Ocean Forecasting

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Application of the Generic Harvard Ocean Prediction System (HOPS)
to Real-Time Forecasting with Adaptive Sampling
off the Central California Coast During AOSN-II

Sippican Philosophical Society
February 9, 2004
http://www.deas.harvard.edu/~robinson

Interdisciplinary Ocean Science Today

- **Research underway on coupled physical, biological, chemical, sedimentological, acoustical, optical processes**

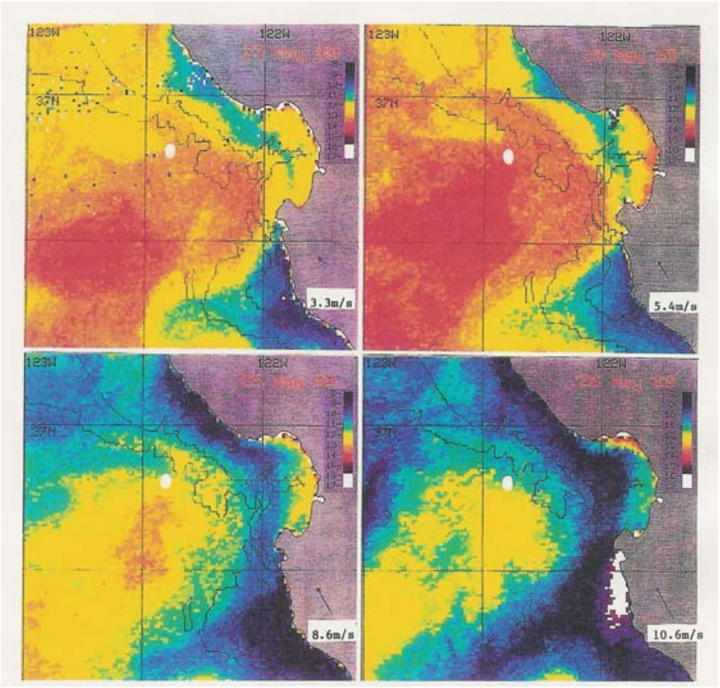
- **Ocean prediction for science and operational applications has now been initiated on basin and regional scales**

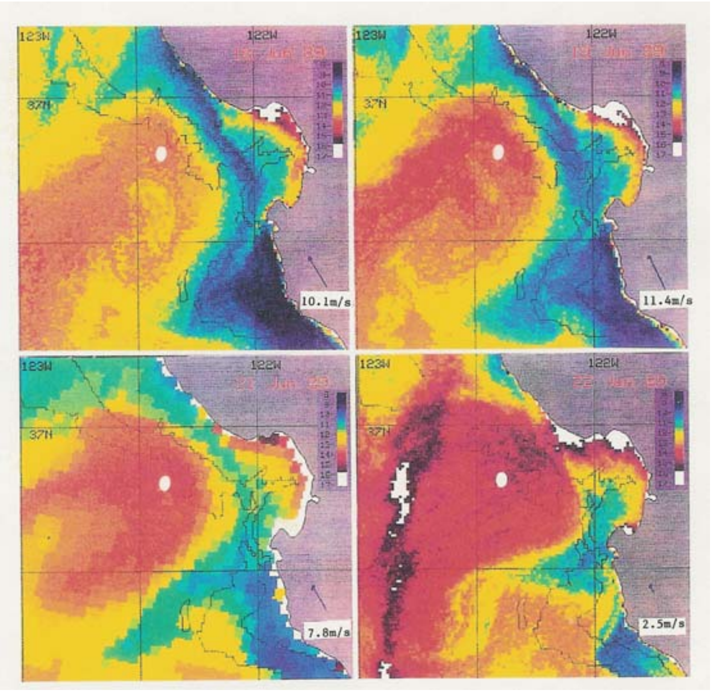
- **Interdisciplinary processes are now known to occur on multiple interactive scales in space and time with bi-directional feedbacks**

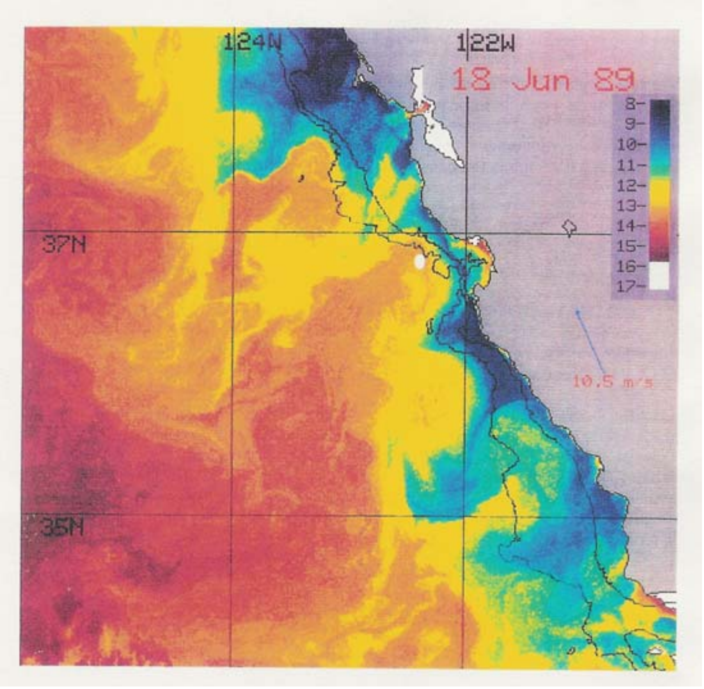
Interactive Scales

- **Oceanic Dynamical Processes Interactive over Multiple Scales in Space and Time Importantly Influence Both Climate and Life in the Sea.**
- **Ocean processes are intermittent and episodic in space and time**
- **Internal Ocean Weather Forecasting is Accelerating Progress in Interdisciplinary Ocean Science and Enabling Powerful New Methods for Operations and Management**

Conceptual model: Rosenfeld *et al*., 1994. Bifurcated flow from an upwelling center







Top left – **Upwelling State** – 23-26 May 1989 – upwelled water from points moves equatorward and seaward – Point Año Nuevo water crosses entrance to Monterey Bay

Top right – **Relaxation State** – 18 -22 June 1989 – California Current anti-cyclonic meander moves coastward

Bottom right – **Larger regional context** – 18 June 1989 – California Current System

System Concept

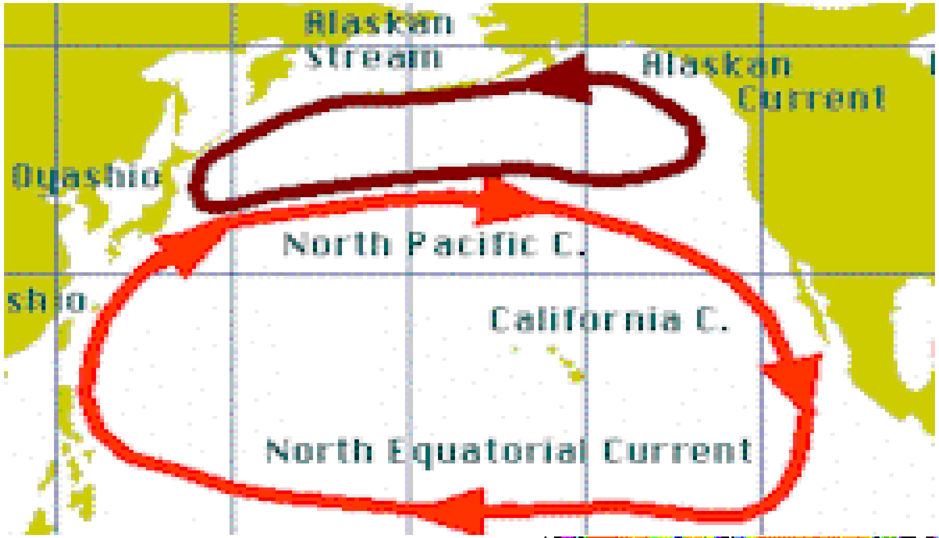
- **The concept of Ocean Observing and Prediction Systems for field and parameter estimations has recently crystallized with three major components**
  - **An observational network: a suite of platforms and sensors for specific tasks**
  - **A suite of interdisciplinary dynamical models**
  - **Data assimilation schemes**

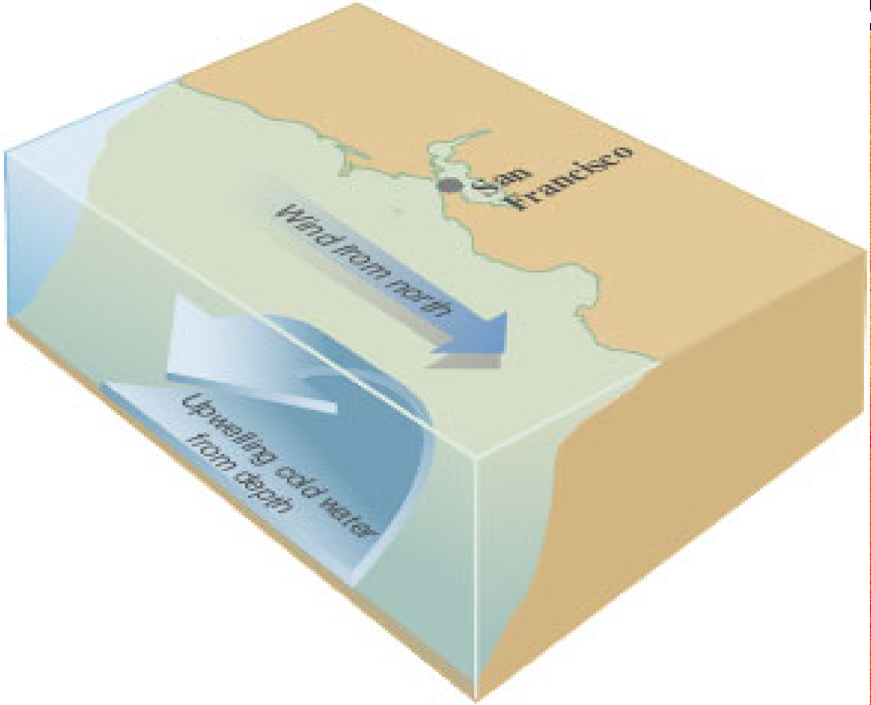
- **Systems are modular, based on distributed information providing shareable, scalable, flexible and efficient workflow and management**

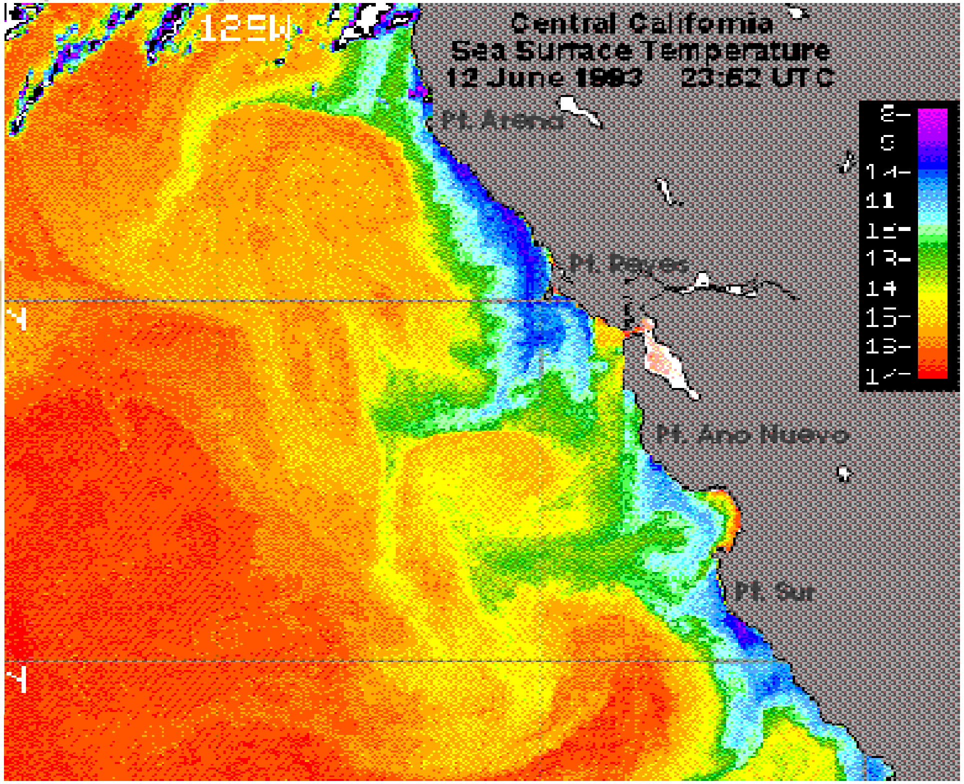
Roles of Models in the System

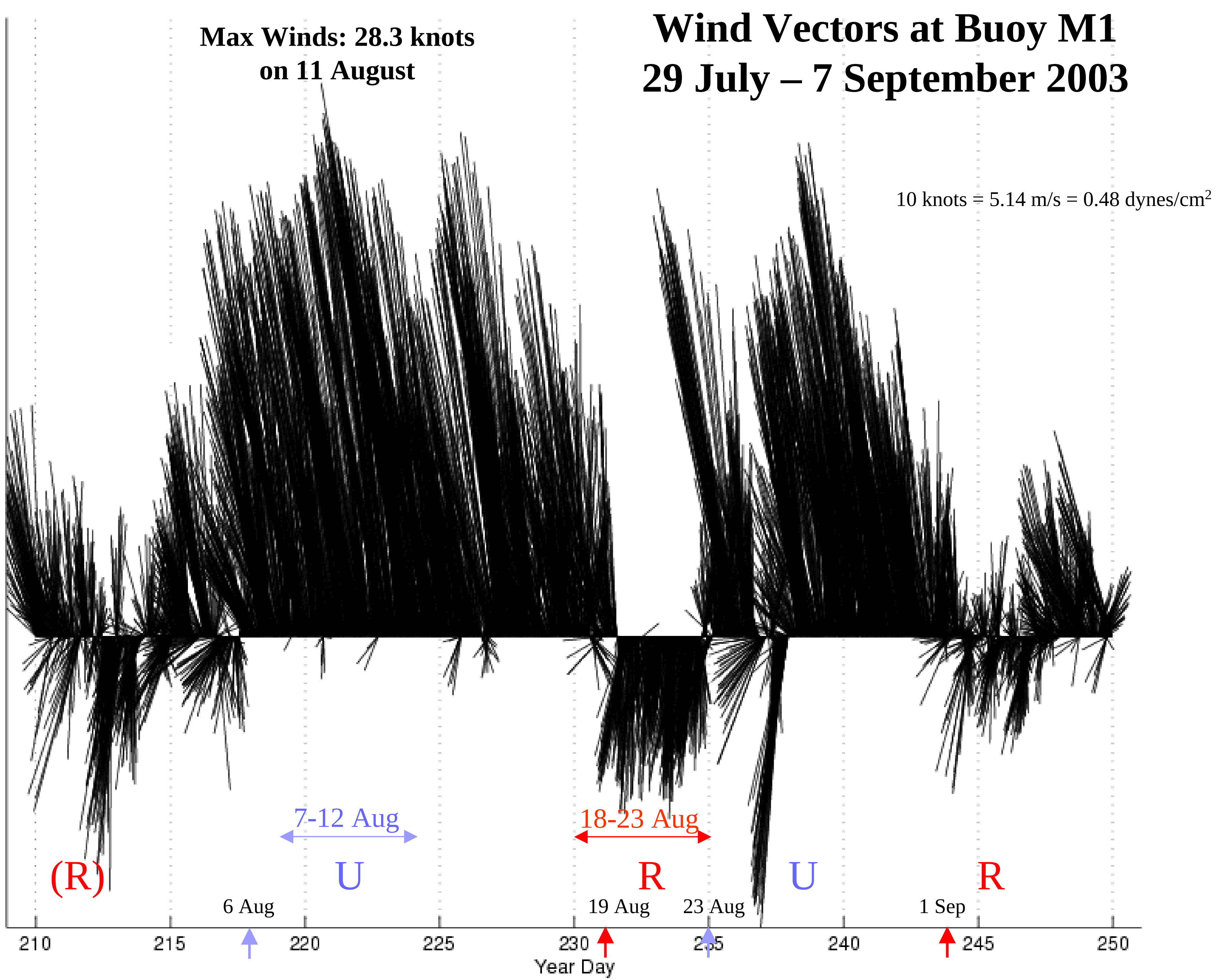
- **Numerical ocean circulation models are an essential component of integrated ocean observing and predictive systems**
- **Represent fundamental dynamics of regional processes of interest and provide basis for assimilation of observational data from system's suite of platforms and sensors**
- **Data fusion via assimilation dynamically adjusts and interpolates observations in space and time within error bounds of data and models**
- **Ocean forecasts made by data assimilation in real-time followed by dynamical runs into the future, analogous to numerical weather prediction in the atmosphere.**
- **Regional ocean forecasts driven by: regional atmospheric forcings; larger scale ocean flow-through; and internal dynamical processes, i.e. the internal weather of the sea.**
- **Coupling bio-geo-chemical/ecosystem model to physical model allows coupled forecasting – biological models very complex and interdisciplinary forecasting just now being initiated.**

