Multiplatform Autonomous Adaptive Sampling

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Special Thanks to Michel Rixen, Pierre Lermusiaux, Ed Gough

View from the Top

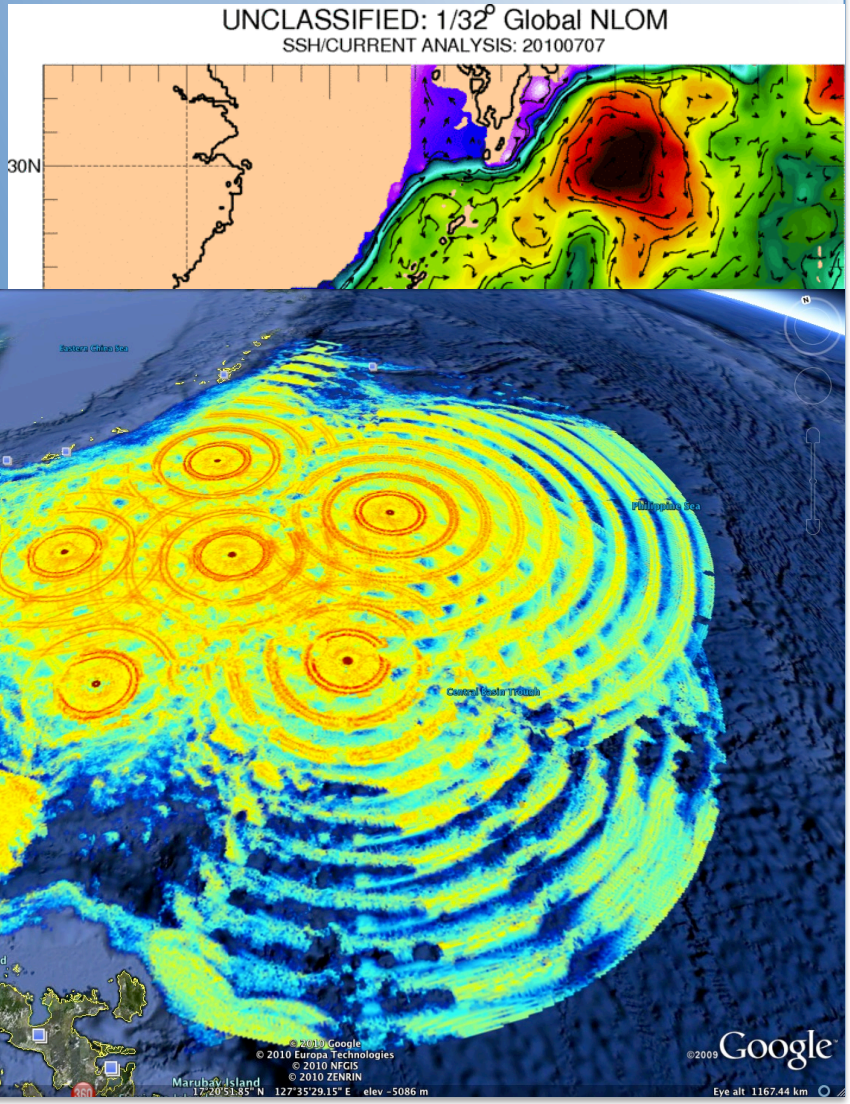
Transfer and reduction of uncertainty from ocean sampling – through acoustic propagation

- "Optimal is in the eye of the beholder"

The Naval uncertainty problem is:

- Multi-Disciplinary (not just inter..)
  - Ocean Dynamics (Physics)
  - Acoustics (Physics)
  - Signal Processing (EE)
  - Military Application
- Nonlinear (T/S-P-TL-DCLT)
- Complex
  - Fronts/Eddies/Bathymetry/ducts/waves
- Multiple Scales
  - Large scale circulation
  - Small scale variability – not well understood or surveyed
- Perpetually undersampled and understaffed

Inherently involves motion (target/receiver/ocean) and 3D environment



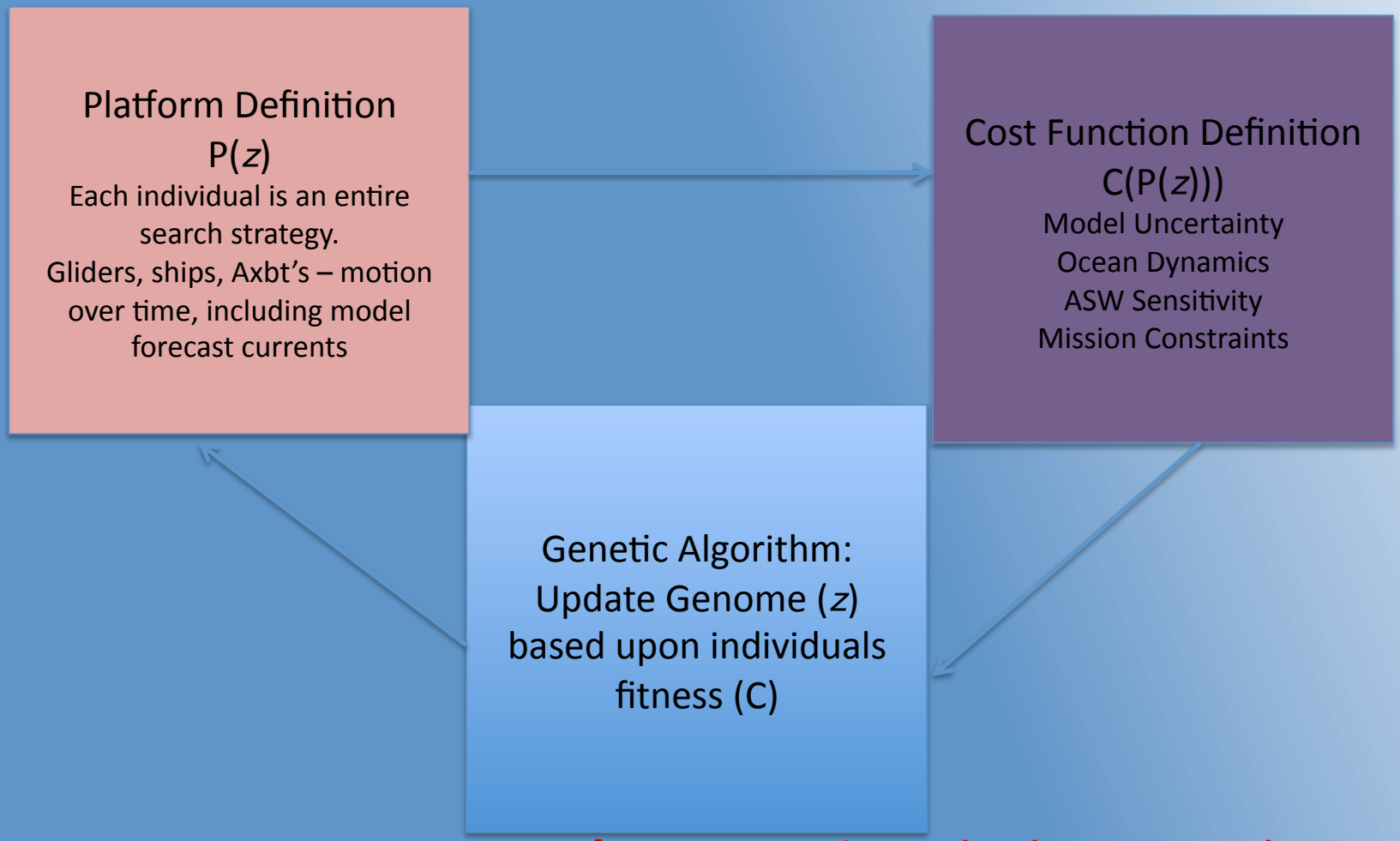
The EMPath Algorithm

(Environmental Measurements Path planner)

The EMPATH Algorithm History

- 2004 SBIR out of SPAWAR for OASIS (MATLAB, GA)
  - Experiment: SW06
- 2007 Transition to NAVOCEANO/NRL via LBSFI (C, GAlib)
  - Experiment: Valiant Shield 07
  - Experiment: Rimpac 08
  - Experiment: ANNUALEX 09
- 2010 OSSE and VTR with NRL (C, internal GA, GoogleEarth)
- ONR QPE Experiment: Taiwan 2008, 2009
- Experiment: Rep10
- VTR for operational use at NAVOCEANO 2011.

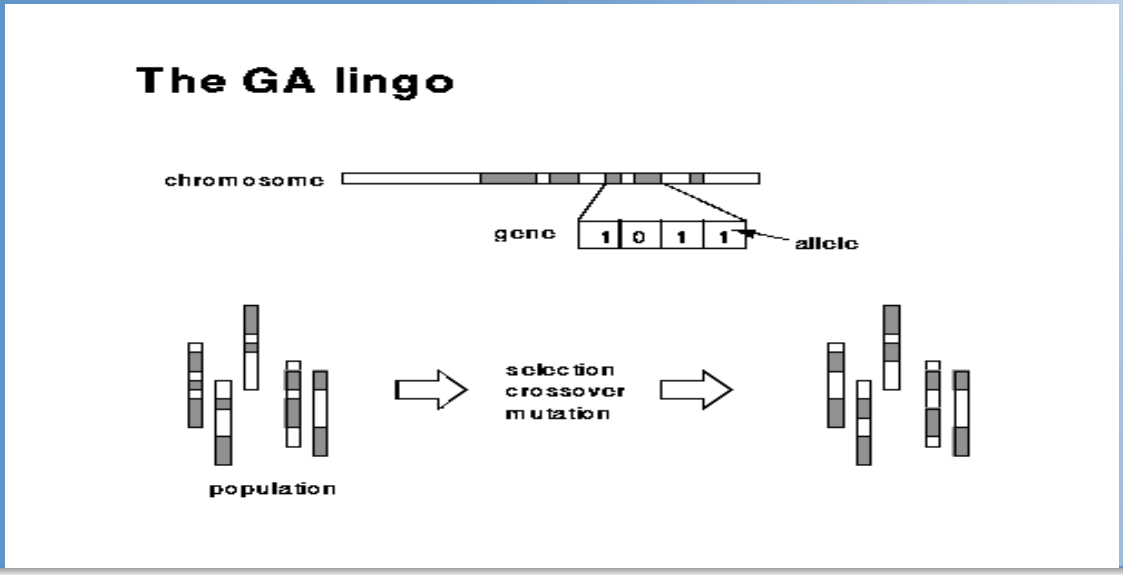
EMPath (Environmental Measurements Path planner)



[Heaney, Lermusiaux and Duda, JFR-2007 and OM-2010]

Genetic Algorithm Solutions

- Solution method to non-linear multi-dimensional scalar space.
- Based upon evolutionary biology –
  - Population of individuals (search planning algorithms)
  - Each search parameter is coded into a gene, the individual is the aggregated gene (chromosome)
  - Each individual's fitness is evaluated (Cost function evaluation)
  - Next generation is reproduced from fittest parents
    - Selection (of fit individuals)
    - Cross-over (of parents genes)
    - Mutation – random perturbation to escape local minima



Initial Cost Functions

- Spatial Variability:

$$T_{spatial} = \frac{1}{N}\sum_{i}\int d\vec{r}_i \left(T\left(\vec{r}\right) - \bar{T}\left(\vec{r}\right)\right)^2$$

- Temporal/Ensemble Variance:

$$T_{temporal} = \frac{1}{N}\sum_{i}\int d\vec{r}_i \sigma_t^2\left(T\left(\vec{r},t\right)\right)$$

