CIE Review Panel: Modeling Larval Transport and Connectivity in Hawaiian Waters

Donald R. Kobayashi
Research Fishery Biologist
Ecosystems and Oceanography Division
Pacific Islands Fisheries Science Center, NMFS, NOAA

4-day outline

Convene:
- **Introductions and opening remarks**
- **Agenda review, TOR, task assignments**

Presentations:
- **PIFSC Overview by Sarah Malloy (representing Directors Office)**
- **FMP issues related to connectivity**
- **Brief historical overview of relevant connectivity research in Hawaii**
- **General discussion of data and methods**
- **Present review documents**
- **Identify additional analyses, sensitivities, corrections**
- **Present ongoing and future work**
- **Continue deliberations, as needed**

PIFSC Overview

Presented by:

Sarah Malloy, Management & Program Analyst, Directors Office, Pacific Islands Fisheries Science Center.

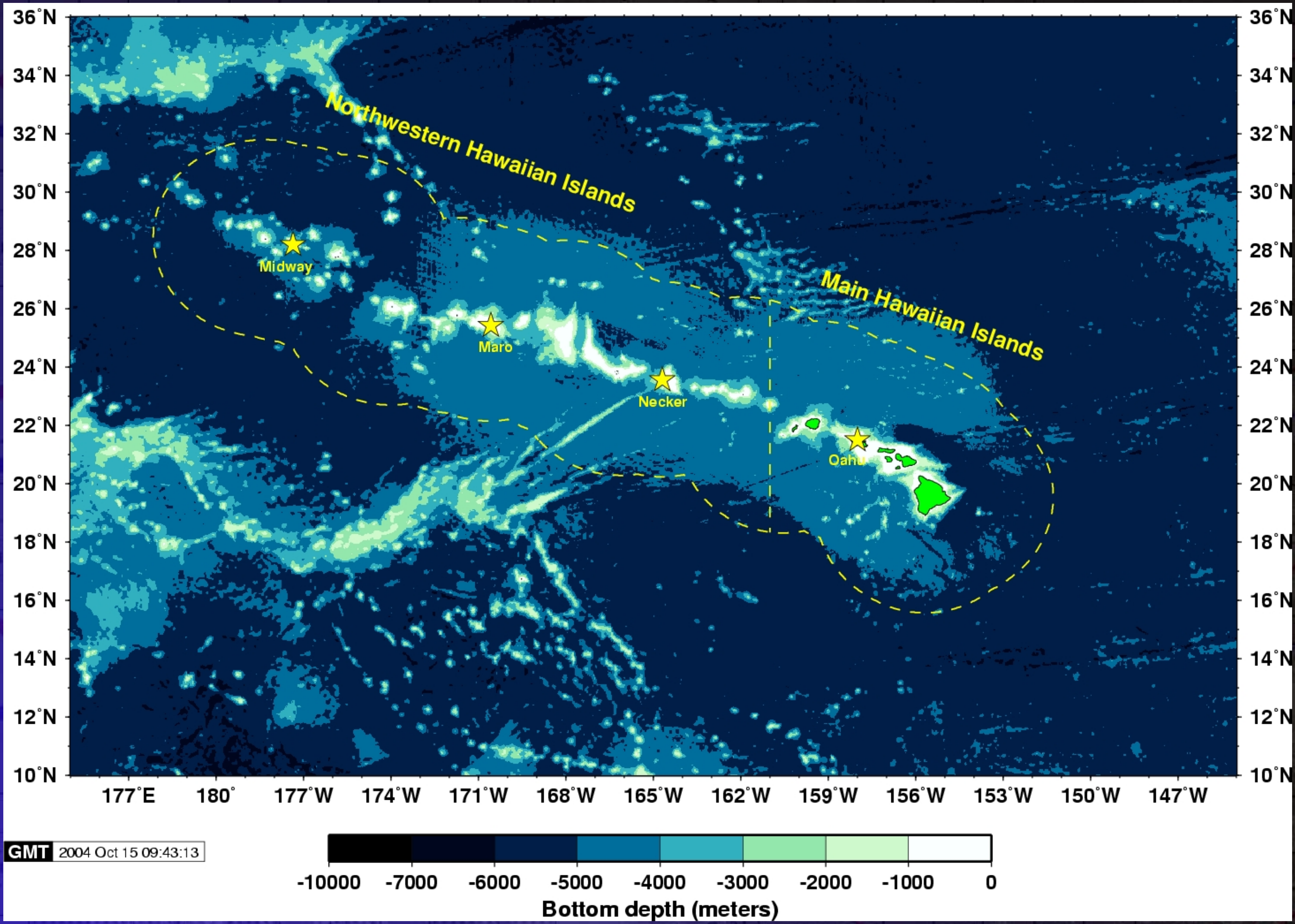
EOD - Ecosystems & Oceanography Division

- Eleven staff under Division Chief Jeffrey Polovina.

  - Melanie Abecassis, Ray Boland, Eric Cruz,
  - Reka Domokos, Don Hawn, Evan Howell,
  - Don Kobayashi, Lucas Moxey, Frank Parrish,
  - Su Situ, Hidetada Kiyofuji.

- EOD relies heavily on satellite remotely-sensed data and modeled data products (CoastWatch program administers much of this data via new LAS), and other technologies such as satellite tags, active/passive acoustics, mixed-gas diving, submersibles, and computer simulation modeling.
- Recent EOD research include protected species (sea turtle, seabird, cetacean) bycatch in the pelagic longline fishery, sea turtle and monk seal foraging ecology (crittercam), deepwater coral communities, fishery oceanography of tunas and billfish, stock assessment of deepwater bottomfish, ecosystem modeling, acoustic surveys to assess fish and fish forage, and larval transport and connectivity modeling.

Hawaiian Archipelago



North Pacific Oceanography

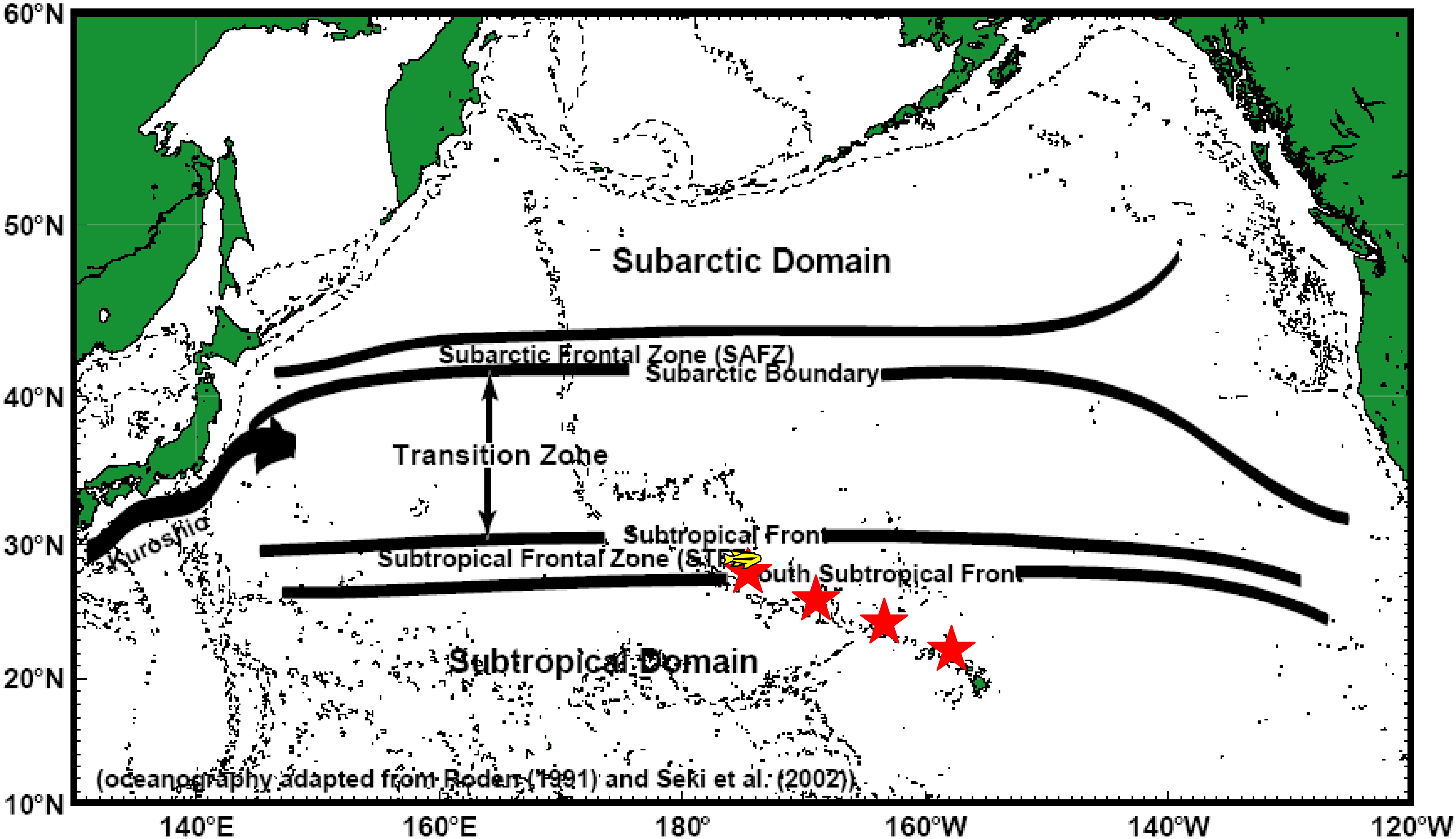
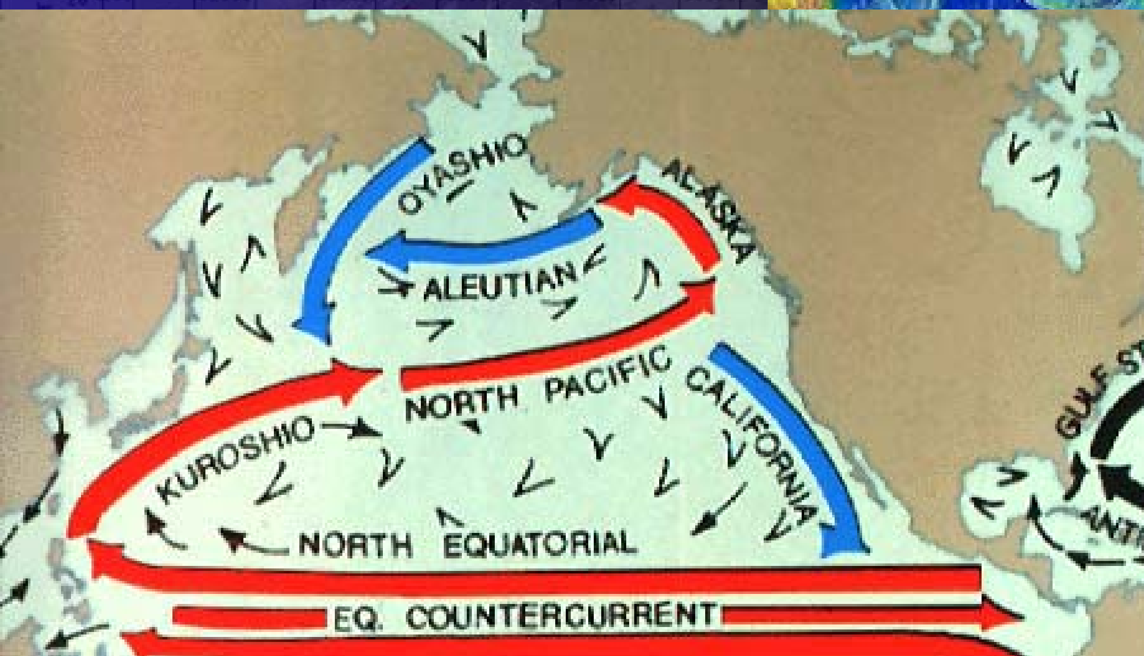