California Coastal Oceanography: Eastern Boundary (or California) Current





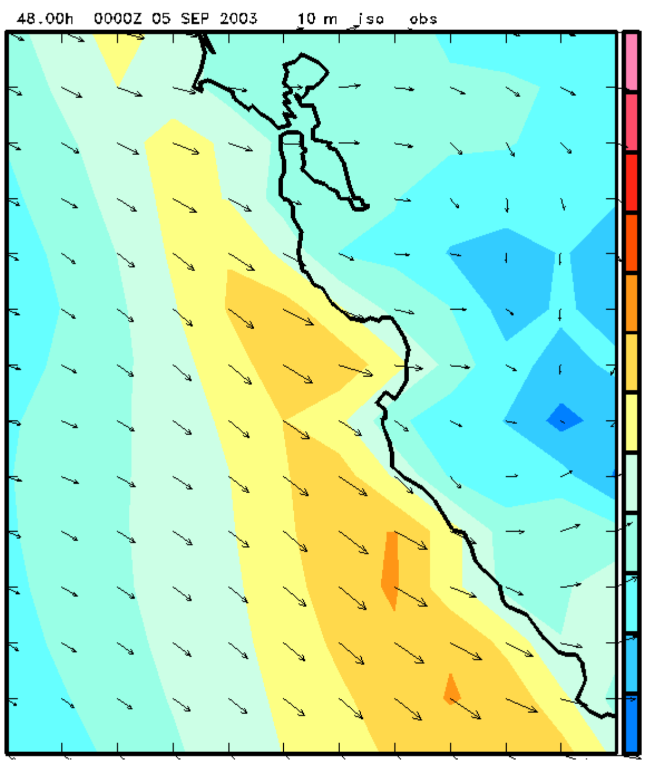




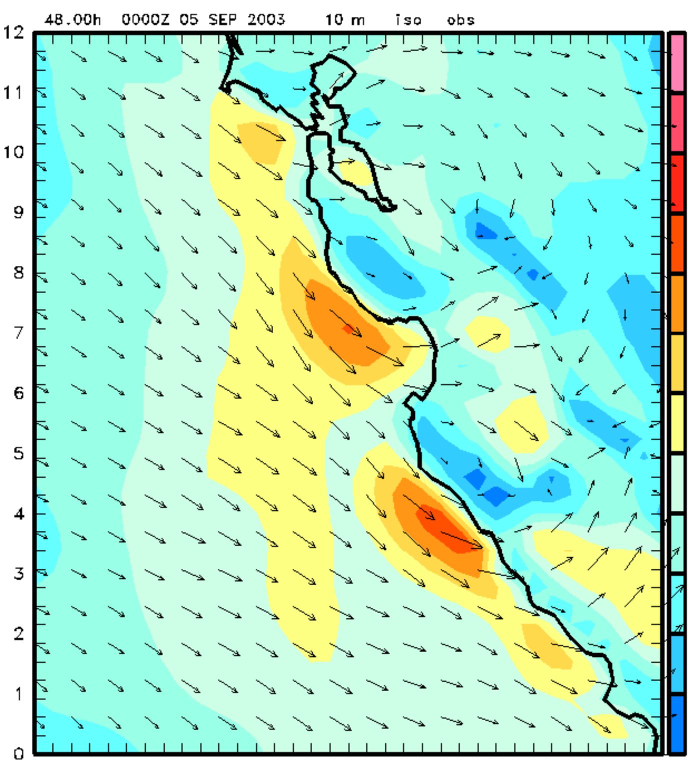
Wind Vectors at Buoy M1
29 July – 7 September 2003
Max Winds: 28.3 knots
on 11 August
10 knots = 5.14 m/s = 0.48 dynes/cm^2
7-12 Aug
18-23 Aug
(R)
U
R
U
R
6 Aug
19 Aug
23 Aug
1 Sep
210
215
220
225
230
235
240
245
250
Year Day

Horizontal Resolution Sensitivity

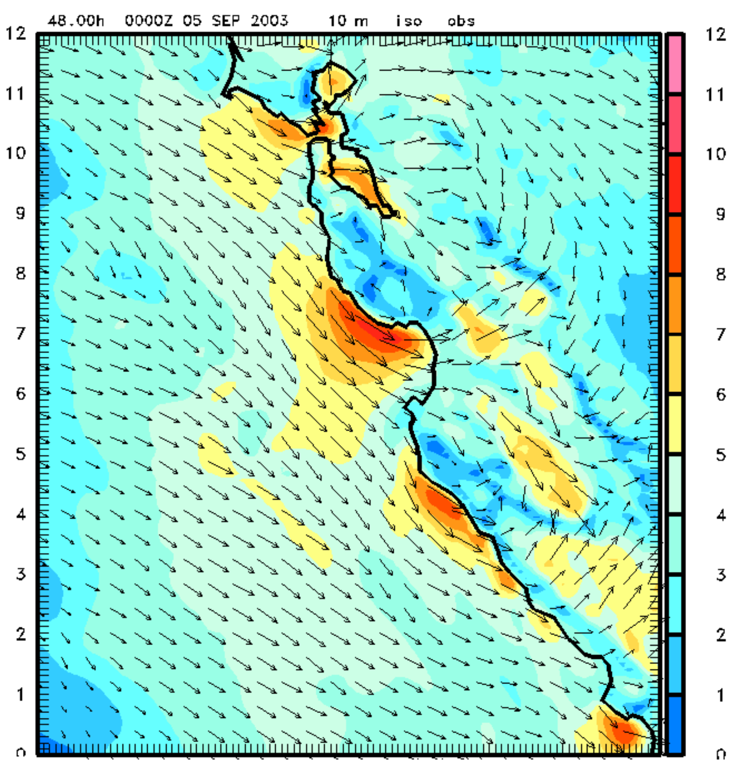
27 km



9 km

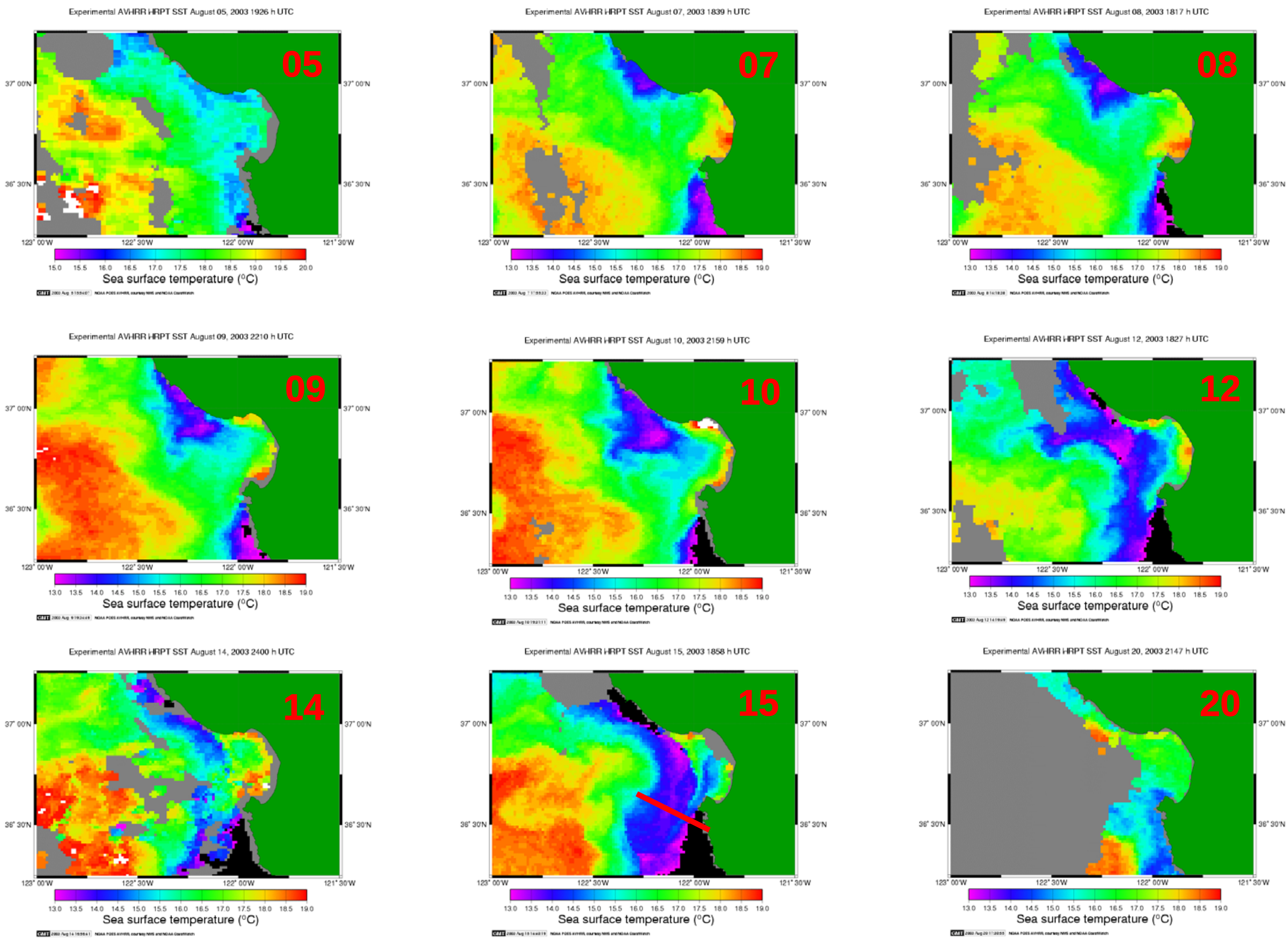


3 km

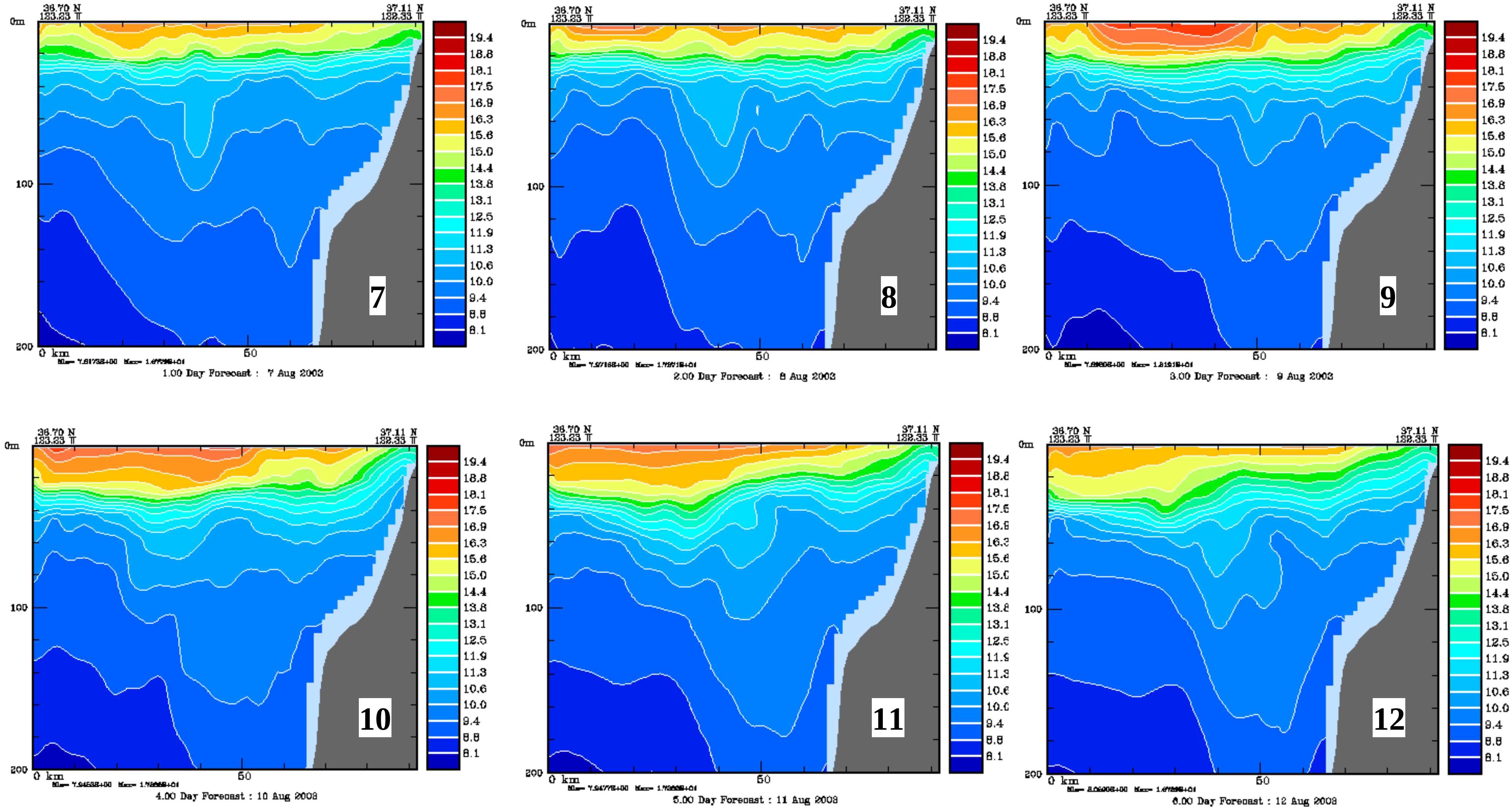


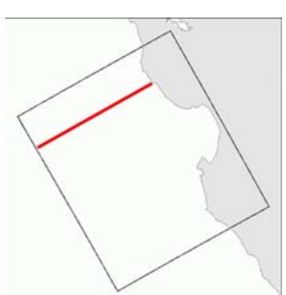
Representation of Coastal Jets & Coastal Shear Zone Improved

Satellite SST (Aug 5-21)