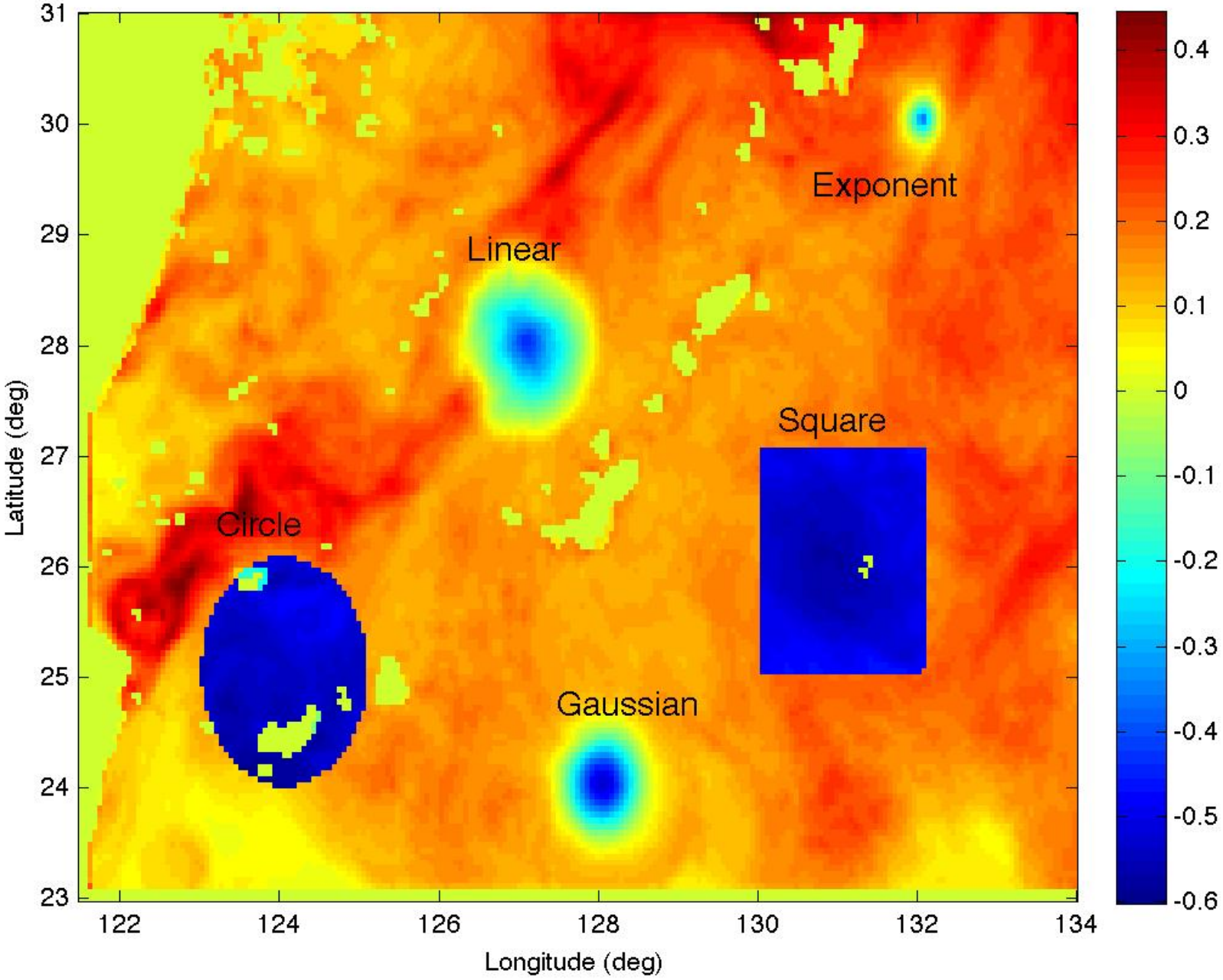
Constituent Cost Functions

- Central Forecast (Single forecast run)
  - Temporal Variability (dynamics)
  - Spatial Variability (Gradients/fronts)
  - Acoustic Sensitivity
- Ensemble Forecasts:
  - Ensemble Spread (T/S @ depth)
  - Acoustic Computation Sensitivity
    - Area Coverage Variance
    - Below Layer Gradient
    - Mixed Layer Depth
    - …
  - Impact of measurements on Target Area (Coelho TOFU).
- Operational Constraints
  - Operational Safety
    - Bathymetry
    - Currents
  - Collection of Vehicles
  - Waterspace Constraints… Aussie subs… ;)

Normalized Weighted Linear Sum

$$E(\vec{r}) = \sum_i \frac{W_i C_i(\vec{r})}{\sigma(C_i)} + W_b C_b(\vec{r}) + W_{dp} C_{dp}(\vec{r})$$

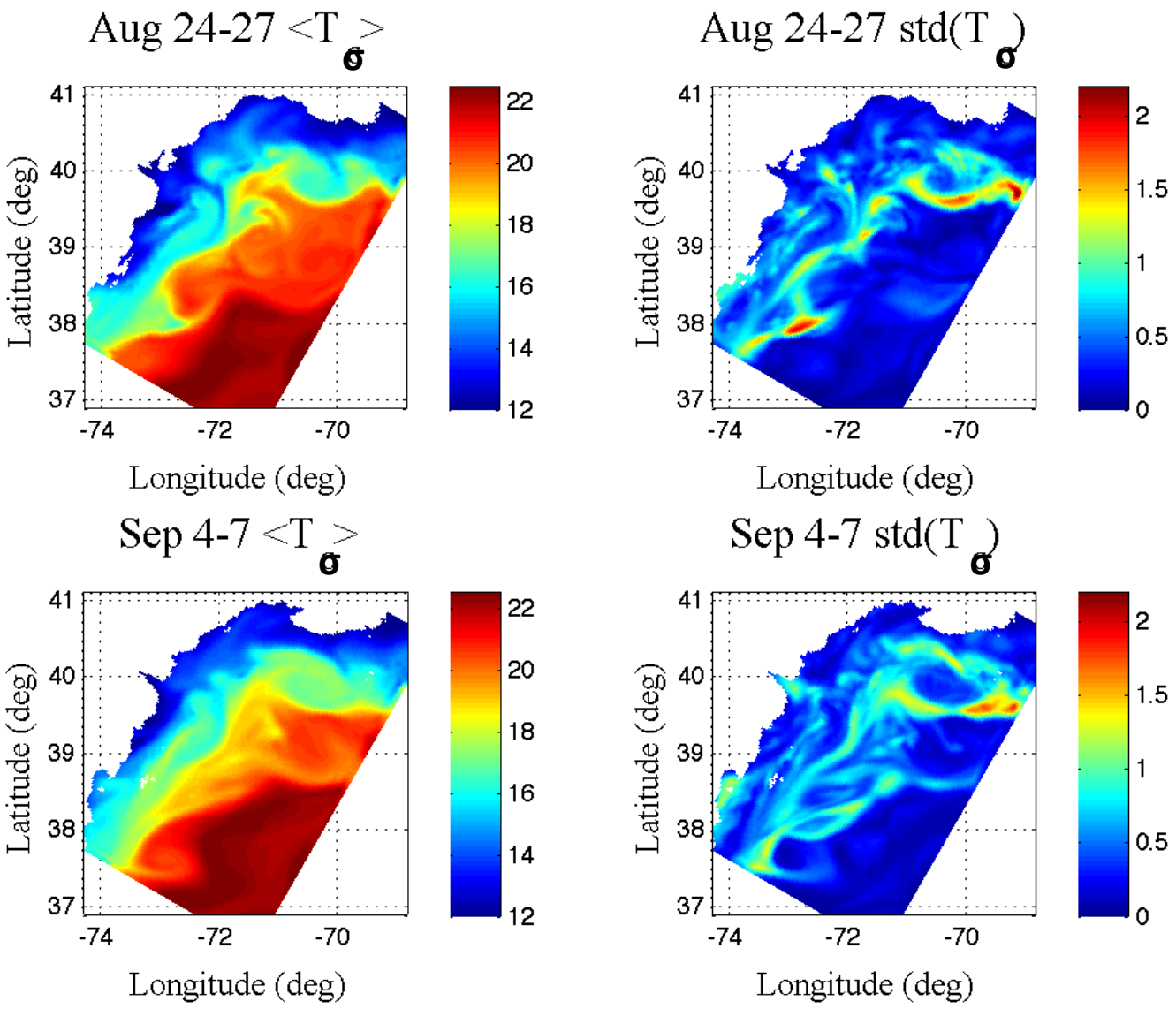
$$C_{dp} = \left\{ \left(\frac{\hat{r}}{\Delta r + \alpha \hat{r}} \right)^2 + 1 \right\} \left\{ \left(\frac{\hat{t}}{\Delta t + \alpha \hat{t}} \right)^2 + 1 \right\} - 1$$


WaterSpace Examples
Exponent
Linear
Square
Circle
Gaussian
Latitude (deg)
Longitude (deg)
31
30
29
28
27
26
25
24
23
122
124
126
128
130
132
134
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6

HOPS Model Hindcasts for Shallow Water 2006 – NJ SHelf

Before Tropical Storm Ernesto

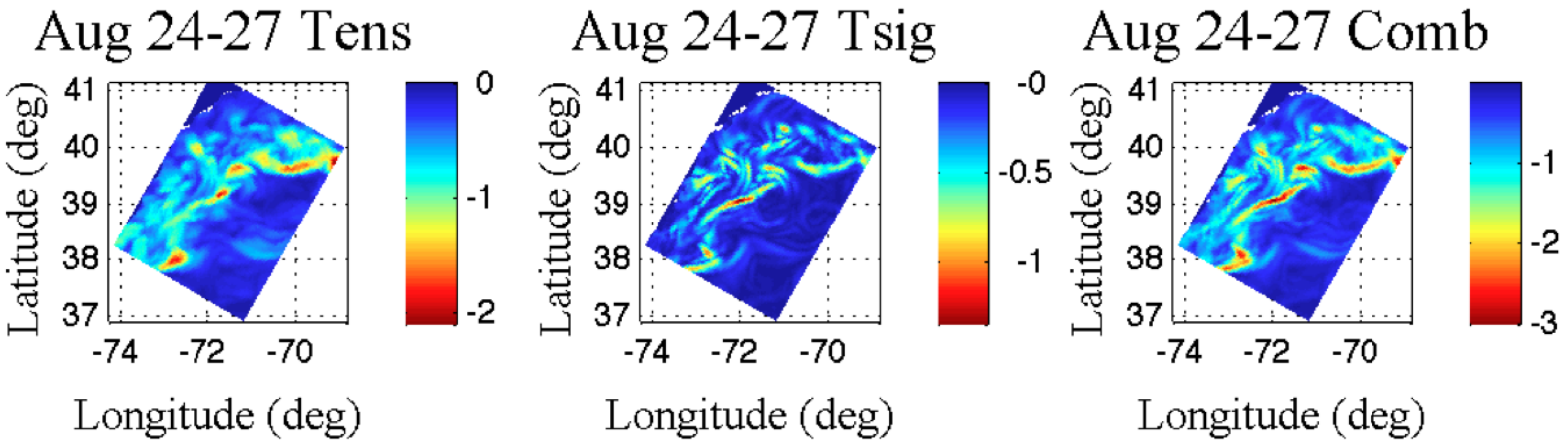
After Tropical Storm Ernesto

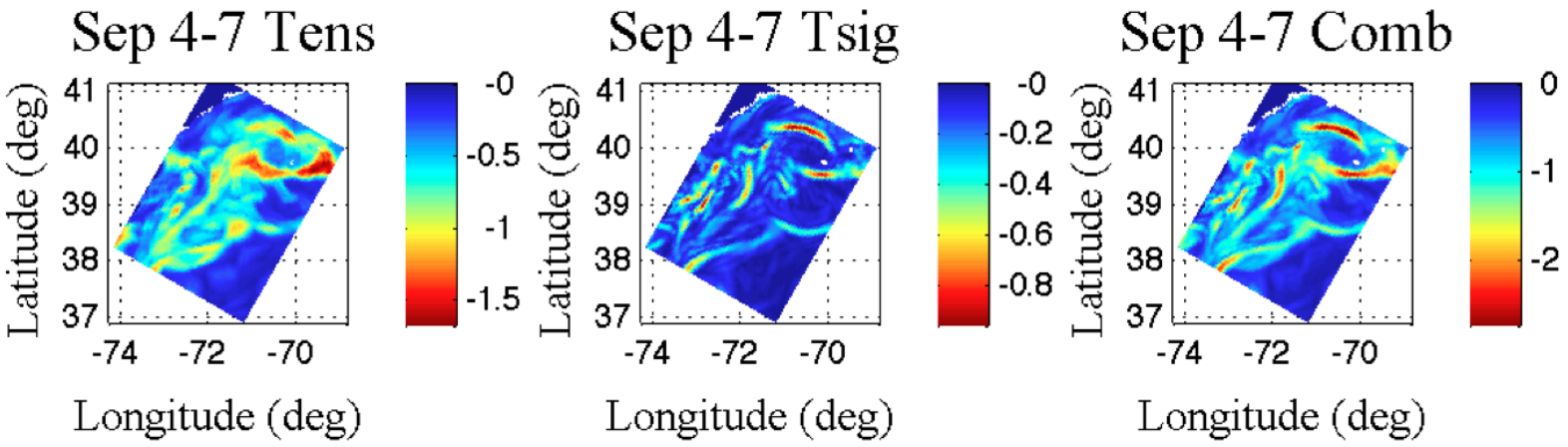


Time-Averaged Temperature
(T_s = T along the 24.7 g/cm^3 isopycnal)