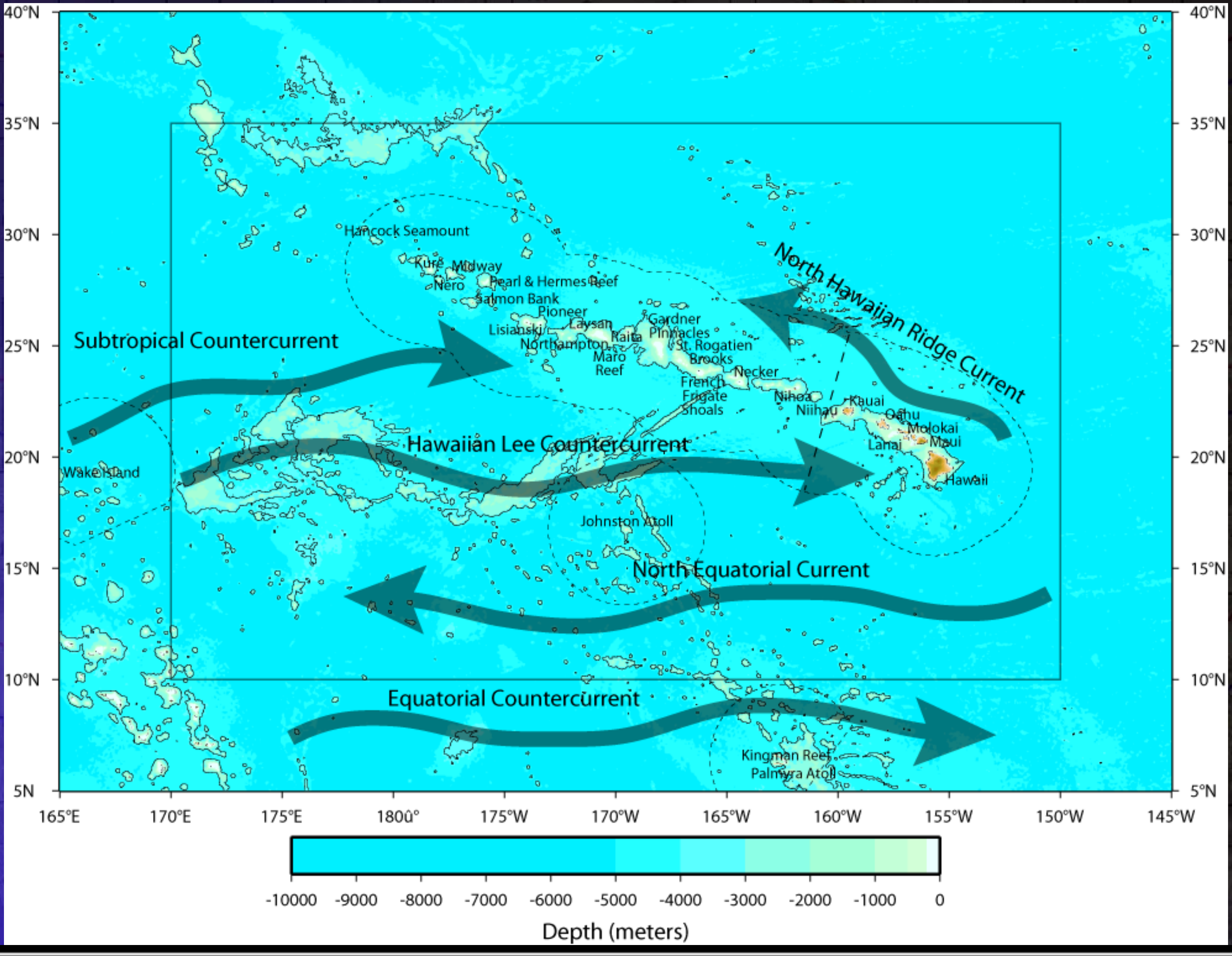
FIGURE 126 SCHEMATIC REPRESENTAITON OF THE NORTH PACIFIC TRANSITION ZONE AND ITS RELATION TO THE MAJOR FEATURES OF THE NORTH PACIFIC OCEAN.

North Pacific currents

Dominated by North Pacific subtropical gyre =>

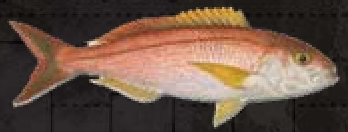


Currents around Hawaii



Connectivity in Hawaii

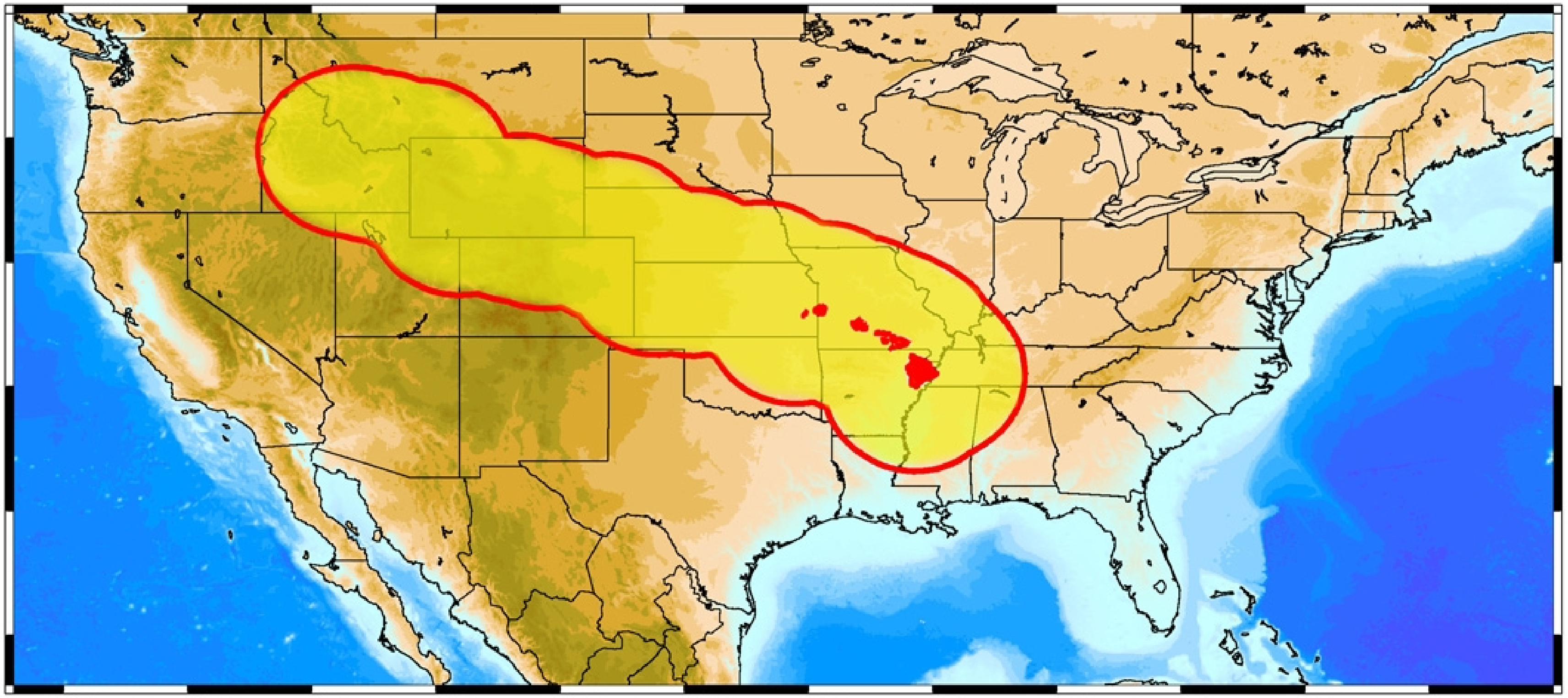
- Hawaiian archipelago contains many important ecosystems (coral reef, pelagic, deepwater benthic, etc.).



- Many endemic species (~20%).
- Many species of commercial or political importance, several Fishery Management Plans.
- Concerns of population declines and recruitment failure in some species.

- Knowledge of connectivity for all species in all ecosystems is vital in this spatial network of habitats.

Comparison of the Hawaiian Archipelago EEZ with the mainland United States



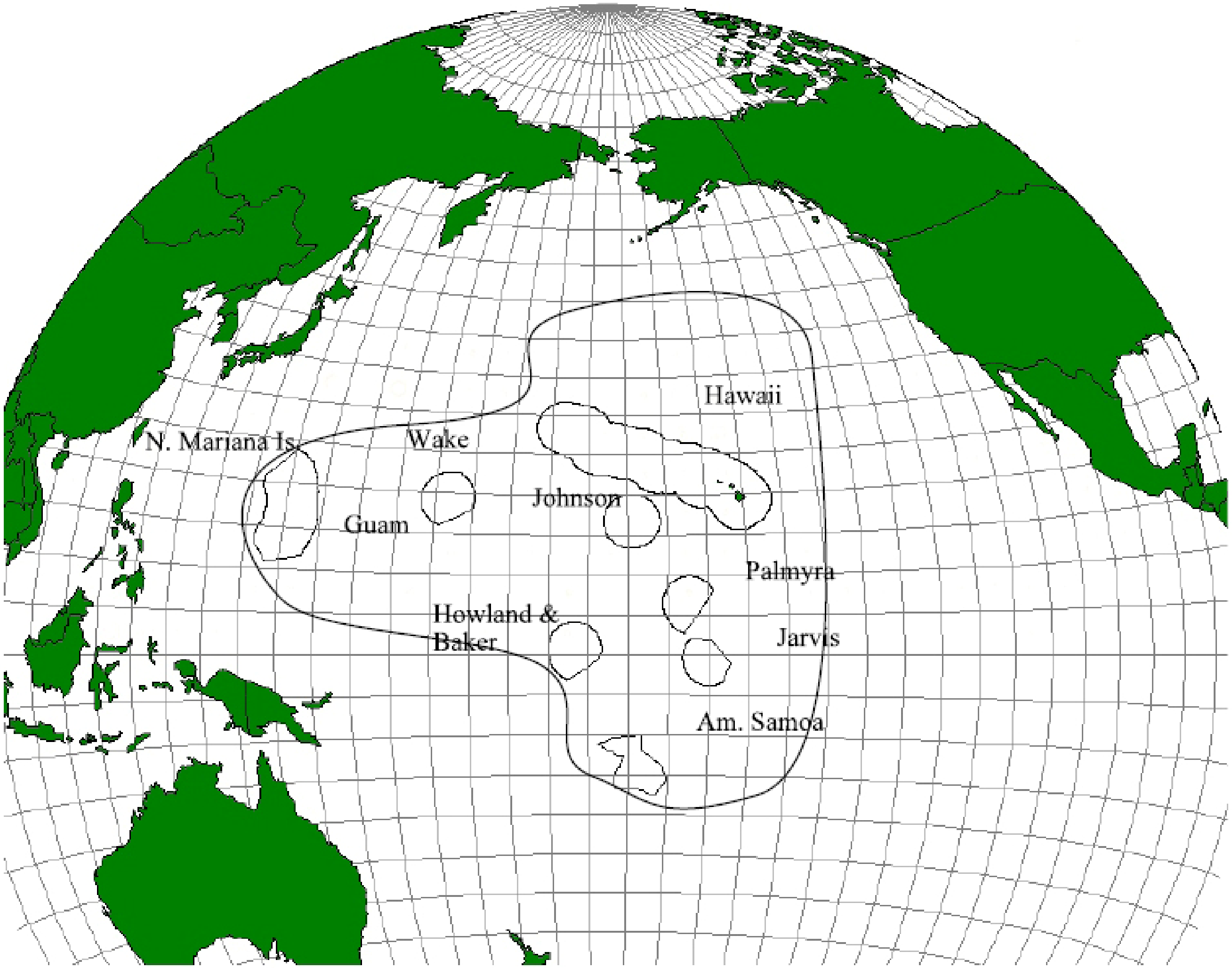
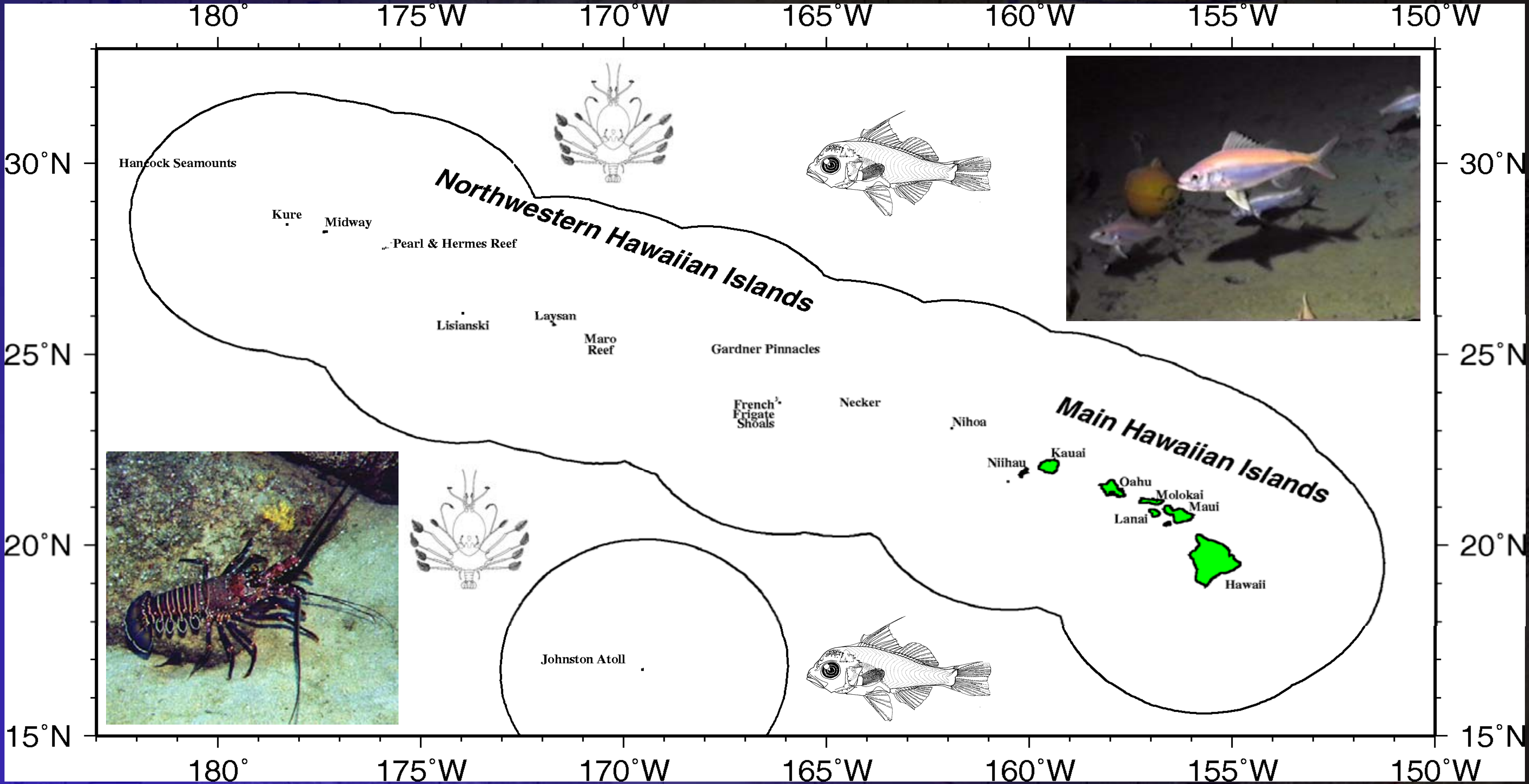


