Dawn in the age of robotic oceanography

Oscar Schofield, Scott Glenn, Josh Kohut, Ulrich Kremer, Travis Miles, Nicole Couto, Xu Yi (Rutgers)
Doug Martinson, Darren Mckee (Lamont)
William Fraser (Polar Associates)

COASTAL OCEAN OBSERVATION LAB
RUTGERS UNIVERSITY

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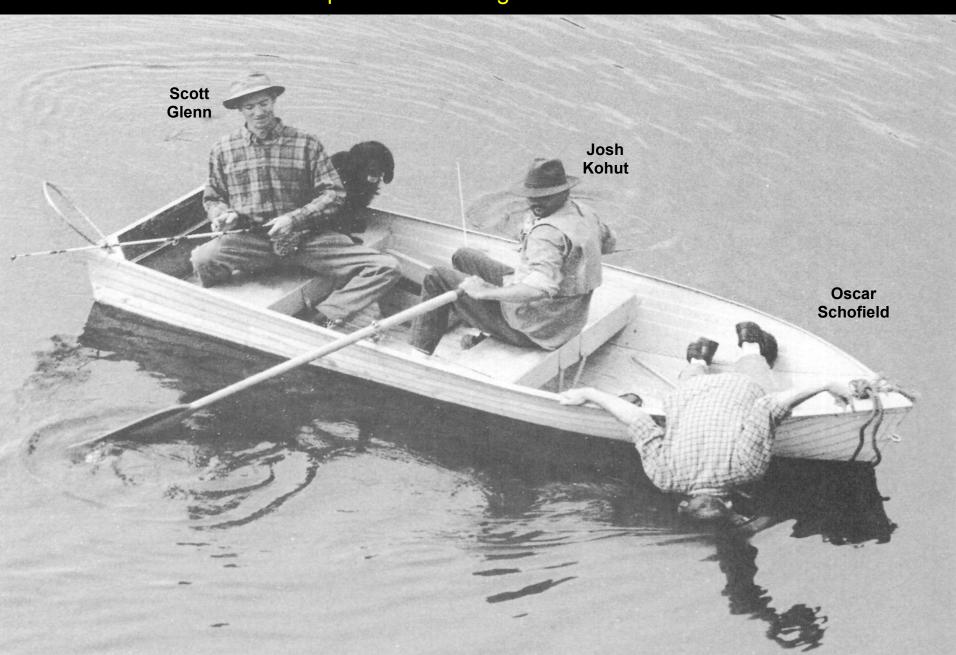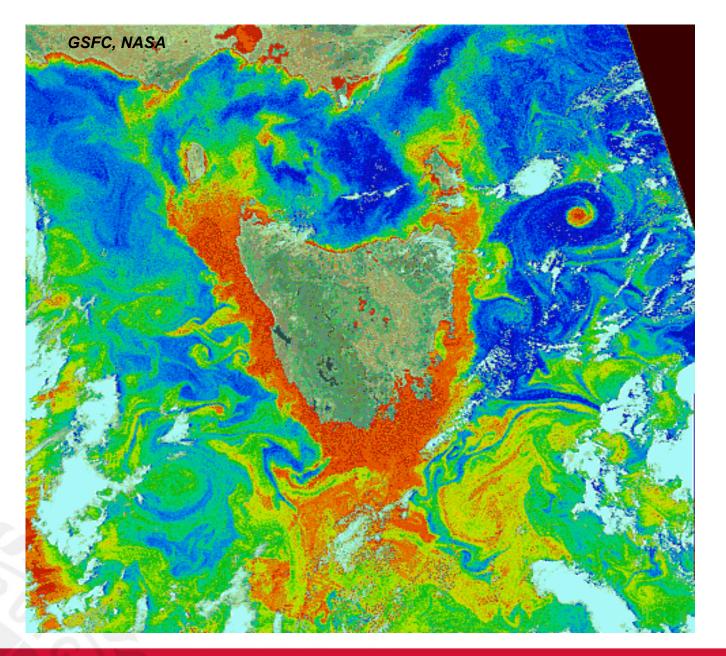
Oceans are complex and central to the Earth system

Global Carbon Cycle

Photosynthesis
Respiration

Gas Exchange Between Air and Ocean

Net Accumulation in Ocean

Photosynthesis Respiration

Rivers and watersheds

Circulation

Ginger Armbrust

Global Carbon Cycle

Photosynthesis
Respiration

Gas Exchange Between Air and Ocean

Combustion   Land Use Changes

Net Accumulation in Ocean

Photosynthesis Respiration

Rivers and watersheds

Circulation

Geological Reservoir

Ginger Armbrust

Despite heroic efforts, the ocean is chronically under-sampled. We need a permanent sustained presence making SPATIAL time series.

Scott Glenn

Josh Kohut

Oscar Schofield

GSFC, NASA

Rutgers University - Coastal Ocean Observation Lab
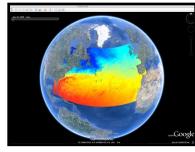
CODAR Network
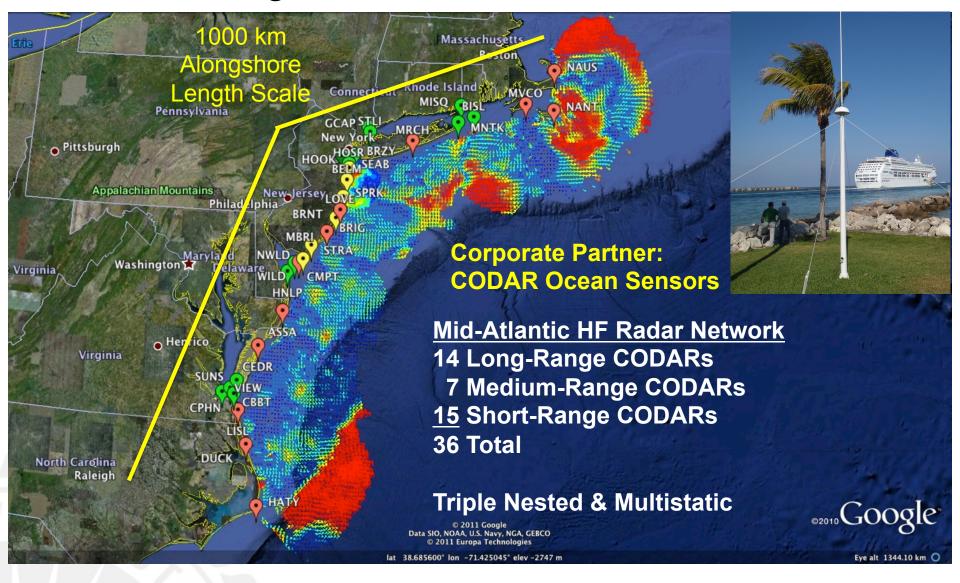

L-Band & X-Band Satellite Receivers
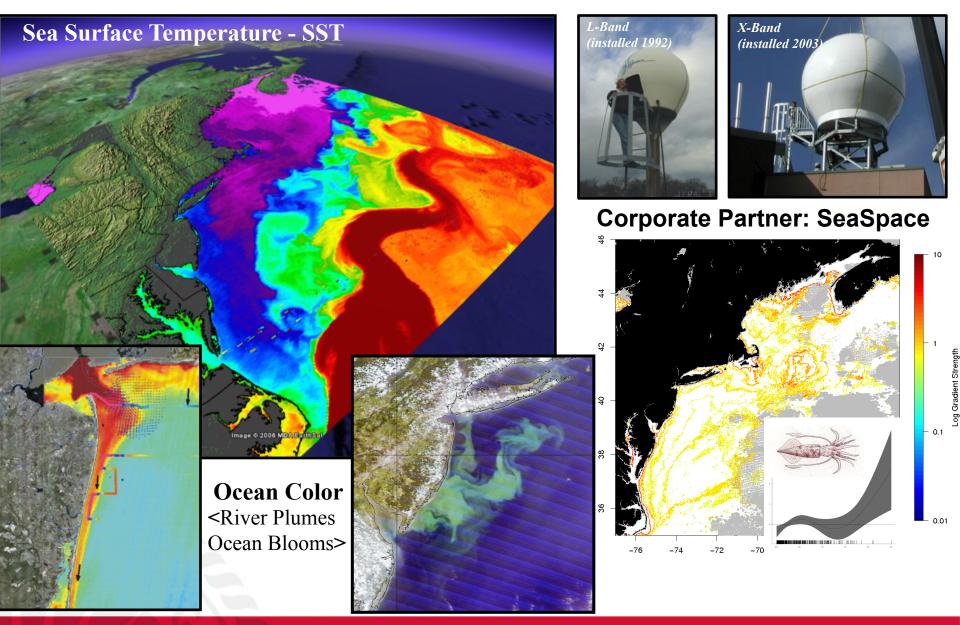
Glider Fleet

