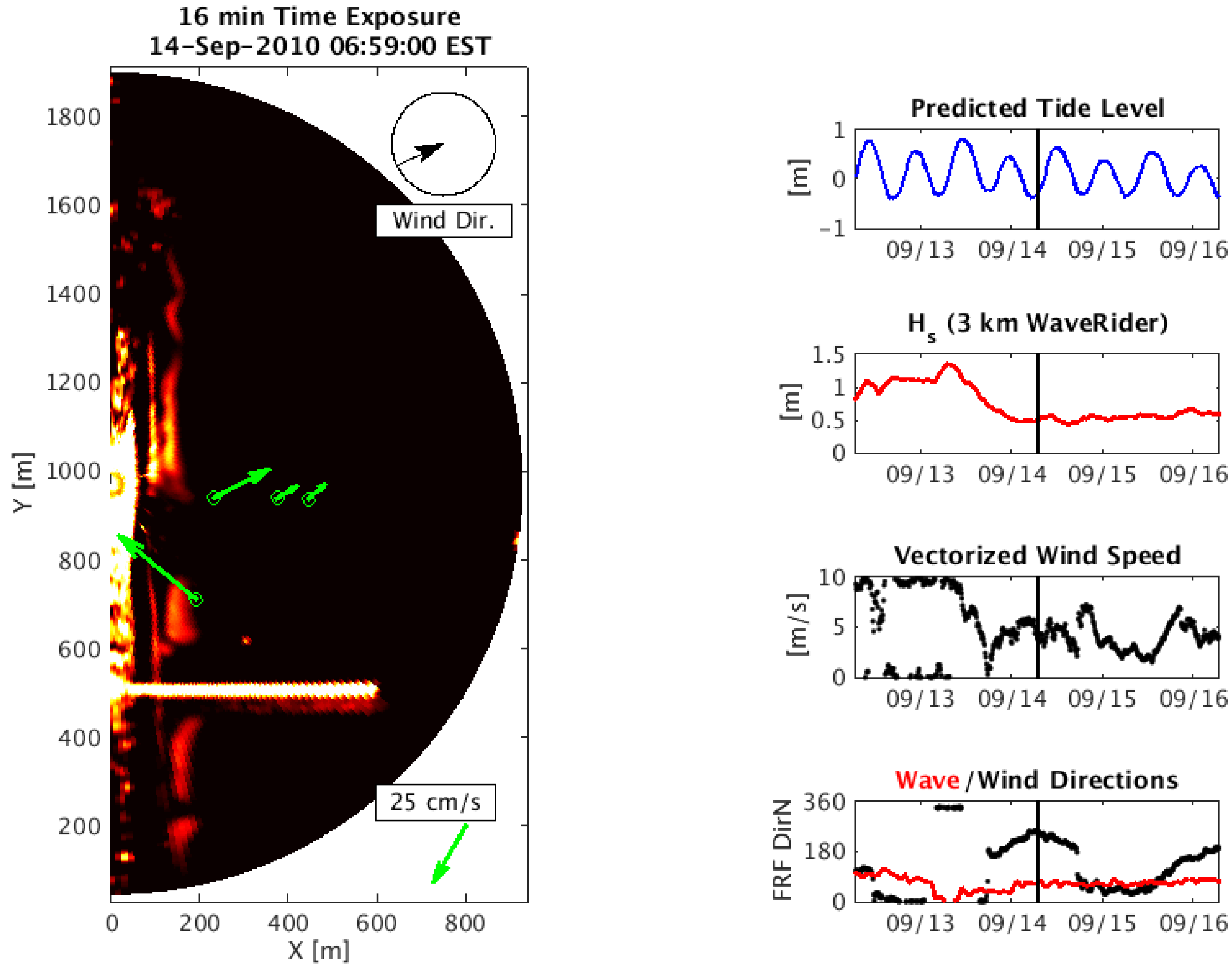

19 min Time Exposure
13-Sep-2010 02:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
1800
1600
1400
1200
1000
800
600
400
200
0
200
400
600
800
Predicted Tide Level
[m]
1
0
-1
H$_s$ (3 km WaveRider)
1.5
1
0.5
0
Vectorized Wind Speed
[m/s]
10
5
Wave/Wind Directions
FRF DirN
360
180
09/12
09/13
09/14
09/15


16 min Time Exposure
13-Sep-2010 14:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
0
200
400
600
800
1000
1200
1400
1600
1800

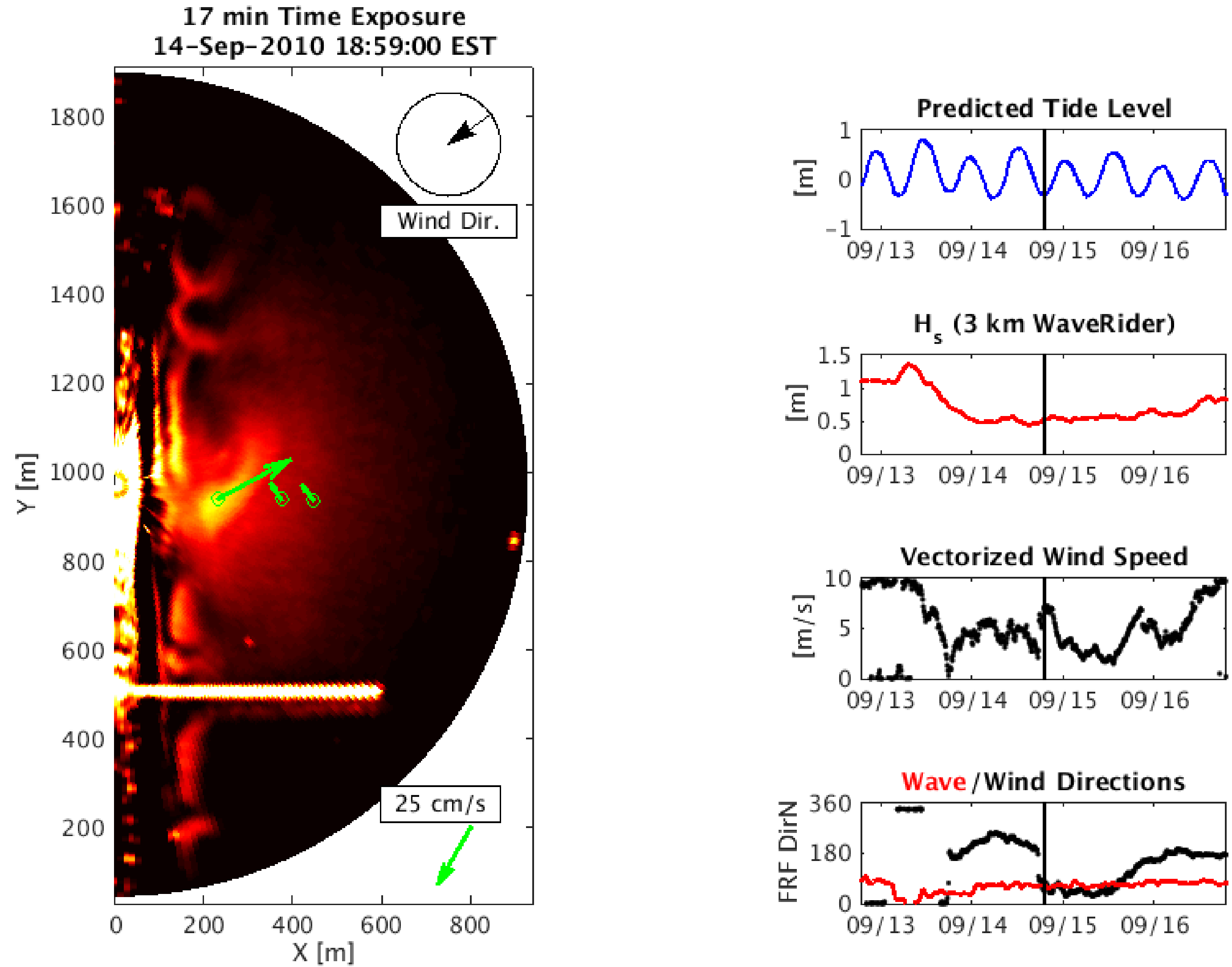

Predicted Tide Level
[m]
H_s (3 km WaveRider)
Vectorized Wind Speed
[m/s]
Wave/Wind Directions
FRF DirN
09/12
09/13
09/14
09/15


16 min Time Exposure
13-Sep-2010 17:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
1800
1600
1400
1200
1000
800
600
400
200
0
200
400
600
800