Figure 1. Map of the Pacific Ocean showing the approximate extent of fishing by longline vessels managed under the Pelagics FMP based in Hawaii and American Samoa.

Importance of connectivity to effective fisheries management

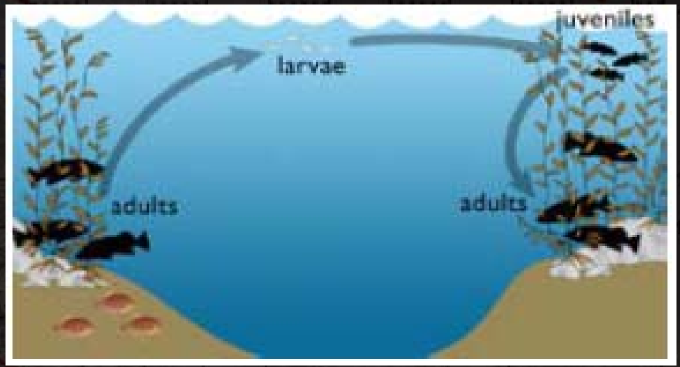


Challenges in insular species ecology

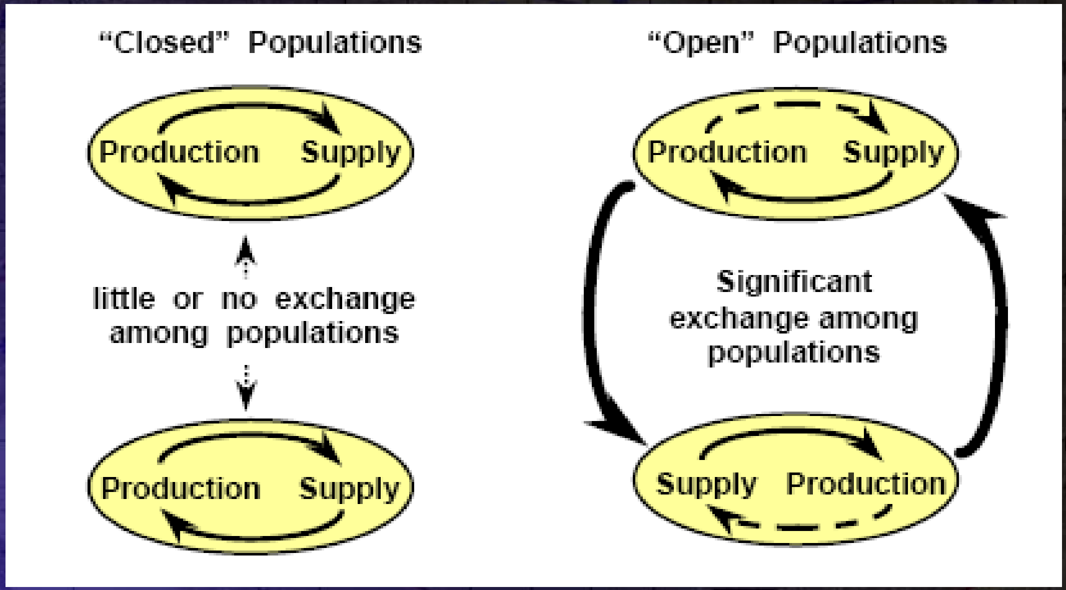
- **Most insular fish and invertebrate species have a complex life cycle with dispersive eggs and larvae. Understanding population dynamics is therefore problematic.**

- **One approach is to use oceanographic movement models coupled with demography to investigate this transitional life history stage.**

- **This could enable improved management for harvested, protected, threatened, or recovering species.**

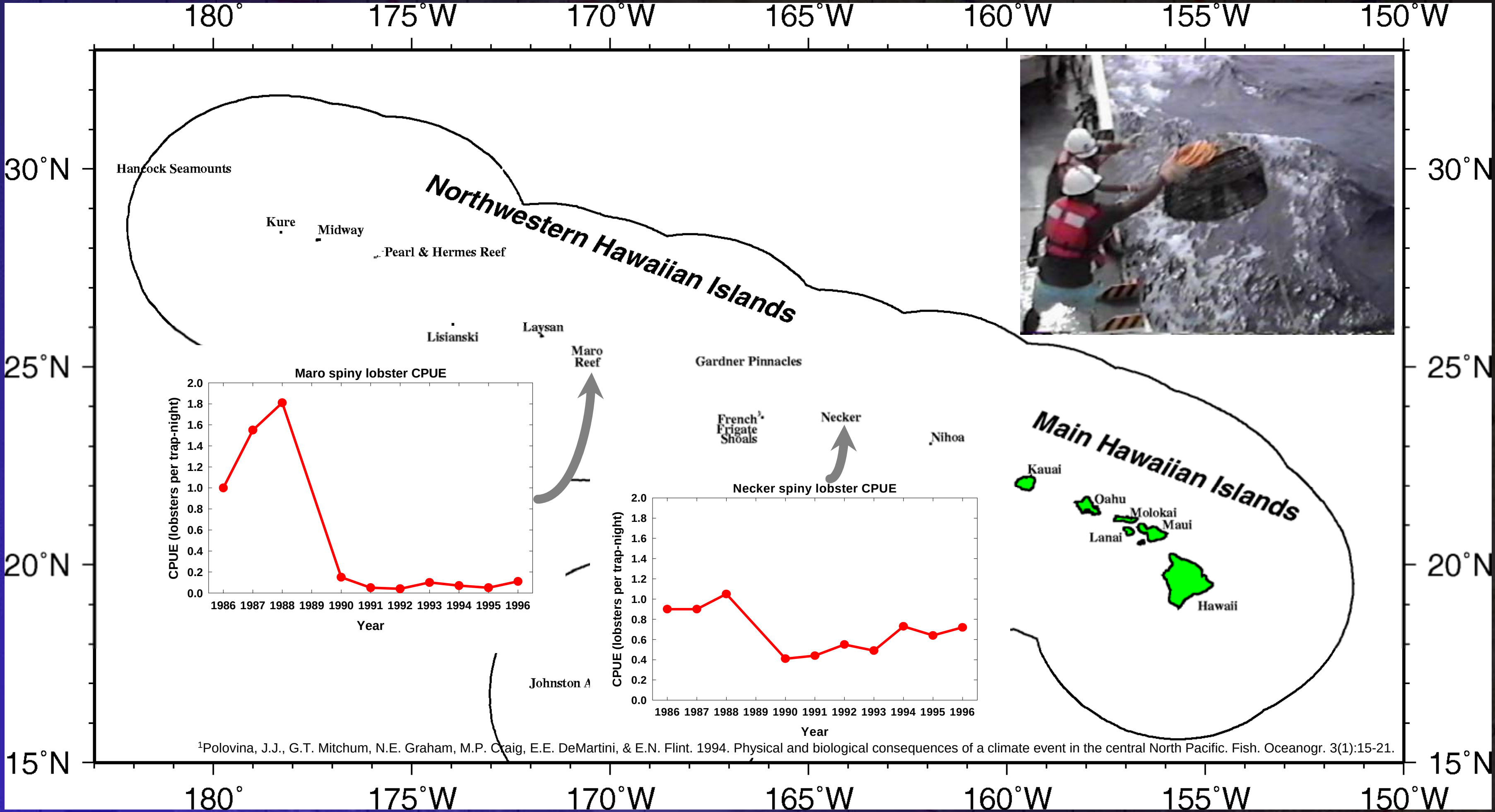


"metapopulations"