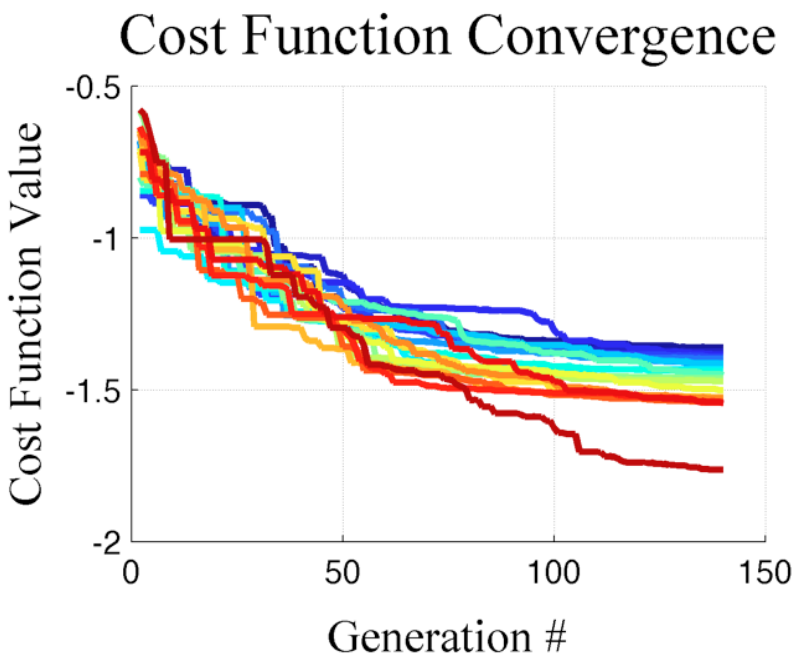
Temperature Uncertainty
(Ensemble standard deviation)

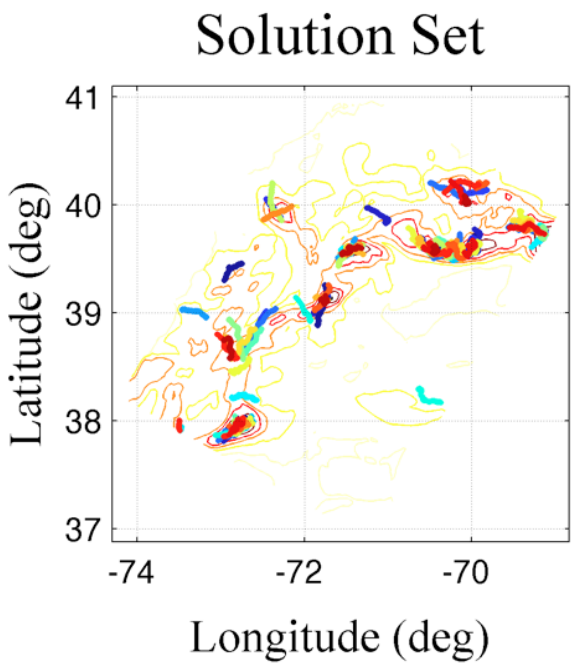
Cost Function Morphology

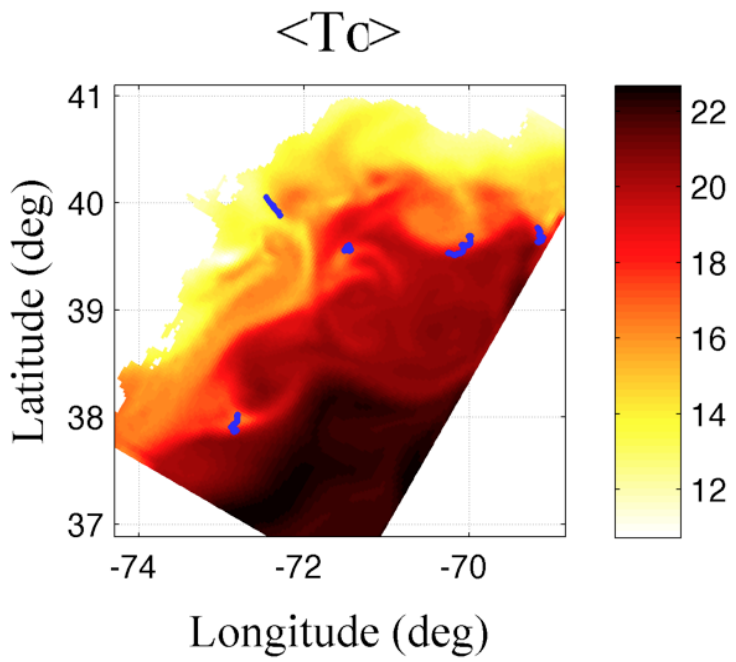


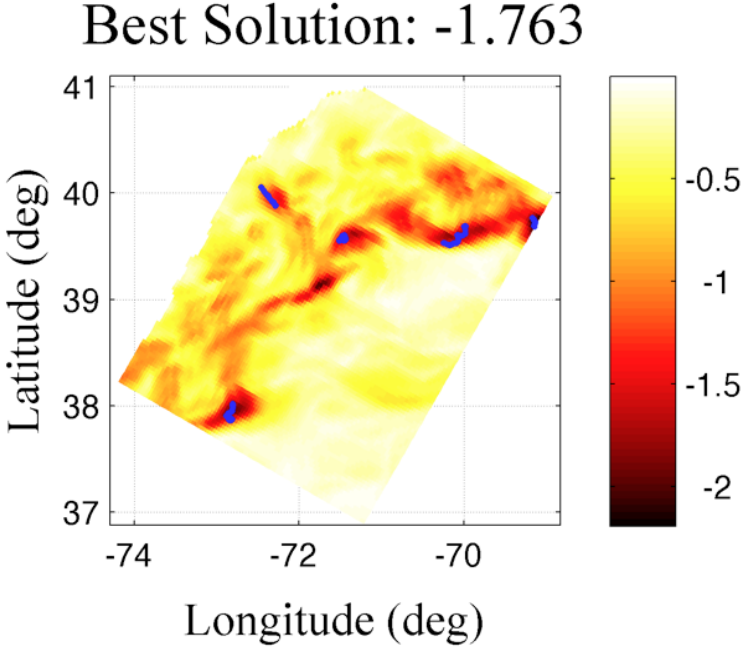


$T_{ensemble}$

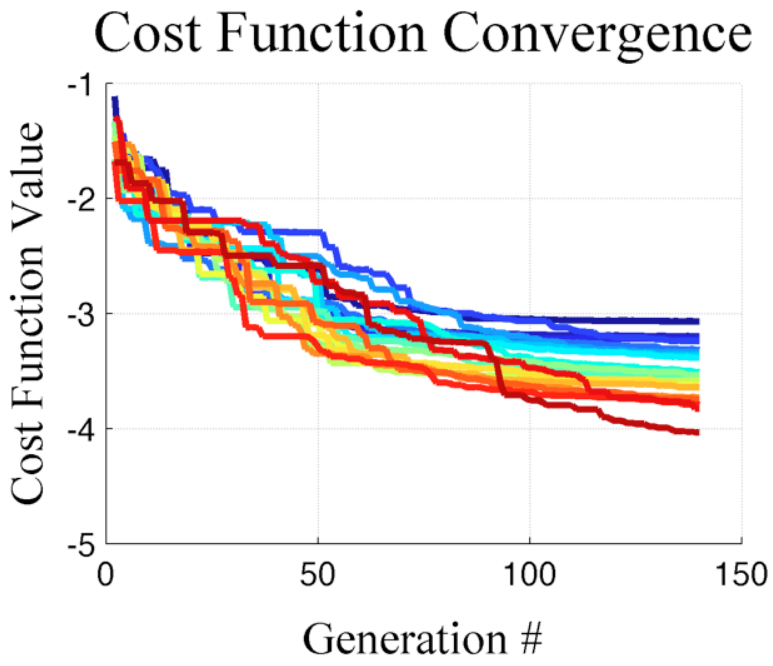

Cost Function Convergence
Cost Function Value
-0.5
-1
-1.5
-2
0
50
100
150
Generation #

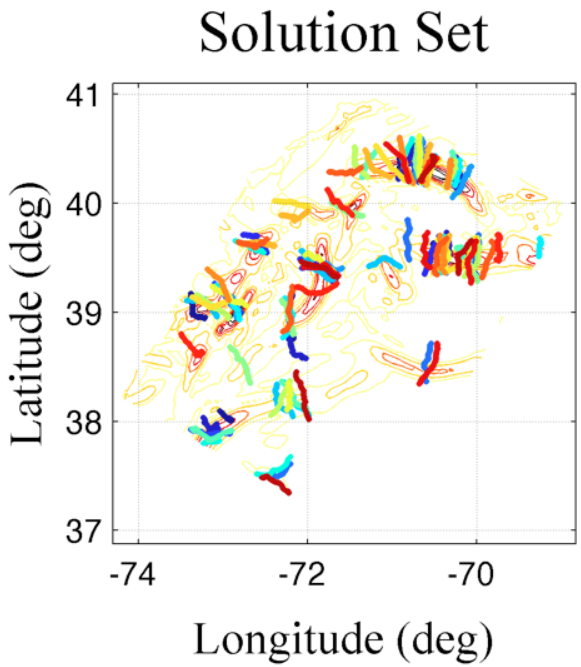

Solution Set
Latitude (deg)
41
40
39
38
37
-74
-72
-70
Longitude (deg)

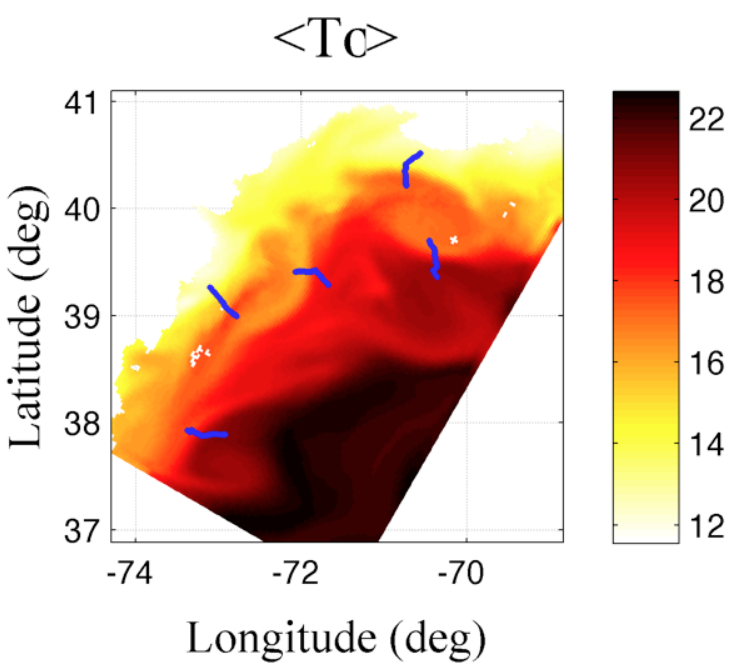

<Tc>
Latitude (deg)
41
40
39
38
37
-74
-72
-70
Longitude (deg)
22
20
18
16
14
12

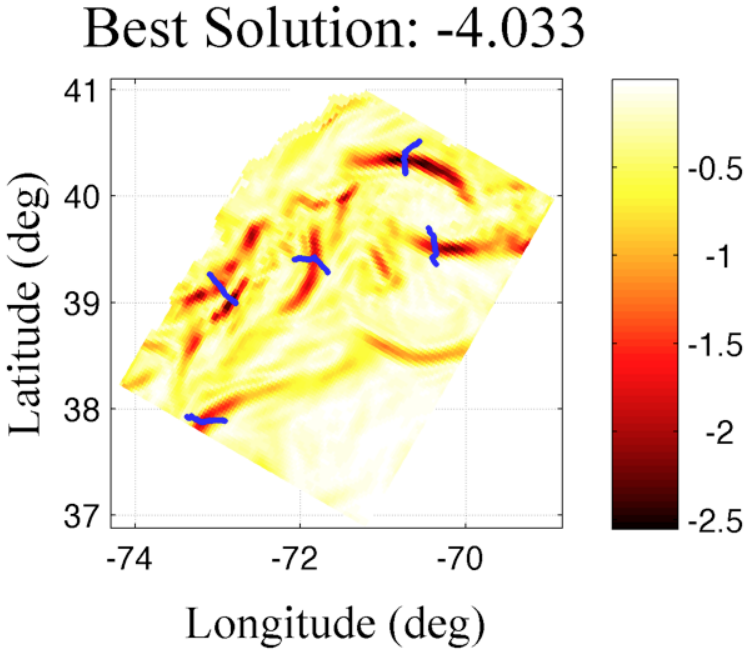

Best Solution: -1.763
Latitude (deg)
41
40
39
38
37
-74
-72
-70
Longitude (deg)
-0.5
-1
-1.5
-2