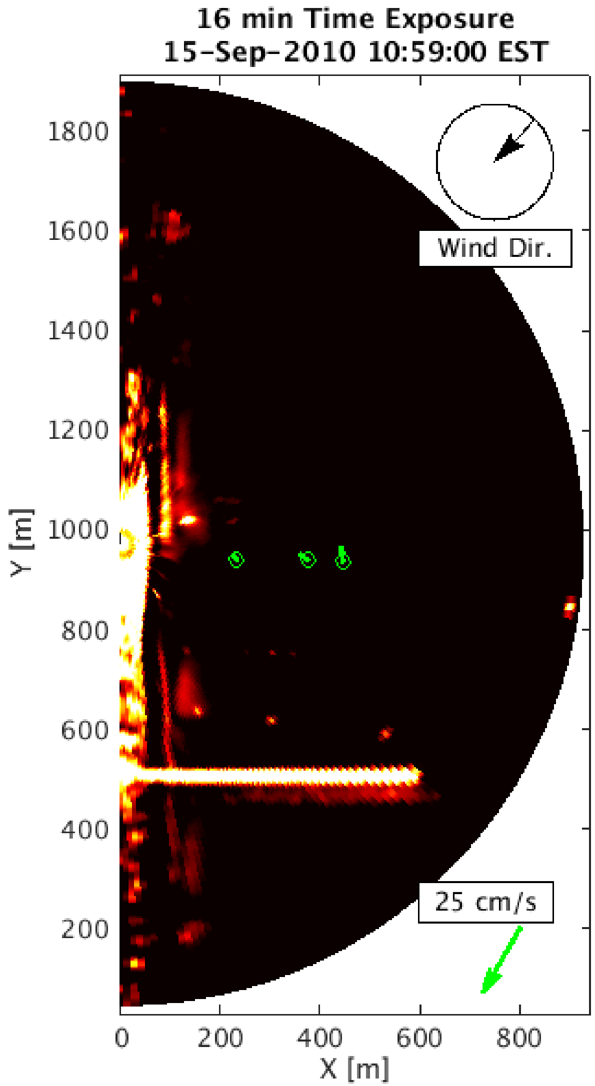

Predicted Tide Level
[m]
1
0
-1
H_s (3 km WaveRider)
[m]
1.5
1
0.5
0
Vectorized Wind Speed
[m/s]
10
5
0
Wave/Wind Directions
FRF DirN
360
180
0
09/12
09/13
09/14
09/15

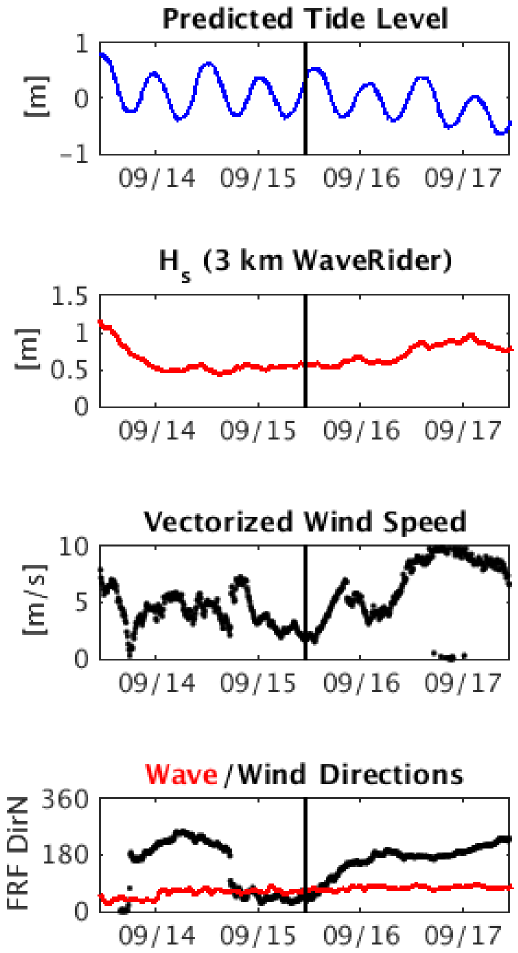


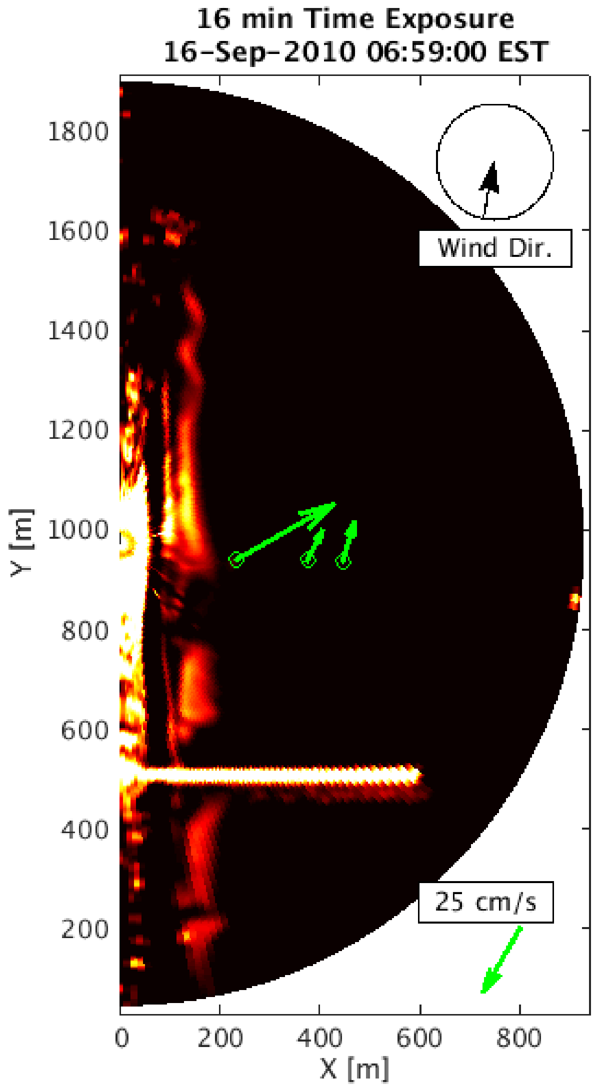
16 min Time Exposure
14-Sep-2010 06:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
Predicted Tide Level
[m]
H_s (3 km WaveRider)
Vectorized Wind Speed
[m/s]
Wave/Wind Directions
FRF DirN
09/13
09/14
09/15
09/16

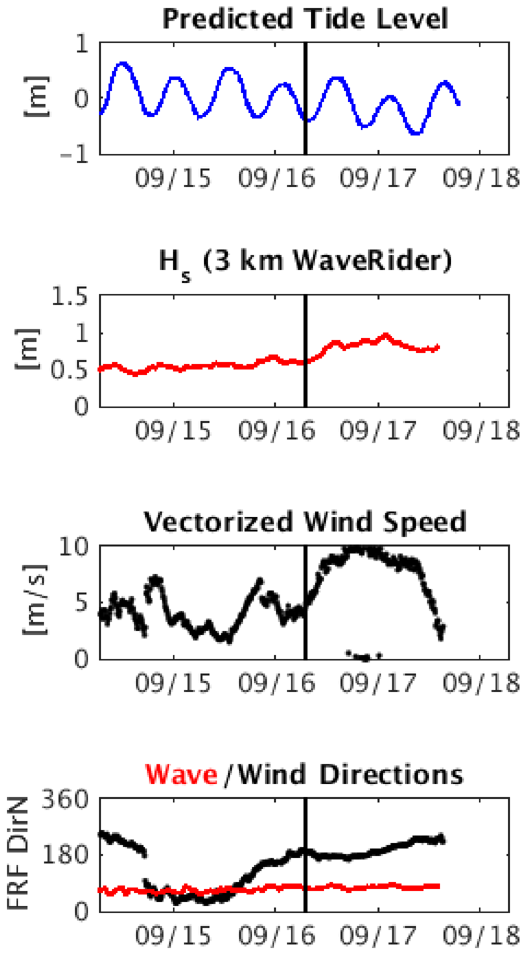


17 min Time Exposure
14-Sep-2010 18:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
1800
1600
1400
1200
1000
800
600
400
200
0
200
400
600
800
Predicted Tide Level
[m]
1
0
-1
H_s (3 km WaveRider)
1.5
1
0.5
0
Vectorized Wind Speed
[m/s]
10
5
0
Wave/Wind Directions
FRF DirN
360
180
0
09/13
09/14
09/15
09/16