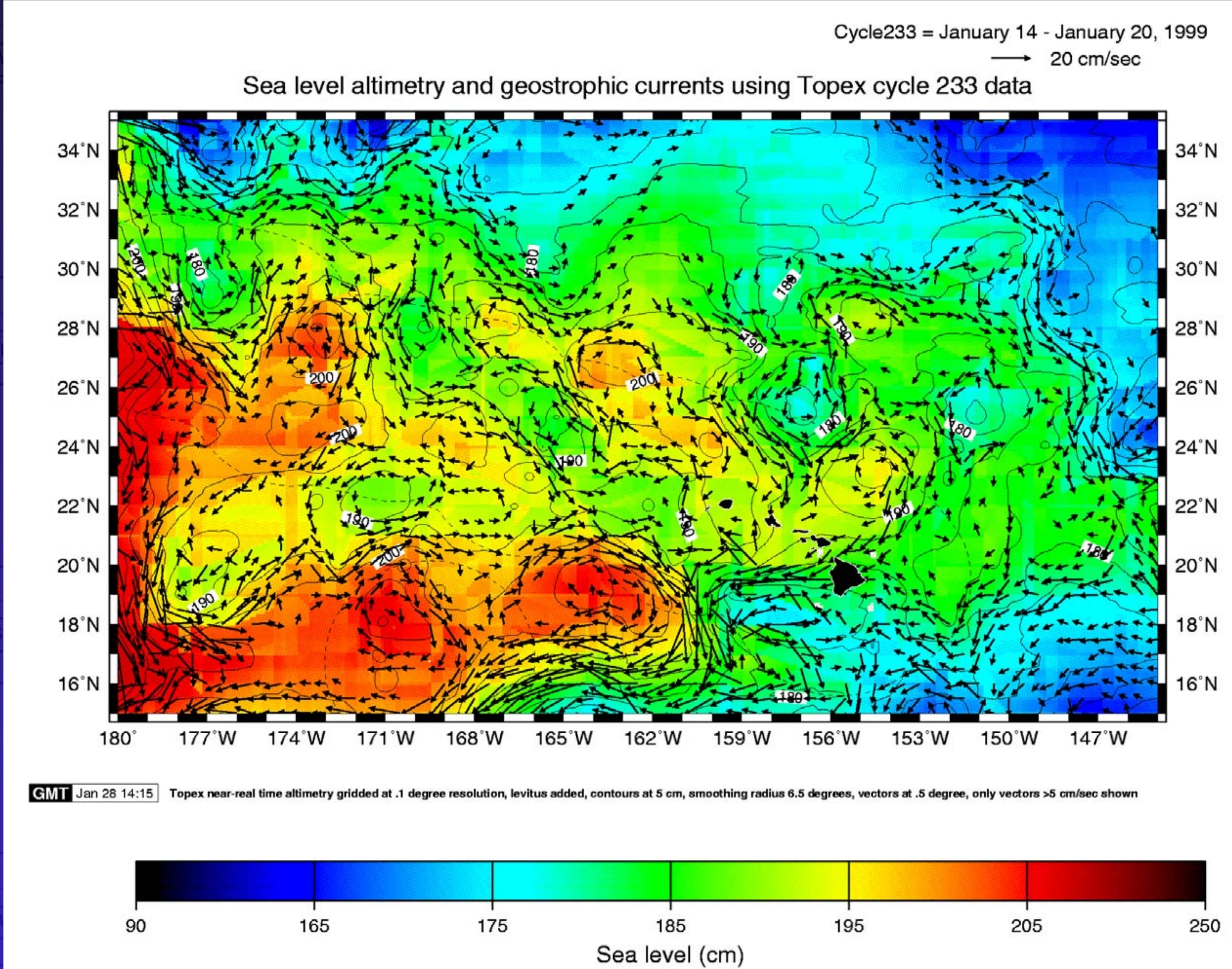


Spiny lobster CPUE from NMFS research surveys

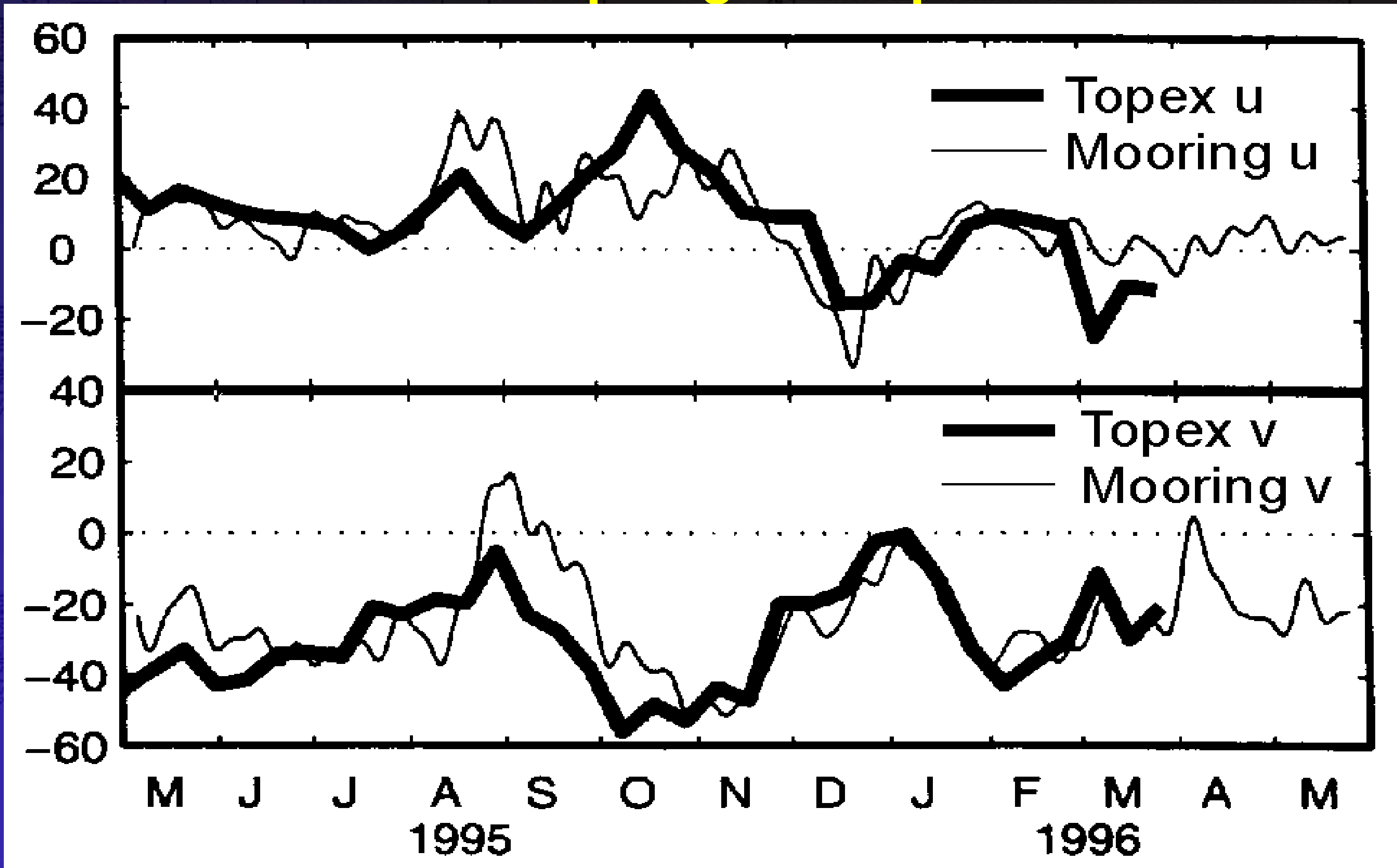
- 1990 decline linked to North Pacific climate/productivity event[1].
- Maro - large decrease with no recovery and no fishery.
- Necker - small decrease with recovery and sustained fishery.



[1]Polovina, J.J., G.T. Mitchum, N.E. Graham, M.P. Craig, E.E. DeMartini, & E.N. Flint. 1994. Physical and biological consequences of a climate event in the central North Pacific. Fish. Oceanogr. 3(1):15-21.

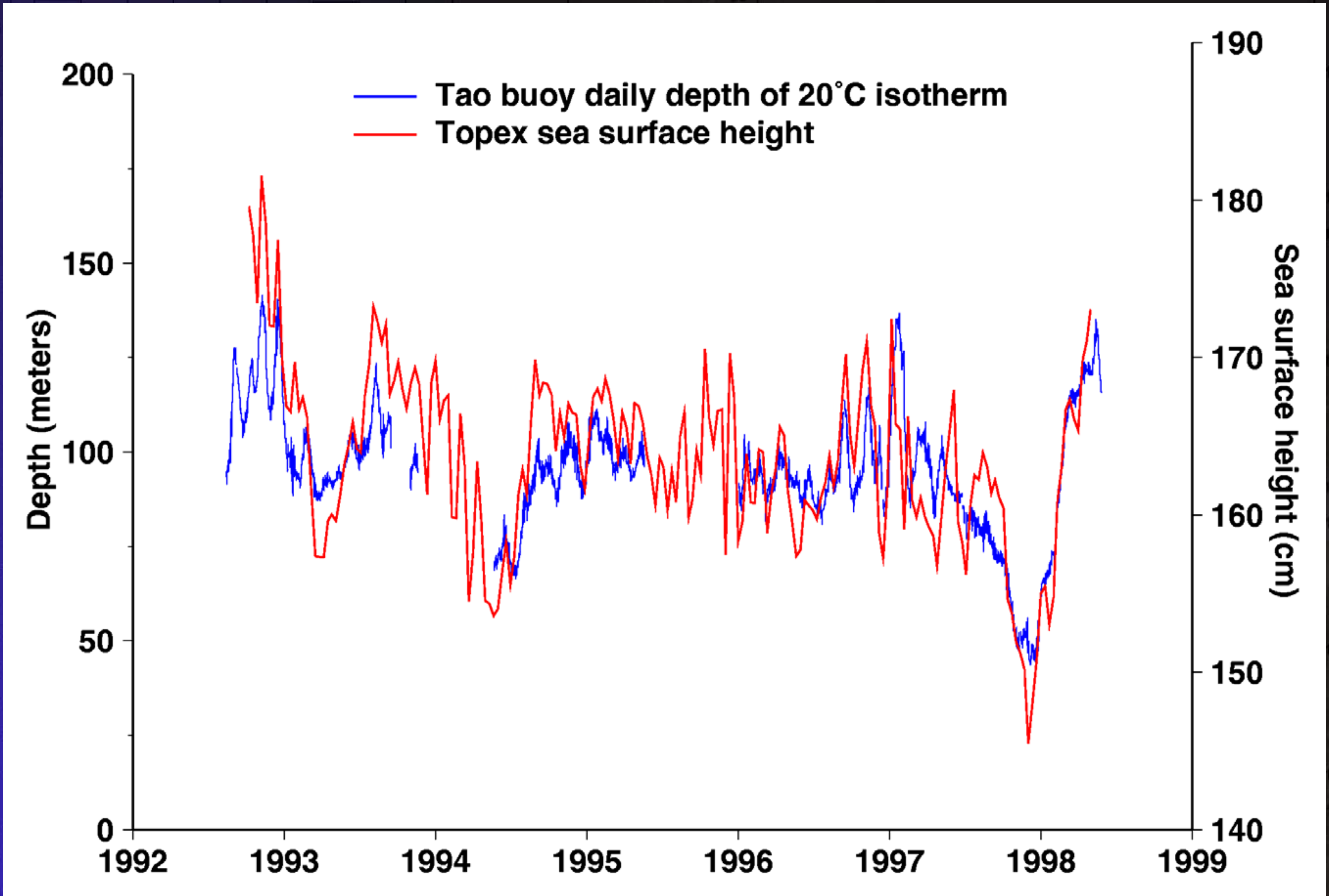

Cycle233 = January 14 - January 20, 1999
20 cm/sec
Sea level altimetry and geostrophic currents using Topex cycle 233 data
34°N
32°N
30°N
28°N
26°N
24°N
22°N
20°N
18°N
16°N
180°
177°W
174°W
171°W
168°W
165°W
162°W
159°W
156°W
153°W
150°W
147°W
GMT Jan 28 14:15
Topex near-real time altimetry gridded at .1 degree resolution, levitus added, contours at 5 cm, smoothing radius 6.5 degrees, vectors at .5 degree, only vectors >5 cm/sec shown
90
165
175
185
195
205
250
Sea level (cm)

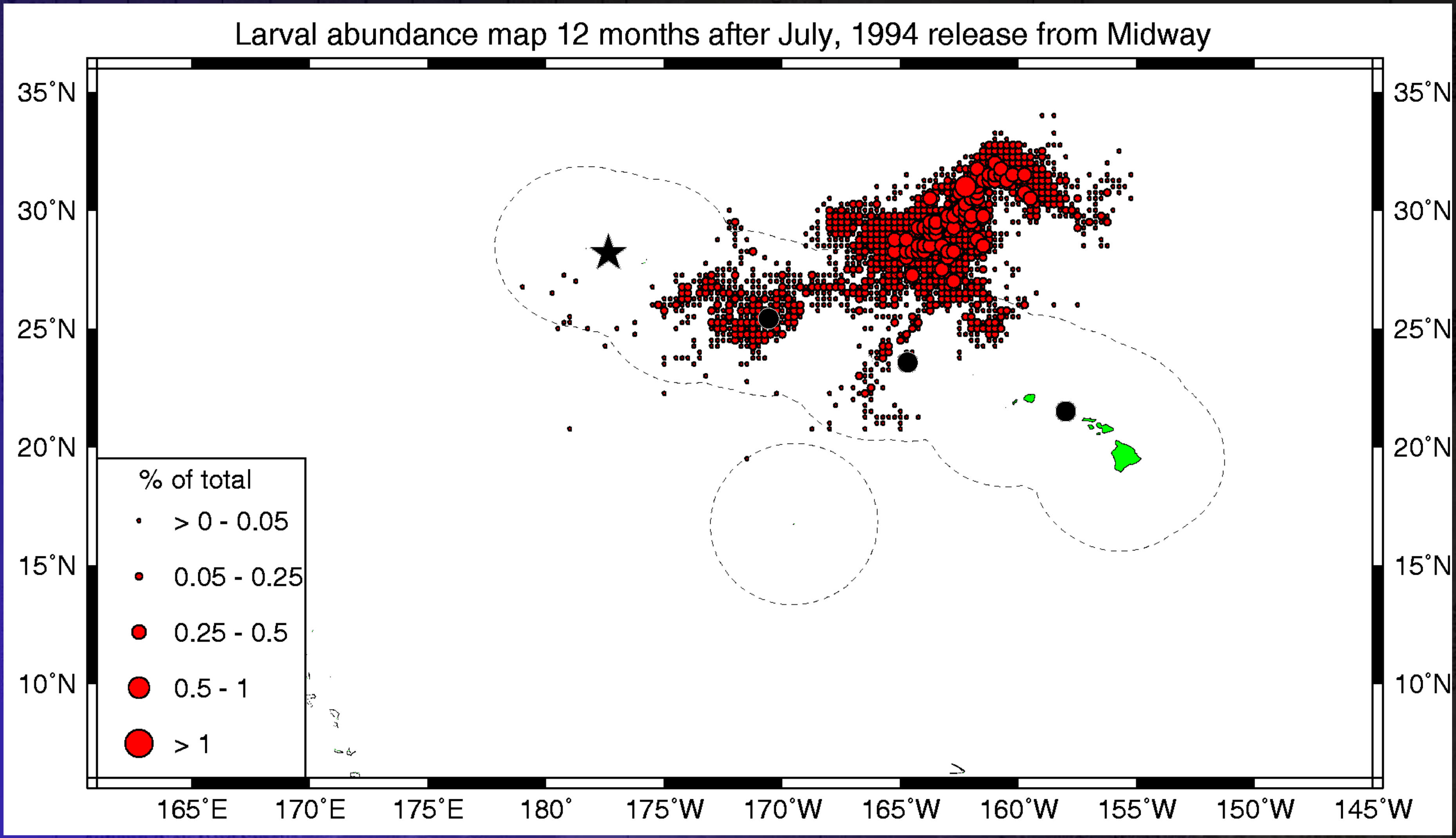
Validation of Topex geostrophic currents[1]