3-D Nowcasts & Forecasts

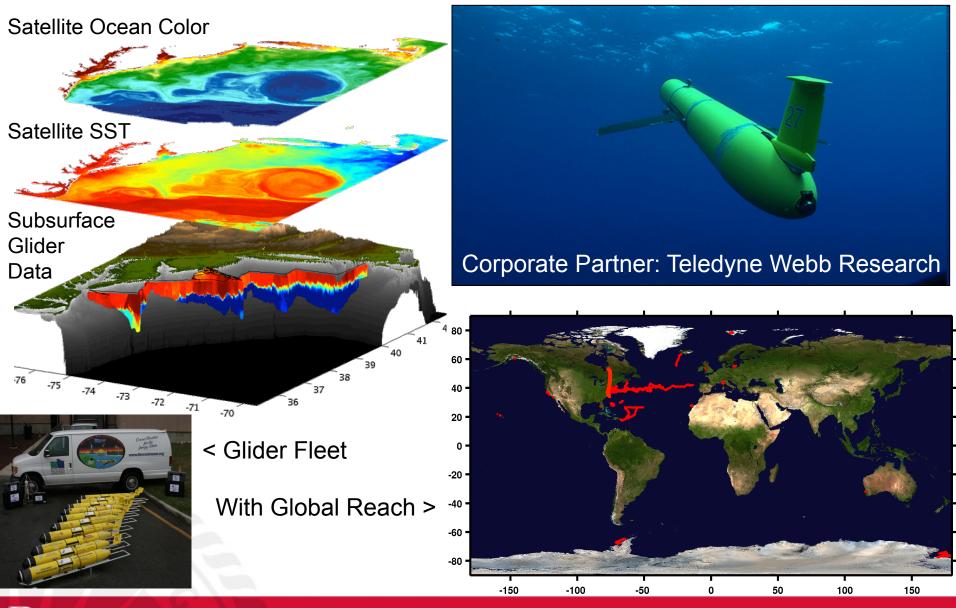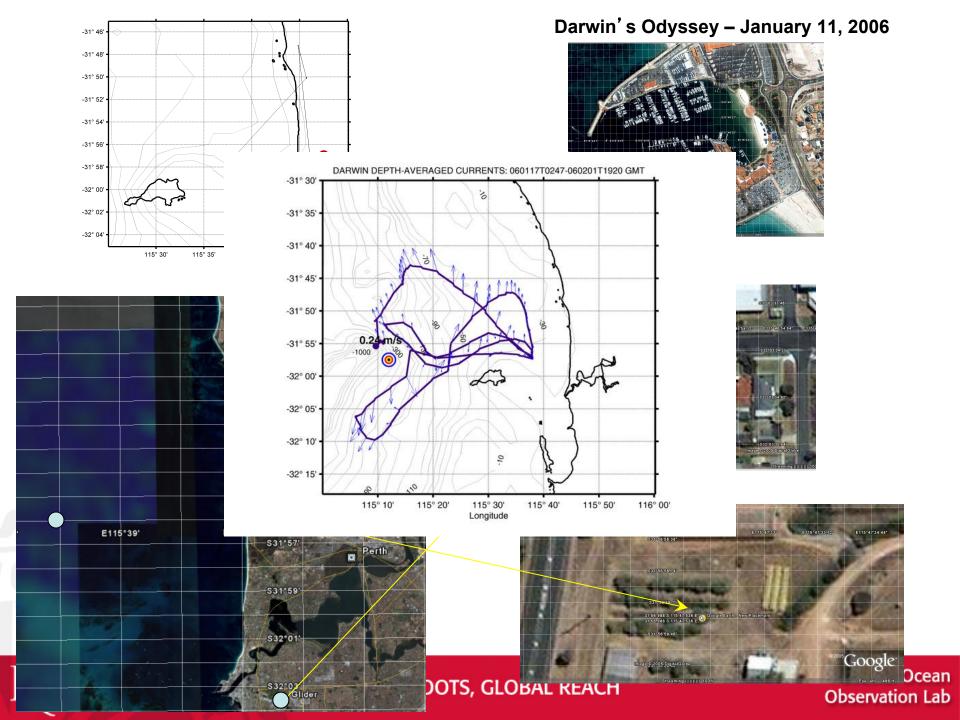# MARACOOS - International Constellation of Satellites – Since 1992

Sea Surface Temperature - SST

L-Band (installed 1992)

X-Band (installed 2003)

Corporate Partner: SeaSpace

Image © 2006 MDA EarthSat

Ocean Color
<River Plumes
Ocean Blooms>

Mid-Atlantic Bight HF Radar Network – Since 1997

1000 km Alongshore Length Scale

Corporate Partner:
CODAR Ocean Sensors

Mid-Atlantic HF Radar Network
14 Long-Range CODARs
 7 Medium-Range CODARs
15 Short-Range CODARs
36 Total

Triple Nested & Multistatic

© 2011 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2011 Europa Technologies

lat 38.685600° lon −71.425045° elev −2747 m

©2010 Google

Eye alt 1344.10 km

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Coastal Ocean
Observation Lab

MARACOOS - Autonomous Underwater Gliders – Since 1998

Satellite Ocean Color

Satellite SST

Subsurface
Glider
Data

Corporate Partner: Teledyne Webb Research

< Glider Fleet

With Global Reach >

Darwin's Odyssey – January 11, 2006

DARWIN DEPTH-AVERAGED CURRENTS: 060117T0247-060201T1920 GMT

0.24 m/s

Ocean Observation Lab

325 deployments - 129580.19km flown - 5930 days
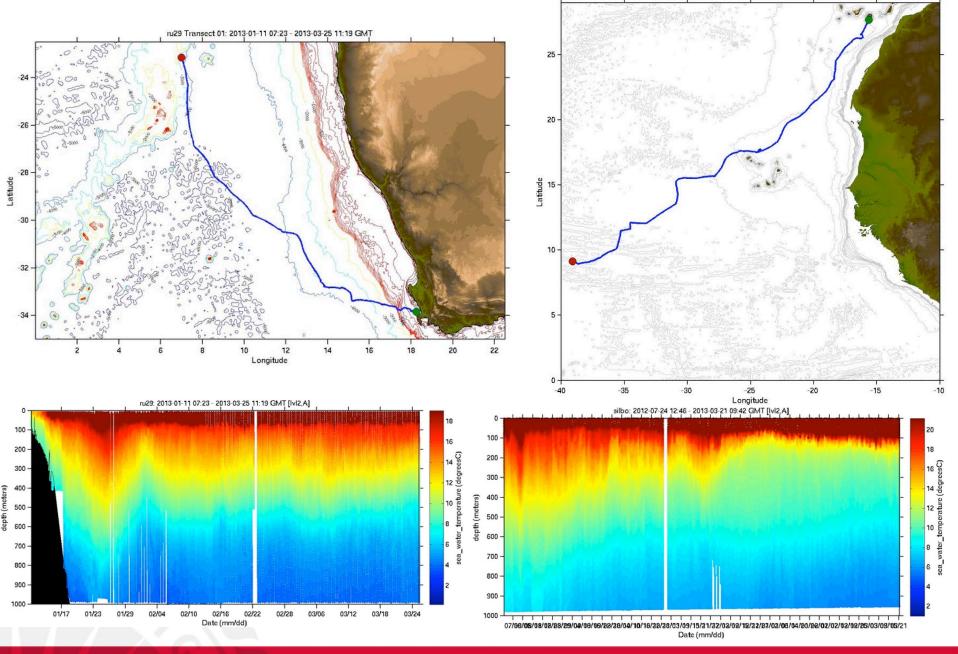
RU-COOL Deployments by Year

Year	Number	Distance (km)	Days
2012	19	5054.31	290.3
2011	37	11975.53	624
2010	46	17003.36	876.6
2009	30	18114.34	761.1
2008	28	16642.28	604.7
2007	27	10277.99	462.9
2006	38	9745.88	538
2005	16	4113.87	207.1
Totals	**241**	**92927.56**	**4364.8**