16 min Time Exposure
15-Sep-2010 10:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]


Predicted Tide Level
[m]
H$_s$ (3 km WaveRider)
[m]
Vectorized Wind Speed
[m/s]
Wave/Wind Directions
FRF DirN
09/14
09/15
09/16
09/17

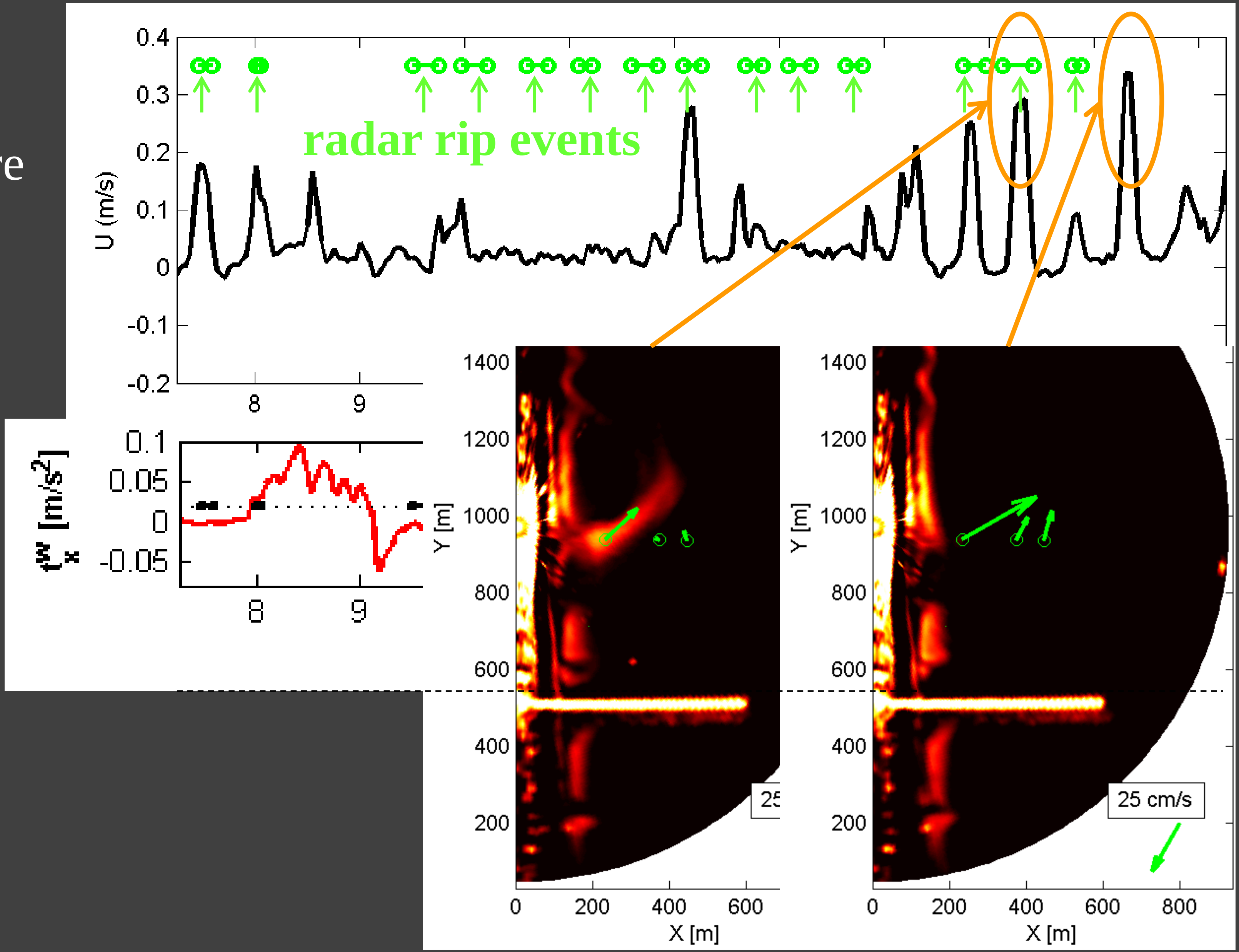

16 min Time Exposure
16-Sep-2010 06:59:00 EST
Wind Dir.
25 cm/s
Y [m]
X [m]
1800
1600
1400
1200
1000
800
600
400
200
0
200
400
600
800


Predicted Tide Level
[m]
1
0
-1
$H_s$ (3 km WaveRider)
1.5
1
0.5
0
Vectorized Wind Speed
[m/s]
10
5
0
Wave/Wind Directions
FRF DirN
360
180
0
09/15
09/16
09/17
09/18

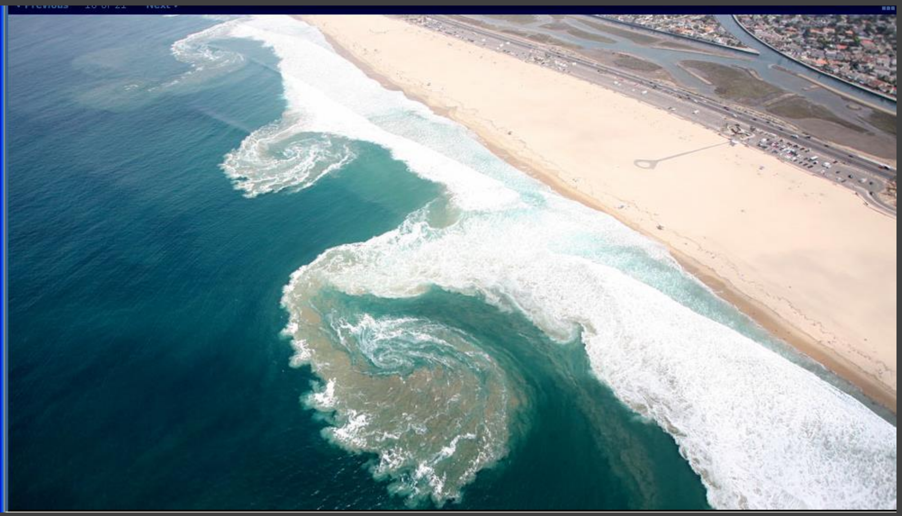
# Effect of cross-shore wind stress

cross-shore velocity (m/s)