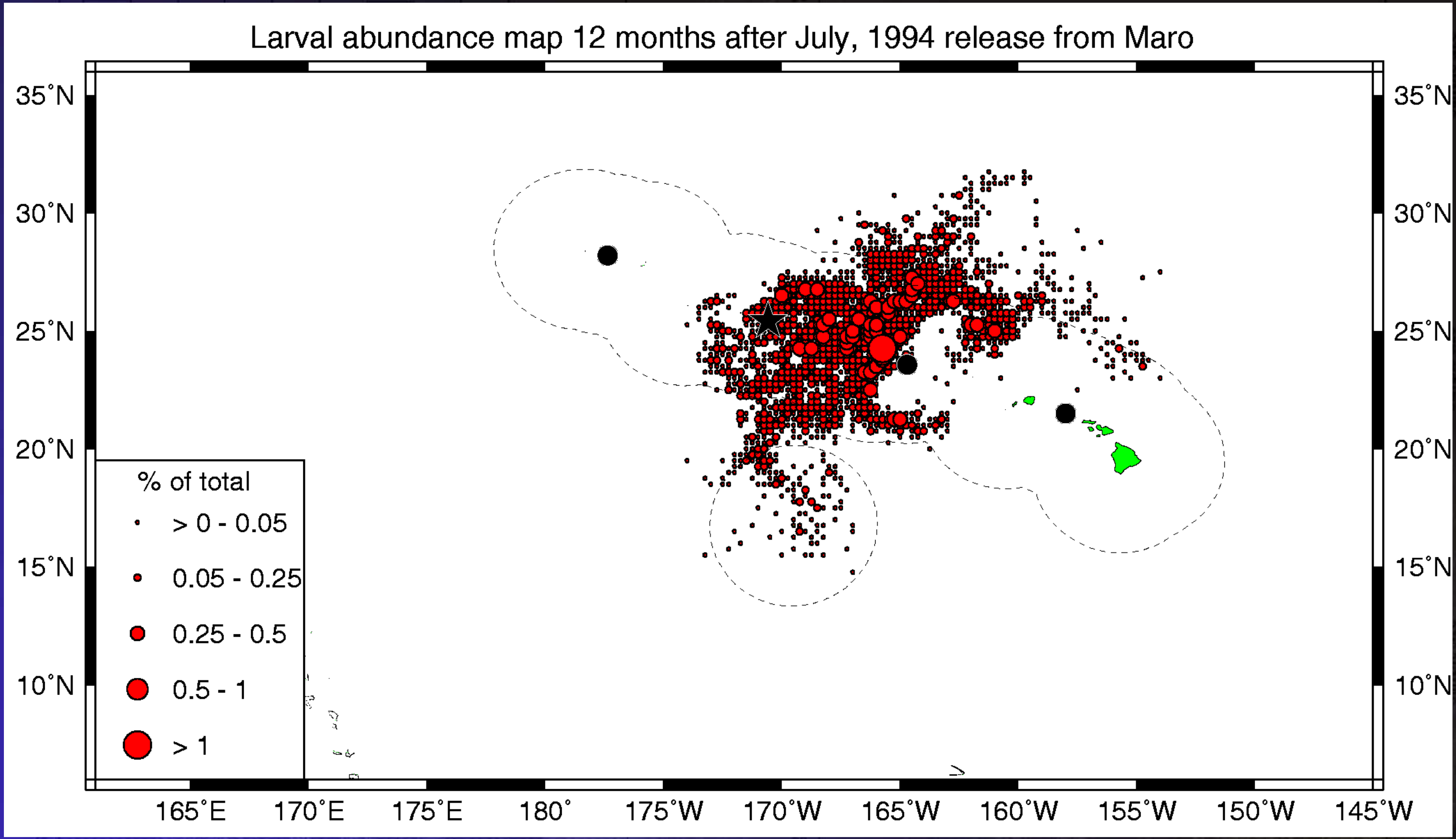


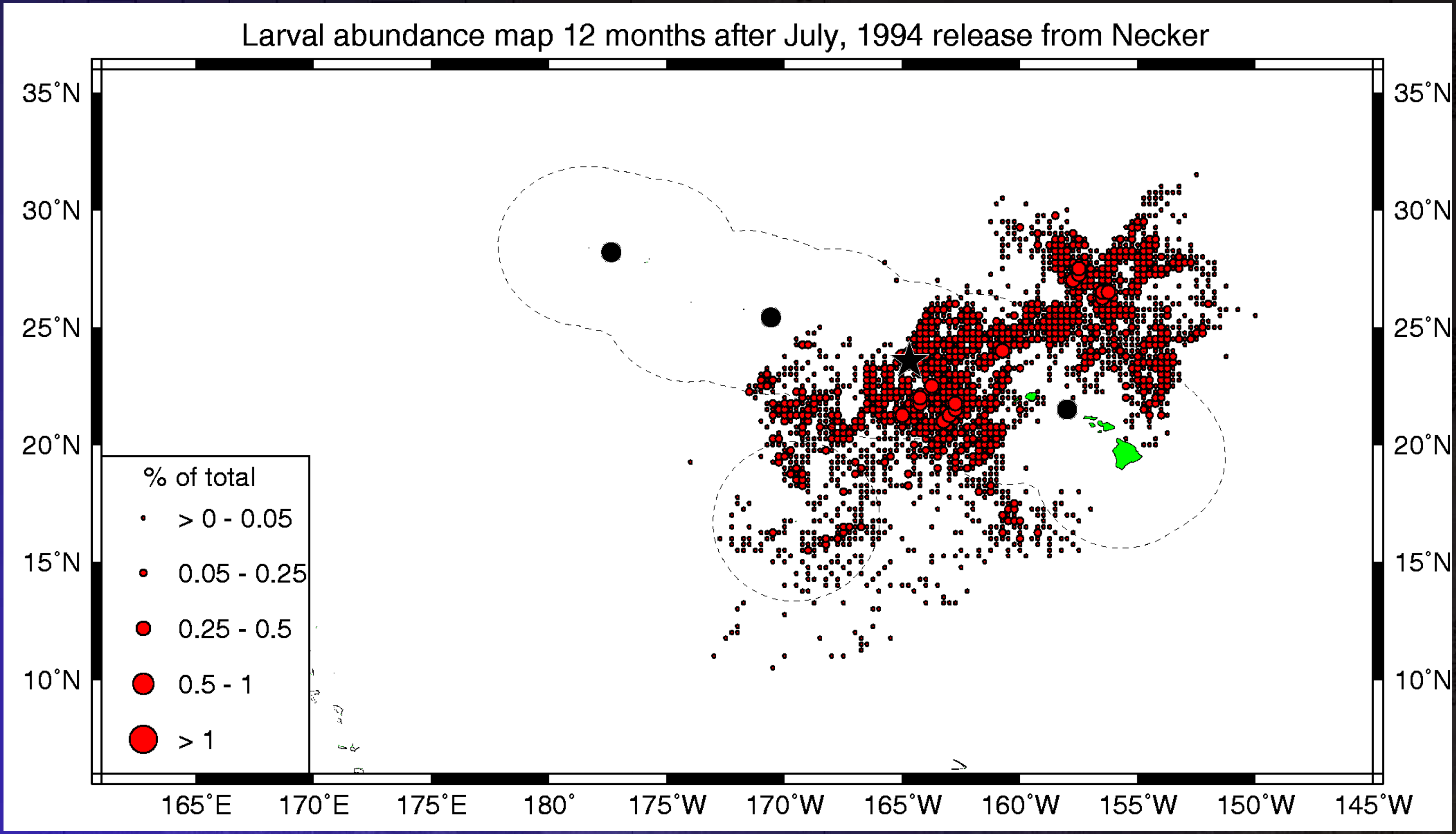
[1]Chiswell, S.M. & D. Roemmich. 1998. The East Cape Current and two eddies: a mechanism for larval retention? N. Z. J. Mar. Fresh. Res. 32:385-397.