Includes all Global deployments
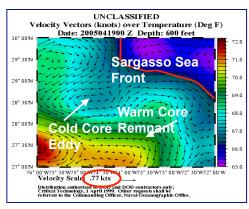
- Since 2005: 241 Global deployments totaling 92,927 km over 4365 days
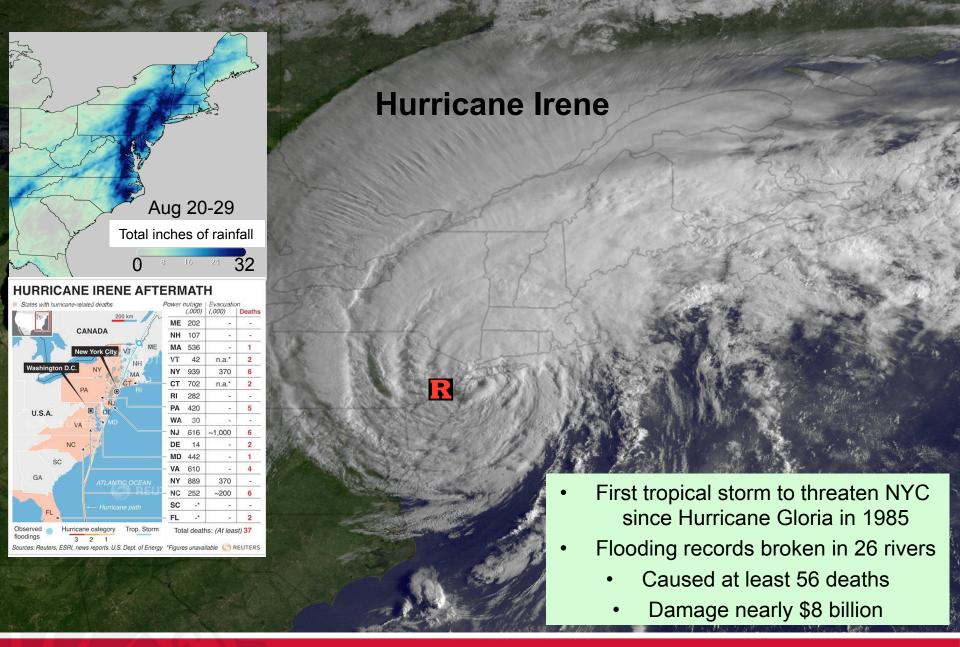- Since 2005: 149 Mid-Atlantic deployments totaling 52,187 km over 2628 days

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ru29 Transect 01: 2013-01-11 07:23 - 2013-03-25 11:19 GMT
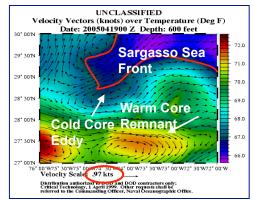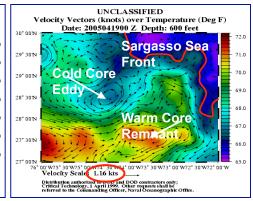
silbo Transect 01: 2012-07-24 12:46 - 2013-03-21 09:42 GMT

ru29: 2013-01-11 07:23 - 2013-03-25 11:19 GMT [lvl2,A]

silbo: 2012-07-24 12:46 - 2013-03-21 09:42 GMT [lvl2,A]

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Models improved with in situ data via data assimilation

Hurricane Irene

Aug 20-29

Total inches of rainfall

0 8 16 24 32

HURRICANE IRENE AFTERMATH

States with hurricane-related deaths

200 km

CANADA

New York City

Washington D.C.

U.S.A.

ATLANTIC OCEAN

Hurricane path

Observed floodings   Hurricane category   Trop. Storm
3 2 1

Sources: Reuters, ESRI, news reports. U.S. Dept. of Energy   *Figures unavailable

	Power outage (,000)	Evacuation (,000)	Deaths
ME	202	-	-
NH	107	-	-
MA	536	-	1
VT	42	n.a.*	2
NY	939	370	6
CT	702	n.a.*	2
RI	282	-	-
PA	420	-	5
WA	30	-	-
NJ	616	~1,000	6
DE	14	-	2
MD	442	-	1
VA	610	-	4
NY	889	370	-
NC	252	~200	6
SC	-*	-	-
FL	-*	-	2
Total deaths: (At least)			37

- First tropical storm to threaten NYC since Hurricane Gloria in 1985
- Flooding records broken in 26 rivers
- Caused at least 56 deaths
- Damage nearly $8 billion

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Hurricanes

Sunday, 02.19.12 Welcome Guest •

HOME **NEWS** **SPORTS** **ENTE**

Miami-Dade | Broward | Keys |

Posted on Friday, 09.02.11

HURRICANE SEASON

Intensity remain

f Like ‹ 1

The National Hurricane Cer
it wasn't the first time — bu
the increasing standards of

BY CURTIS MORGAN
MORGAN@MIAMIHERALD.COM

The New York Times

U.S.

WORLD U.S. N.Y. / REGION BUSINESS TECHNOLOGY SCIENCE HEALTH SPORTS OPINION

POLITICS EDUCATION BAY AREA CHICAGO TEXAS

Challenges in Predicting the Intensity of Storms

GARDEN STATE PARKWAY CLOSED
SOUTH
V TO PREPARE FOR THE HURRICANE AND A LOOK AT LOCAL EV   80° 4:27

Andy Newman/Associated Press

Scientists say that it is much easier to accurately predict what path a hurricane will take.
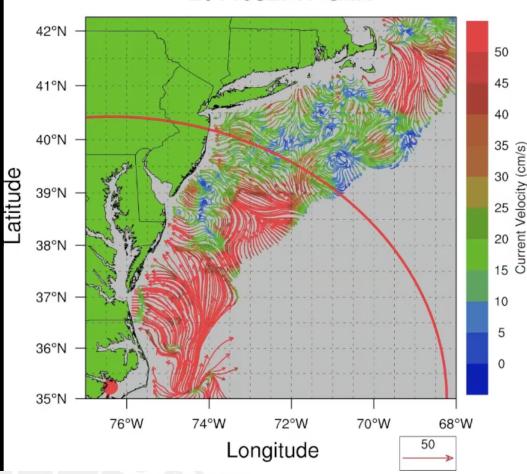
By HENRY FOUNTAIN
Published: August 27, 2011

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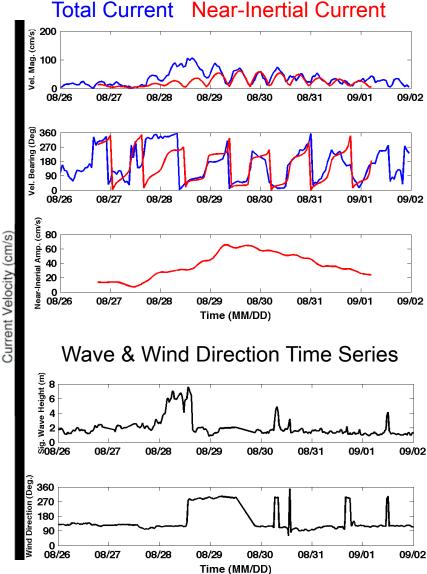
Hurricane Irene

Long Range Radar Network
Sea Surface Currents
2011082717 GMT
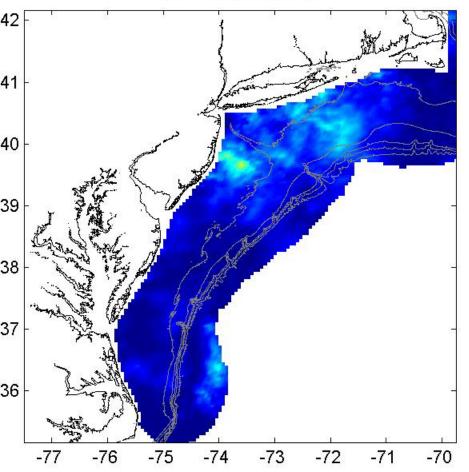
39.5N 73W Surface Current Time Series
Total Current   Near-Inertial Current

Wave & Wind Direction Time Series

Hurricane Irene

Direct Wind Forcing

Mean Wavelet Power between Period 20 h and 30 h
2011-08-23 00:00:00

Inertial Response

Mean Wavelet Power between Period 16 h and 20 h
2011-08-23 00:00:00

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Two Gliders
Deployed by MARACOOS
in Hurricane Irene

Buzzards Bay

Vineyard Sound

Deployment Location

Long Island Sound

Last Surfacing

RU23

Last Surfacing

RU16

rent Waypoint: ru16

e Bay

RU16
• Deployed for EPA.
• Map bottom dissolved oxygen.
• Provided data on mixing during storm.

RU23
• Deployed for MARACOOS.
• Map subsurface T/S structure for fisheries.
• Damaged early - drifter
• Recovered by fisherman
• Provided data on inertial currents during storm.