x-shore wind stress

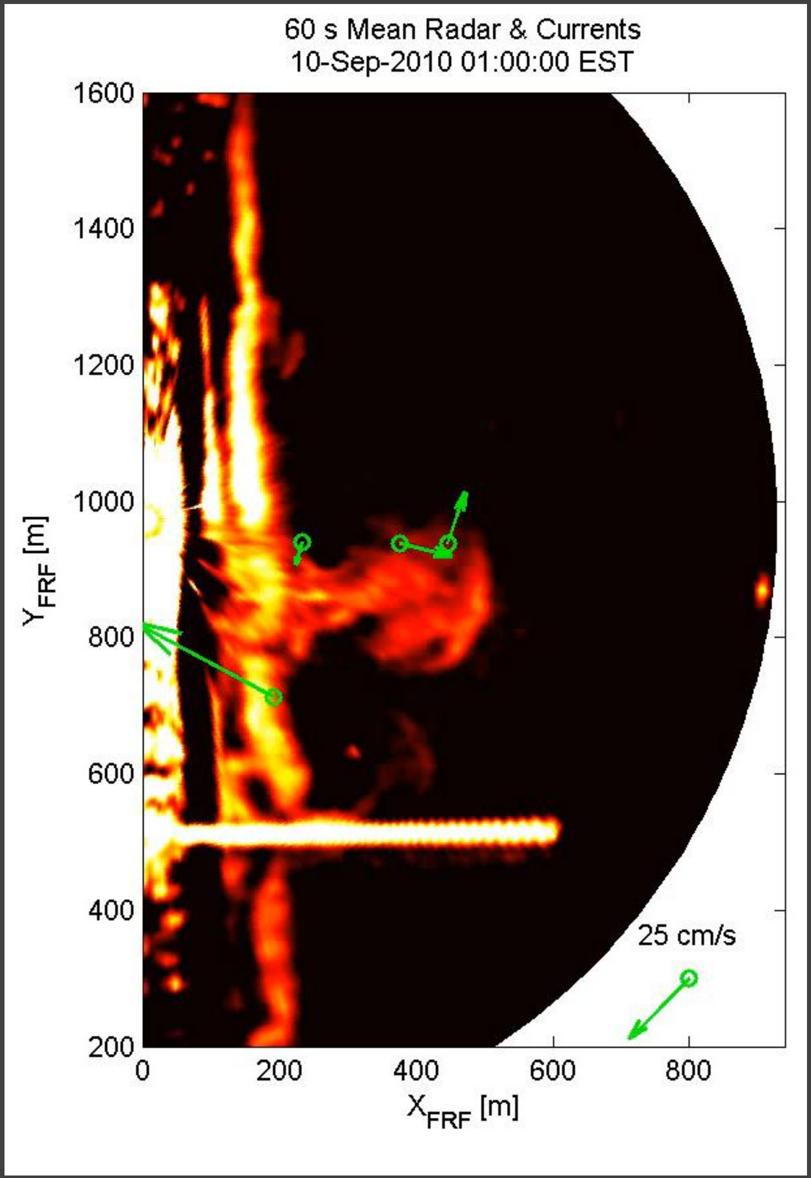


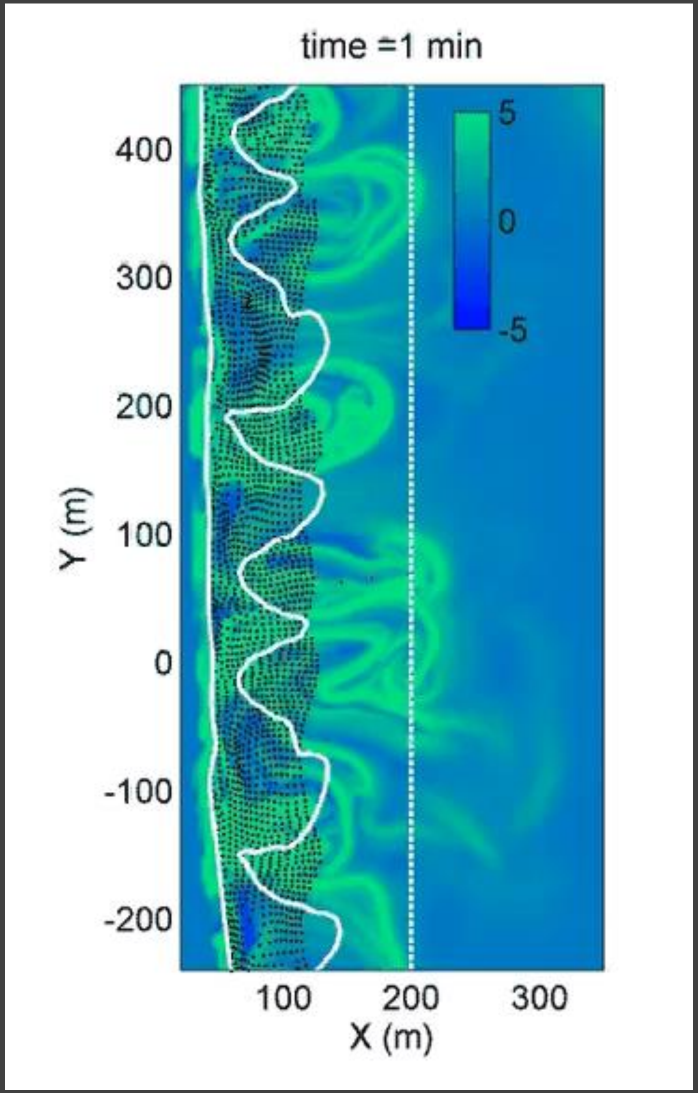
# How are rip currents imaged?



# How are rip currents imaged?

# Lagrangian Coherent Structures




Reniers et al., “Rip-current pulses tied to Lagrangian coherent structures”, *GRL*, Vol. 37, 2010

# Effect of current divergence and strain on surface roughness

Conservation of wave action: $$\frac{\partial N}{\partial t} = k_j \frac{\partial u_j}{\partial x_i} \frac{\partial N}{\partial k_i} + \frac{S}{\omega}$$

Relaxation approach: $$N = N_0(k) + \widetilde{N}(x, k, t)$$

Action anomaly due to currents: $$\widetilde{N}(x, k) = \tau_c k_j \frac{\partial u_j}{\partial x_i} \frac{\partial N_0}{\partial k_i}$$

Rascle et al., "Surface roughness imaging of currents shows divergence and strain in the wind direction", *J. Phys. Oceanogr*., August, 2014.

# Effect of current divergence and strain on surface roughness

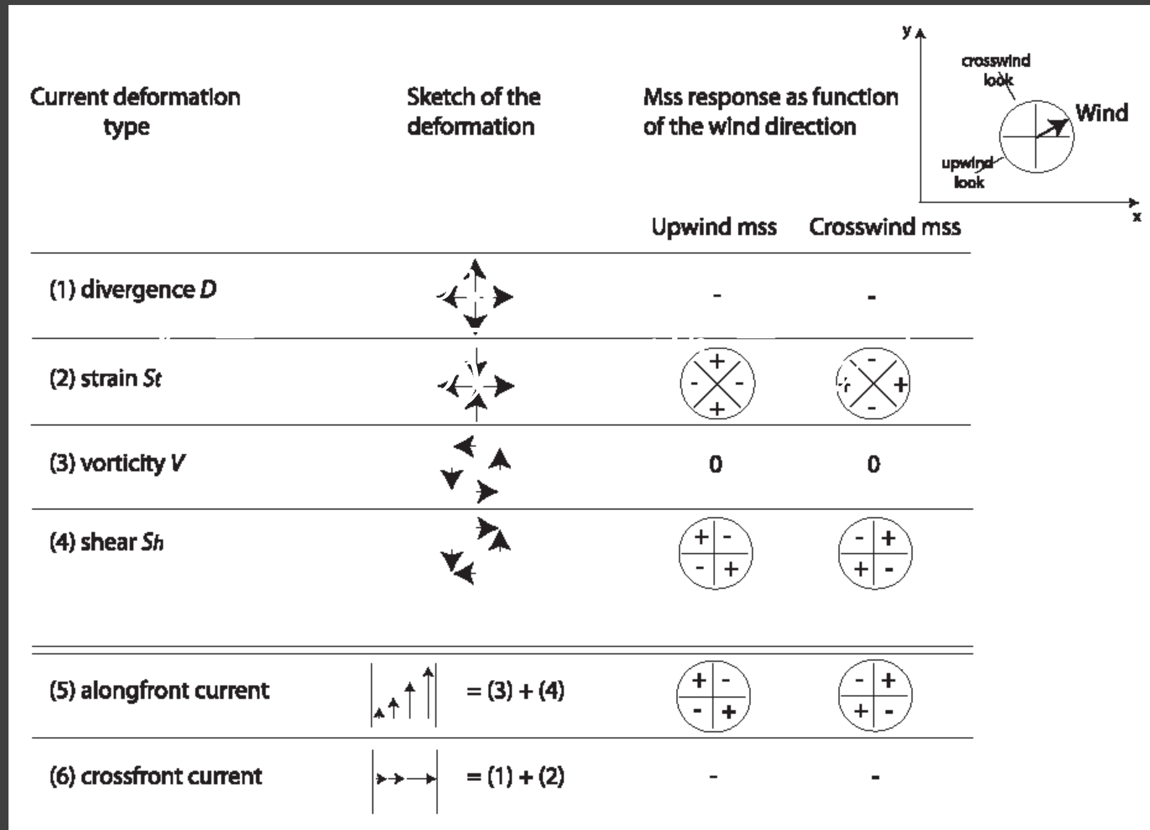
$$D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, \qquad S_t = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$$

$$V = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \qquad S_h = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$$

$$\tilde{N}(x,k,\varphi) = \frac{\tau_c N_0}{2}\left\{D m_k - V m_\varphi + S_t\left[\cos(2\varphi)\, m_k - \sin(2\varphi) m_\varphi\right] + S_h\left[\sin(2\varphi) m_k + \cos(2\varphi) m_\varphi\right]\right\}$$

Rascle et al., "Surface roughness imaging of currents shows divergence and strain in the wind direction", *J. Phys. Oceanogr.*, August, 2014.