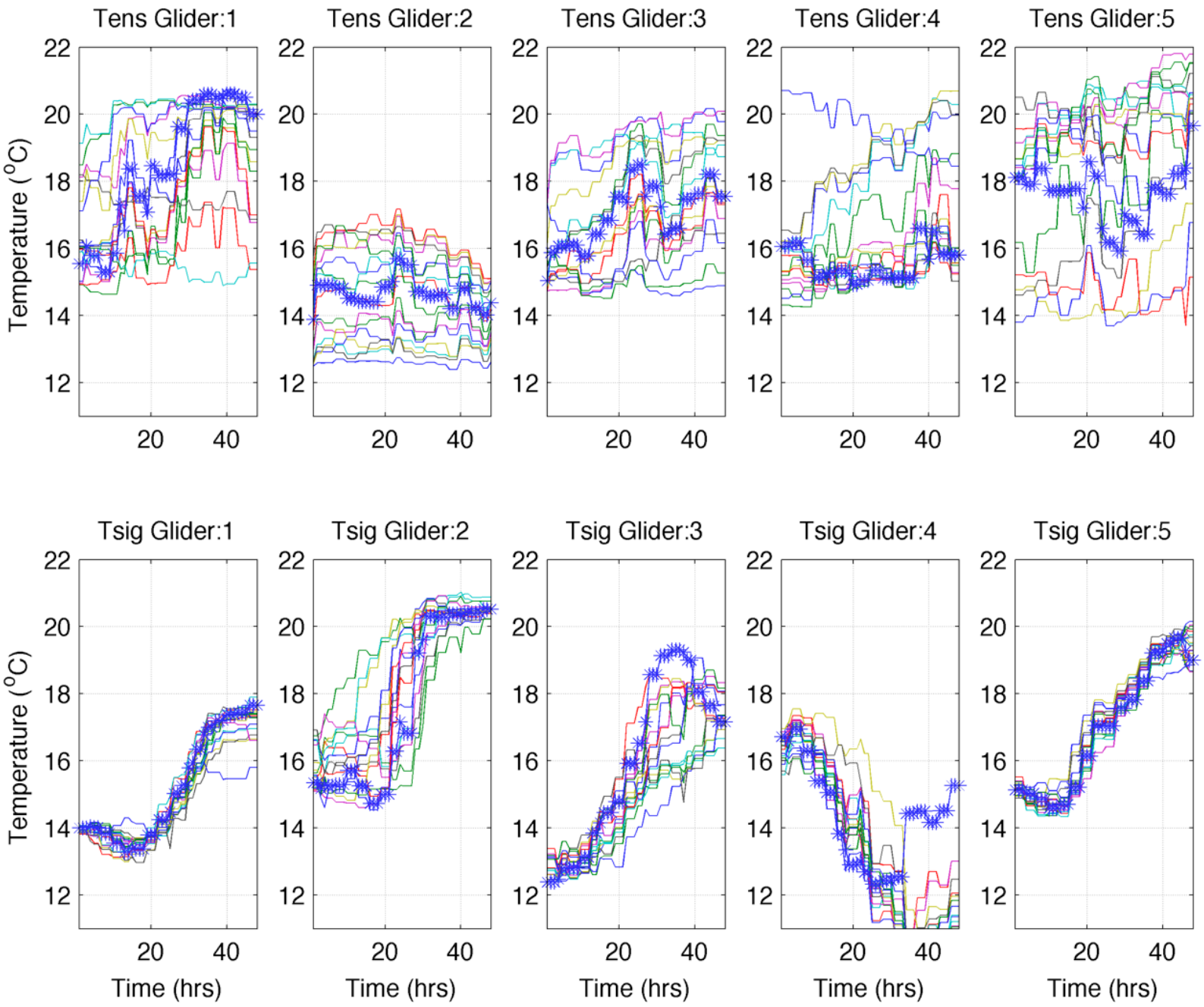
$T_{spatial}$


Cost Function Convergence
Cost Function Value
-1
-2
-3
-4
-5
0
50
100
150
Generation #


Solution Set
Latitude (deg)
41
40
39
38
37
-74
-72
-70
Longitude (deg)


<Tc>
Latitude (deg)
41
40
39
38
37
-74
-72
-70
Longitude (deg)
22
20
18
16
14
12


Best Solution: -4.033
Latitude (deg)
41
40
39
38
37
-74
-72
-70
Longitude (deg)
-0.5
-1
-1.5
-2
-2.5

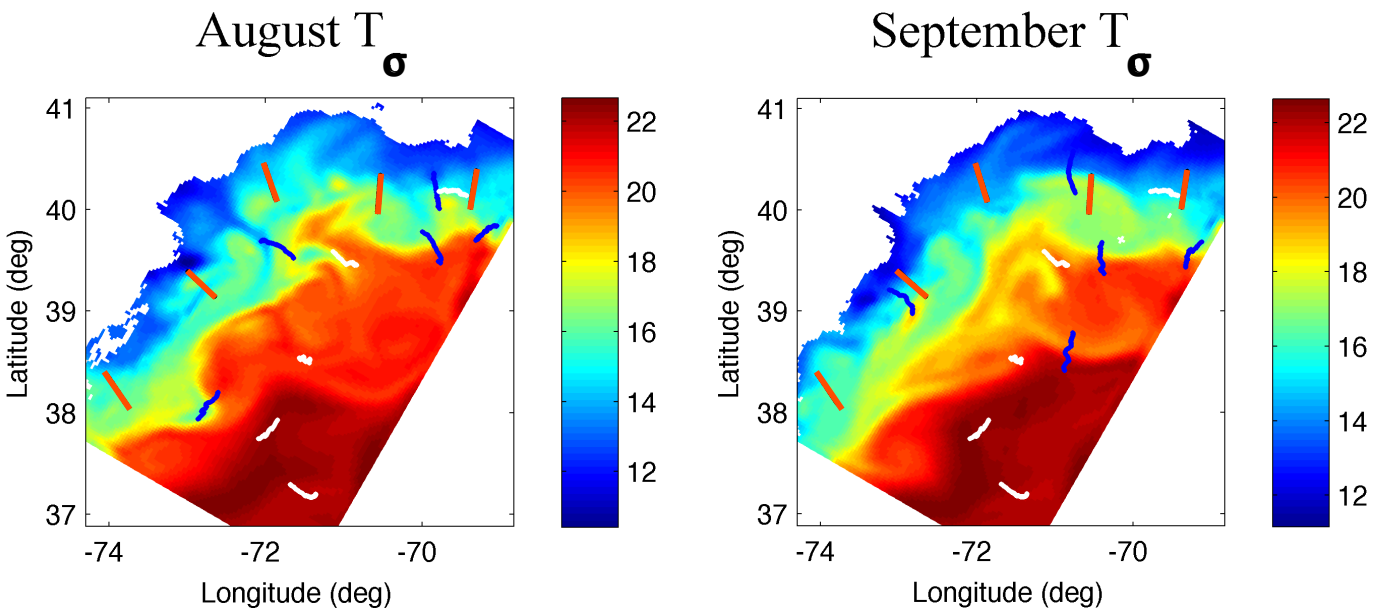

Tens Glider:1
Tens Glider:2
Tens Glider:3
Tens Glider:4
Tens Glider:5
Tsig Glider:1
Tsig Glider:2
Tsig Glider:3
Tsig Glider:4
Tsig Glider:5
Temperature (°C)
Time (hrs)
22
20
18
16
14
12
20
40

c) GA Scheme Evaluation: Comparing Strategies using Data-Assimilation

Three Types of Strategies

[Heaney, Lermusiaux, Haley and Duda, 2009]

Two dynamic situations: before (Aug) and after (Sep) Ernesto



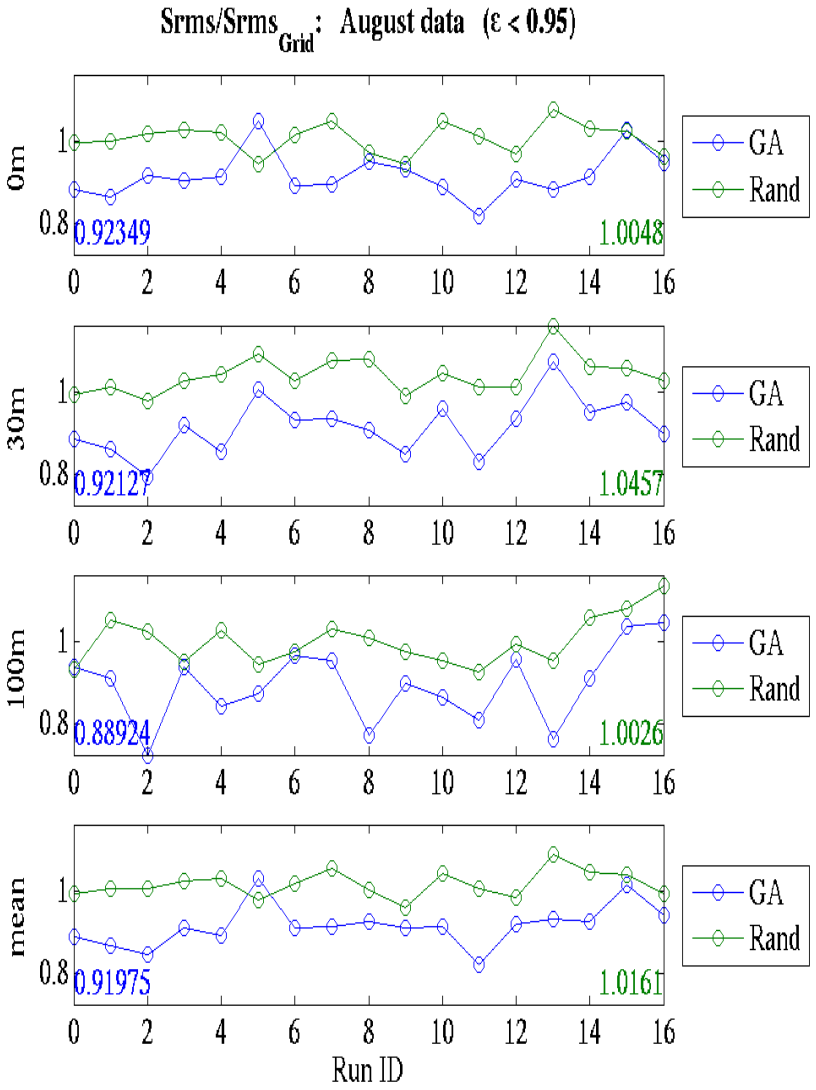
Five gliders to be optimized over 48 hours of sampling within large domain