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Coastal Ocean
Observation Lab

Hurricane Irene

Hurricane Irene

temperature

26

14

salinity

33

29

% oxygen

105

60

depth

depth

depth

8/12   date   9/07

Long Island Sound

Buzzards Bay

Last Surfacing

RU16

Current Waypoint: ru16

Delaware Bay

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WARM: RTG+SPoRT(8/27)   Init: 2011-08-27_00:00:00

RTG,SPoRT(9/06)+AVHRR(8/31) Init: 2011-08-28_06:00:00

27/1200→28/0600

28/0600→29/0600

Sea Surface Temperature (K)

Sea Surface Temperature (K)

Sea Surface Temperature (K)

Sea Surface Temperature (K)

280 282 284 286 288 290 292 294 296 298 300 302 304

280 282 284 286 288 290 292 294 296 298 300 302 304

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Wind Speed at 10 m [kts]

RU-WRF Atmospheric Forecast Model

Key
- ● NHC Best Track
- ○ GFS 0.5 deg 06Z
- ● WRF 6km (Warm SST, 06Z, 06hr)

Maximum Sustained Wind Speed (10m)

- ■— NHC Best Track
- ■— NHC Forecast
- ■— Warm SST (RTG only)

Data SIO, NOAA,
© 2012 C

38°07'08.13" N 72°

WARM (RTG only)

COLD "Update" (AVHRR)

Wind Speed at 10 m [kts]

RU Coastal Ocean Observation Lab: WRF–ARW 6 KM
http://marine.rutgers.edu/cool/weather

Model Initialized 00Z27AUG2011
Valid 00Z27AUG2011 (Sat) | Forecast Hour 0

Wind Speed at 10 m [kts]

RU Coastal Ocean Observation Lab: WRF–ARW 6 KM
http://marine.rutgers.edu/cool/weather

Model Initialized 00Z27AUG2011
Valid 00Z27AUG2011 (Sat) | Forecast Hour 0

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Coastal Ocean
Observation Lab

Date/Time (UTC)	NHC Forecast	Warm (RTG only)	Warm (RTG only, OML Model)	Cold "Update" (AVHRR)
27/1200	5	-17.22	-17.23	-6.17
27/1800	10	4.1	4.2	5.88
28/0000	10	1.39	-2.14	3.96
28/0600	5	-1.2	-1.04	-1.21
28/1200	15	2.39	4.79	0.5
28/1800	15	4.97	3.51	-2.67
29/0000	15	3.62	1.93	-0.89
29/0600	10	10.48	9.84	4.52
Sum of Squares	800	457	452	118
RMSE	9.43	7.13	7.09	3.61

Temperature / Salinity — Glider and Model comparison, 24-Aug through 29-Aug
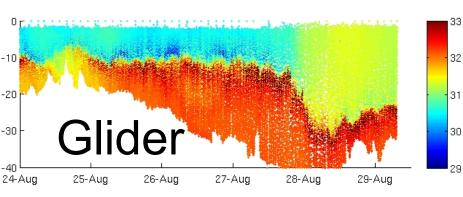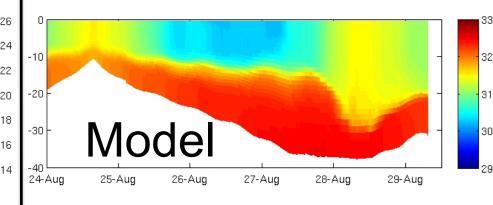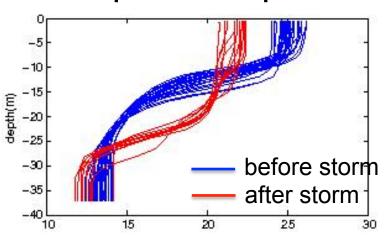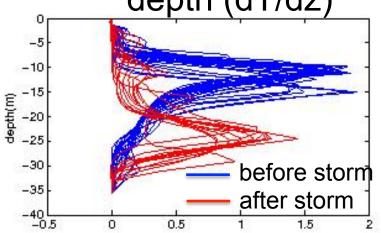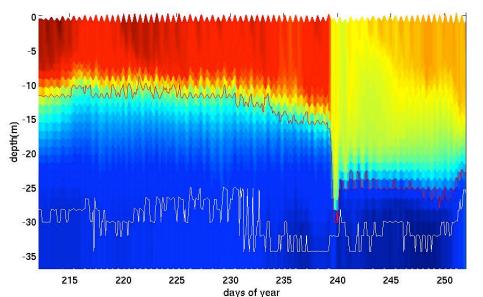
Temperature profile
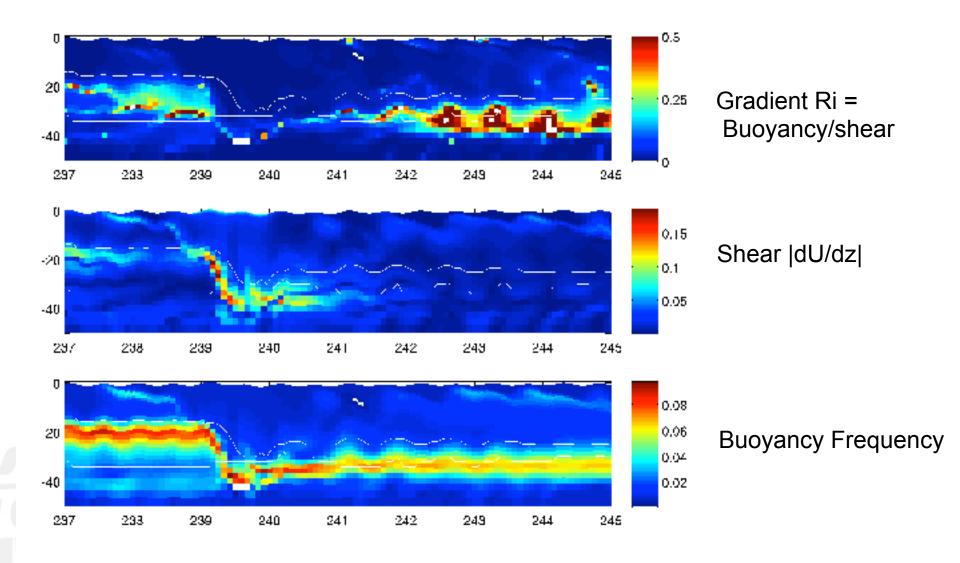
Temperature change with depth (dT/dz)
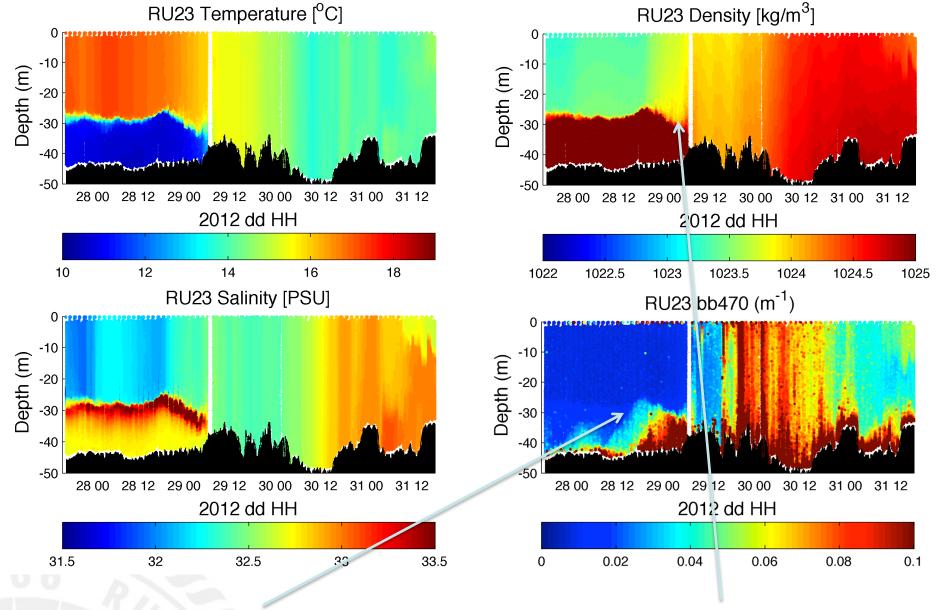
Mixed layer depth = max(dT/dz)

Transition layer= dT/dz< 0.01

Gradient Ri = Buoyancy/shear

Shear |dU/dz|

Buoyancy Frequency

RU23 Temperature [°C]

RU23 Density [kg/m³]

RU23 Salinity [PSU]