# Effect of current divergence and strain on surface roughness

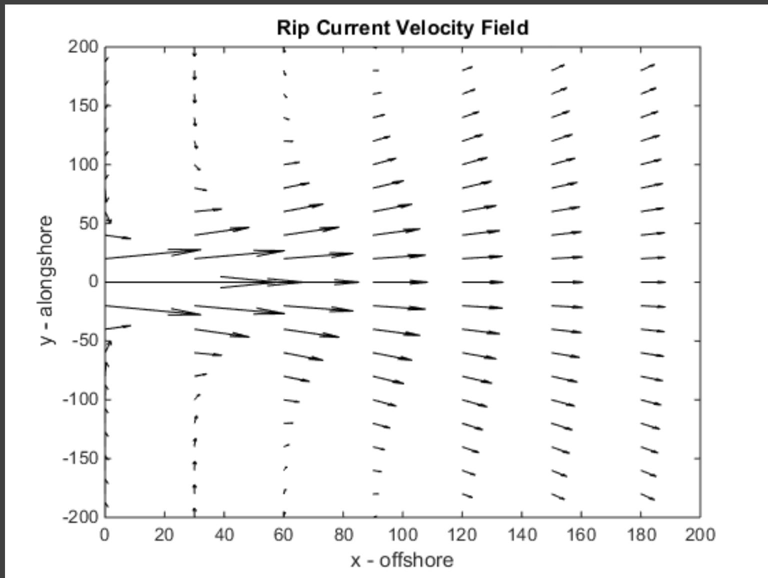


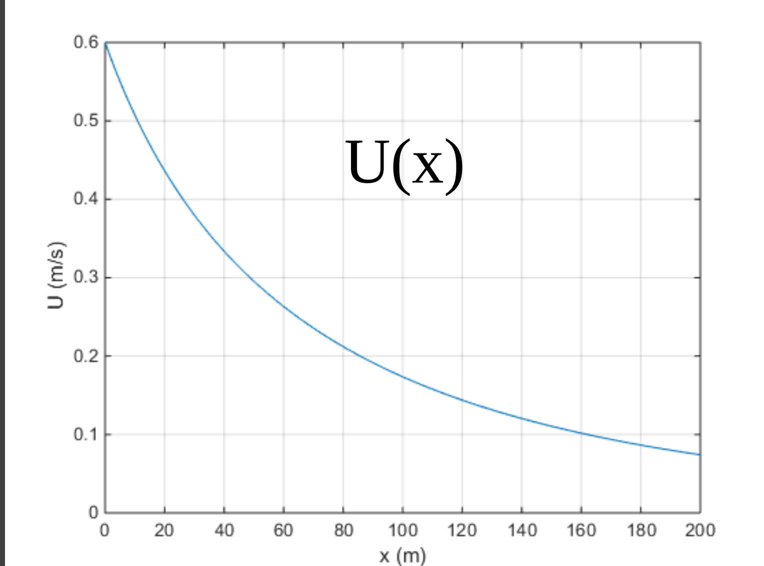

- Mean squared slope response to vorticity is zero
- Mean squared slope response to shear is zero
- Mean squared slope response to divergence & strain is nonzero

# Rip current model

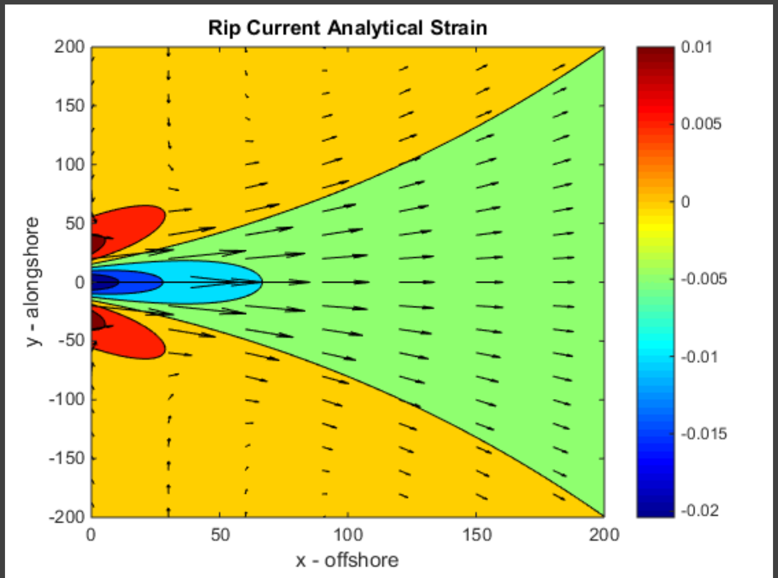
# $\partial u/\partial x - \partial v/\partial y$