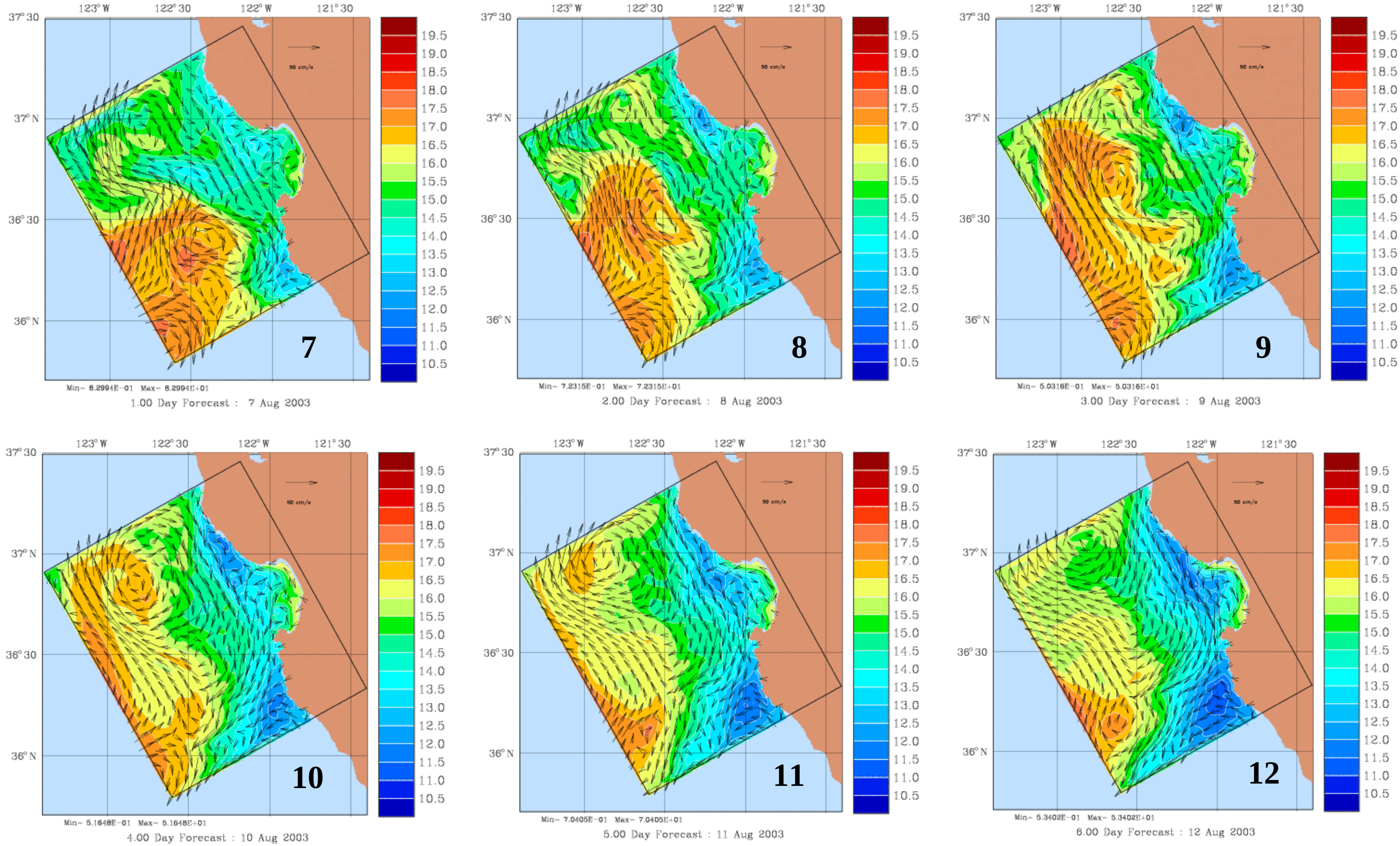


7-12 August – Onset and Sustained Upwelling Conditions



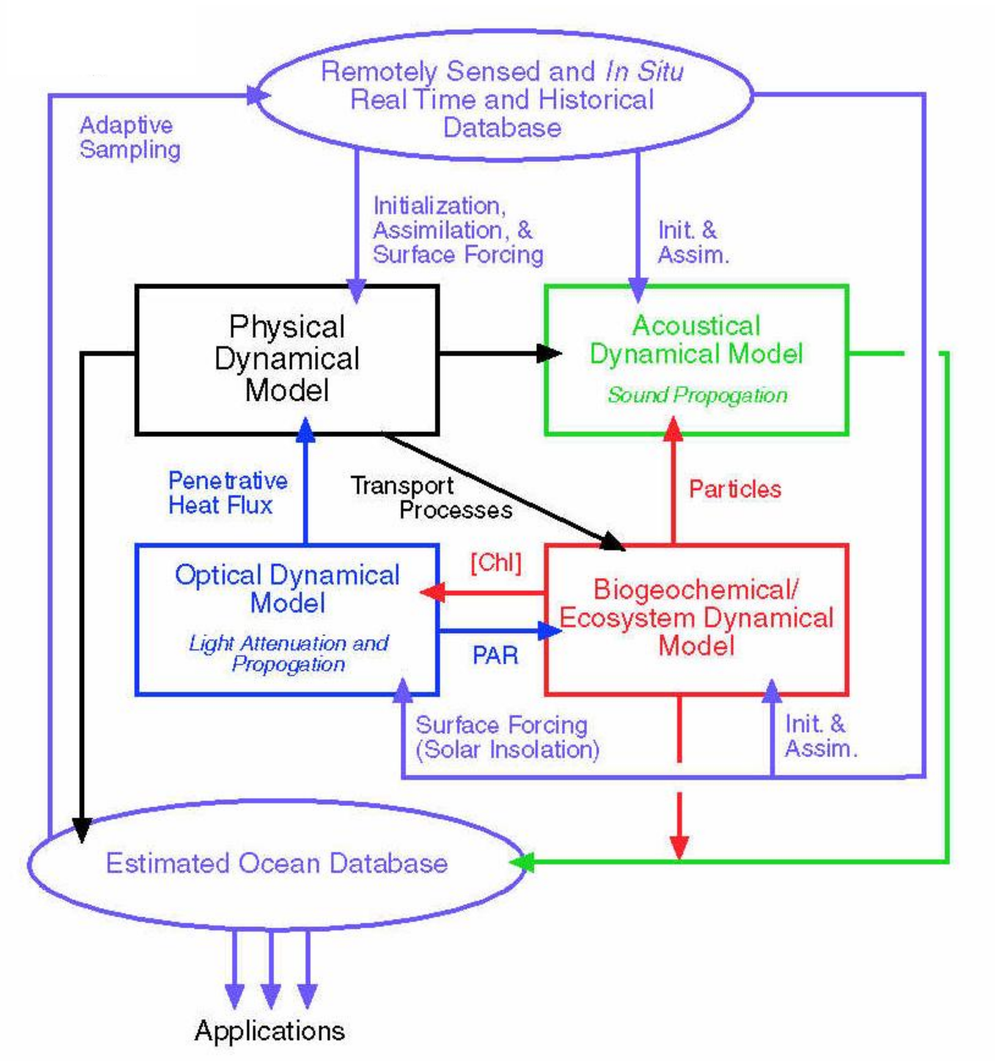


7-12 August – Onset and Sustained Upwelling Conditions



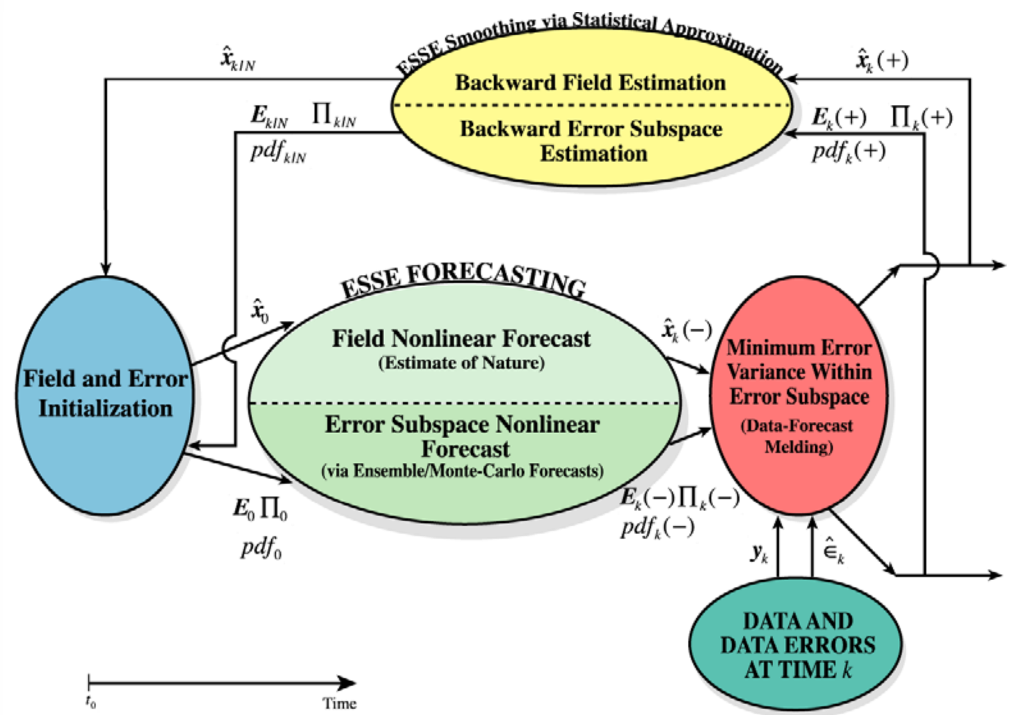
Harvard Ocean Prediction System - HOPS

Multivariate Coupled Physical-Acoustical-Biological System



Data Assimilation: combines model and data for best ocean estimate: optimal interpolation (OI) or

Error Subspace Statistical Estimation (ESSE)



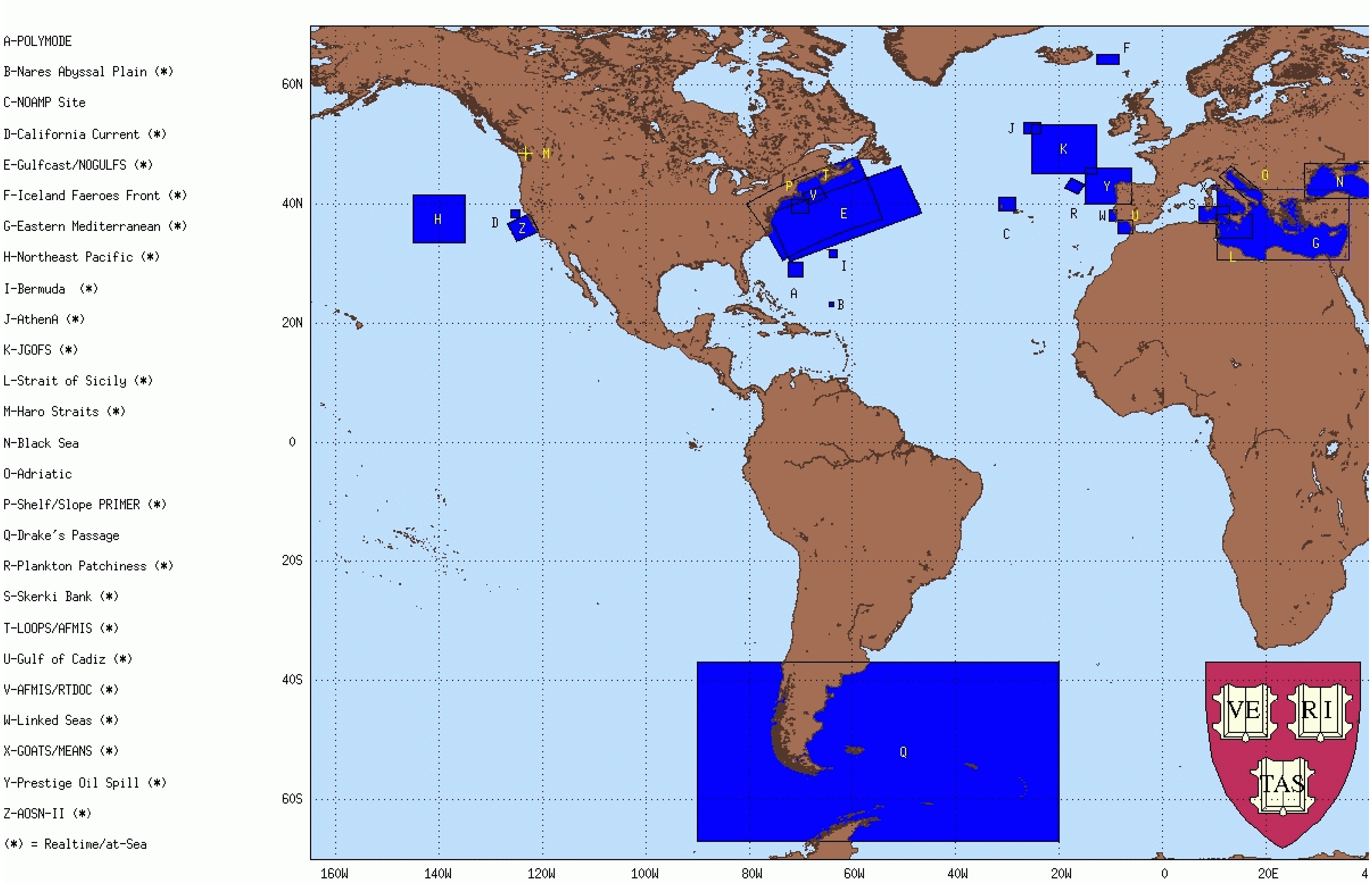
HOPS – Regional Forecast Methodology

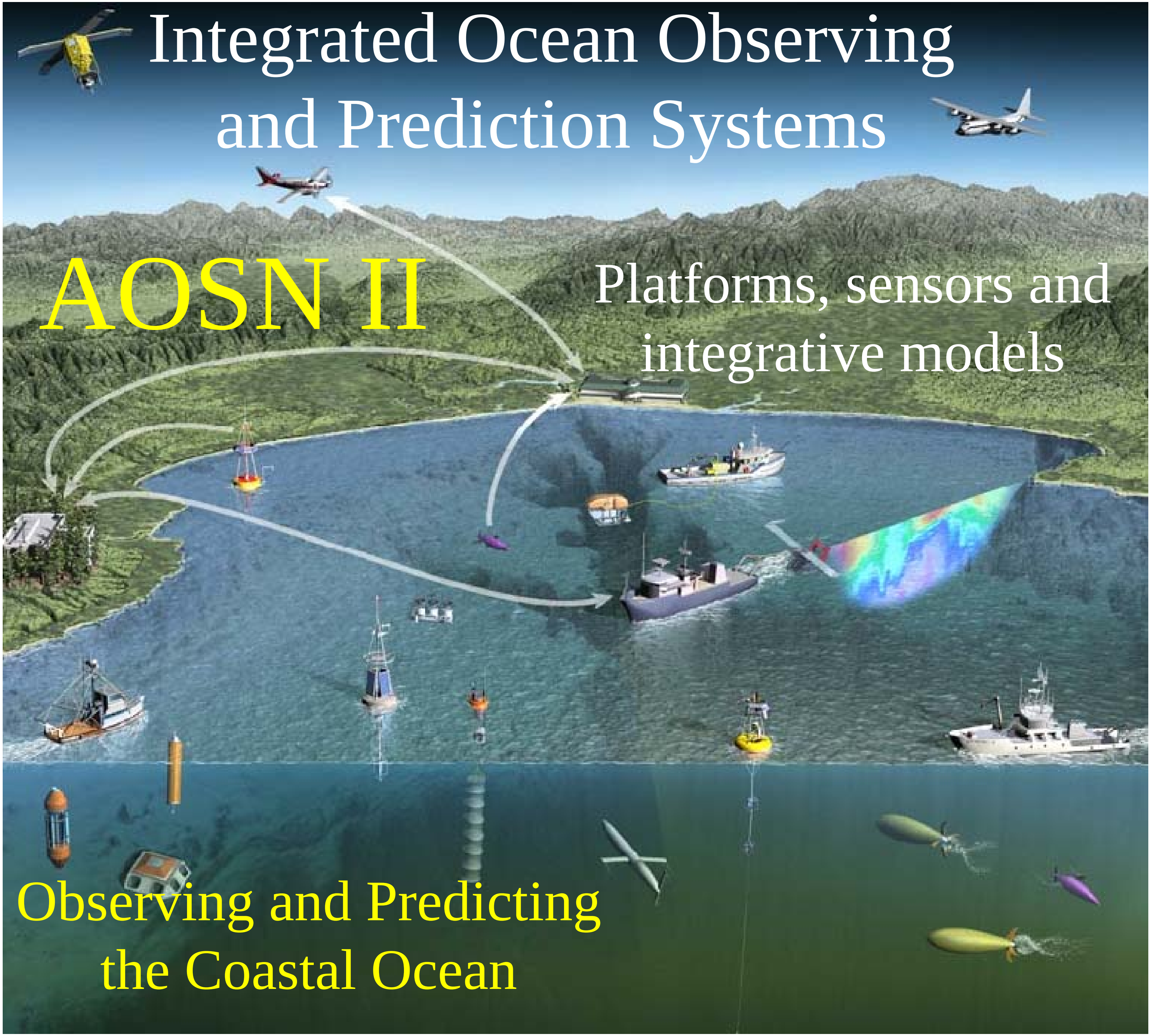
- Region of operational forecast interest is generally two-way nested with larger influential regional domain(s)
- Largest domain (which can be stand-alone operational interest domain) has open boundary conditions
- Initialization via a combination of: historical synoptic data; feature models (synoptic climatology); and contemporary synoptic mesoscale data
- Contemporary data gradually replaces prior options and is assimilated throughout the course of the operation
- Open boundary condition options include: specification of fields, fluxes; and radiation conditions in various forms and combinations
- Assimilates data from satellites, aircraft, ships, drifters, autonomous underwater vehicles (AUVs), gliders, and moorings

R/V Alliance (NATO) in Massachusetts Bay (June 2001)

Dr. Pat Haley
and
Wayne Leslie

- **HOPS – a generic, relocatable, regional forecast system**
- **Coastal shelf, slope and deep sea regions**
- **Real-time forecasts of internal ocean weather, atmospheric forcing response, and their non-linear interactions**




Integrated Ocean Observing
and Prediction Systems
AOSN II
Platforms, sensors and
integrative models
Observing and Predicting
the Coastal Ocean

AOSN II Objectives:

To design and build an adaptive coupled observation/modeling system. The system should be sustainable in its operation and capable of being readily relocated, in its final form.