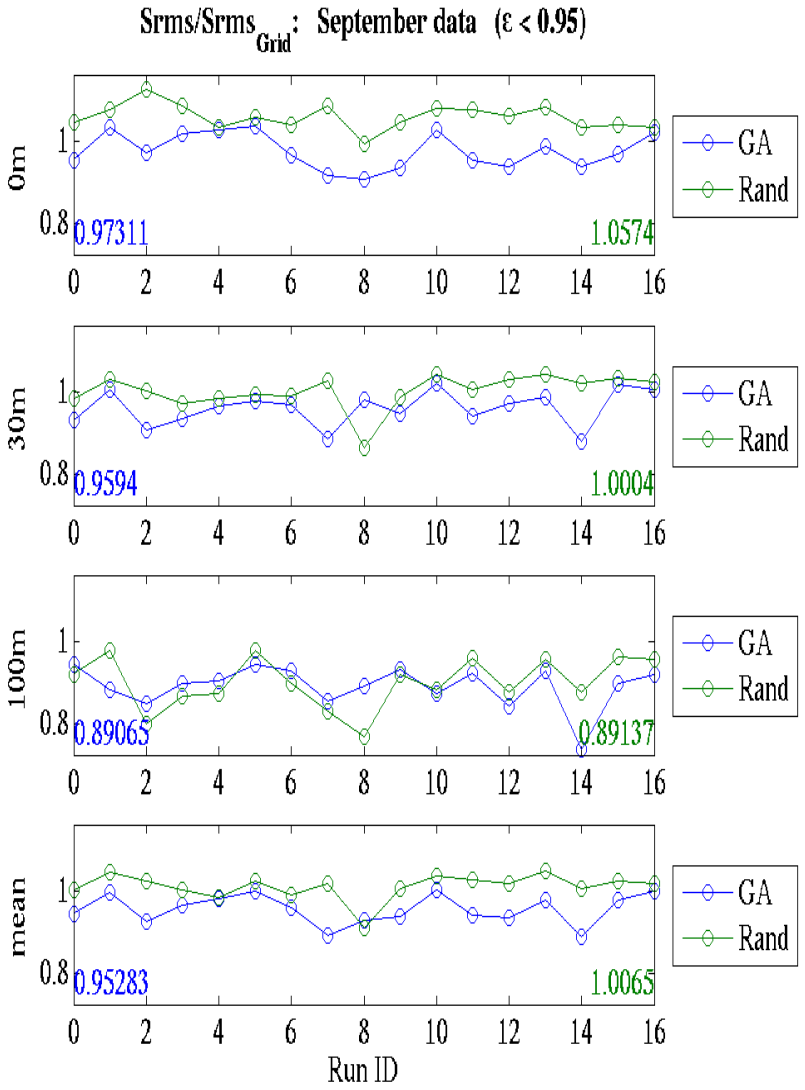
Three Types of Sampling Paths

- *Grid* (red): the "smart" oceanographer
- *Random* (white)
- *Genetic Algorithm* (blue): GA paths computed to minimize chosen cost function

Paths overlaid on T_s surface for August 24-27 (left) and September 4-7 (right)

5-10% Gain over Random



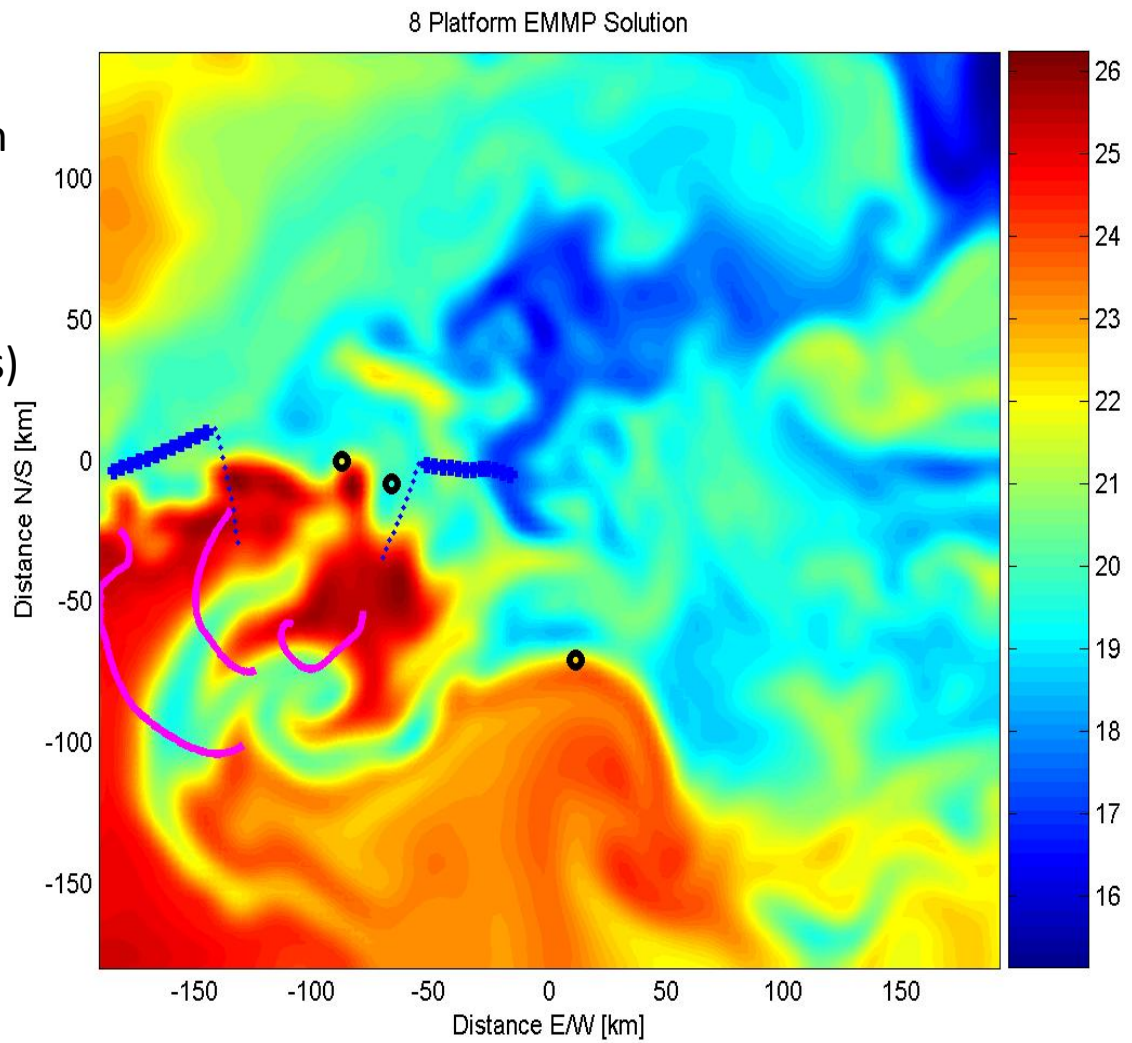


[Heaney, Lermusiaux, Haley and Duda, To be submitted-2010]

Multi-Platform Dynamic

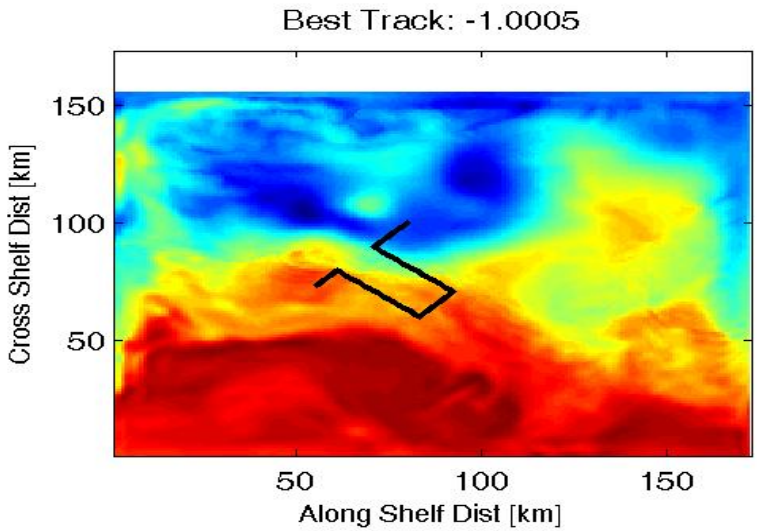
Time Dependent Optimization
With:

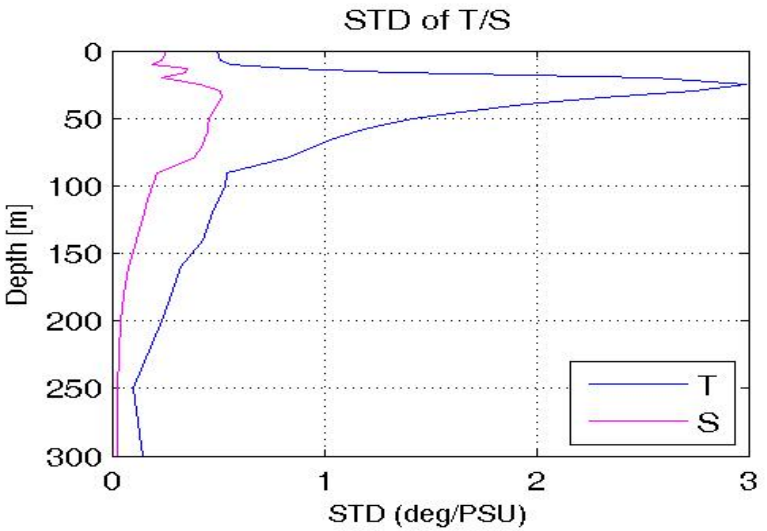
- 3 – moorings (1 week)
- 3 – gliders (1 week)
- 2 – powered AUVs (24 hours)

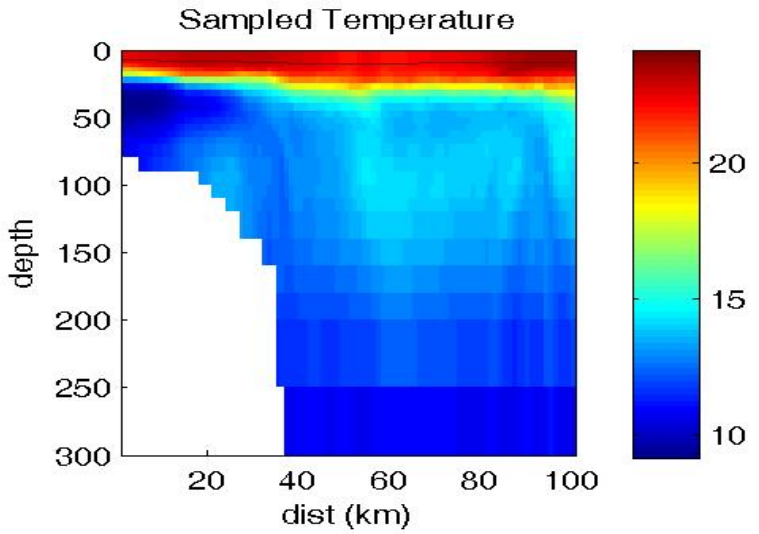


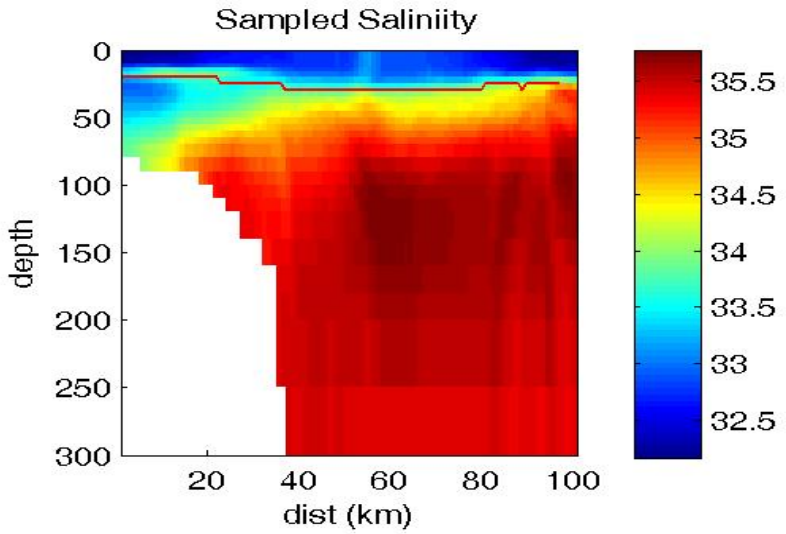
Movie…(hopefully)

ScanFish Survey – SW06









20 Oct 2010

FORECAST SYSTEM AND ADAPTIVE SAMPLING IN SUPPORT OF REP_10

The NRLSSC Team:

Germana Peggion, E. Coelho, C. Rowley, L. Smedstad, K. Heaney, P. Spence, and D. Sitton.