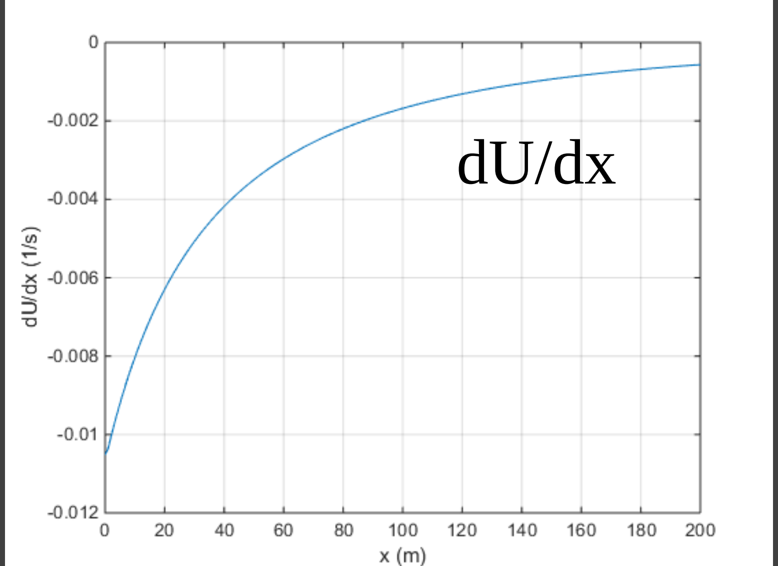
Alongshore




Alongshore




Cross-shore

Cross-shore

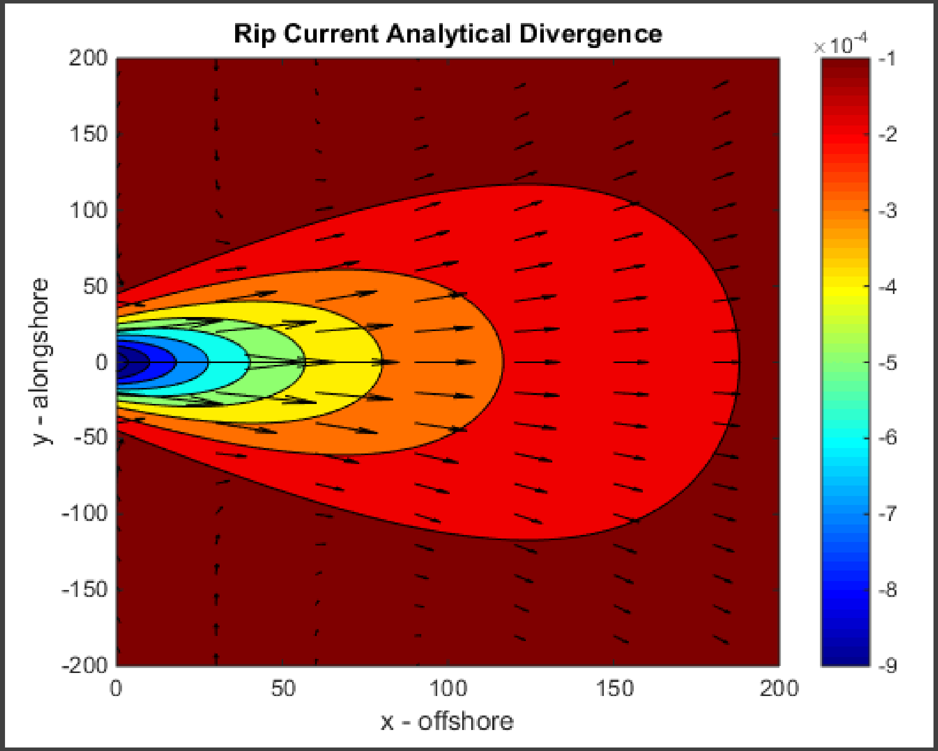
# Rip current deformation tensors

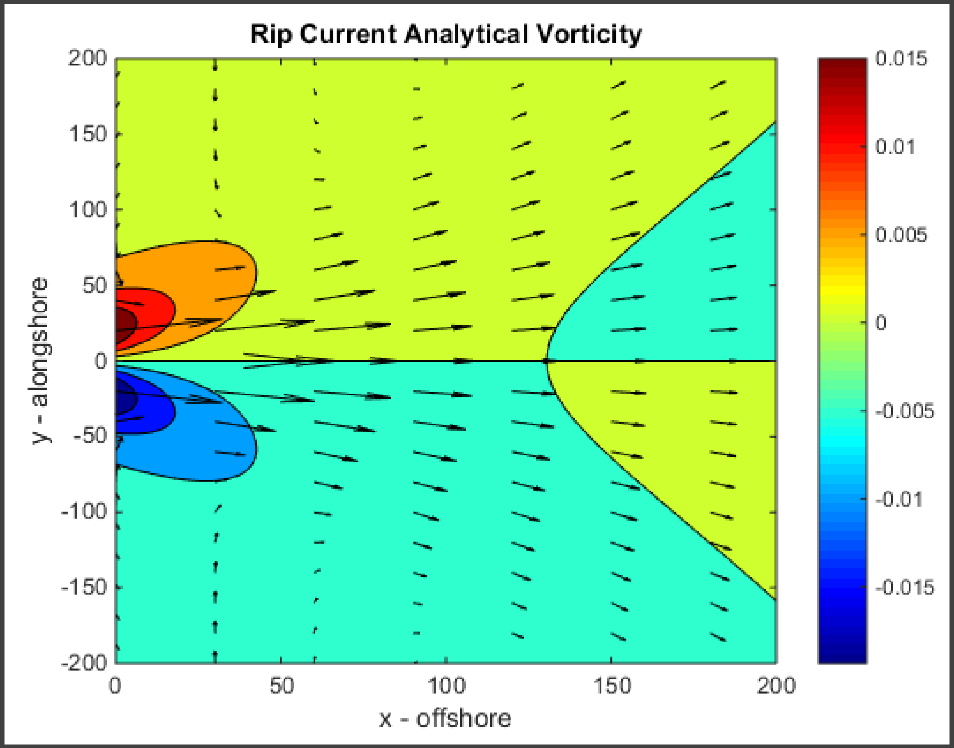
## Divergence

$$\partial u/\partial x + \partial v/\partial y$$

## Vorticity

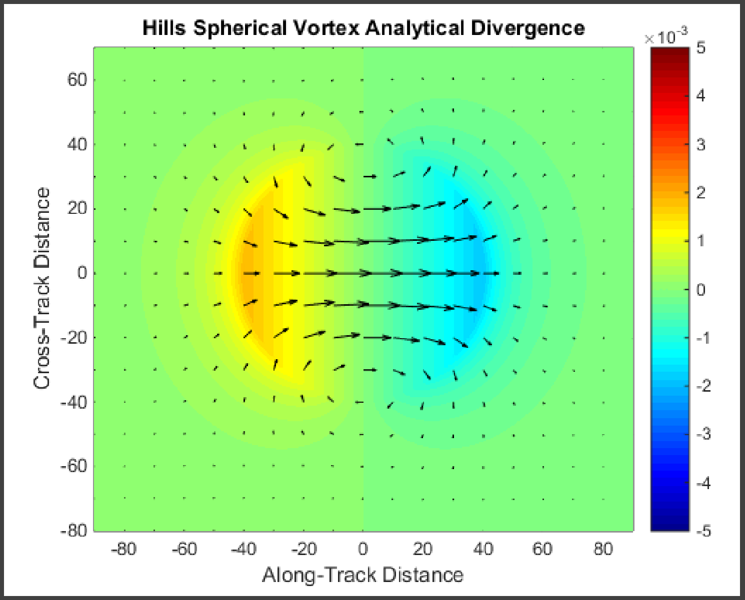
$$\partial v/\partial x - \partial u/\partial y$$