RU23 bb470 (m⁻¹)
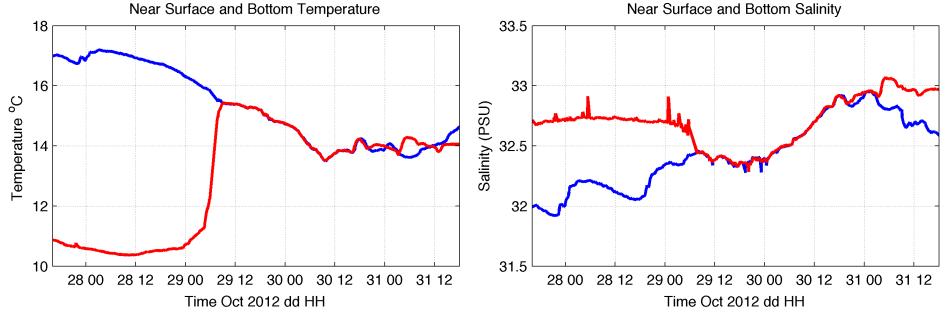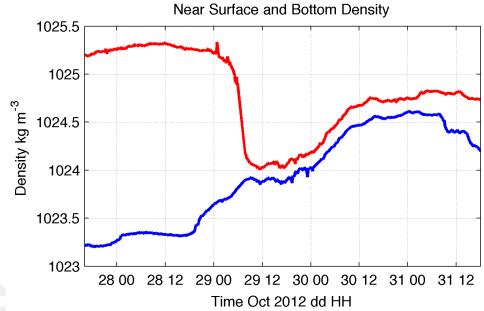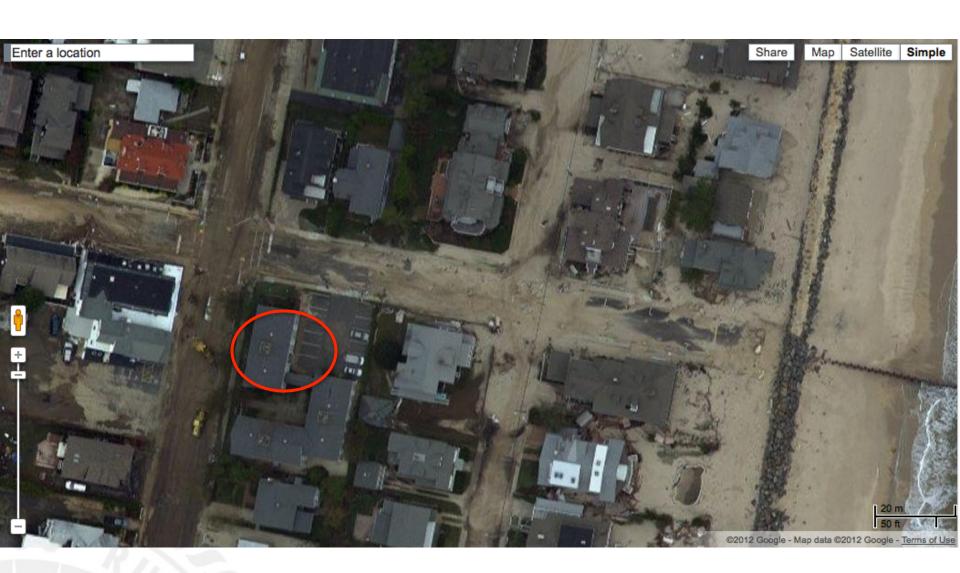
WBL grows and mixes from the bottom up
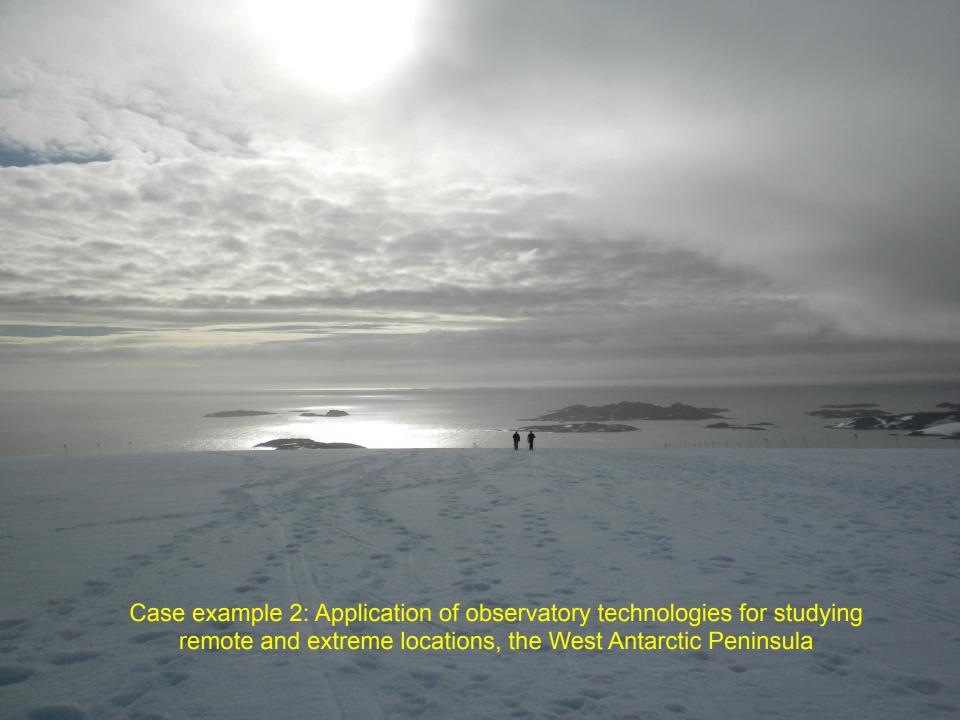
Winds mix from the top down

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Near Surface and Bottom Temperature

Near Surface and Bottom Salinity

Near Surface and Bottom Density

Case example 2: Application of observatory technologies for studying remote and extreme locations, the West Antarctic Peninsula
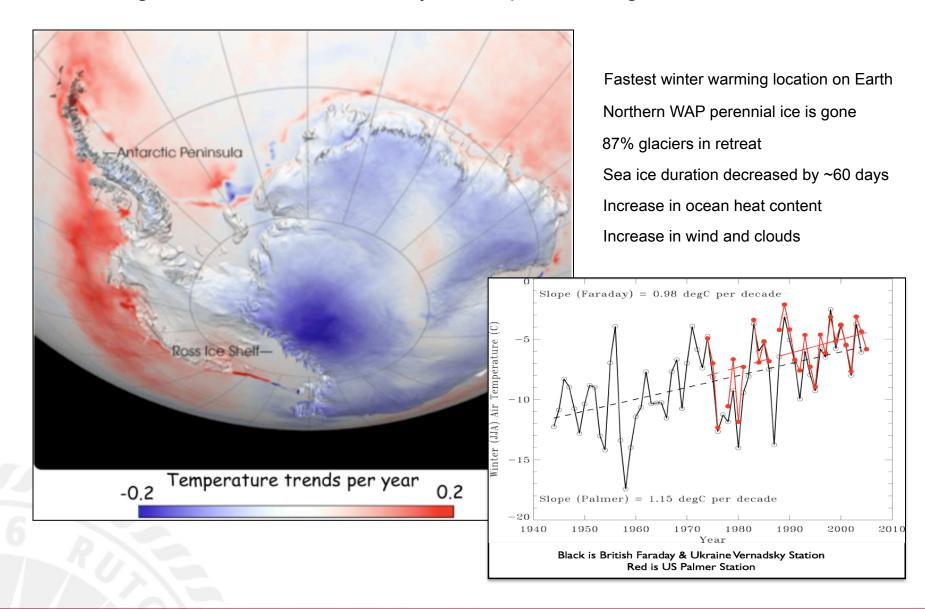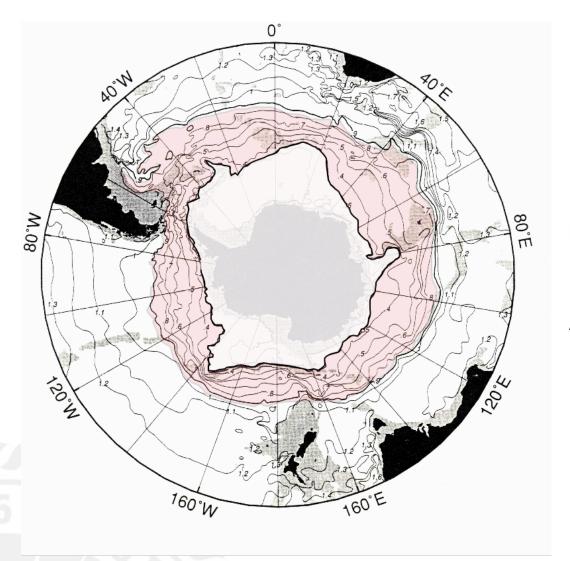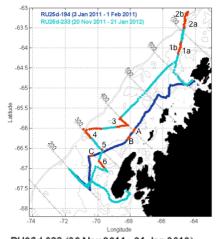
We are using the WAP as zone to study how rapid warming can shift the food web