Tao buoy isotherm depth and Topex sea surface height at 8°N - 155°W

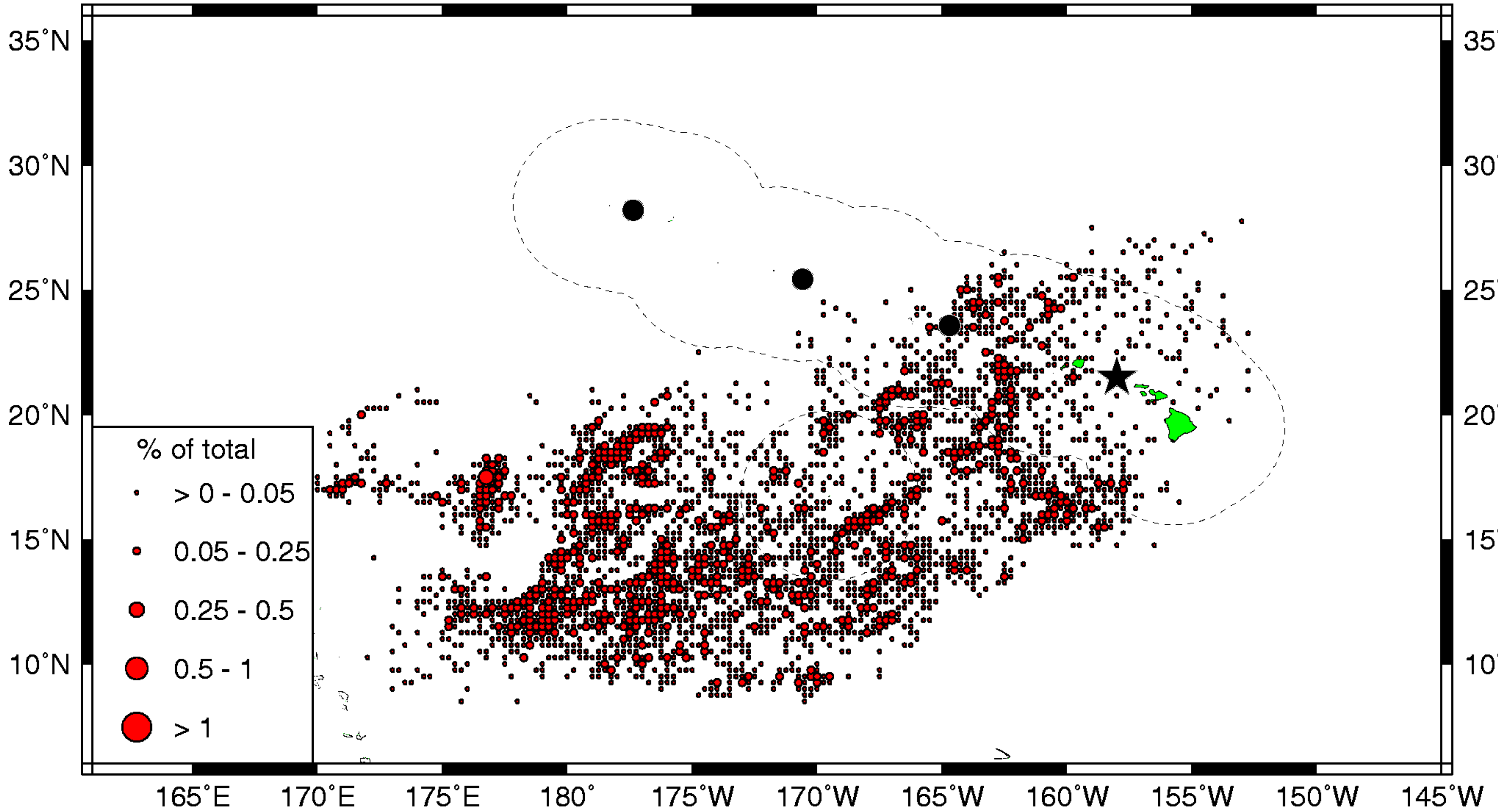


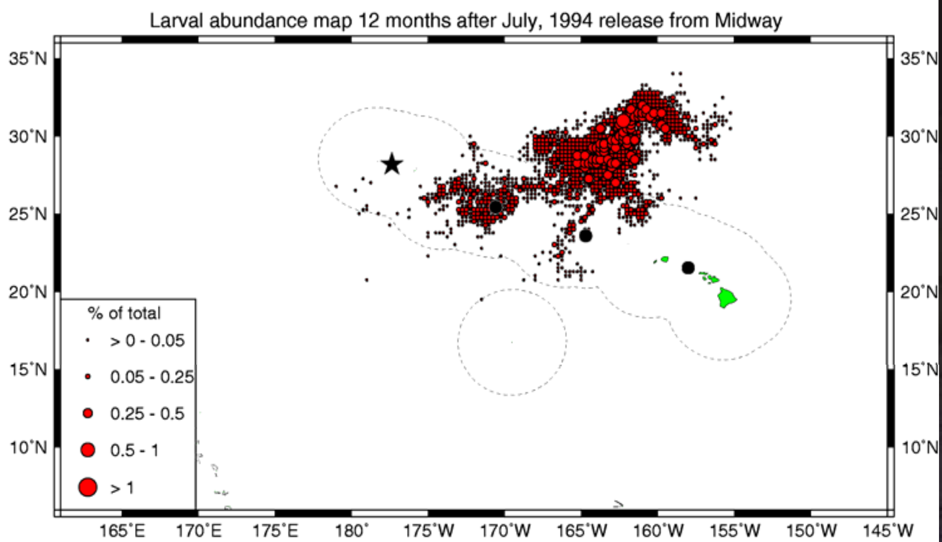

Larval abundance map 12 months after July, 1994 release from Midway
35˚N
30˚N
25˚N
20˚N
15˚N
10˚N
165˚E
170˚E
175˚E
180˚
175˚W
170˚W
165˚W
160˚W
155˚W
150˚W
145˚W
% of total
> 0 - 0.05
0.05 - 0.25
0.25 - 0.5
0.5 - 1
> 1

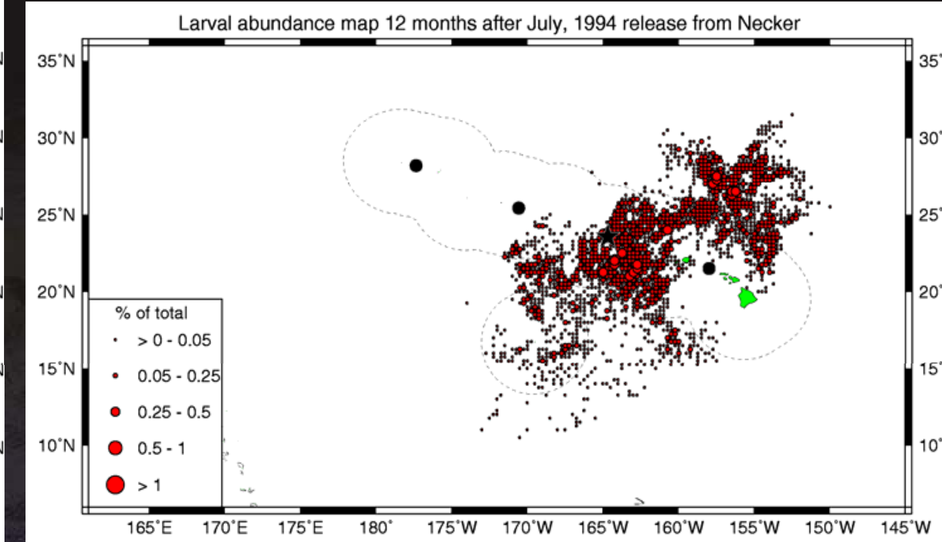

Larval abundance map 12 months after July, 1994 release from Maro
35°N
30°N
25°N
20°N
15°N
10°N
% of total
> 0 - 0.05
0.05 - 0.25
0.25 - 0.5
0.5 - 1
> 1
165°E
170°E
175°E
180°
175°W
170°W
165°W
160°W
155°W
150°W
145°W

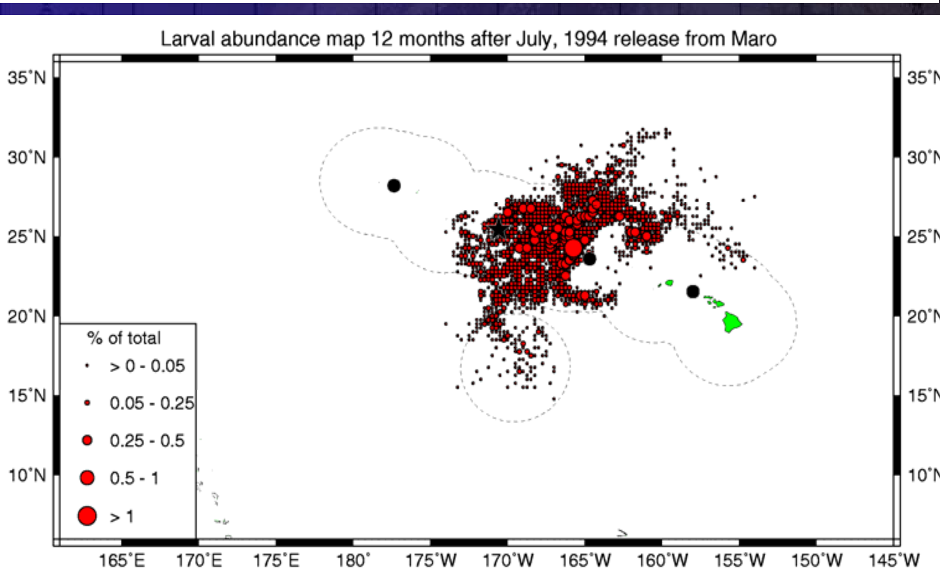

Larval abundance map 12 months after July, 1994 release from Necker
35°N
30°N
25°N
20°N
15°N
10°N
% of total
> 0 - 0.05
0.05 - 0.25
0.25 - 0.5
0.5 - 1
> 1
165°E
170°E
175°E
180°
175°W
170°W
165°W
160°W
155°W
150°W
145°W

Larval abundance map 12 months after July, 1994 release from Oahu




Larval abundance map 12 months after July, 1994 release from Midway
35°N
30°N
25°N
20°N
15°N
10°N
165°E 170°E 175°E 180° 175°W 170°W 165°W 160°W 155°W 150°W 145°W
% of total
> 0 - 0.05
0.05 - 0.25
0.25 - 0.5
0.5 - 1
> 1


Larval abundance map 12 months after July, 1994 release from Necker
35°N
30°N
25°N
20°N
15°N
10°N
165°E 170°E 175°E 180° 175°W 170°W 165°W 160°W 155°W 150°W 145°W
% of total
> 0 - 0.05
0.05 - 0.25
0.25 - 0.5
0.5 - 1
> 1


Larval abundance map 12 months after July, 1994 release from Maro
35°N
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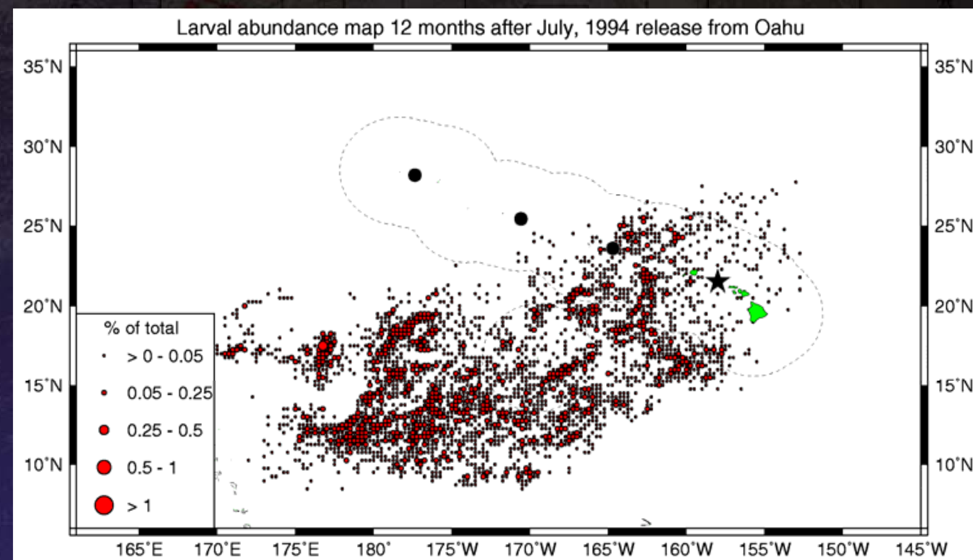
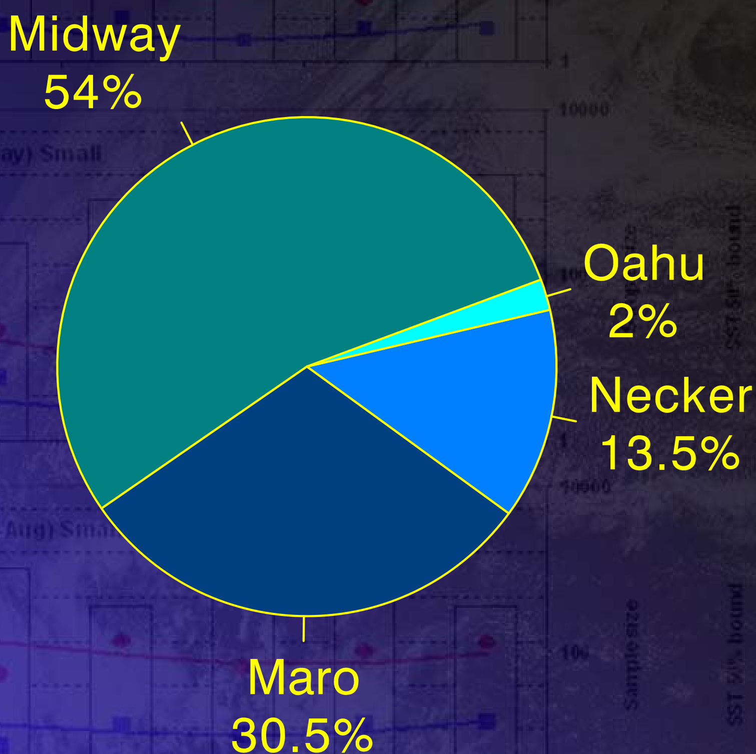
25°N
20°N
15°N
10°N
165°E 170°E 175°E 180° 175°W 170°W 165°W 160°W 155°W 150°W 145°W
% of total
> 0 - 0.05
0.05 - 0.25
0.25 - 0.5
0.5 - 1
> 1


Larval abundance map 12 months after July, 1994 release from Oahu
35°N
30°N
25°N
20°N
15°N
10°N
165°E 170°E 175°E 180° 175°W 170°W 165°W 160°W 155°W 150°W 145°W
% of total
> 0 - 0.05
0.05 - 0.25
0.25 - 0.5
0.5 - 1
> 1

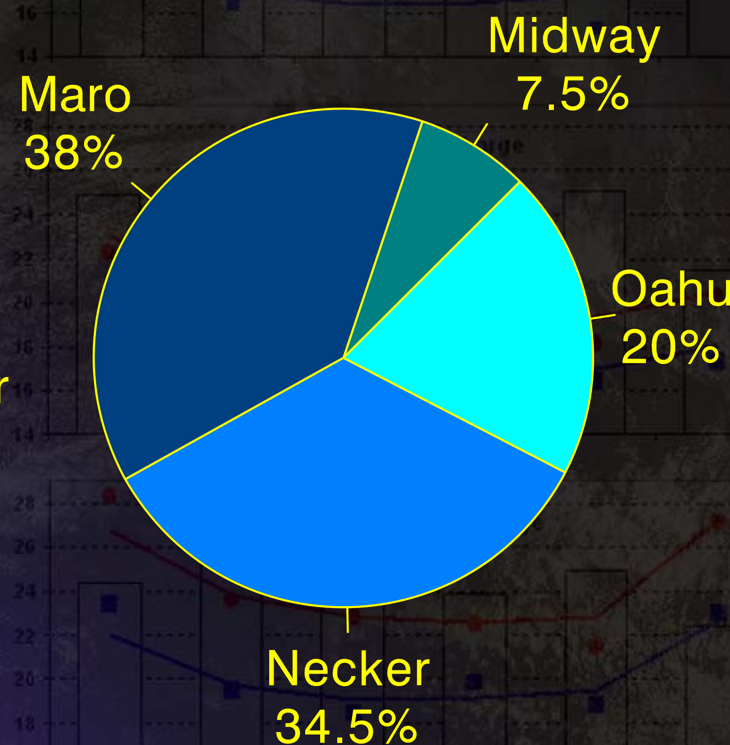
Source of Recruitment

(percentage of total)



Recruitment to Maro

(Retention=9.6%)



Recruitment to Necker

(Retention=16.7%)

1999 Fishery Bulletin paper

- Used 10-day, 0.5 degree latitude/longitude geostrophic flow fields derived from Topex-POSEIDON altimetry.
- Found strong spatial differences in retention and influx of larvae from other sites.
- Simulation results helped explain lack of recovery of northerly fishing grounds.