The wind team: M. Phelps, P. Posey
The computer team: B. Maloy, D. Goolsby

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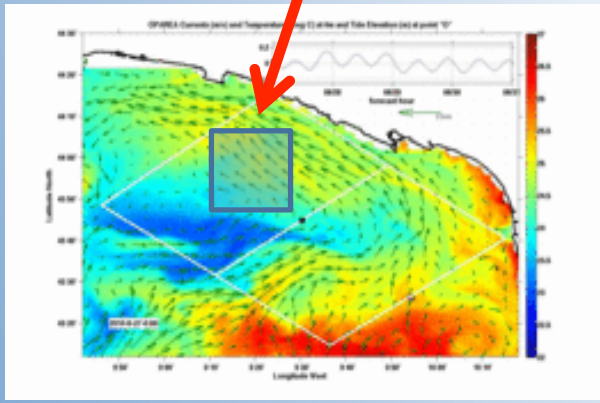
Sampling Strategies

MREA10 Test Case

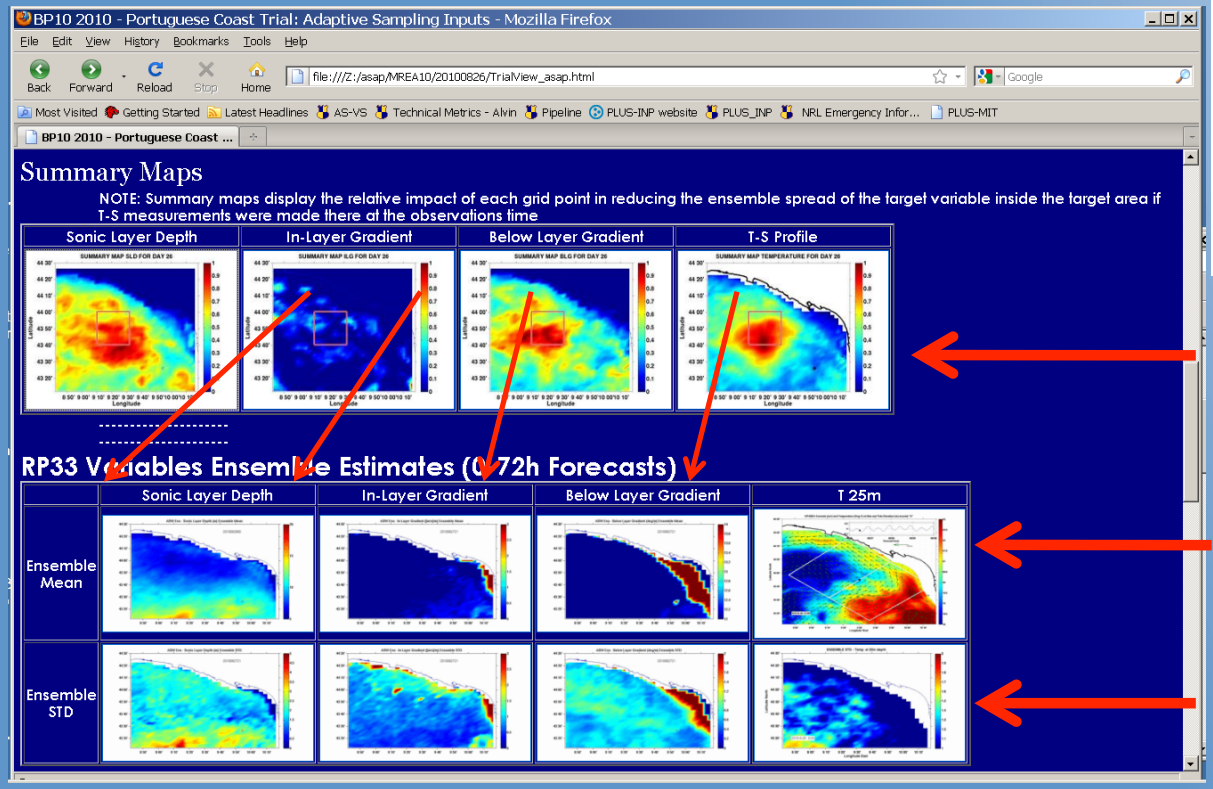
TARGET AREA



TOFU PROCESSING

ENSEMBLE AND COST FUNCTIONS FOR KEY VARIABLES

SLD – ILD – BLG – Temp/Sal Prof



Sensitivity (summary) Maps for target area

Space-Time Variability

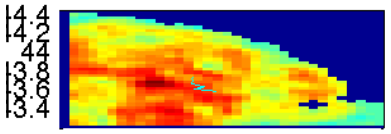
Ensemble Spread (uncertainty)

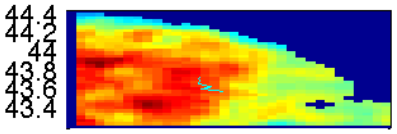
Cost Function Morphologies

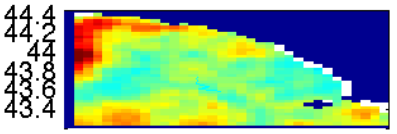
Central Forecast

0m **25m** **100m**

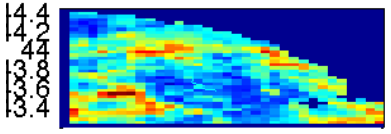
Ens_Spread_T

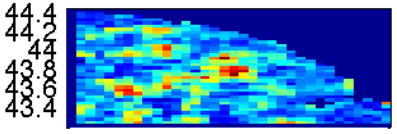


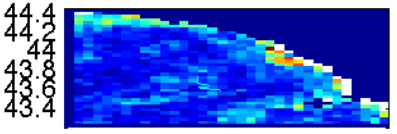




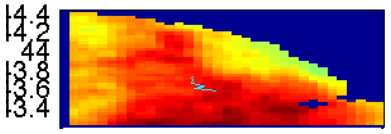
Ens_Mean_T

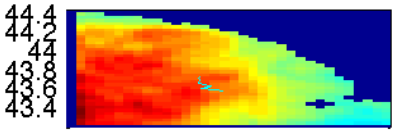


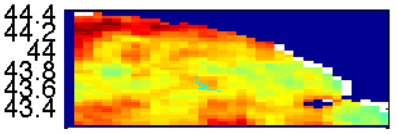




Mean_Spread_T_ over_time

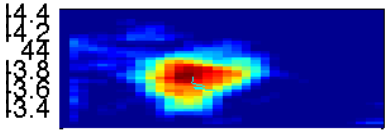


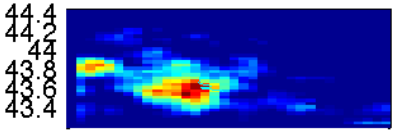


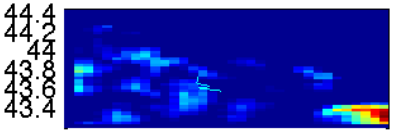


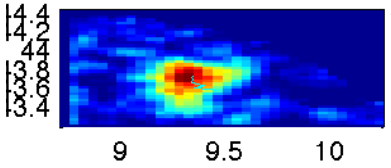
TOFU

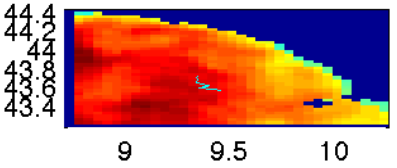
- **CF Temp**
- **CF BLG**
- **CF ILG**
- **CF SLD**
- **Combined**