Fastest winter warming location on Earth

Northern WAP perennial ice is gone

87% glaciers in retreat

Sea ice duration decreased by ~60 days

Increase in ocean heat content

Increase in wind and clouds

Slope (Faraday) = 0.98 degC per decade

Slope (Palmer) = 1.15 degC per decade

Black is British Faraday & Ukraine Vernadsky Station
Red is US Palmer Station
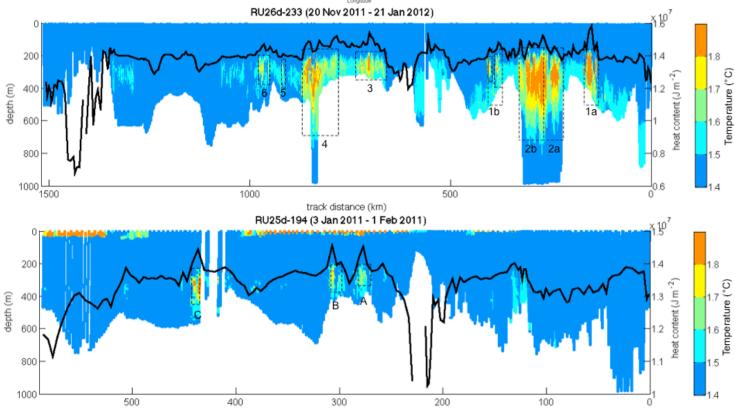
Heat engine melting the WAP
is the ACC
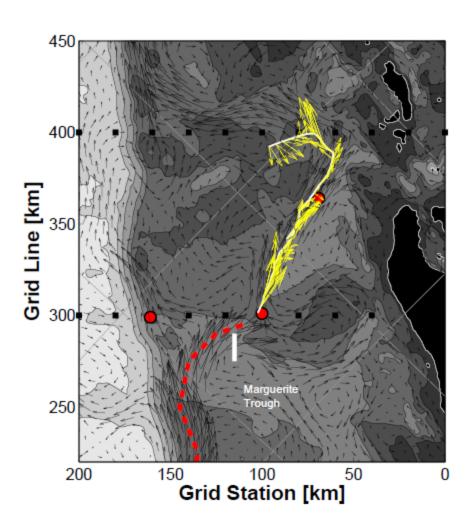
ACC upwelling is rapid flushing
events (time scale of weeks)

RU26d-233 (20 Nov 2011 - 21 Jan 2012)

RU25d-194 (3 Jan 2011 - 1 Feb 2011)
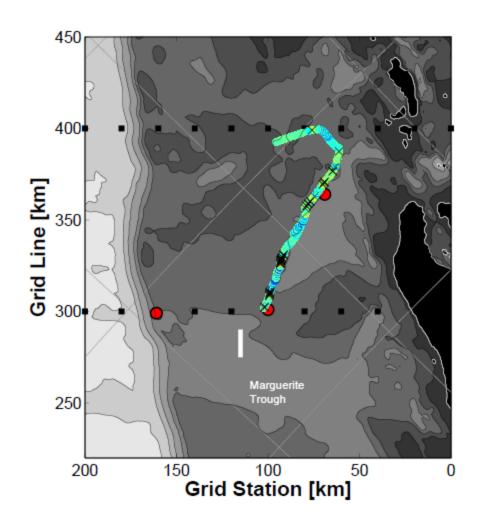
- Glider depth-averaged currents: agree well with moorings + model!
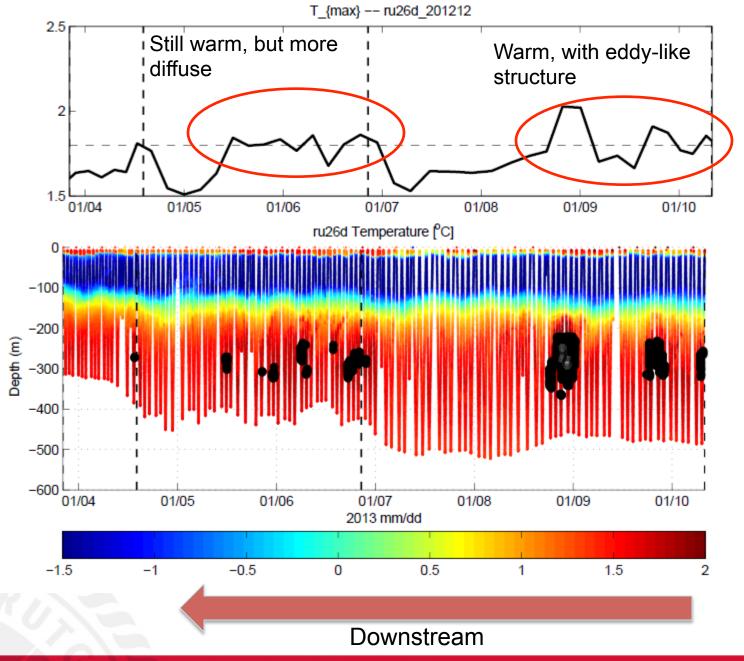
Thanks Lamont team
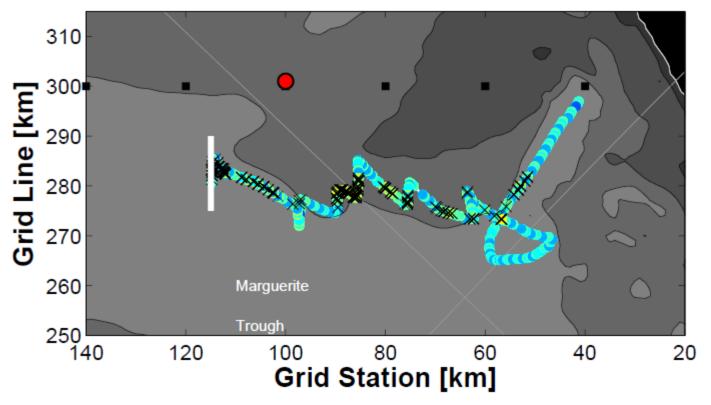
- Glider depth-averaged currents: agree well with moorings + model!

- Glider deep water (> 220 db) temperatures: episodic warming!

T_{max} -- ru26d_201212

Still warm, but more diffuse

Warm, with eddy-like structure

ru26d Temperature [°C]

Downstream

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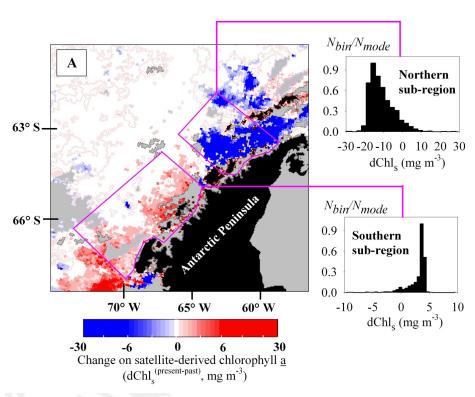
•After about 3 days at the fence, we begin tracking.

•Divert north/south to wait for feature to catch up if we exit ($v_g \sim 3v_{bg}$).

•Follow feature for about 6 days.
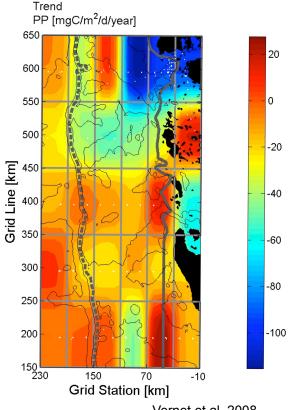
There are indications in changes in the primary production

Remote Sensing (Decadal changes)

Montes-Hugo et al. 2009

Ship Observed (Decadal changes)
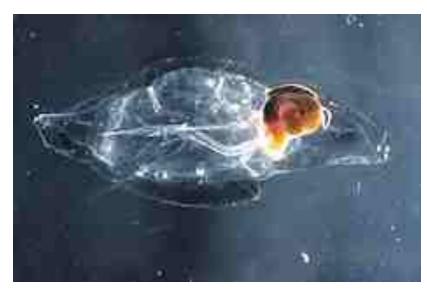
Vernet et al. 2008
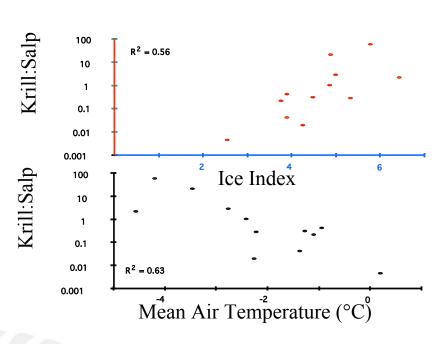
Antarctic krill
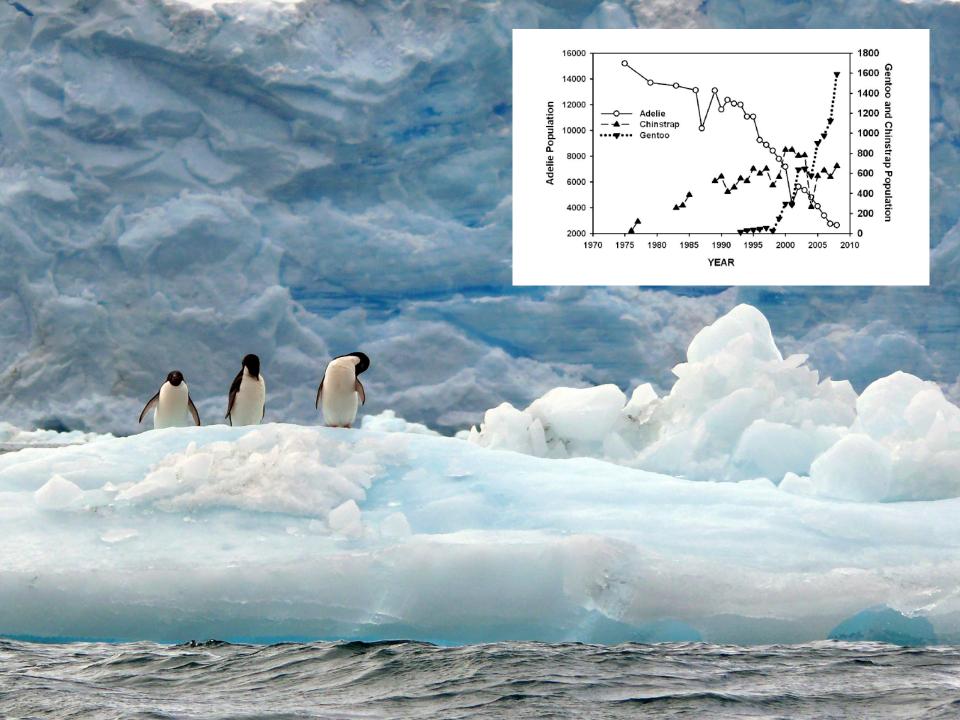
Antarctic Salp