- Use autonomous *in situ* platforms to achieve economic operation.
- Use oceanographic models to assimilate data from a variety of platforms and sensors into synoptic views of oceanographic fields and fluxes.
- Adapt deployment of mobile assets to improve performance.
- Test performance of the system in a quantitative fashion.
- Post results in real-time.
- Use the results of those tests to guide research and development to improve system performance.

Monterey Bay 2003 – Participants 1

Modeling

- **Harvard – Numerical Ocean Modeling / Mesoscale Circulation (Robinson – also Project Deputy)**
- **JPL – Numerical Ocean Modeling / Atmospheric forcing (Chao)**
- **NRL-Stennis – Numerical Ocean Modeling / Small Scale Dispersion (Shulman)**
- **NRL-MRY – Atmospheric Forcing (COAMPS) / Targeted Observations (Doyle/Bishop)**

Ecosystem Dynamics

- **MBARI – Bioluminescence program (Haddock)**
- **CalPoly – Bioluminescence program (Moline)**
- **UCSB – Bioluminescence sensors (Case)**

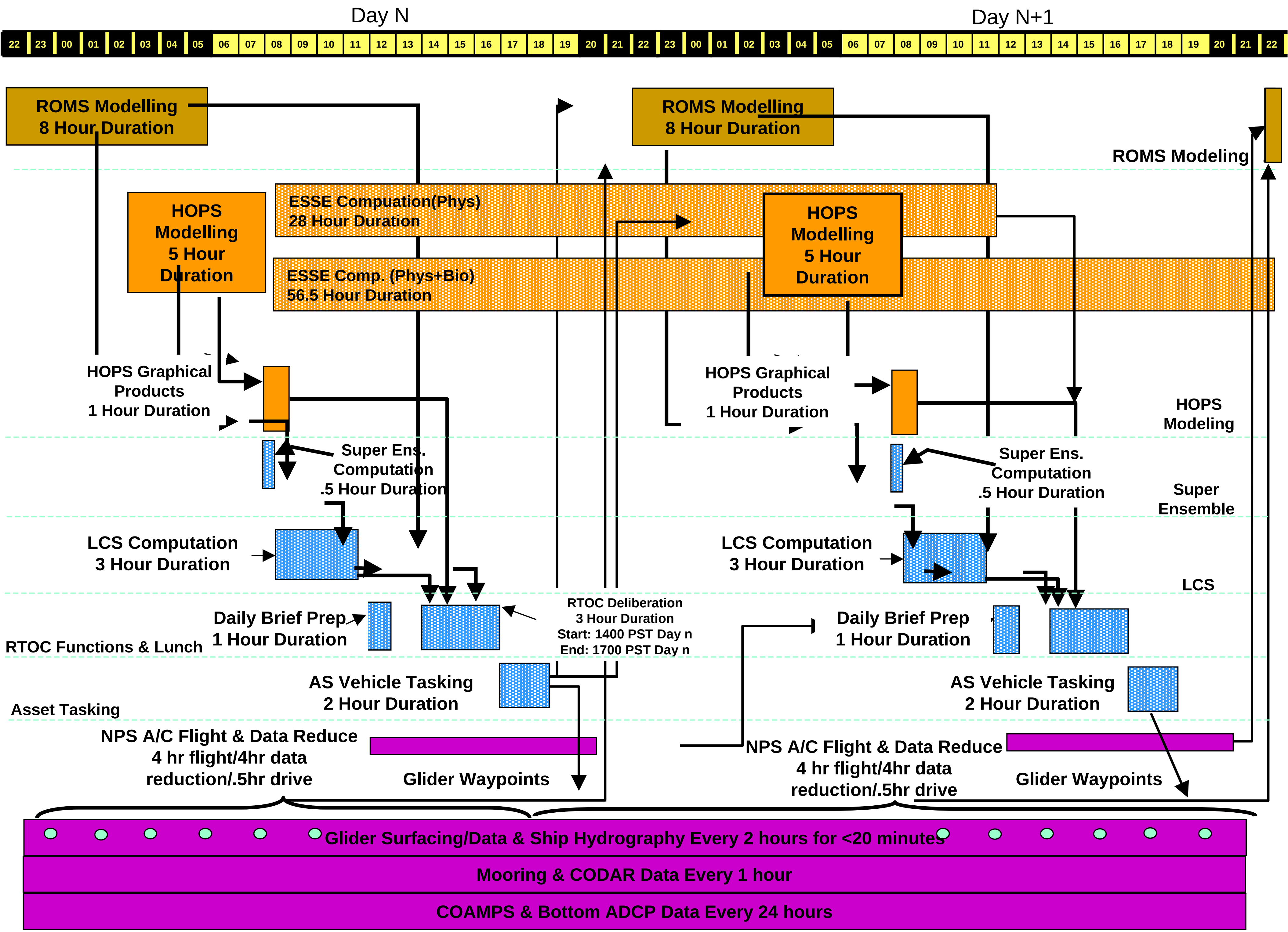
Monterey Bay 2003 – Participants 2

Observations

- **MBARI – Project coordination, definition, infrastructure, AUV and mooring observations, hosting (Bellingham, Chandler, Chavez, Johnson, Ryan)**
- **SIO – Deep gliders (Davis)**
- **UCSC – Ship hydrographic survey (McMannus)**
- **WHOI – Physical Observations / Glider Network, Floats, Lagrangian Drifters (Fratantoni)**
- **NPS – Surface Currents (CODAR) / Sea Surface Fields (Aircraft) / AXBT (Paduan, Ramp)**

Adaptive Sampling/Model-Derived Products

- **Princeton – Glider Dynamics, Control, Adaptive Sampling (Leonard, Rowley)**
- **Cal Tech – Dynamical Systems Modeling (Coulliette, Marsden)**


Day N
Day N+1
22 23 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22
ROMS Modelling
8 Hour Duration
ROMS Modelling
8 Hour Duration
ROMS Modeling
HOPS
Modelling
5 Hour
Duration
ESSE Compuation(Phys)
28 Hour Duration
ESSE Comp. (Phys+Bio)
56.5 Hour Duration
HOPS
Modelling
5 Hour
Duration
HOPS Graphical
Products
1 Hour Duration
HOPS Graphical
Products
1 Hour Duration
HOPS
Modeling
Super Ens.
Computation
.5 Hour Duration
Super Ens.
Computation
.5 Hour Duration
Super
Ensemble
LCS Computation
3 Hour Duration
LCS Computation
3 Hour Duration
LCS
Daily Brief Prep
1 Hour Duration
RTOC Deliberation
3 Hour Duration
Start: 1400 PST Day n
End: 1700 PST Day n
Daily Brief Prep
1 Hour Duration
RTOC Functions & Lunch
AS Vehicle Tasking
2 Hour Duration
AS Vehicle Tasking
2 Hour Duration
Asset Tasking
NPS A/C Flight & Data Reduce
4 hr flight/4hr data
reduction/.5hr drive
Glider Waypoints
NPS A/C Flight & Data Reduce
4 hr flight/4hr data
reduction/.5hr drive
Glider Waypoints
Glider Surfacing/Data & Ship Hydrography Every 2 hours for <20 minutes
Mooring & CODAR Data Every 1 hour
COAMPS & Bottom ADCP Data Every 24 hours