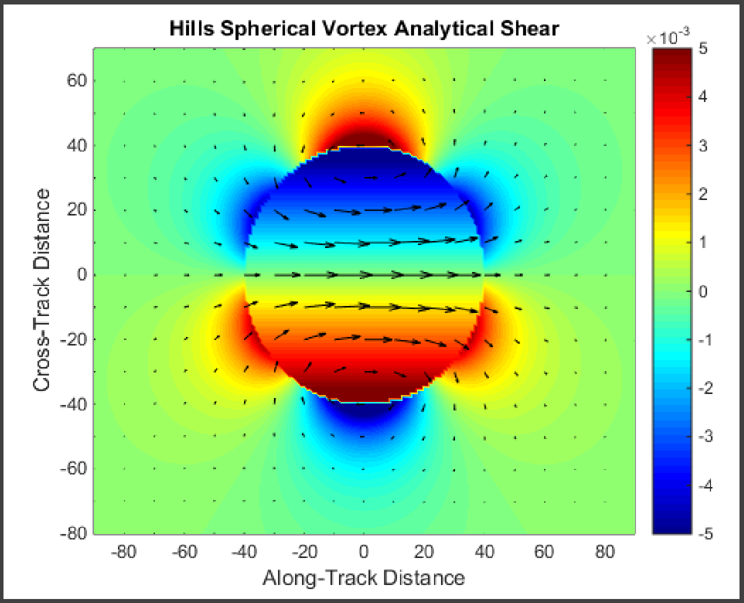



# Hill's Vortex deformation tensors

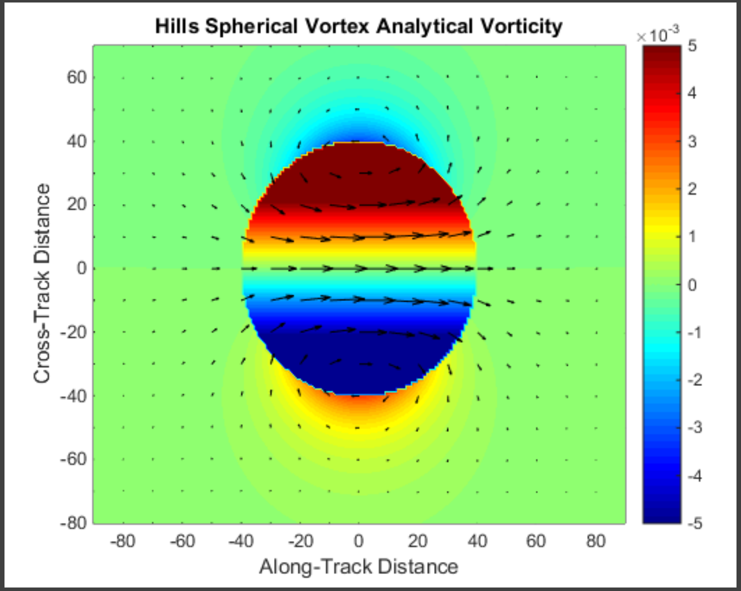
$D$



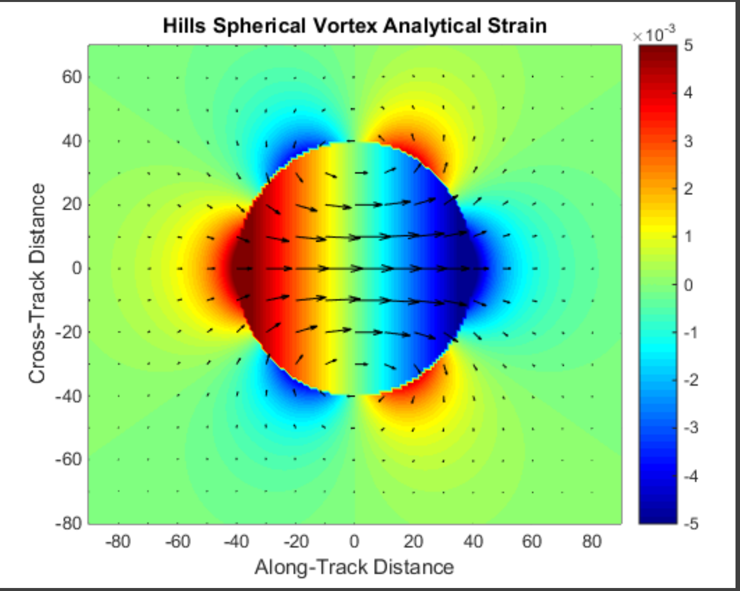

$S_h$




$V$

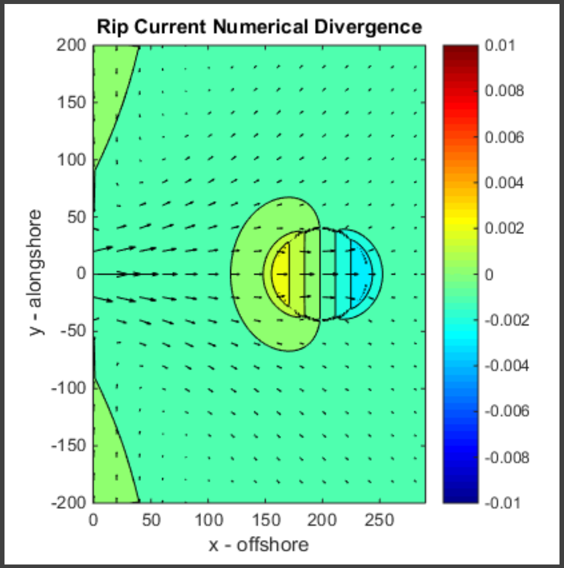



$S_t$

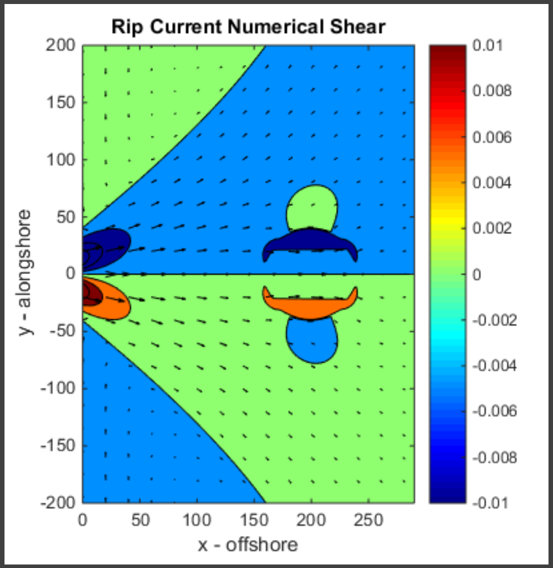


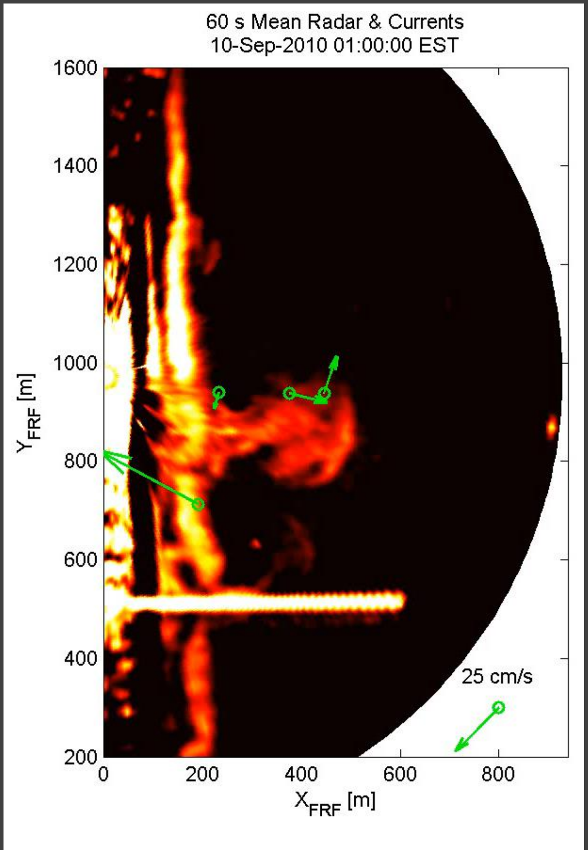
# Rip + Vortex pair deformation tensors

$D$

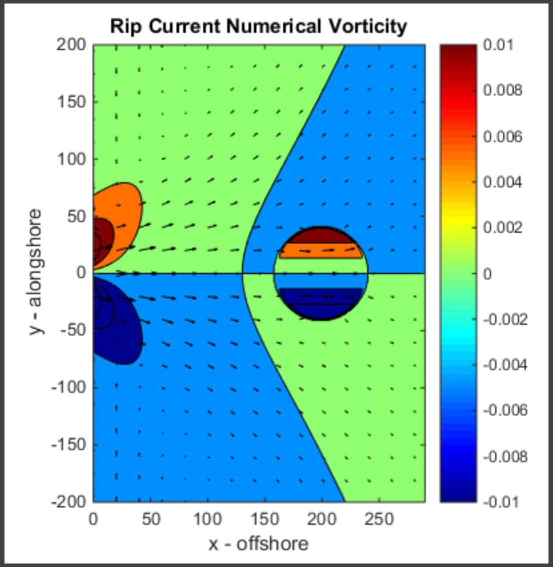



$S_h$

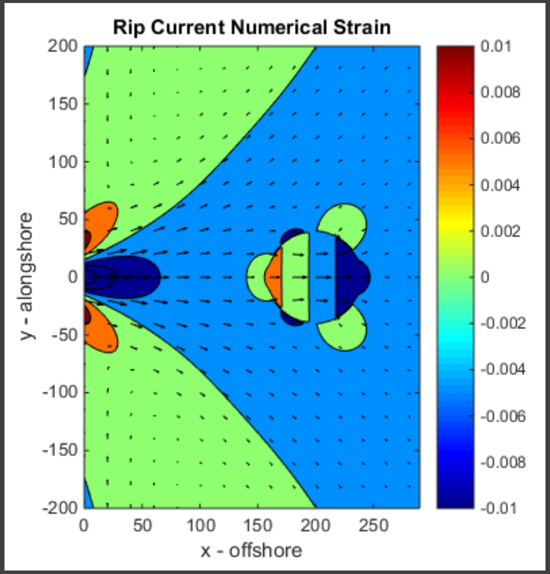



$V$

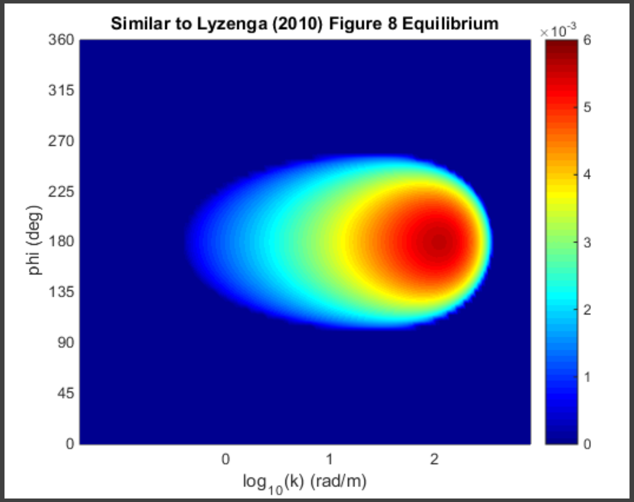


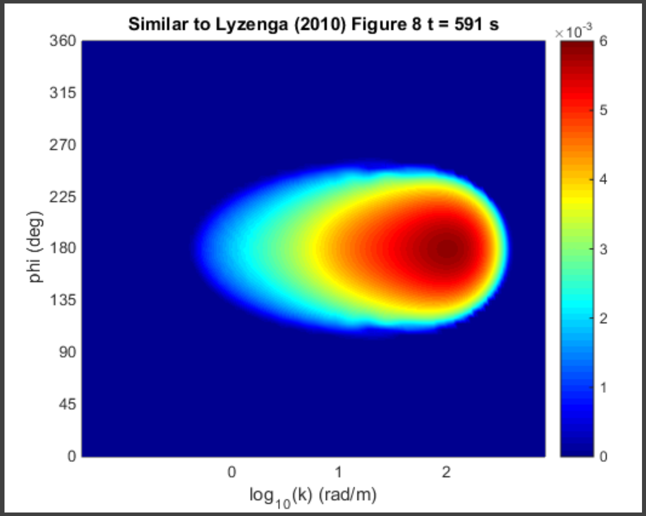

$S_t$

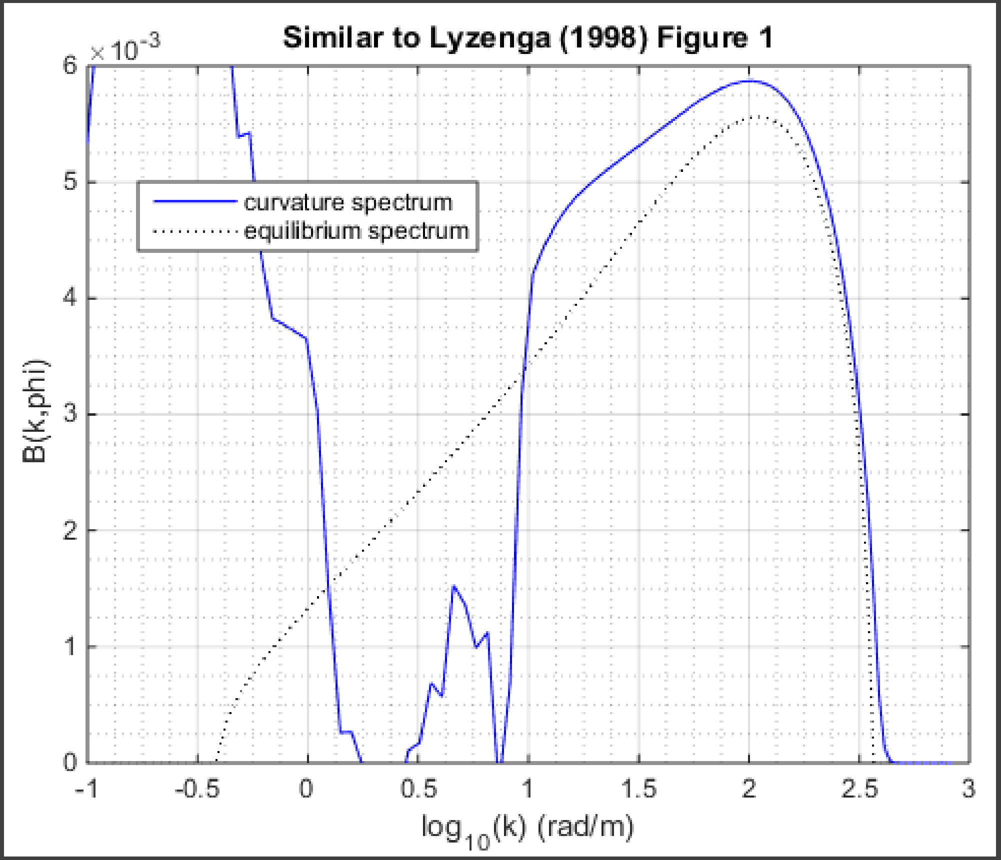