There are indications in changes in the zooplankton communities

Krill:Salp

$R^2 = 0.56$

Ice Index

Krill:Salp

$R^2 = 0.63$

Mean Air Temperature (°C)
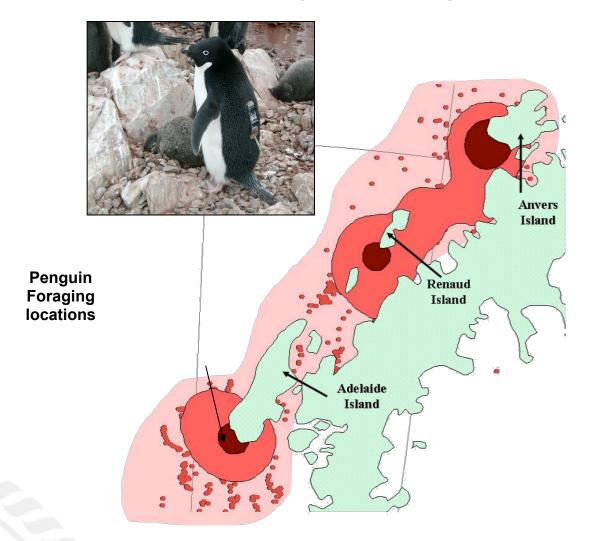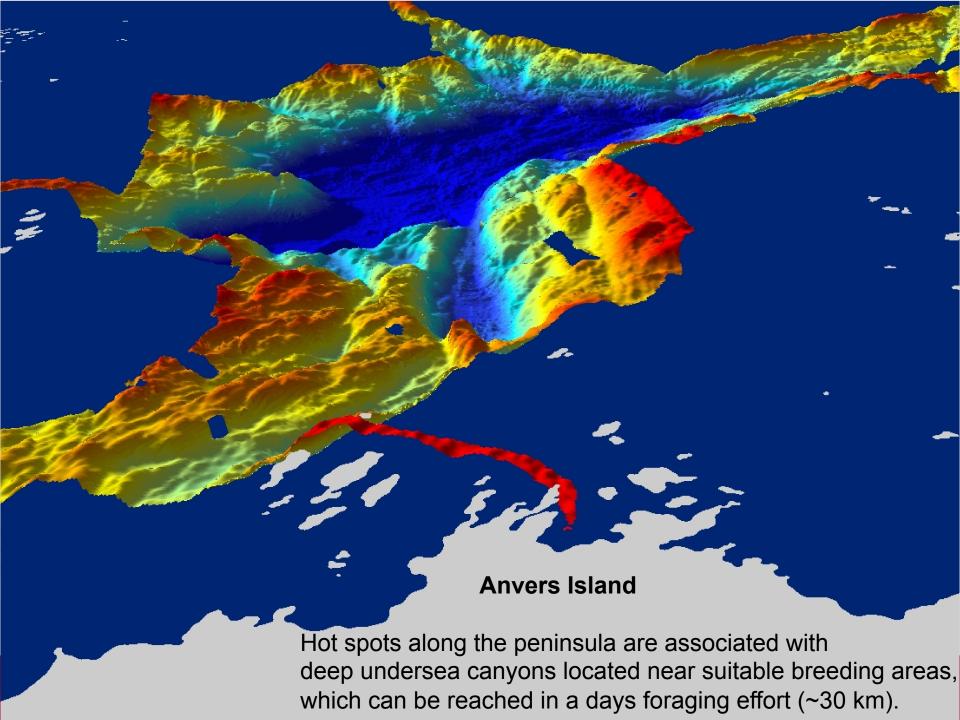
Loeb et al. 1997
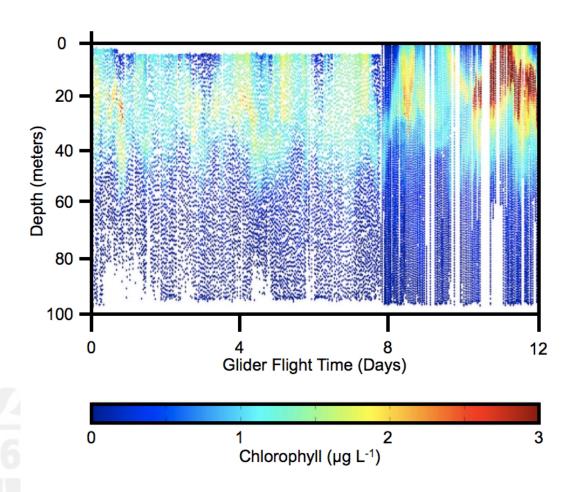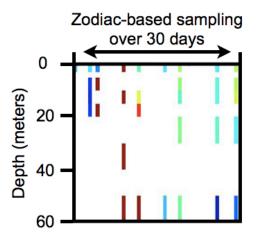
Adaptive Sampling of Penguin Habitats

Penguin Foraging locations

Anvers Island

Renaud Island

Adelaide Island

Anvers Island

Hot spots along the peninsula are associated with
deep undersea canyons located near suitable breeding areas,
which can be reached in a days foraging effort (~30 km).

Zodiac-based sampling over 30 days

Chlorophyll (µg L⁻¹)

Coastal Ocean
Observation Lab

Mark Moline & Bill Frazer

Chlorophyll a

Design, Testing and Deploy

Observatory (simulated) data

Models

Sensor & Platform

~3 km

~100 m

Virtual Ocean

I-COOL
International Coalition of Ocean Observing Laboratories

Data Assimilation

Data Analysis
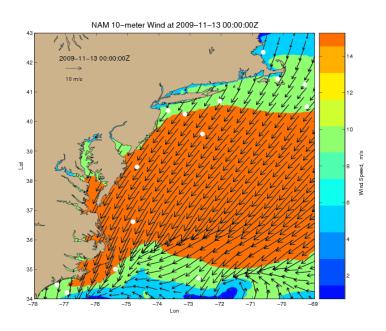
Science Questions & Drivers
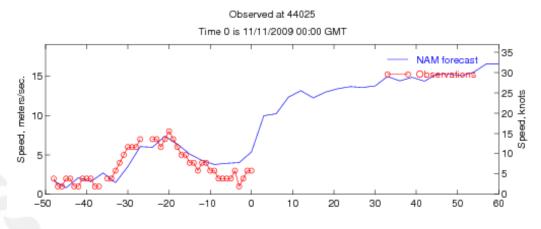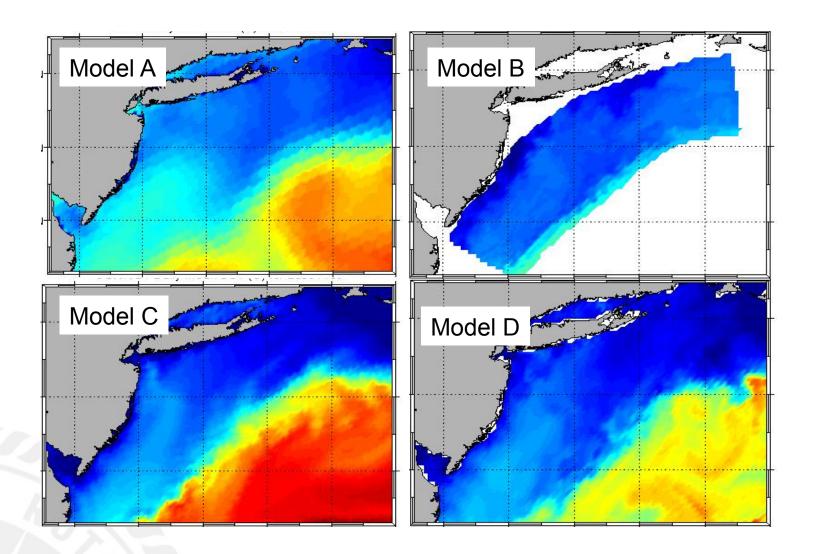
Data Synthesis: Nowcast & Data Impact
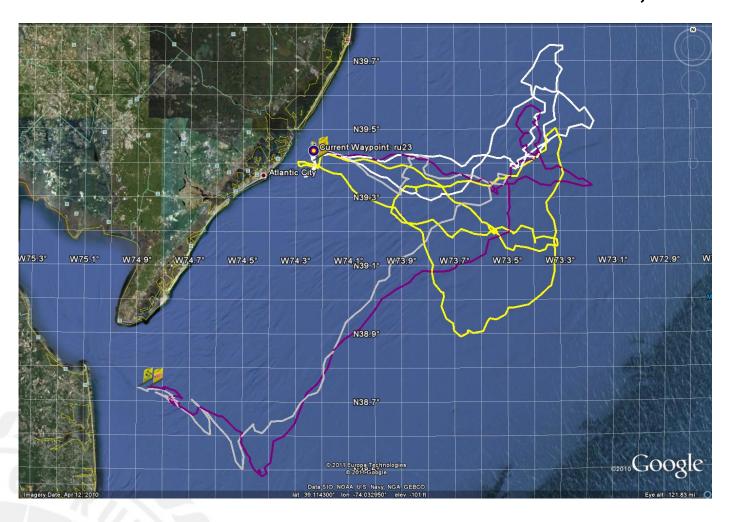
58