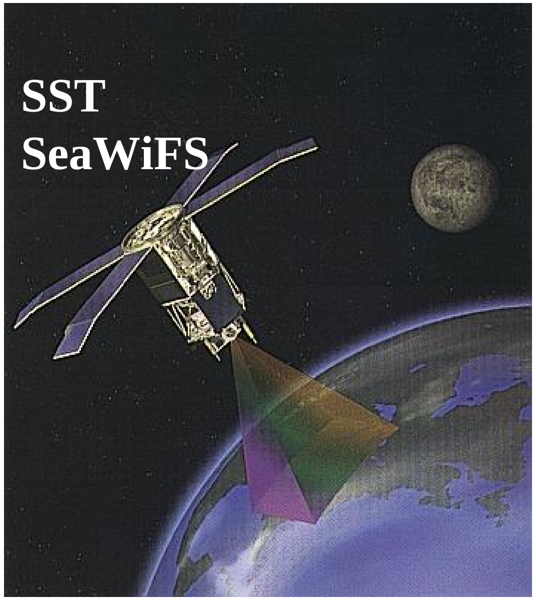
Physical Observations

AUV

Aircraft

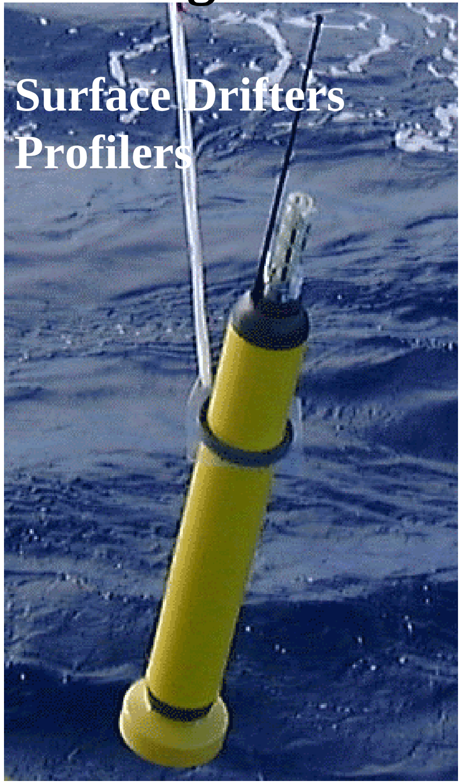
Ships

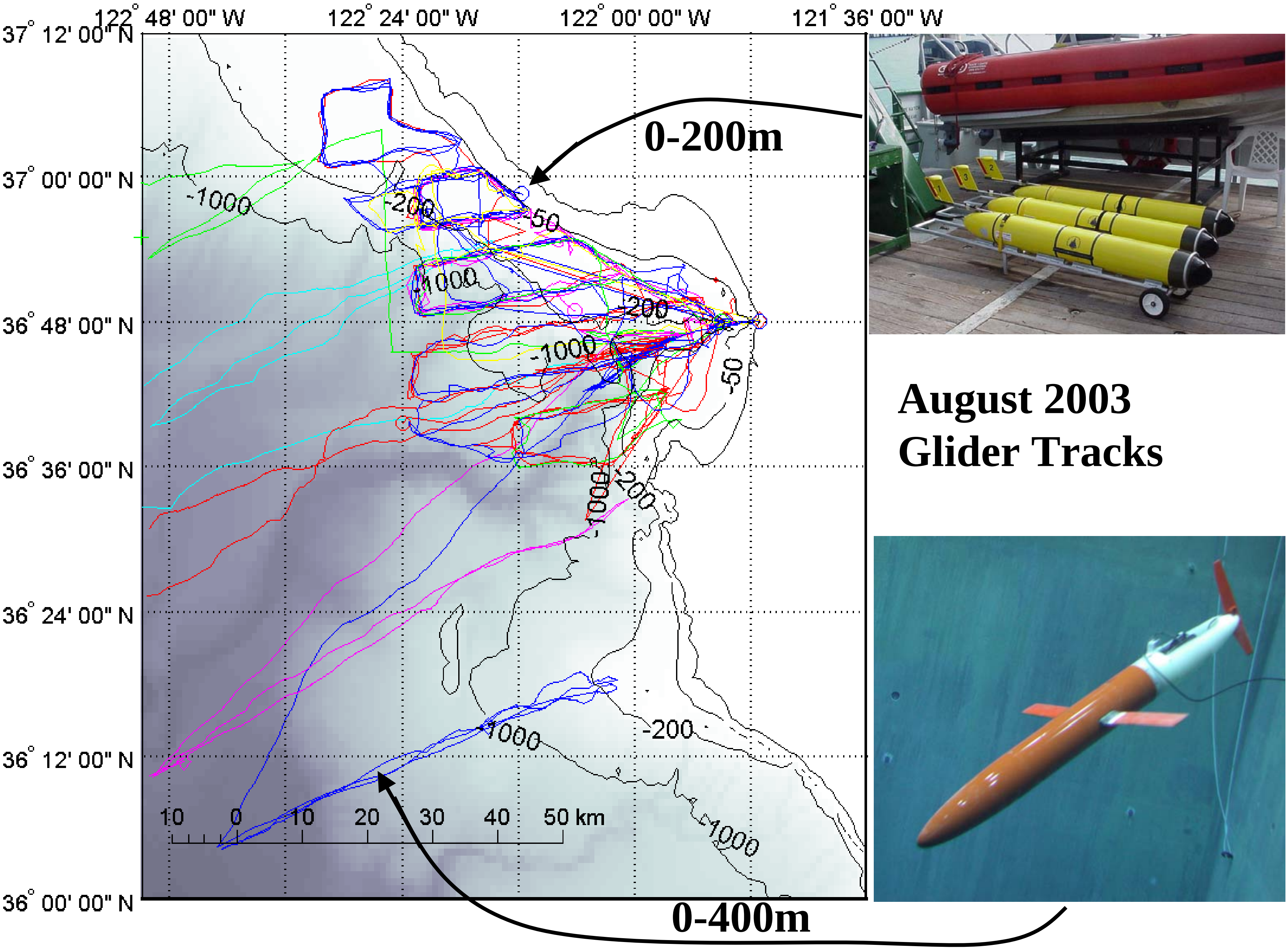
Satellite



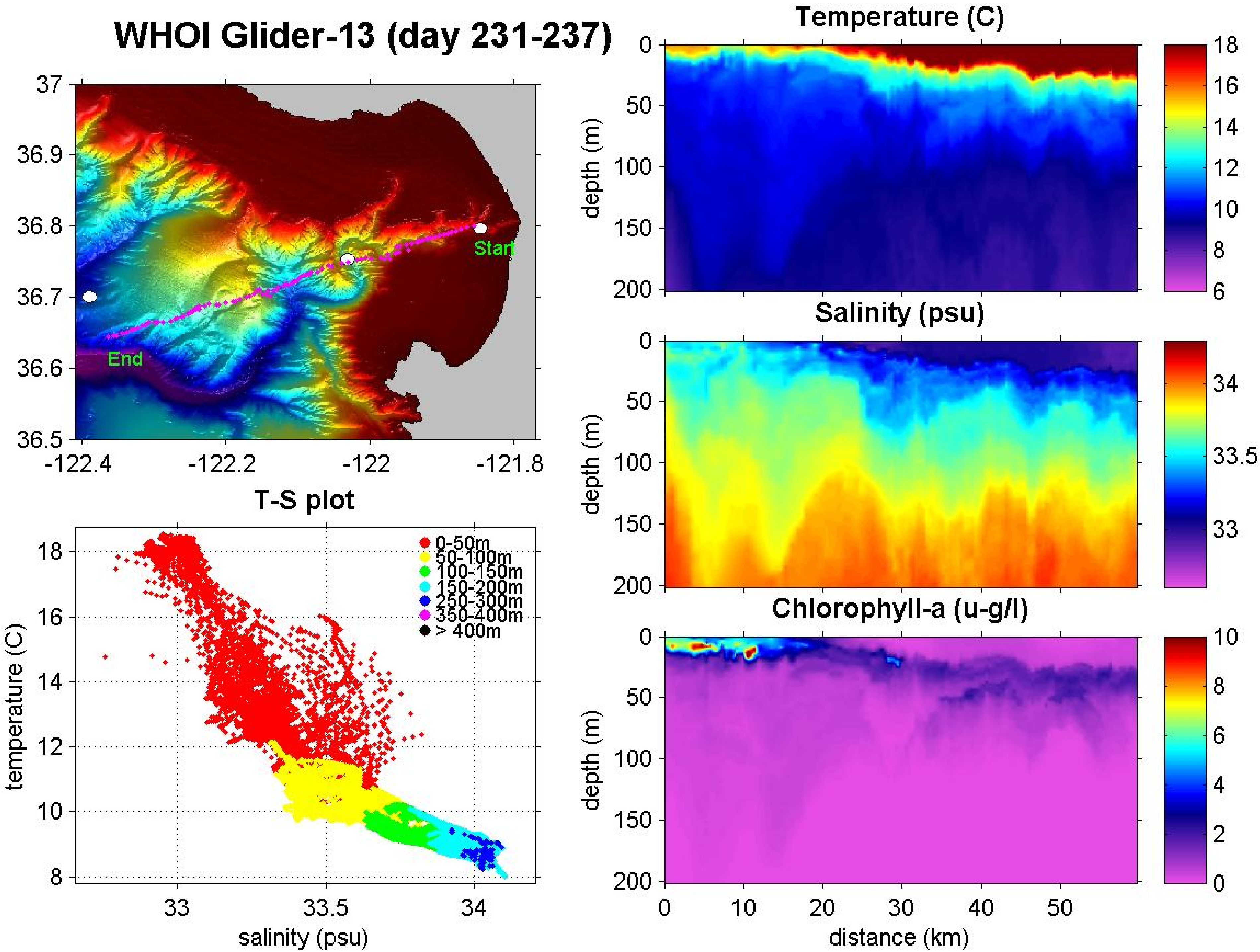
Moored/Fixed

Drifting

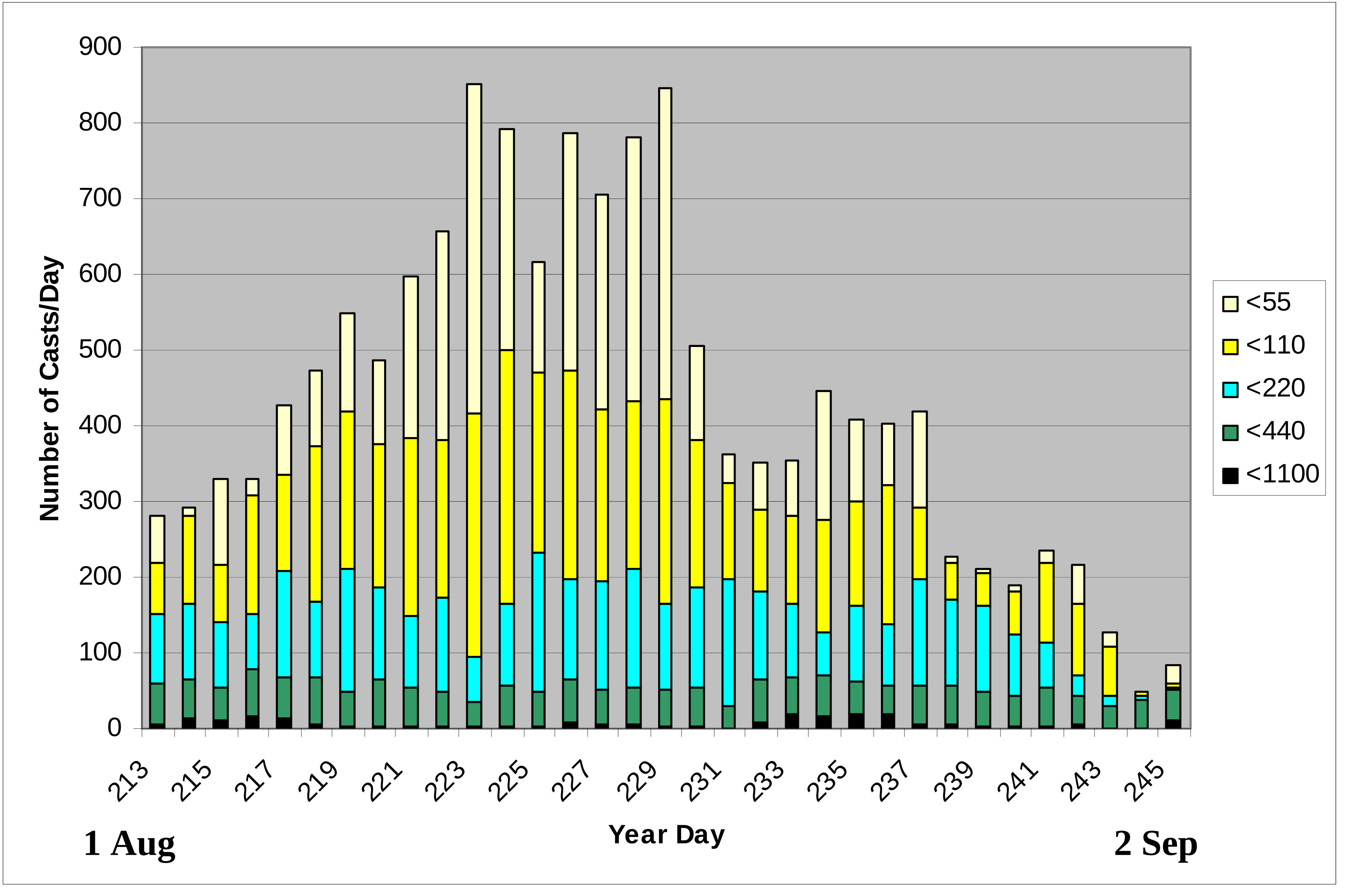




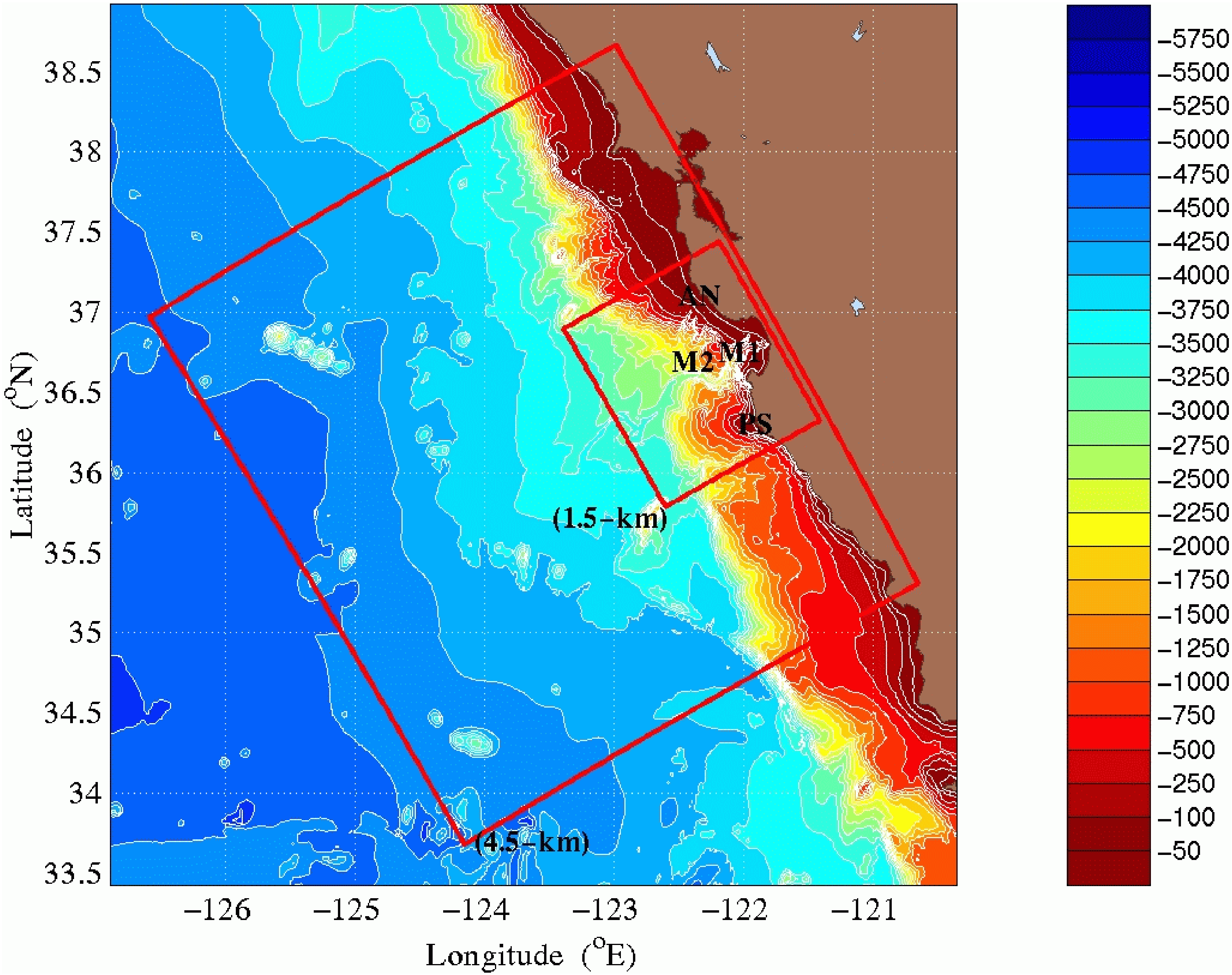
122° 48' 00" W
122° 24' 00" W
122° 00' 00" W
121° 36' 00" W
37° 12' 00" N
37° 00' 00" N
36° 48' 00" N
36° 36' 00" N
36° 24' 00" N
36° 12' 00" N
36° 00' 00" N
-1000
-200
-50
-1000
-200
-1000
-50
-1000
-200
-1000
-200
-1000
10 0 10 20 30 40 50 km
0-200m
August 2003
Glider Tracks
0-400m


WHOI Glider-13 (day 231-237)
37
36.9
36.8
36.7
36.6
36.5
-122.4
-122.2
-122
-121.8
Start
End
T-S plot
temperature (C)
salinity (psu)
0-50m
50-100m
100-150m
150-200m
250-300m
350-400m
> 400m
Temperature (C)
Salinity (psu)
Chlorophyll-a (u-g/l)
depth (m)
distance (km)

Observations/Day by Depth



HOPS – Real-time Nested Modeling Domains
4 August – 3 September 2003



HOPS – AOSN-II Real-Time Forecasting

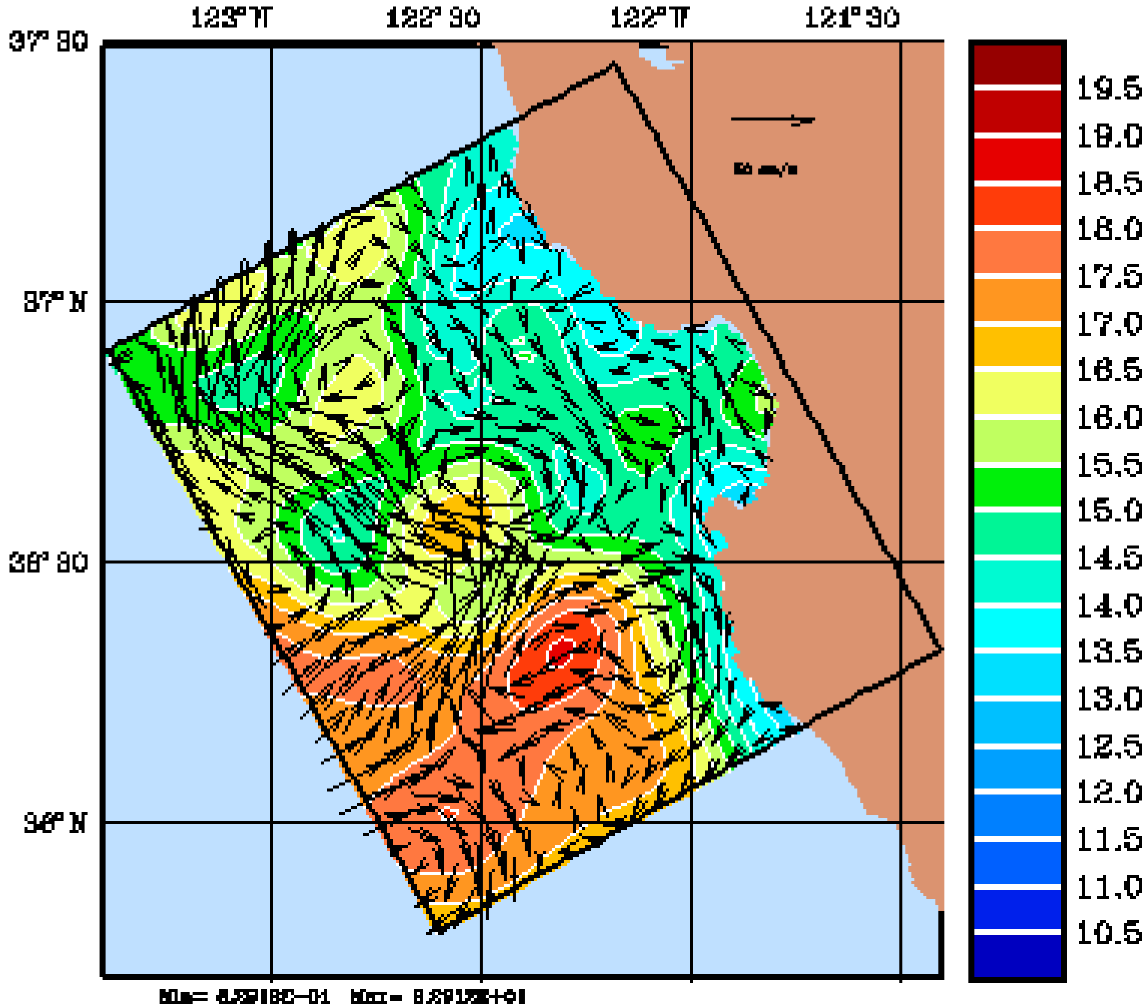
- 23 sets of real-time nowcasts and forecasts of temperature, salinity and velocity released from 4 August to 3 September
- Forcing by 3km COAMPS fluxes and Cal. Current System flow-through
- Data from glider fleets, aircraft, ships, etc. archived in real-time at MBARI. Daily ftp to Harvard for quality control and analysis at 9AM EDT. Processed for initialization by 2PM EDT.
- Real-time daily operational five day runs with OI (two assimilation days, nowcast, two forecast days) were available for post-processing at 4PM.
- Forecast features analyzed and described daily formed the basis for adaptive sampling recommendations for the 2PM (PDT) Real-Time Operational Committee (RTOC) meetings at MBARI.
- Web: http://www.deas.harvard.edu/~leslie/AOSNII/index.html for distribution of field and error forecasts, scientific analyses, data analyses, special products and control-room presentations
- 10 sets of real-time ESSE forecasts issued from 4 Aug. to 3 Sep. – total of 4323 ensemble members (stochastic model, BCs and forcings), 270 – 500 members per day

10m Temperature

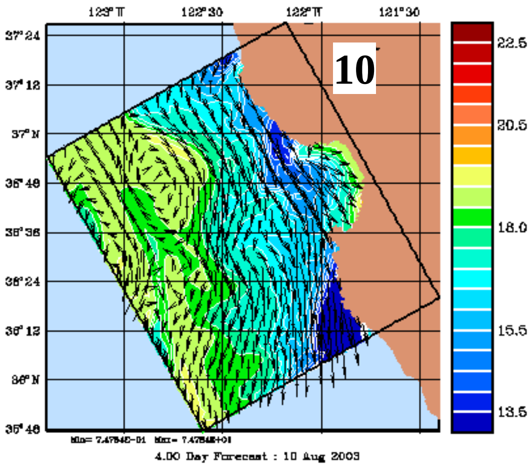
AOSN-II (run 486)

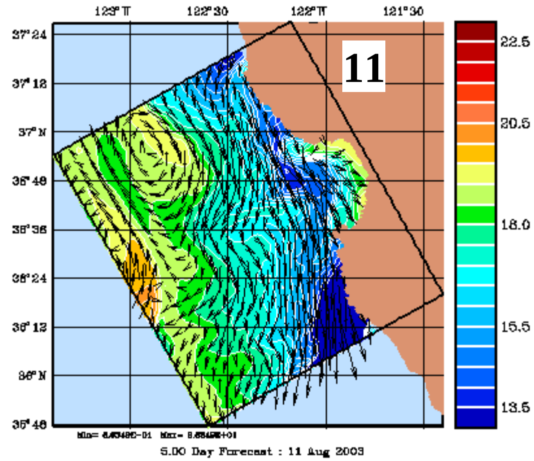
Aug 2– Sep 6 Pt Sur, Martin & Lobos CTD, WHOI & SIO gliders; NPS SST