# Conservation of wave action (more complete):

$$\frac{\partial N}{\partial t} + (Cg_x + u)\frac{\partial N}{\partial x} + (Cg_y + v)\frac{\partial N}{\partial y} - \left(k_x\frac{\partial u}{\partial x} + k_y\frac{\partial v}{\partial x}\right)\frac{\partial N}{\partial kx} - \left(k_x\frac{\partial u}{\partial y} + k_y\frac{\partial v}{\partial y}\right)\frac{\partial N}{\partial k_y} = \mathrm{F_s(N)}$$

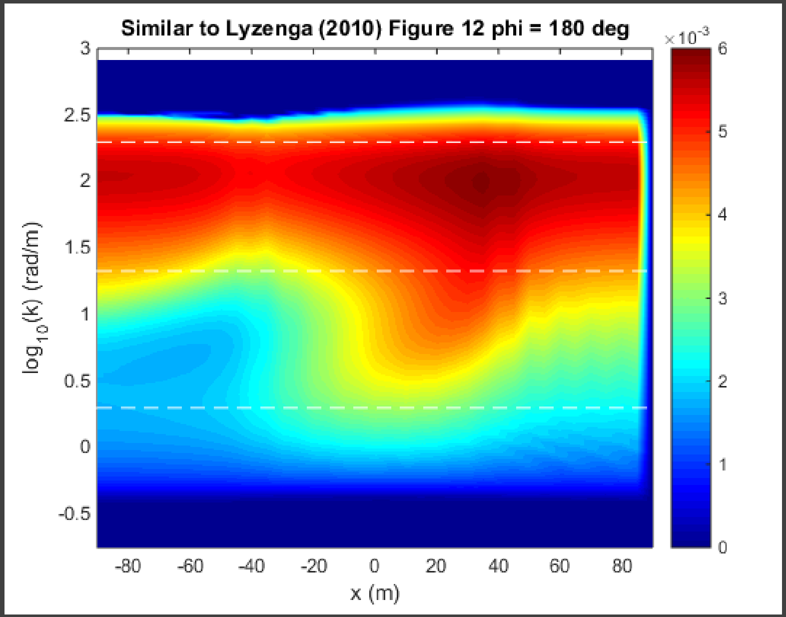


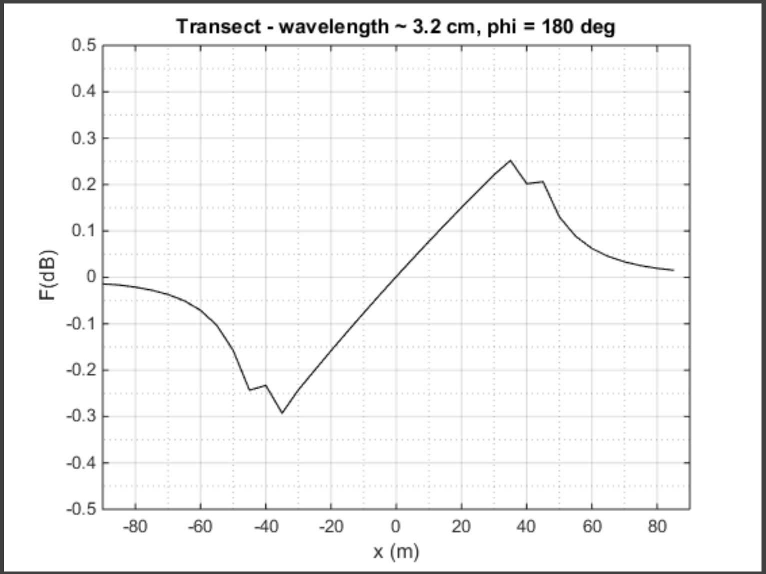



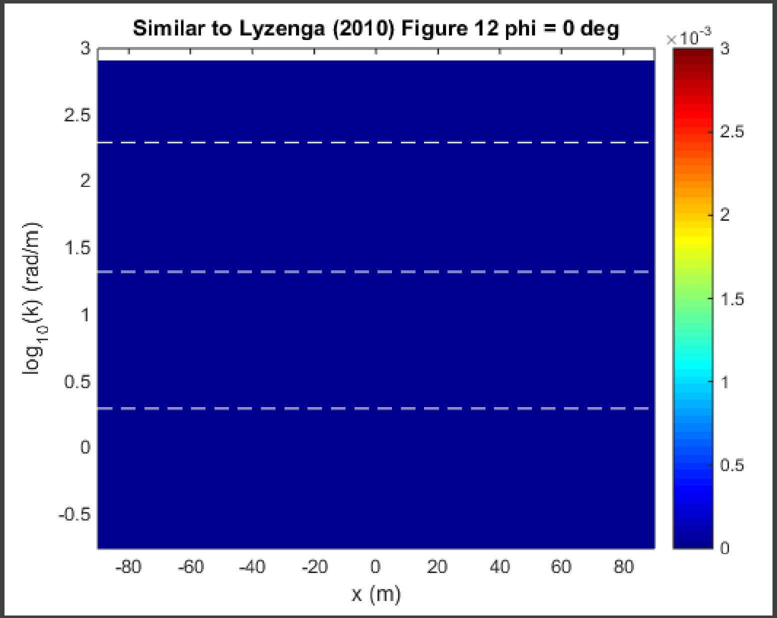
# Curvature spectrum for Hill's vortex

Onshore waves



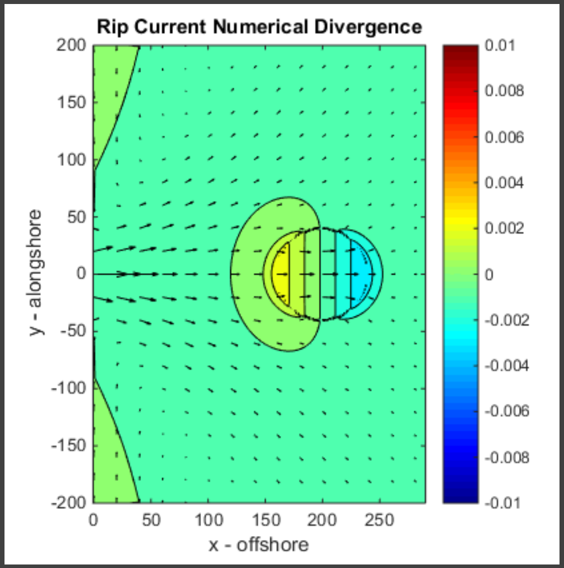




Offshore waves



# Rip current remote sensing

$D$




$S_t$