Weather

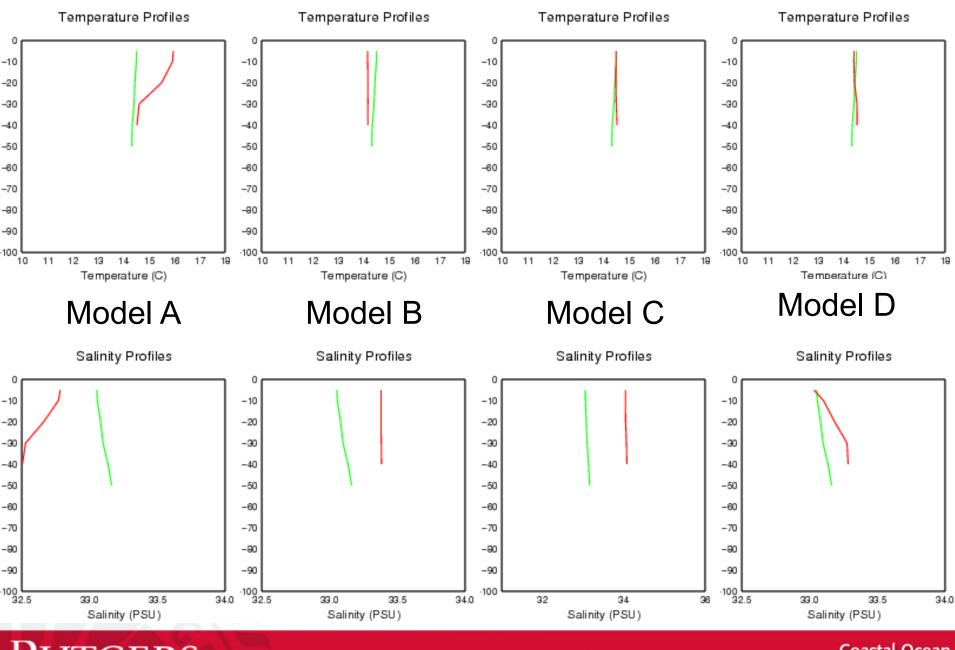# An ensemble of different numerical models run by different laboratories
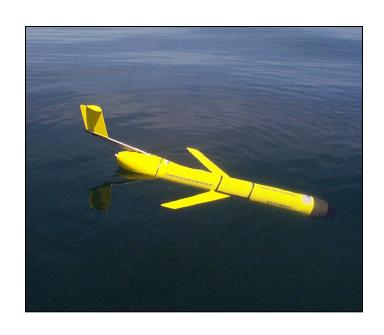
A fleet of four gliders
October 30 – November 20, 2009

4 Deployments
(3 Rutgers, 1
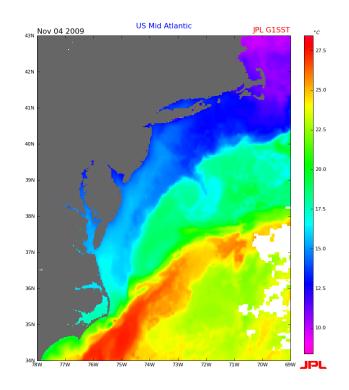University of
Delaware)

77 in-water days

1608 km flown

Model A Model B Model C Model D

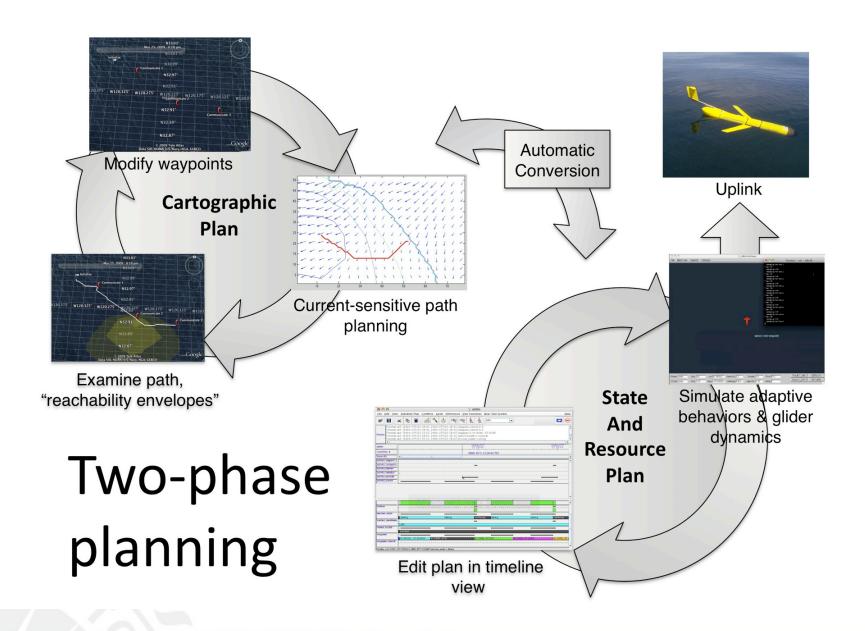# COMBINING THE FIELD ASSETTS WITH OCEAN FORECASTS FOR PLANNING AND PROSECUTION EFFORTS

- Known constraints (slow 0.5 knot, Battery, shipping lanes)

- Uncertain constraints (time-varying 3D currents)

- Operate autonomously & re-plan daily
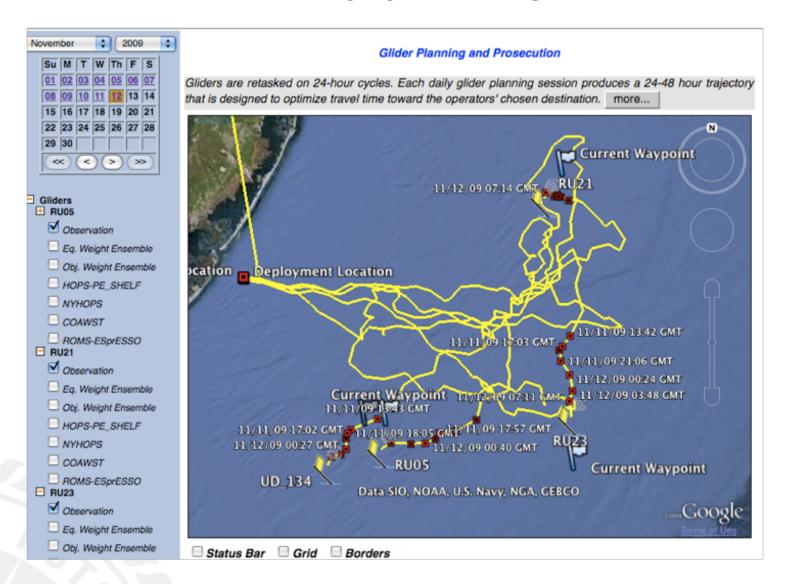
- From A to B in the shortest time

- Follow a time-varying feature (shelf-slope salinity intrusion)

Modify waypoints

Cartographic Plan

Automatic Conversion

Uplink

Current-sensitive path planning

Examine path, "reachability envelopes"

State And Resource Plan

Simulate adaptive behaviors & glider dynamics

Two-phase planning

Edit plan in timeline view

PLANNING FOR THE PRESENT

PLANNING IN THE FUTURE

Plan prediction accuracy

Conclusions:
Ocean robots will be used to sample
the oceans as never before
This is critical as the oceans have undergone
significant change over the last few decades

During RIMPAC 2008 off Hawaii.