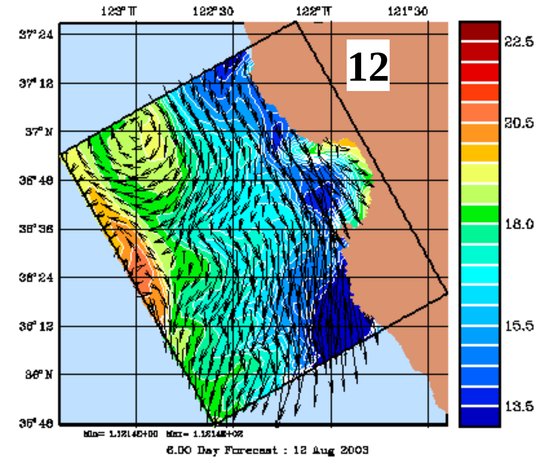
COAMPS atmospheric fluxes



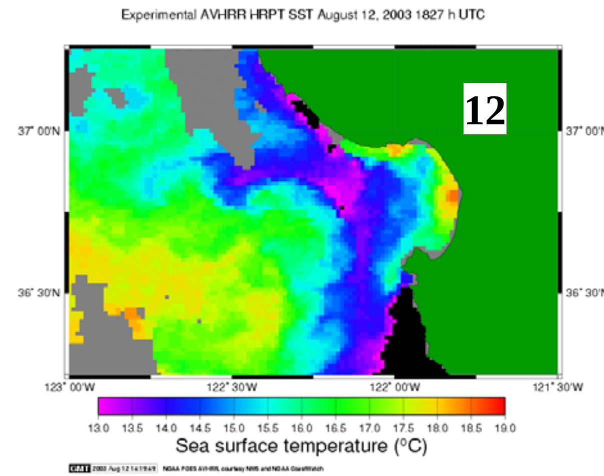
Nowcast : 6 Aug 2003

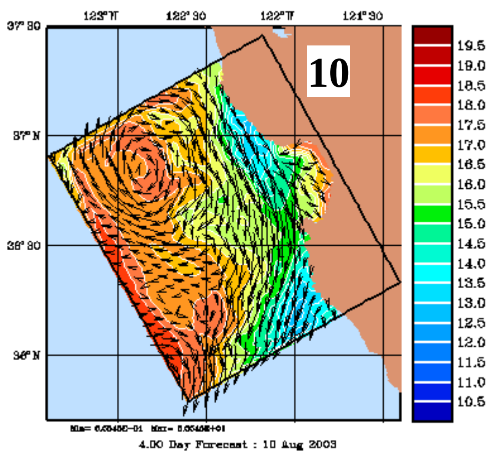


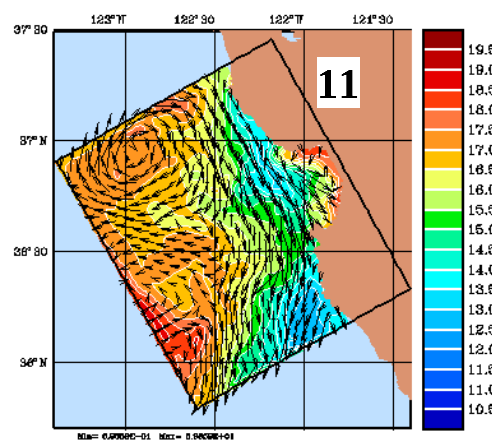


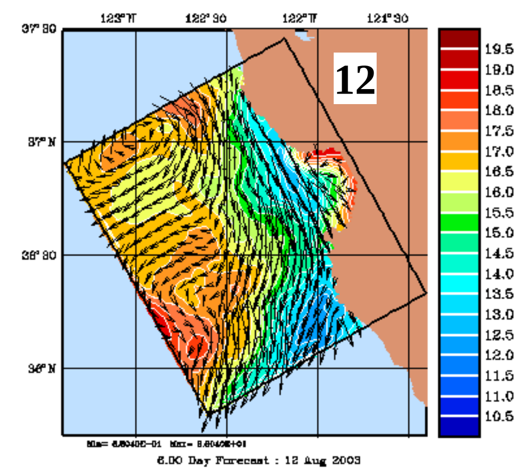


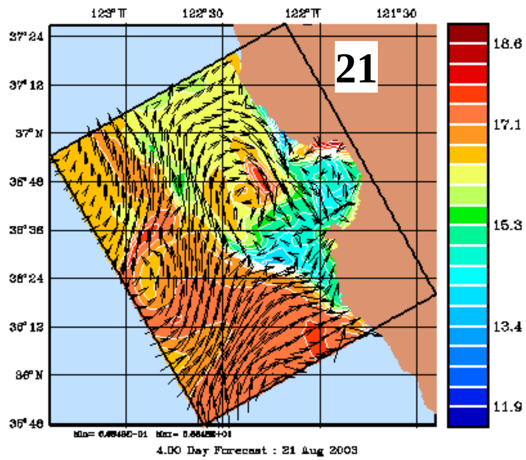
Sustained upwelling: comparison of real-time forecasts (top) with AVHRR SST (right) and re-analysis fields (bottom)

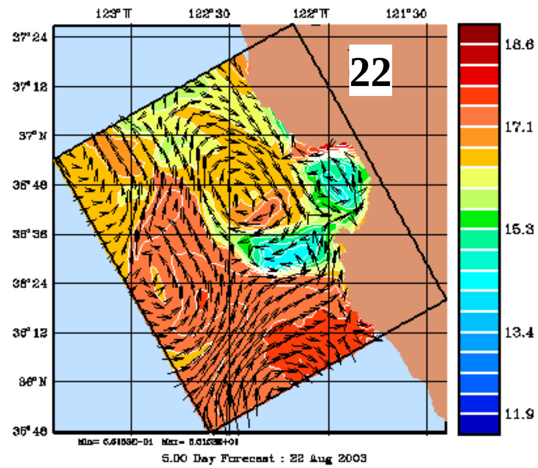


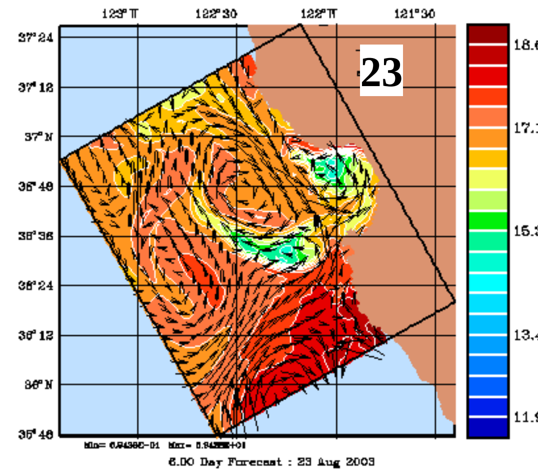




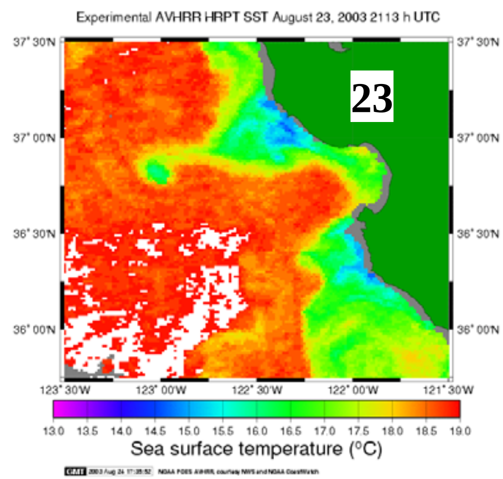


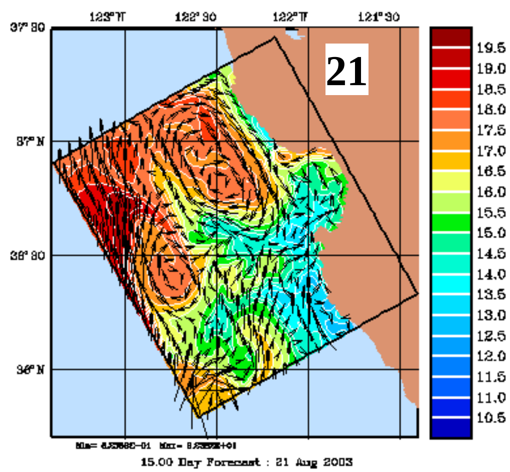


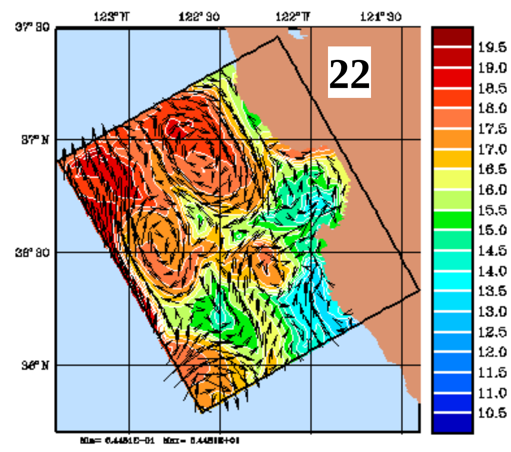


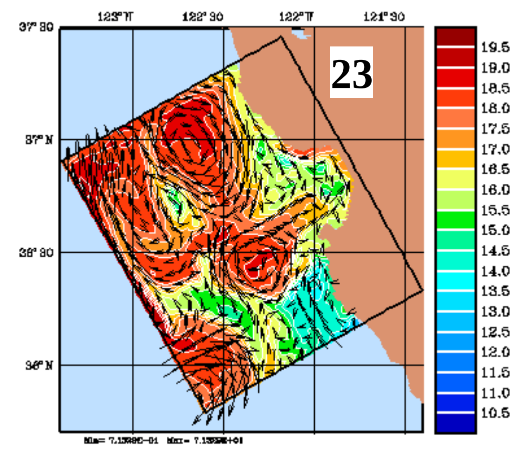


Relaxation: comparison of real-time forecasts (top) with AVHRR SST (right) and re-analysis fields (bottom)



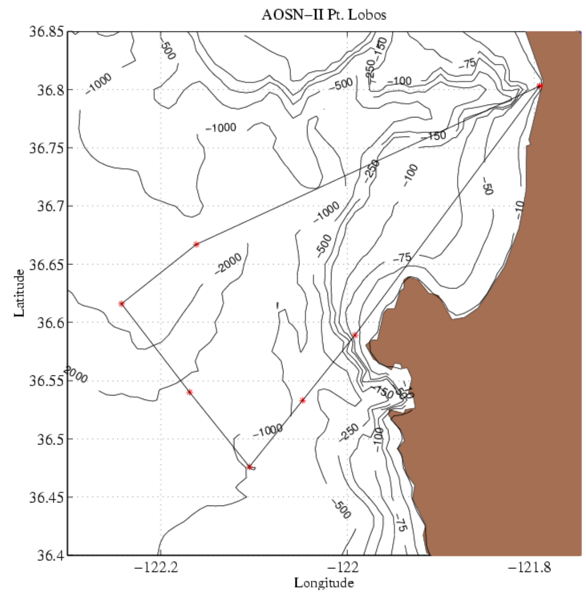




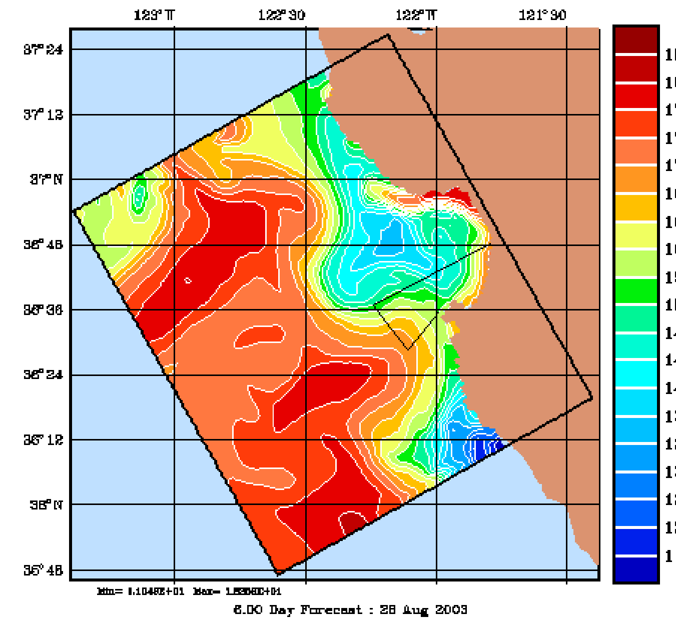


Real-time Adaptive Sampling – Pt. Lobos

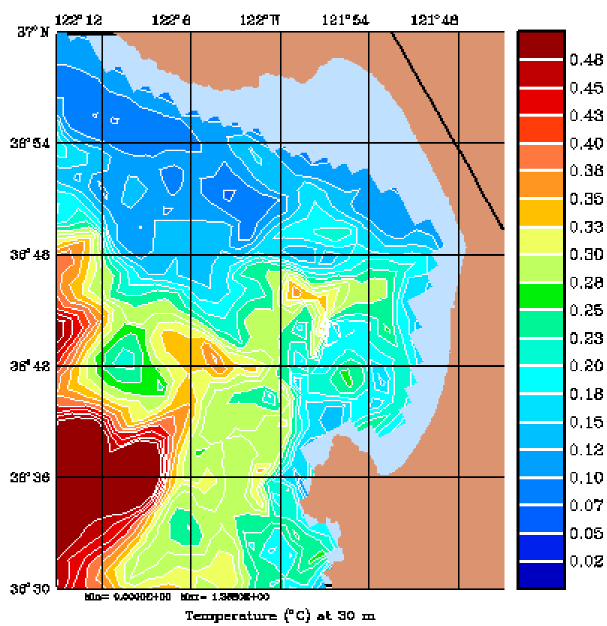
- Large uncertainty forecast on 26 Aug. related to predicted meander of the coastal current which advected warm and fresh waters towards Monterey Bay Peninsula.
- Position and strength of meander were very uncertain (e.g. T and S error St. Dev., based on 450 2-day fcsts).
- Different ensemble members showed that the meander could be very weak (almost not present) or further north than in the central forecast
- Sampling plan designed to investigate position and strength of meander and region of high forecast uncertainty.



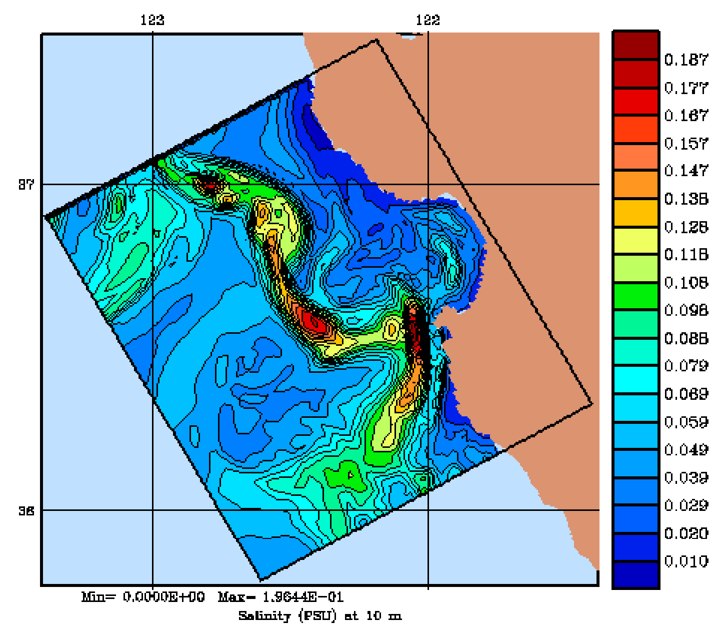
Surf. Temperature Fcst.



Temperature Error Fcst.