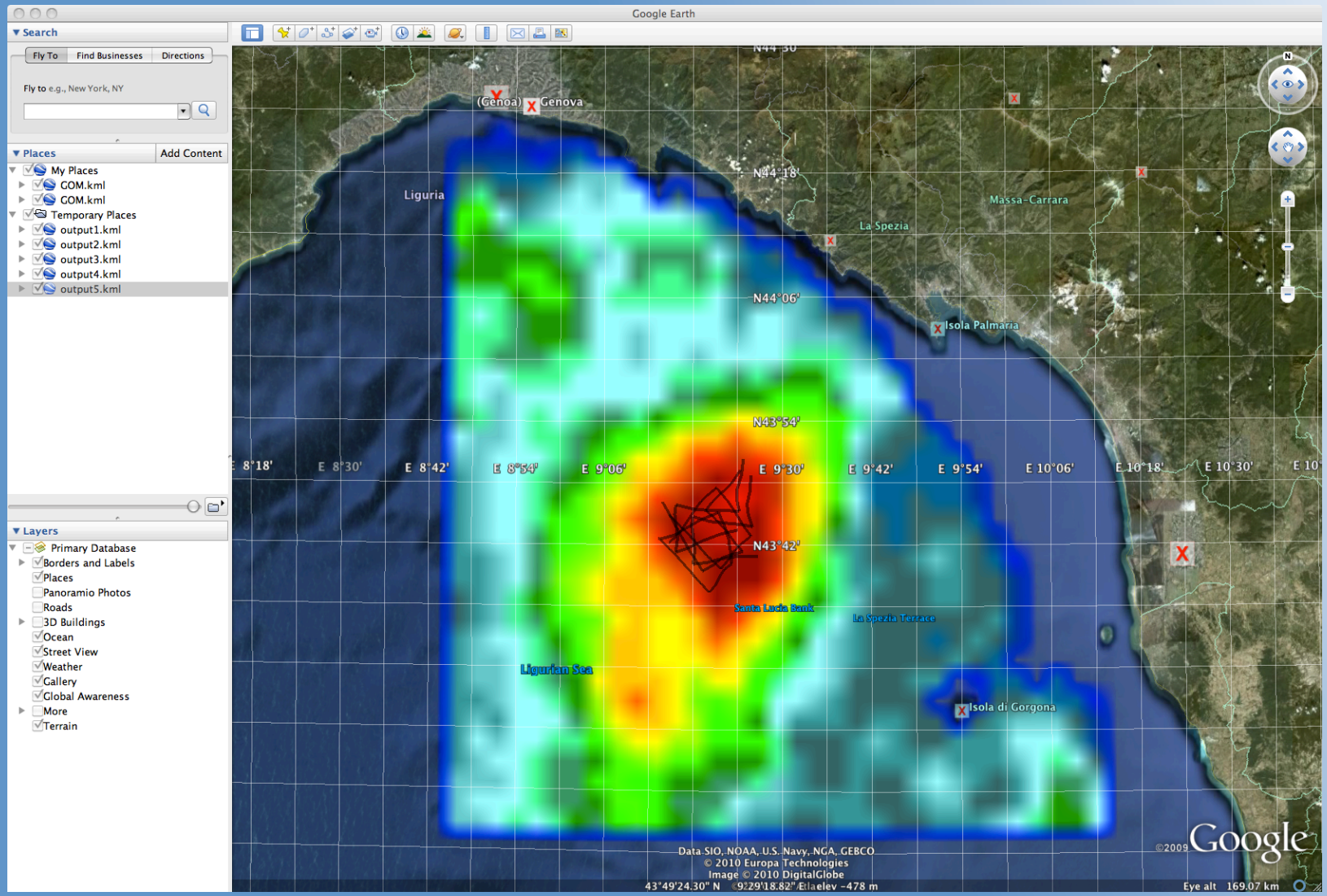




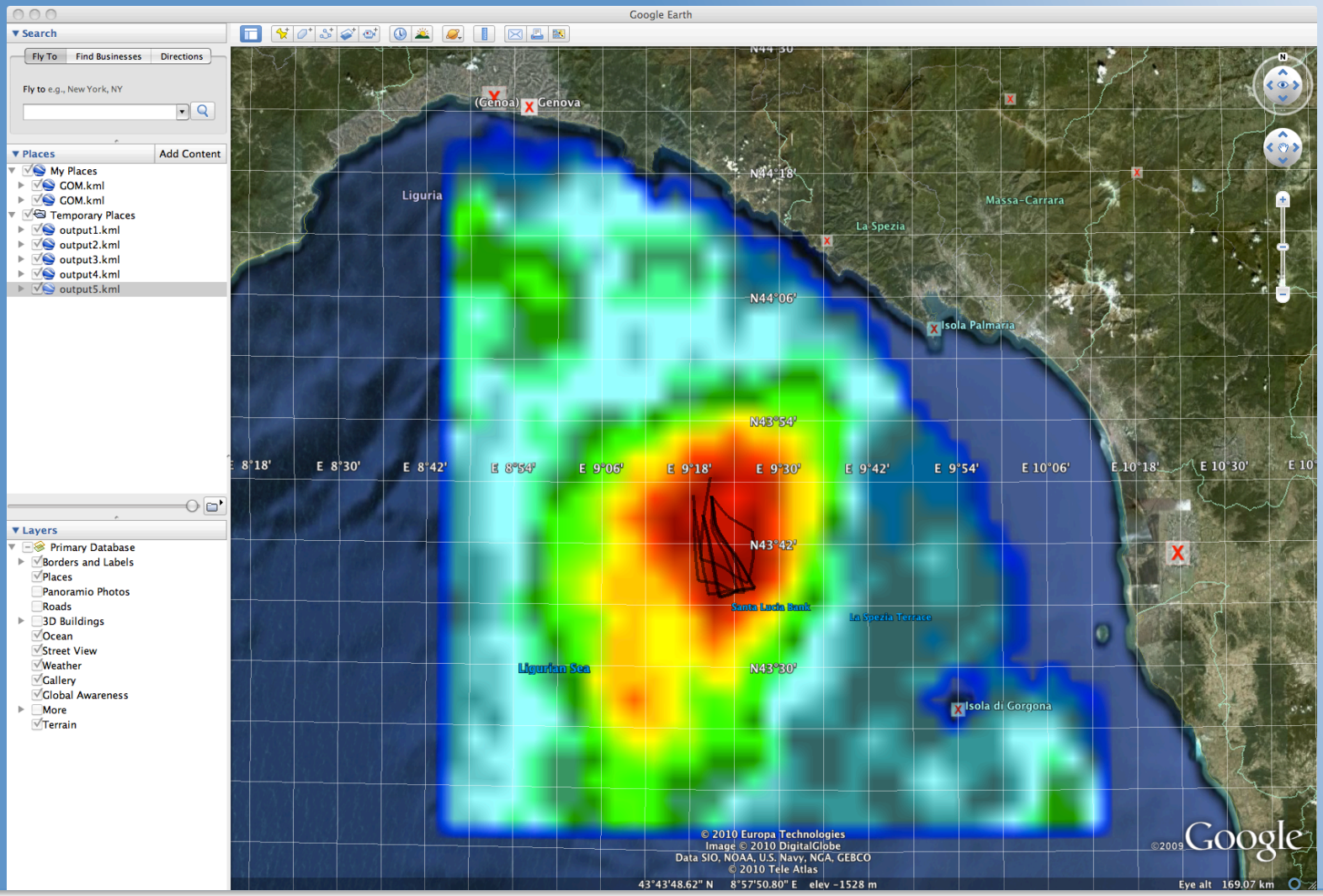




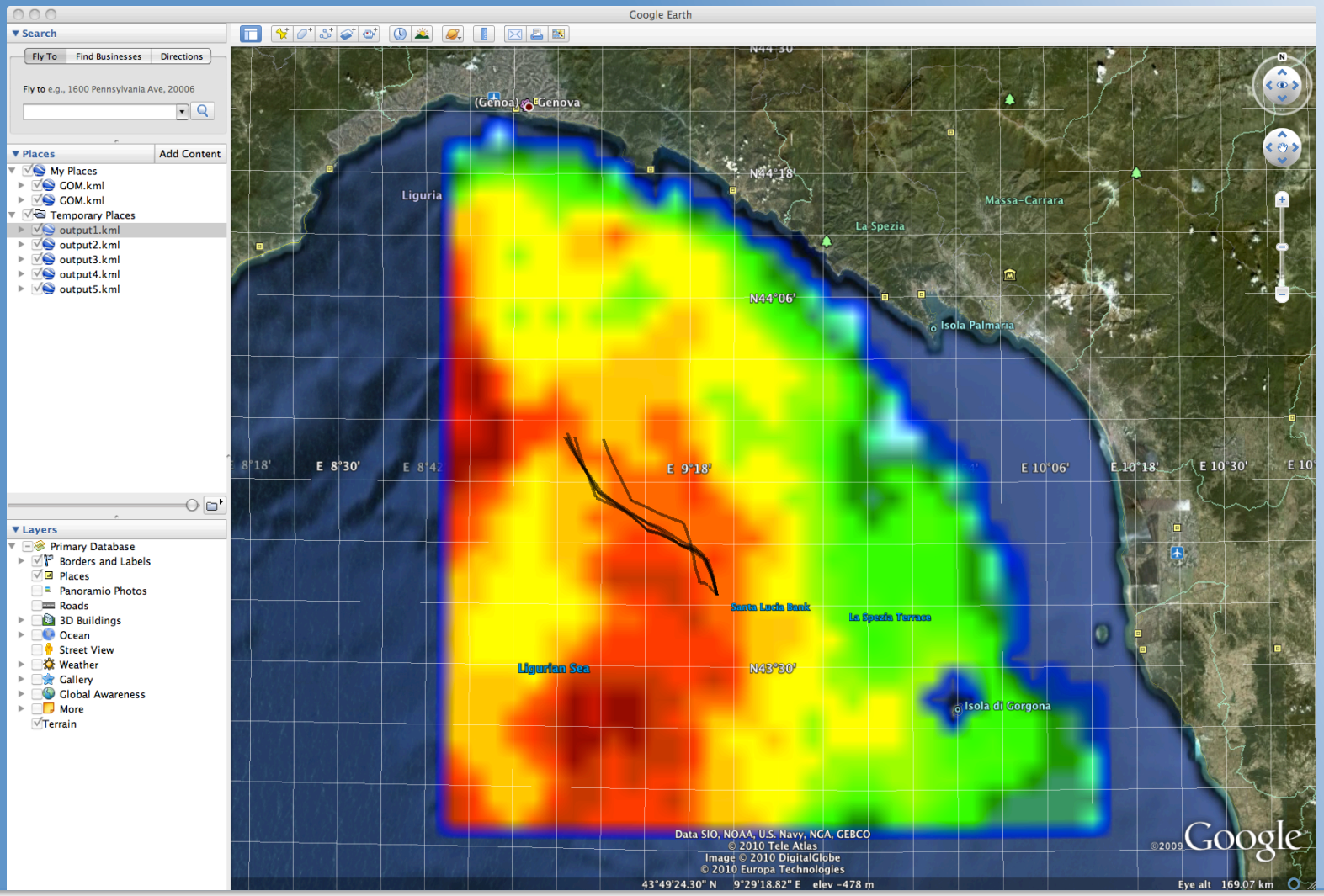
5 Best single glider searches

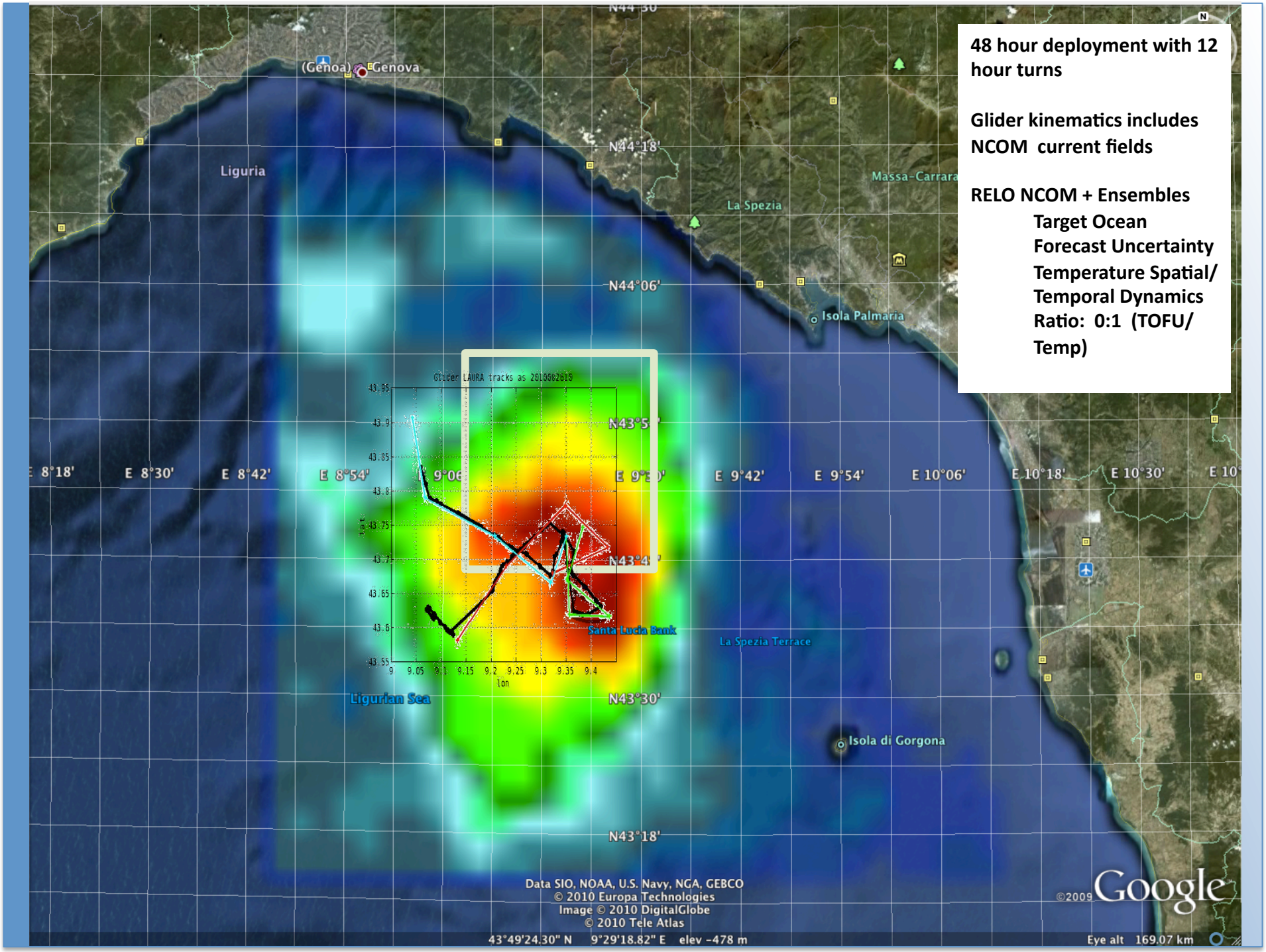


5 Best Solutions – REP 10 Day 1



5 Best Solutions – REP10 Day 6




48 hour deployment with 12 hour turns
Glider kinematics includes NCOM current fields
RELO NCOM + Ensembles
Target Ocean Forecast Uncertainty Temperature Spatial/ Temporal Dynamics Ratio: 0:1 (TOFU/ Temp)
Glider LAURA tracks as 20100826l0
(Genoa)
Genova
Liguria
La Spezia
Massa-Carrara
Isola Palmaria
Santa Lucia Bank
La Spezia Terrace
Ligurian Sea
Isola di Gorgona
N44°18'
N44°06'
N43°30'
N43°18'
E 8°18'
E 8°30'
E 8°42'
E 8°54'
E 9°42'
E 9°54'
E 10°06'
E 10°18'
E 10°30'
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2010 Europa Technologies
Image © 2010 DigitalGlobe
© 2010 Tele Atlas
43°49'24.30" N 9°29'18.82" E elev -478 m
©2009 Google
Eye alt 169.07 km