Application of TOPEX-POSEIDON satellite altimetry to simulate transport dynamics of larvae of spiny lobster, *Panulirus marginatus*, in the Northwestern Hawaiian Islands, 1993–1996

Jeffrey J. Polovina
Pierre Kleiber
Donald R. Kobayashi
Honolulu Laboratory, Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
2570 Dole Street, Honolulu, Hawaii 96822-2396
E-mail address (for J. J. Polovina): Jeffrey.Polovina@noaa.gov

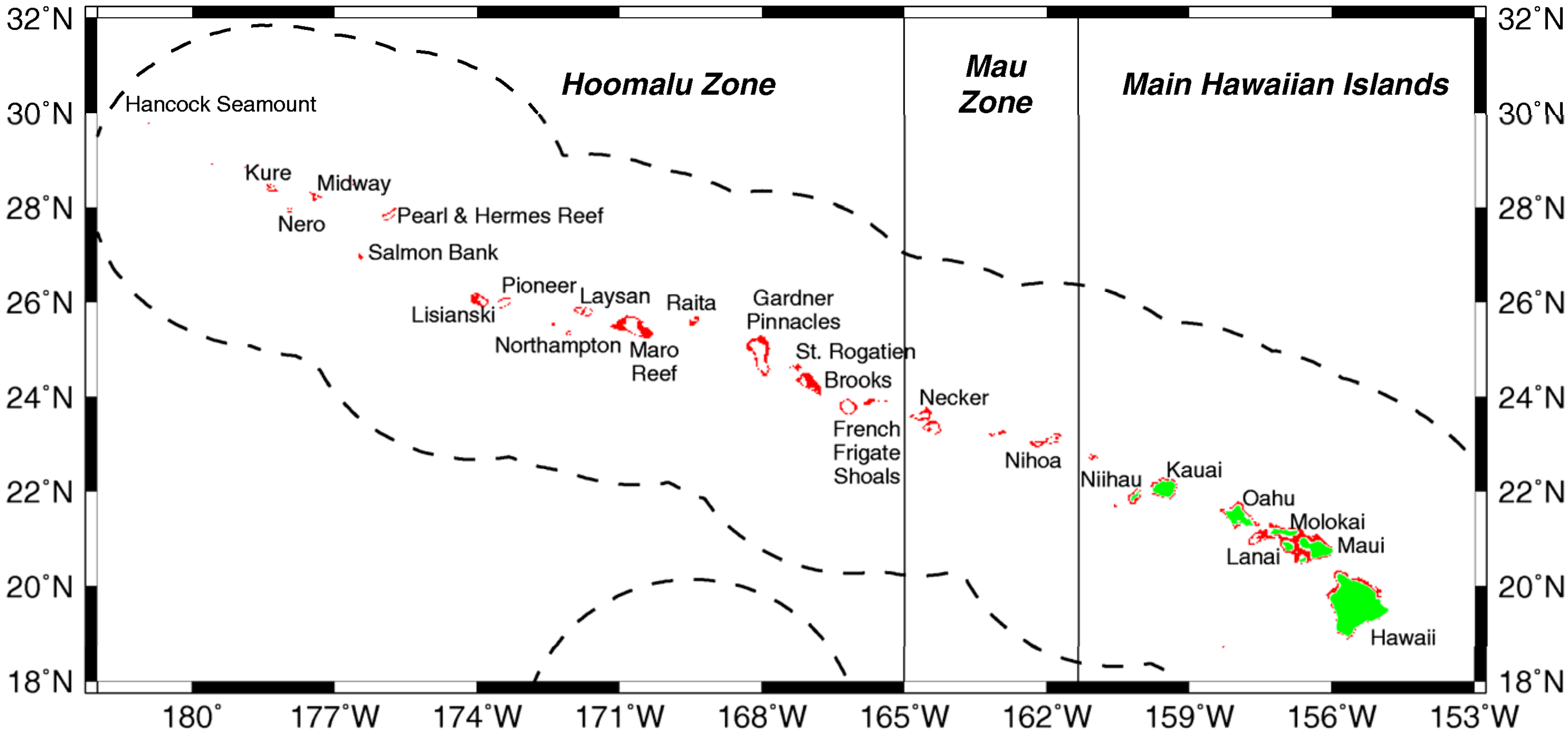
Abstract.—A commercially valuable trap fishery for spiny lobster (*Panulirus marginatus*) has existed in the Northwestern Hawaiian Islands since the late 1970s. Fisheries landings and research trapping show that spawning biomass and recruitment to the fishery collapsed in 1990 in the northern portion of the fishing ground and that there has been no recovery to the present, although recruitment remained strong at banks 670 km to the southeast. An advection-diffusion model is used to investigate larval transport dynamics between these two regions. The movement model is driven by geostrophic currents computed every 10 days from sea surface height obtained from TOPEX-POSEIDON satellite altimetry. The larval transport simulations indicate that even though larvae have a pelagic period of 12 months, banks differ substantially in the proportion of larvae they retain from resident spawners as well as the proportion of larvae they receive from other banks. In particular, recruitment to the northern portion of the fishing grounds is weak due to a very low local spawning biomass and a very limited contribution of larvae from the area of strong recruitment and high spawning biomass in the southeast. The results also suggest that satellite altimetry can provide useful information on physical dynamics for recruitment studies.

Manuscript accepted 18 March 1998.
Fish. Bull. 97:132–143 (1999).

The spiny lobster, *Panulirus marginatus*, is endemic to the Hawaiian Archipelago and Johnston Atoll. The species is found throughout the archipelago and is the target of a trap fishery in the northwestern portion of the archipelago known as the Northwestern Hawaiian Islands (NWHI). From the early 1980s to 1990, the majority of fishery catches came from two banks, Necker Island and Maro Reef, located 670 km northwest of Necker Island (Fig. 1). Catches during this period averaged about 60% from Maro Reef, 40% from Necker Island. However, in 1990 there was a dramatic collapse in recruitment of 3-year-old lobsters to the fishery at Maro Reef, and other banks north of Maro; this collapse has been attributed to climate-induced change in productivity that has impacted various other trophic levels, such as sea birds, monk seals, and reef fishes (Polovina et al., 1994). After the recruitment collapse, the fishery reduced the spawning biomass to very low levels at Maro and at other northern banks, and then fishing ceased in these areas. Even with the absence of fishing at Maro for at least six years, there is still no evidence of a recovery in recruitment as indicated from a time series of the relative abundance of 3-year-olds obtained from a standardized research survey (Fig. 2). However, at Necker, 670 nmi to the southeast, the recruitment drop at the end of the 1980s was much less severe and recovery has occurred in recent years and has supported a fishery (Fig. 2). The striking differences in recruitment levels over the past seven years between the two banks raises the possibility that there is limited larval mixing between the two banks.

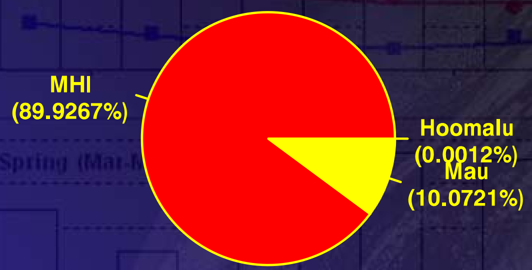
Current management for the lobster fishery is based on the hypothesis that recruitment to the NWHI banks comes from a well-mixed pool of larvae with contributions from the entire archipelago, and this pool of larvae oscillates seasonally along the archipelago, pushed northwest in the spring and summer with tradewind-driven Ekman transport and pushed back southeast in the fall and winter with westerly wind-driven Ekman transport (MacDonald, 1986). A genetic analysis during 1978–80 examined allozyme variation in spiny lobsters from seven banks covering a substantial spatial range of the Hawaiian Archipelago and found no evidence of genetic differentiation between banks (Shaklee and Samollow, 1984). However, a subsequent study in 1987, using a

Estimated bottomfish habitat in Hawaiian Archipelago

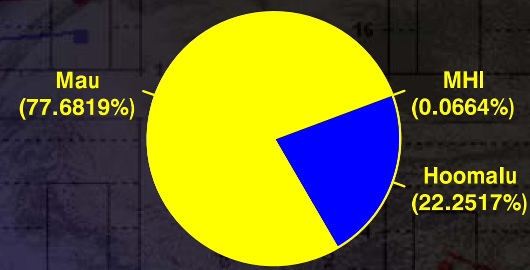


GMT Jan 30 07:56 Smith and Sandwell altimetry-derived bathymetry at 2 minute resolution, habitat range defined 30-200 fathoms, this is file dump_habitat_topo_6.2.ps