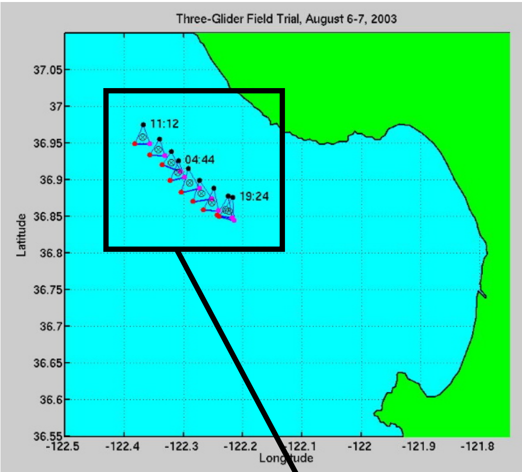


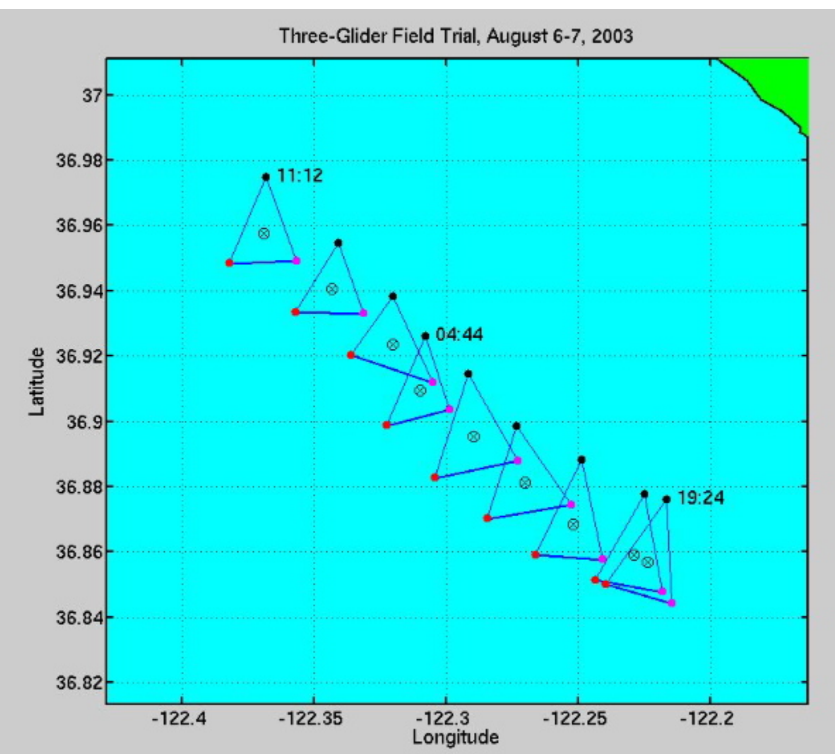
Salinity Error Fcst.

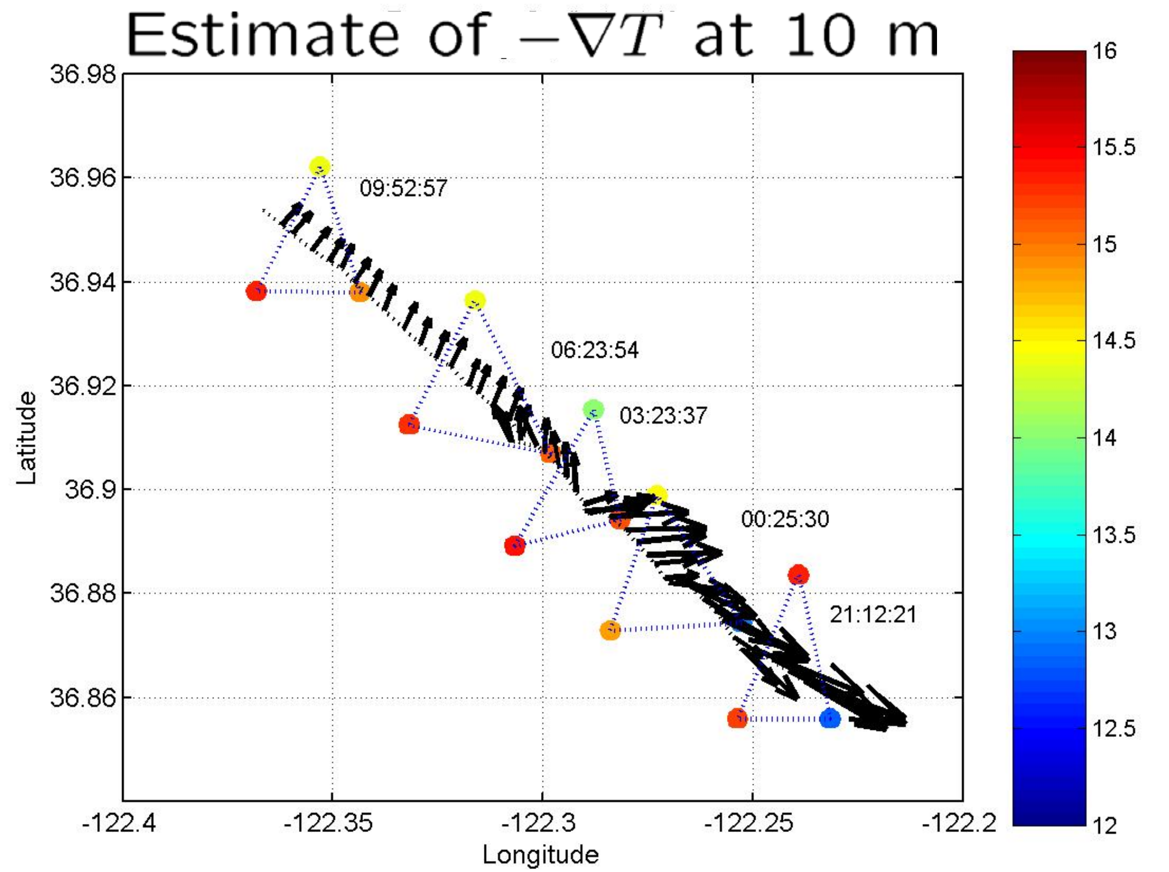


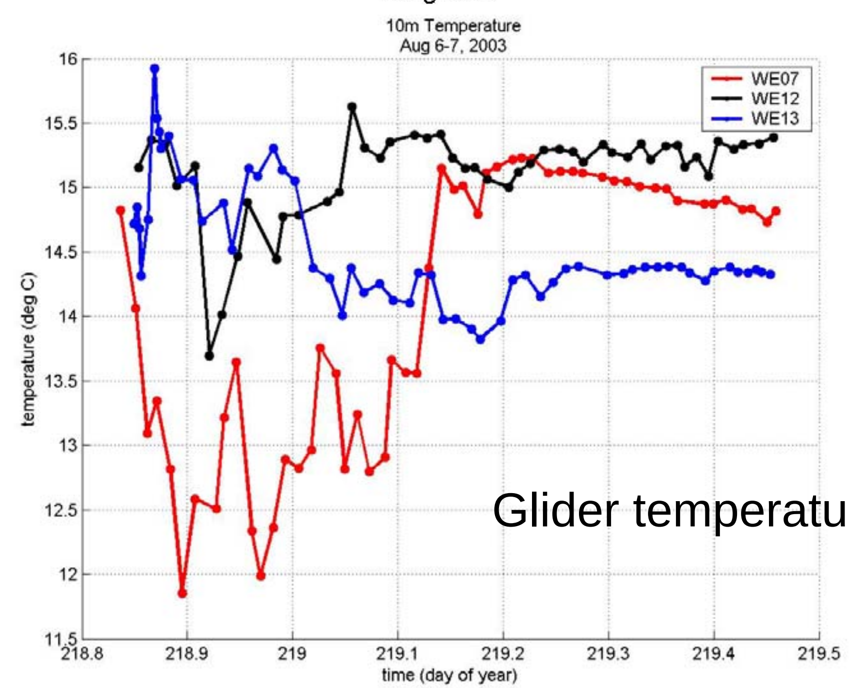
Coordinated 3-Glider Exp. with Gradient Estimate

Aug 6-7, 2003



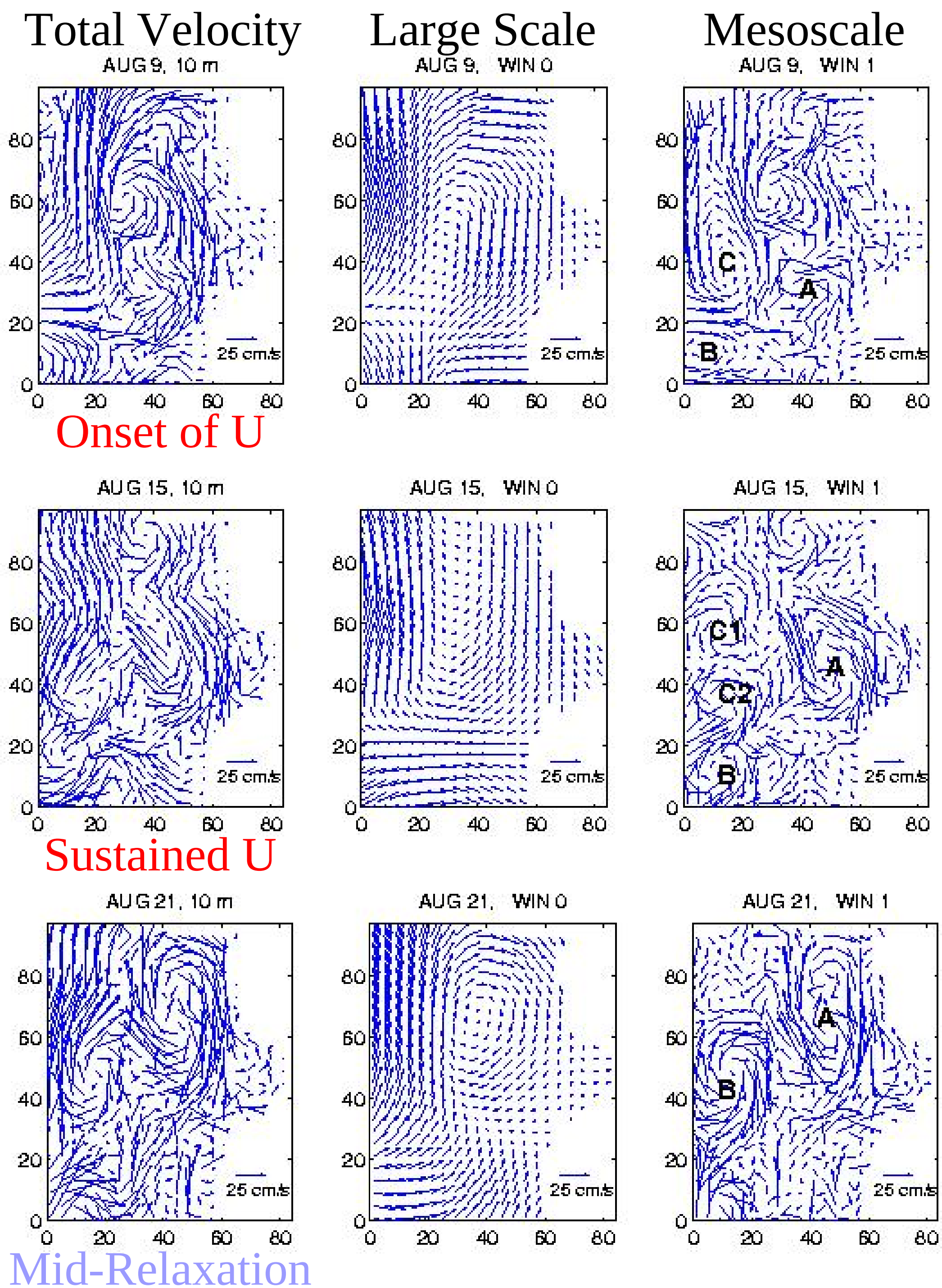






Glider temperature profiles

Multi-Scale Energy and Vorticity Analysis



Anticyclonic Eddy A appears on Aug. 9 off southern Monterey Bay. By Aug. 15, it has strengthened outside the Bay. It remains until Aug. 18, when the wind begins to relax. The southward flow on its eastern flank together with the northward coastal current causes a secondary upwelling within the bay. After the wind relaxes, Eddy A propagates northward, and by Aug. 21, its center is close to Point Ano Nuevo. The current accompanying it and the coastal current lead to a northward progression of the upwelling event along the coast during the relaxation period.

Anticyclonic Eddy B is originally very weak at the southwestern corner (Aug. 9). North of it lies a strong cyclonic eddy C. By Aug. 15, C has been split into a cyclone C1 and an anticyclone C2. C1 then disappears, and B and C2 merges into a large anticyclonic eddy (August 16). The new B propagates northward and by Aug. 21, the whole domain is dominated by two anticyclonic eddies: B and A.

In the large scale window, the circulation is dominated by an anticyclonic gyre, with the coastal side current strengthened and weakened under upwelling and relaxation wind conditions.

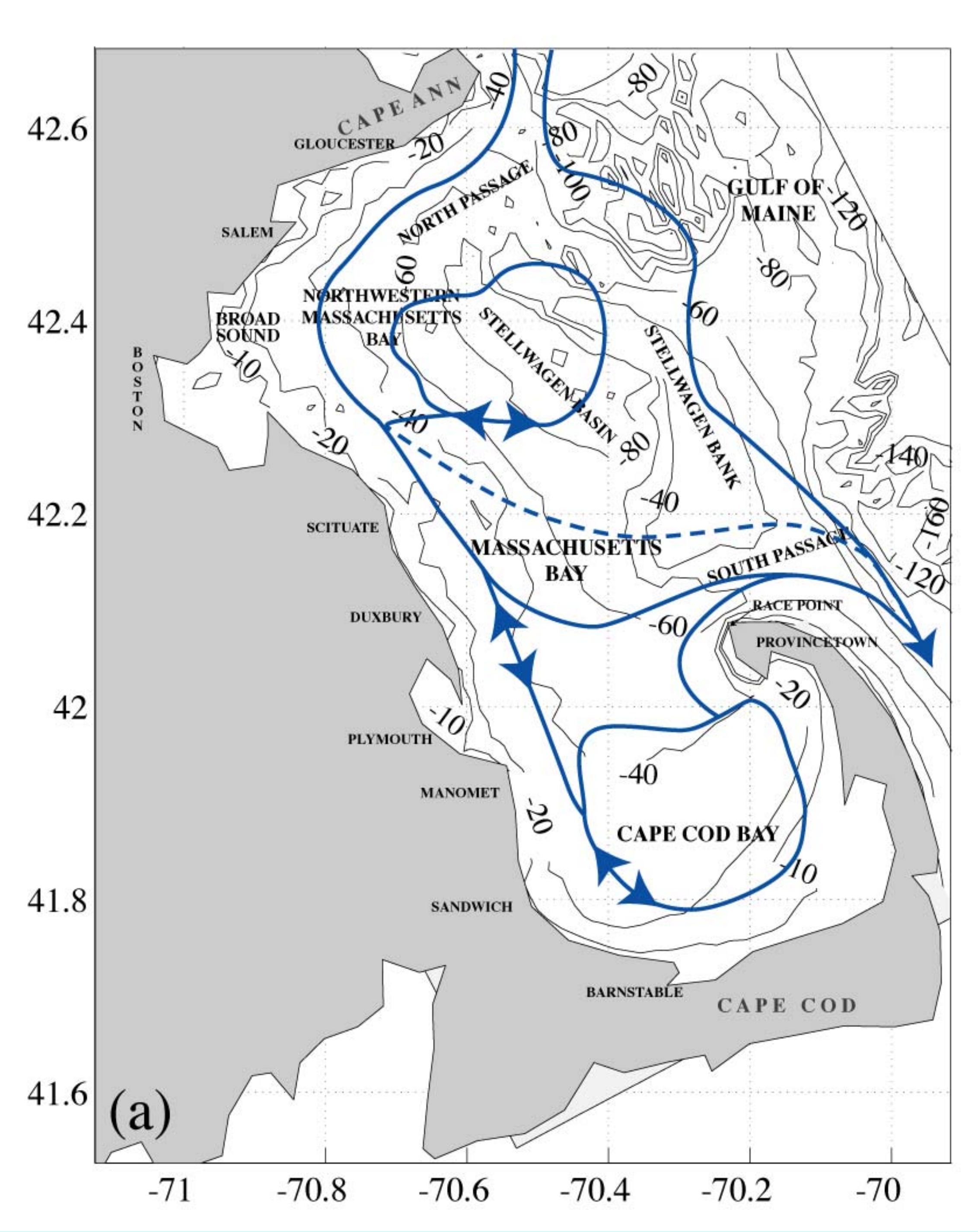
HOPS – AOSN-II Conclusions

- HOPS is a generic, regional, data assimilative forecast system driven by surface fluxes and historical and contemporary synoptic mesoscale data
- From 4 August – 3 September 2003, daily real-time forecasts of 3 days duration assimilated data from two fleets of gliders, aircraft, ships, etc. and identified features for adaptive sampling
- Onset and sustained upwelling and relaxation phenomena were successfully captured, together with their dynamic mesoscale variabilities
- Preliminary results of real-time forecast evaluation indicates generally good RMS values that beat persistence
- Further research includes re-analysis fields, methodology for skill determination, multi-model interpretation of HOPS results together with ROMS results and multi-scale dynamical analyses