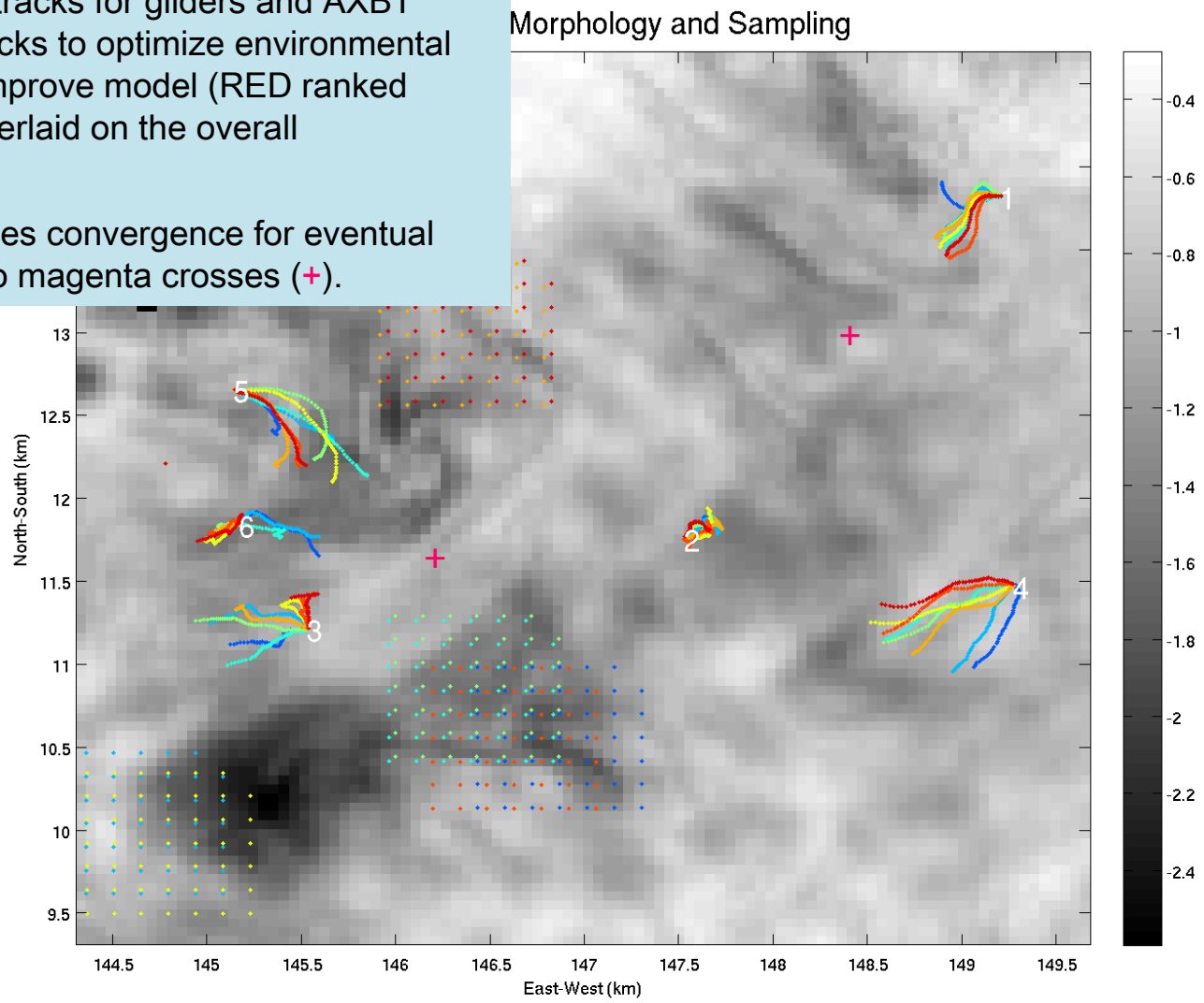
The Main Challenges

- “I could have done that…”
- Communicating results to the operator
  - Did the GA converge? (convergence)
  - Are you sure? (uniqueness/sensitivity)
  - What physics is driving the selection of the path plans? (why?)

2007 Operational Display for Preliminary Op-Test

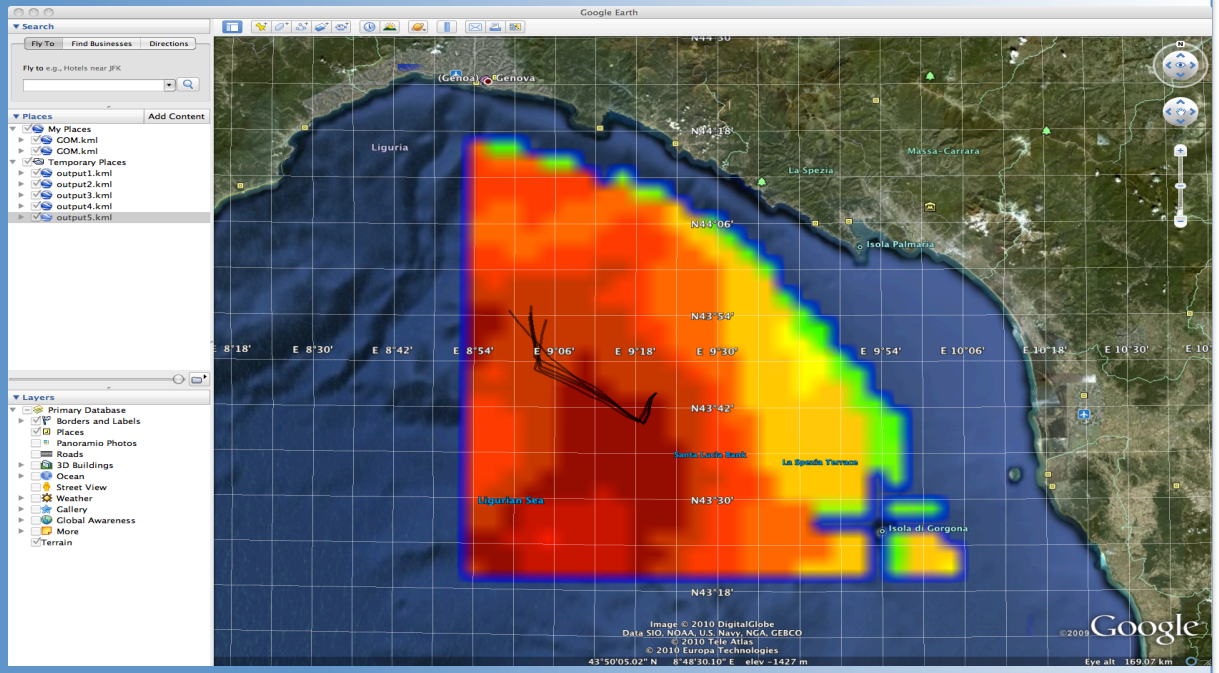
5 possible 48-hour tracks for gliders and AXBT sampling array. Tracks to optimize environmental observations and improve model (RED ranked best). These are overlaid on the overall morphology.

Cost function includes convergence for eventual pick up near the two magenta crosses (+).

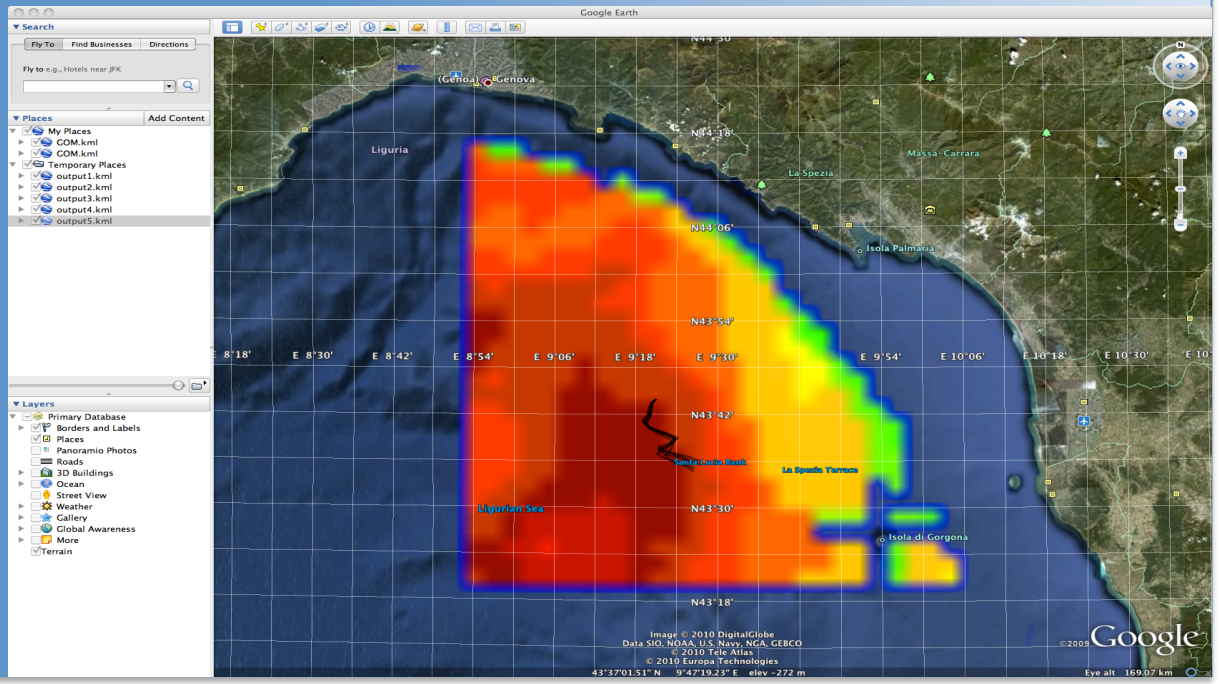


Sensitivity to Glider Velocity

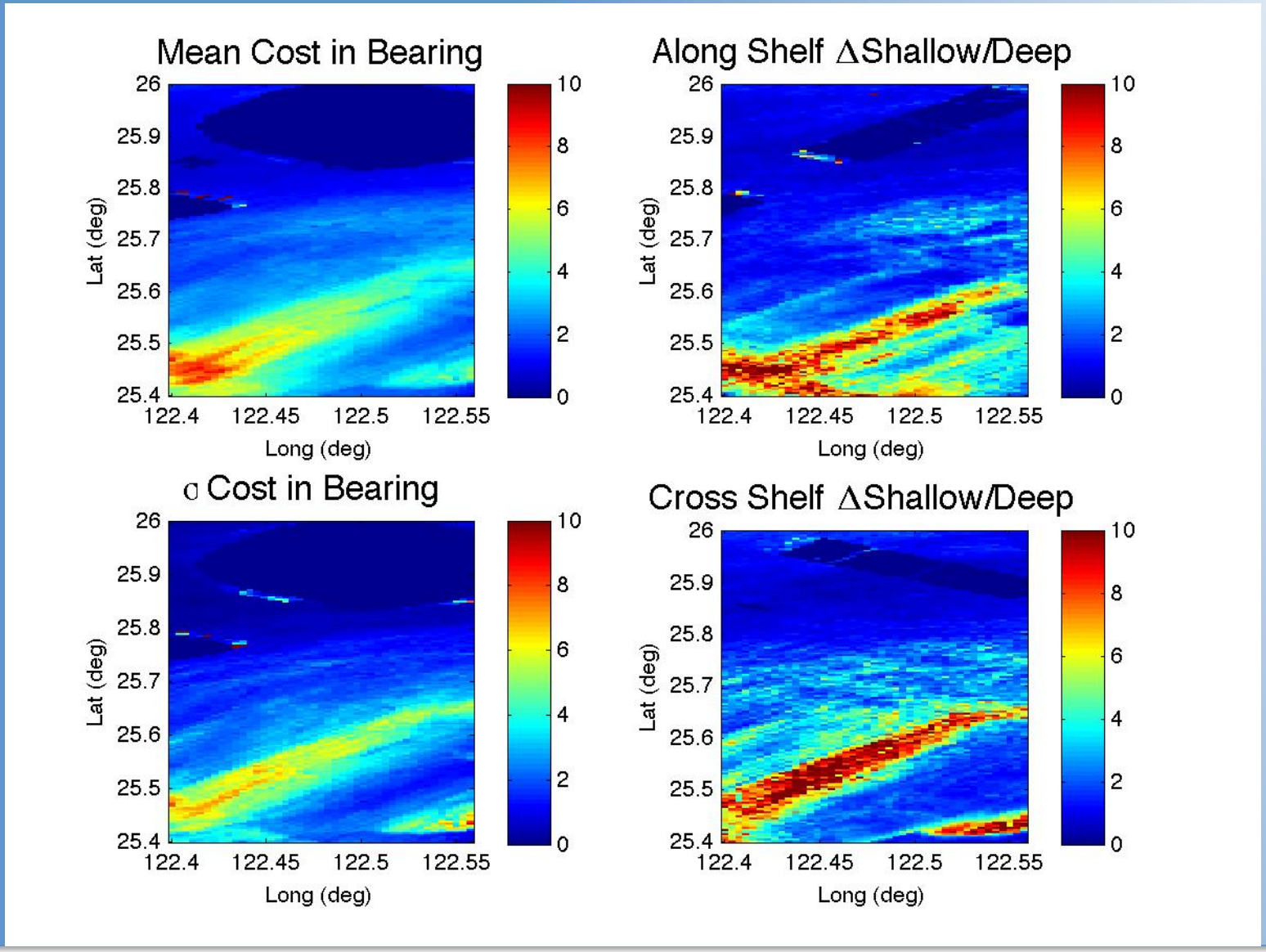
5 knot glider



4 knot glider



Acoustic Adaptive Sampling



Conclusions

EMPath (Cost function, platform model, GA) provides a flexible, robust approach to non-linear automatic optimization of multiple platforms.

The hard part:

- Defining what the user means by “optimal”
- Integrating downstream “costs” into the search plan
- Communicating effectively with end-users
- Demonstrating quantitative value added
- Fielding and directing more than 4 gliders for an extended period of time in the open ocean.

The way forward:

- Incorporation of measurements on future cost function
- Sensor planning within Lagrangian framework (LCS)