AOSN-II Accomplishments

- Highly successful use of autonomous mobile platforms
  - 20 different systems, all successfully operated.
  - Roughly 10 in water at any given time, with peak of 15.
- Coordinated adaptive sampling
- Forecasts forced by COAMPS atmospheric predictions
- Observations generally assimilated into real-time model nowcasts and forecasts within 24 hours of appearance on data server
- Real-time nowcasts and forecasts of temperature, salinity and velocity released over a period of a month
- Extensive observational data set obtained for OSE/OSSE analysis.
- Graphical data products released on web sites in real-time during experiment (www.mbari.org/aosn)

HORIZONTAL CIRCULATION PATTERNS IN MASSACHUSETTS BAY

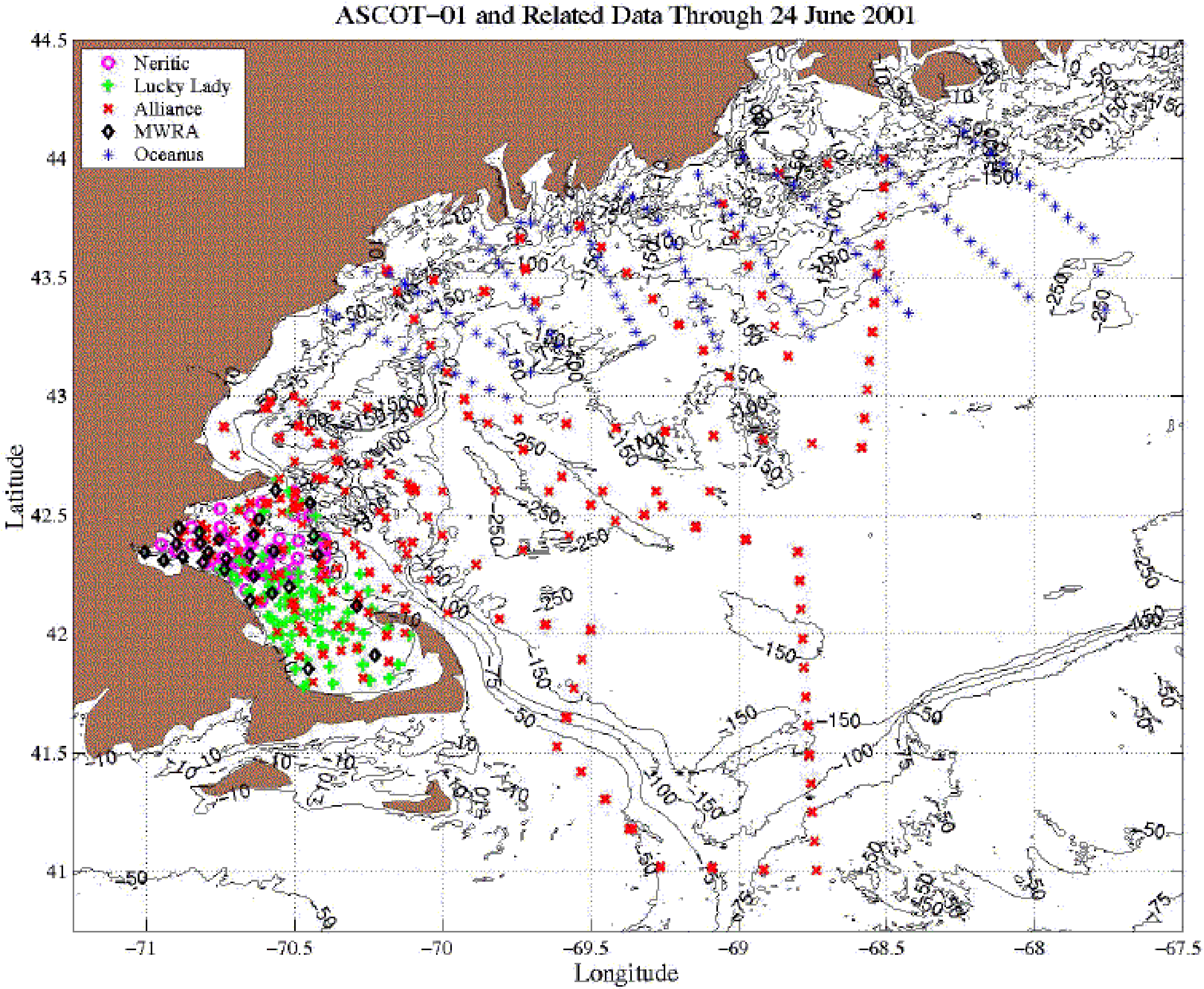


Cartoon of horizontal circulation patterns for stratified conditions in Massachusetts Bay, overlying topography in meters (thin lines).

- **Patterns are not present at all times**
- **Most common patterns (solid), less common (dashed)**
- **Patterns drawn correspond to main currents in the upper layers of the pycnocline where the buoyancy driven component of the horizontal flow is often the largest**

ASCOT-01 (6-26 June 2001) :

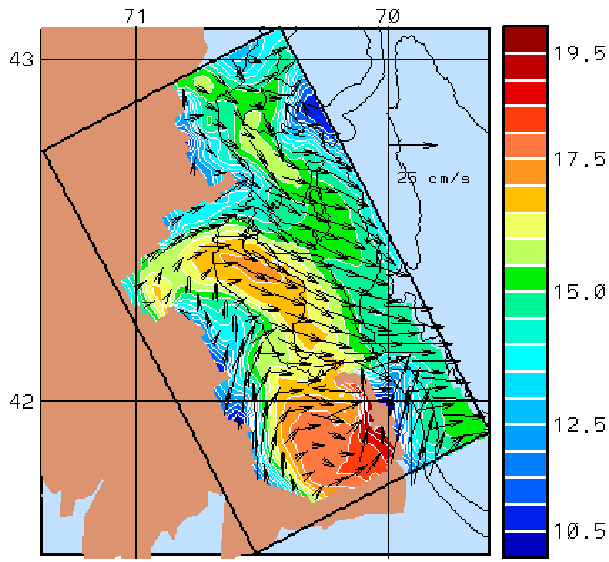
Positions of data collected and fed into models



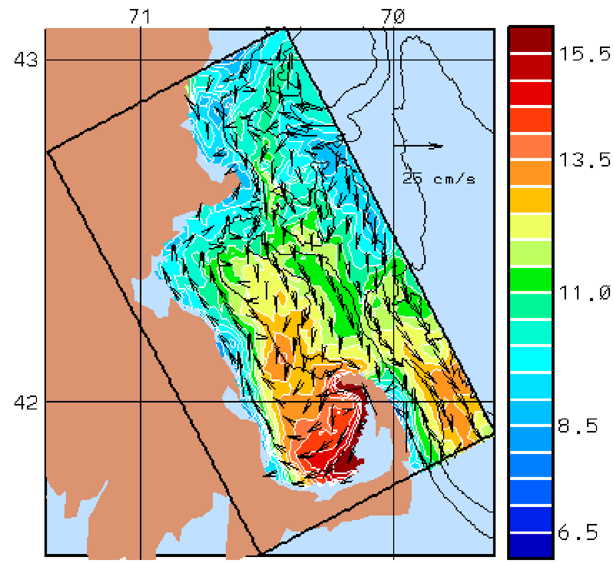
ASCOT-01: Sample Real-Time Forecast Products

Massachusetts Bay

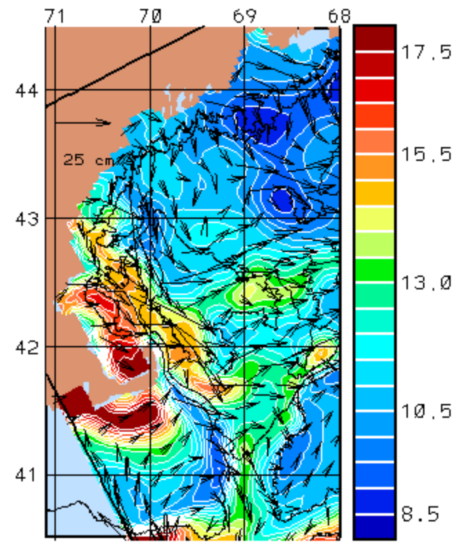
Gulf of Maine



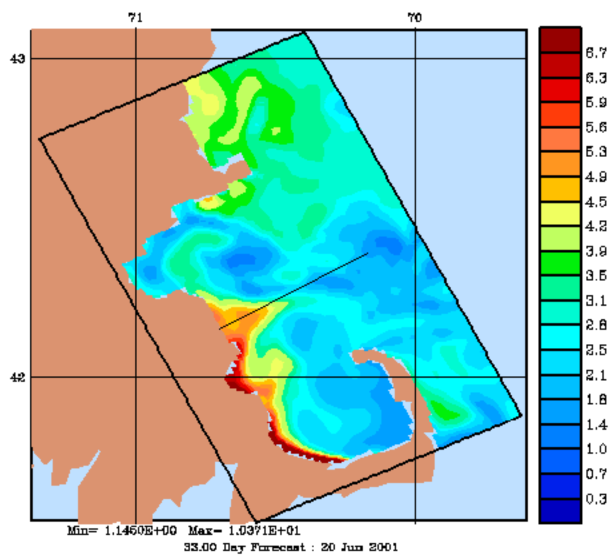
2m Temp.



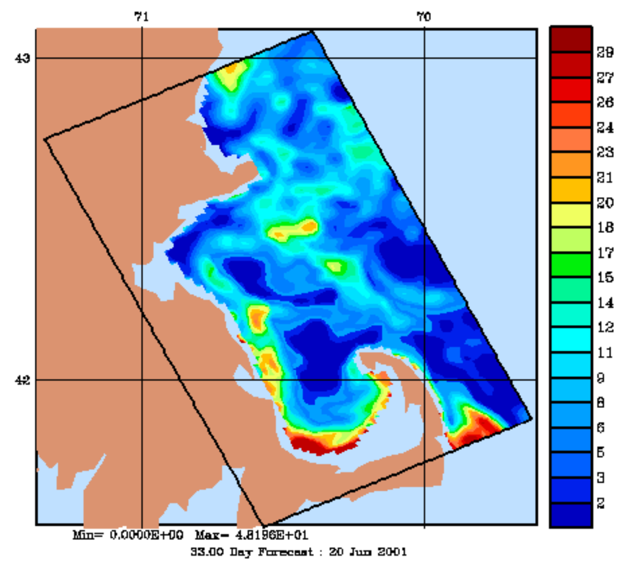
10m Temp.



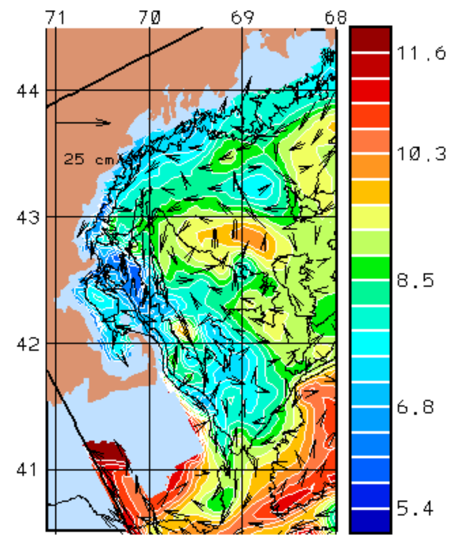
3m Temp.



5m Chlorophyll

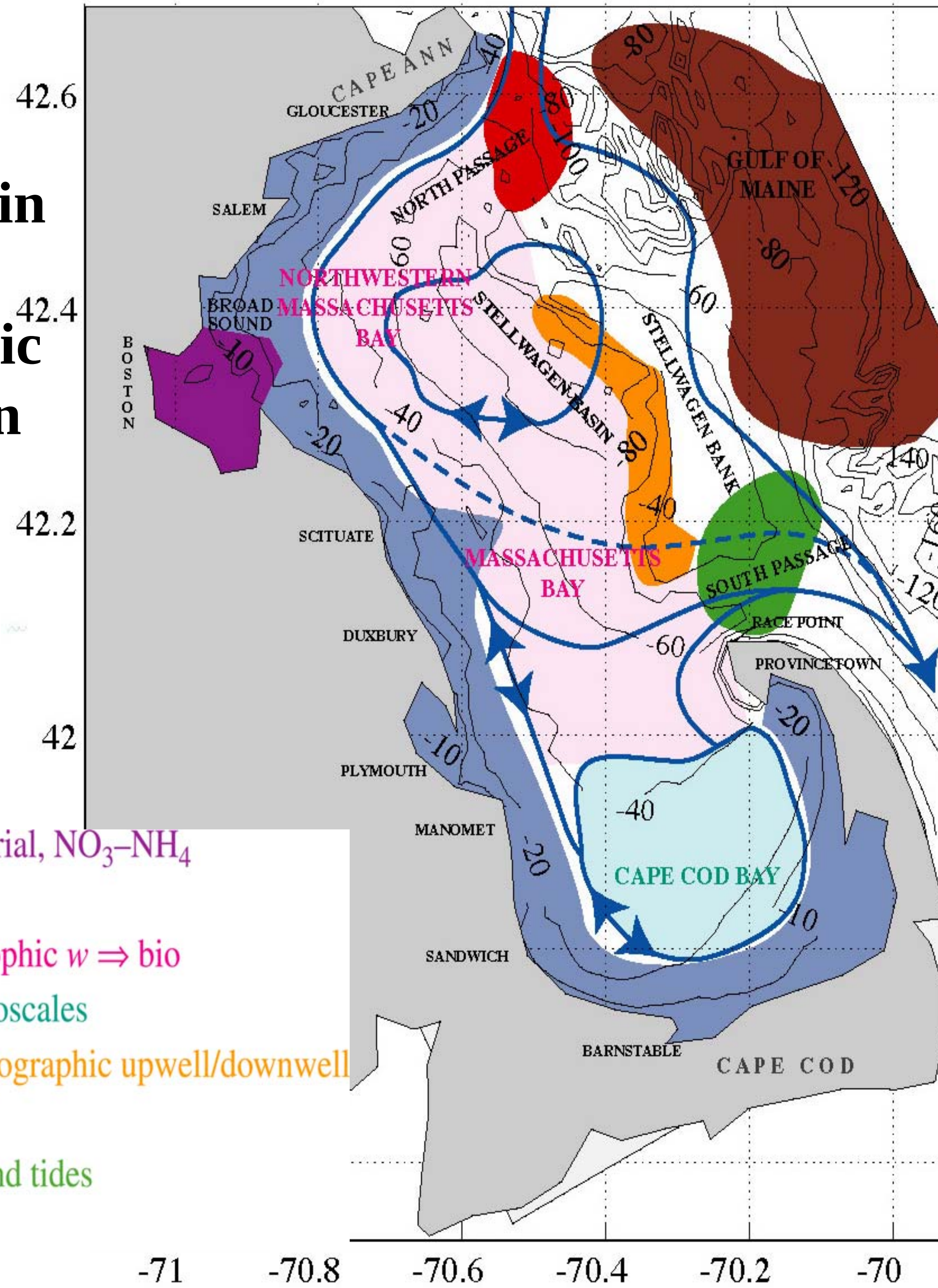


15m Nitrate



25m Temp.

Coupled bio-physical sub-regions of Massachusetts Bay in late summer: Dominant dynamics for trophic enrichment and accumulation



Boston Harbor: Charles River, sediments, toxic material, NO_3–NH_4

Along Coast: upwelling/downwelling ⇒ bio ↑/↓

Open Bay: submesoscale/mesoscale eddies. Ageostrophic *w* ⇒ bio

Cape Cod Bay: Horizontal bio advection and submesoscales

West of Stellwagen Bank: GOM meanders, tides, topographic upwell/downwell

Offshore: GOM meanders

Race Point: Multiple bio advections, accumulation, and tides

Cape Ann: Physical instabilities at GOM inflow