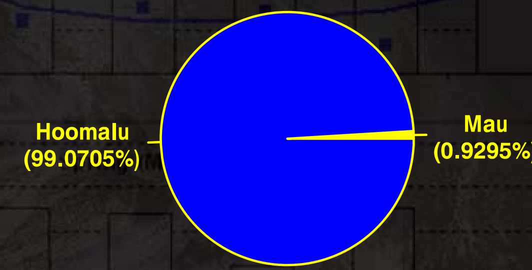
Source of Recruitment



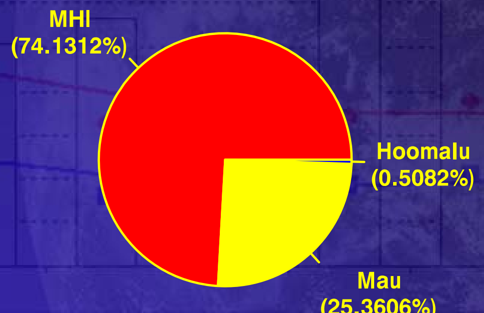
MHI - 3 months



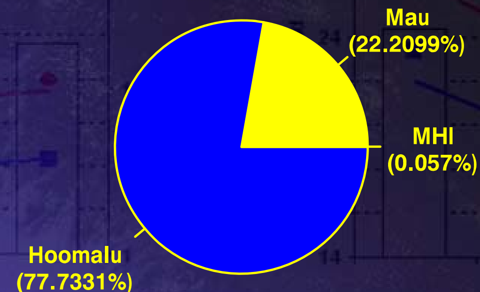
Mau Zone - 3 months



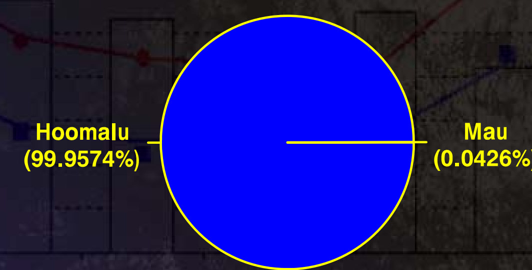
Hoomalu Zone - 3 months



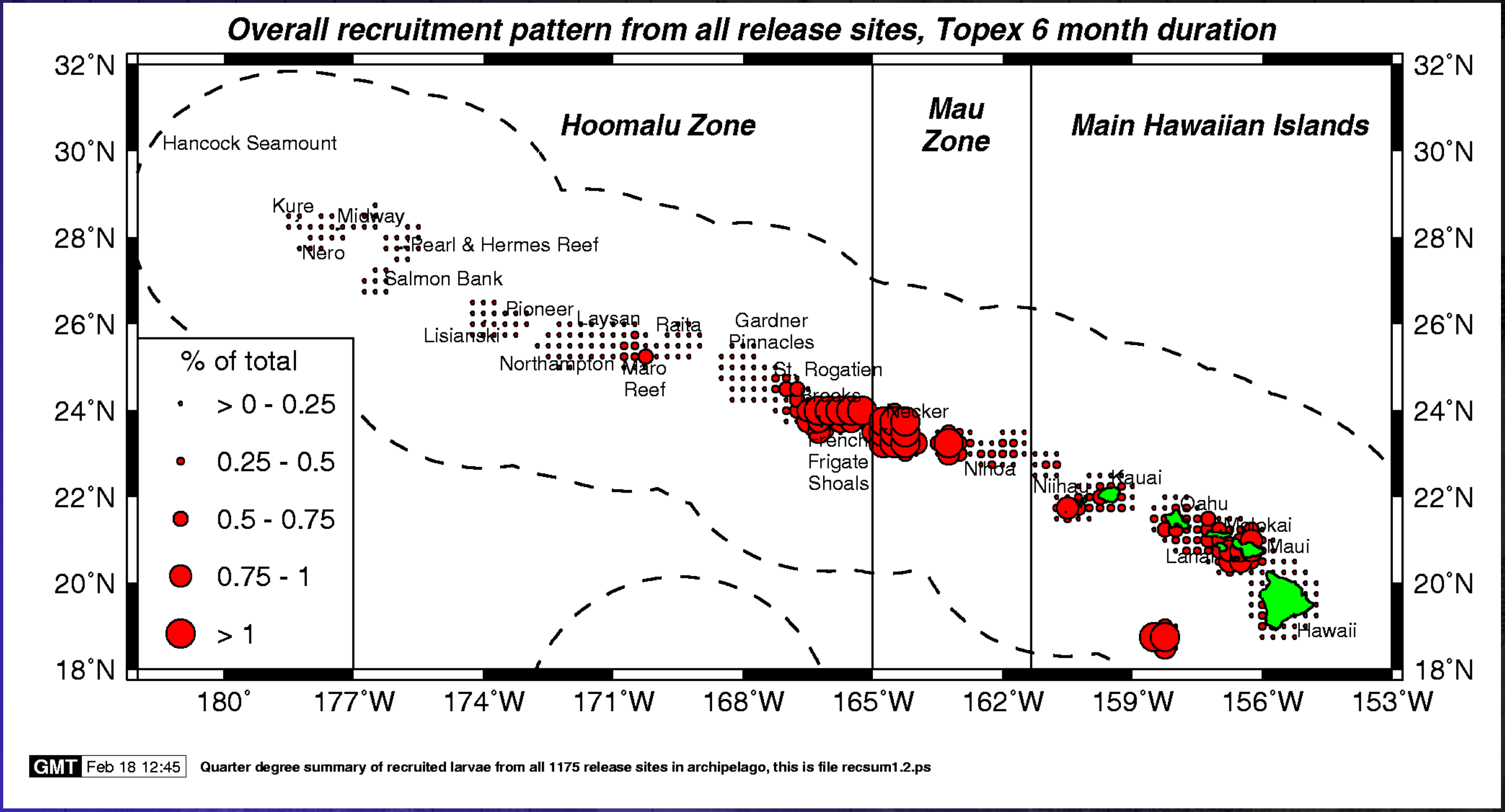
MHI - 6 months



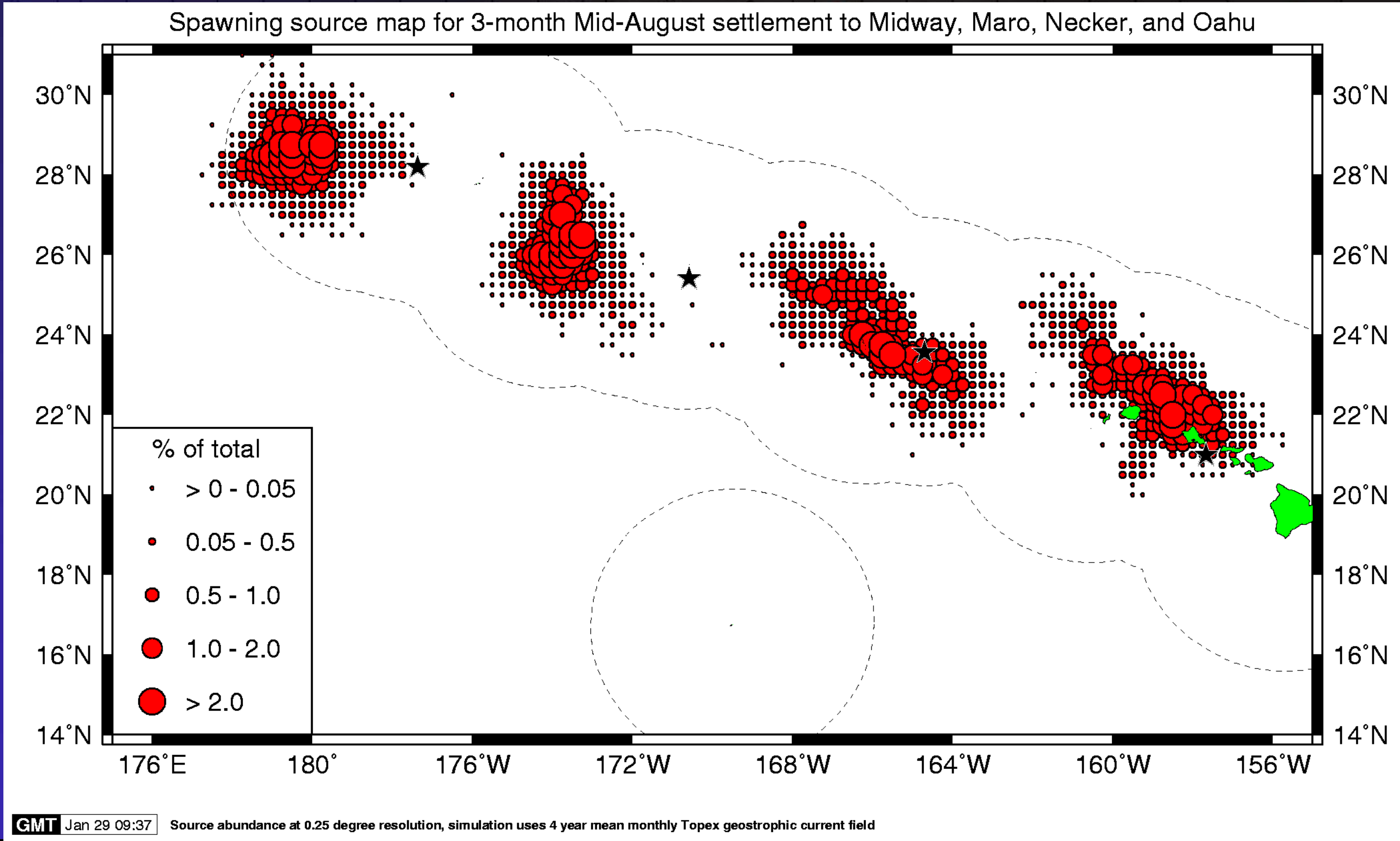
Mau Zone - 6 months



Hoomalu Zone - 6 months



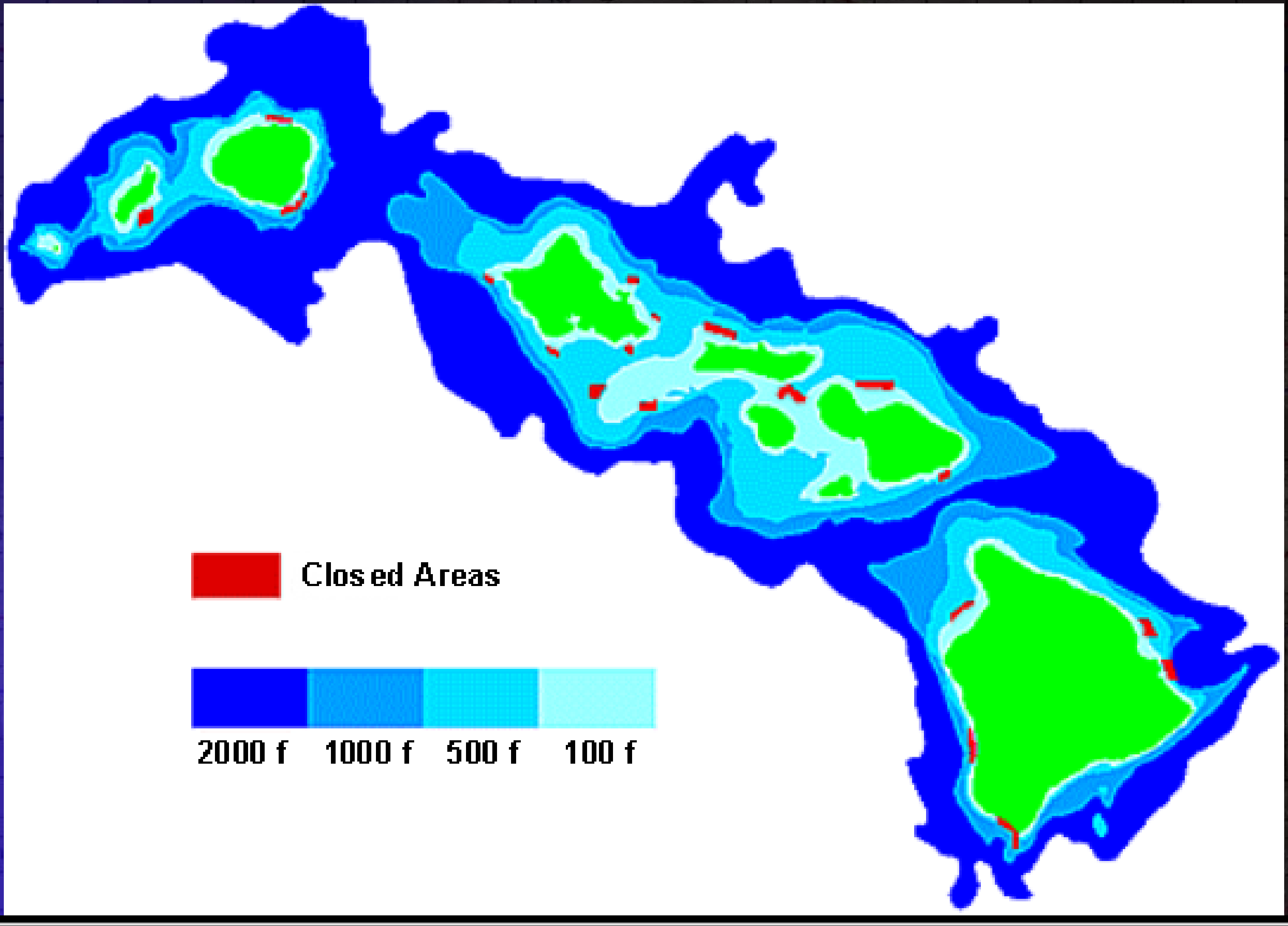
Overall recruitment pattern from all release sites, Topex 6 month duration
Hoomalu Zone
Mau Zone
Main Hawaiian Islands
Hancock Seamount
Kure
Midway
Nero
Pearl & Hermes Reef
Salmon Bank
Pioneer
Lisianski
Laysan
Raita
Northampton
Maro Reef
Gardner Pinnacles
St. Rogatien
Brooks
Necker
French Frigate Shoals
Nihoa
Niihau
Kauai
Oahu
Molokai
Maui
Lanai
Hawaii
% of total
> 0 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
> 1
32˚N
30˚N
28˚N
26˚N
24˚N
22˚N
20˚N
18˚N
180˚
177˚W
174˚W
171˚W
168˚W
165˚W
162˚W
159˚W
156˚W
153˚W
GMT Feb 18 12:45
Quarter degree summary of recruited larvae from all 1175 release sites in archipelago, this is file recsum1.2.ps



Pacific Islands Fisheries Science Center
Ecosystems and Oceanography Division

Pago Pago Room, Imin Center
May 19-22, 2008

Main Hawaiian Islands closed areas for deepwater bottomfish - State of Hawaii, 1998



Summary of earlier work

- Geostrophic current fields derived from TOPEX satellite altimetry were used to drive advection-diffusion larval transport models.
- The spiny lobster analyses showed that larval transport dynamics may explain why the Maro population has not recovered.
- The bottomfish analyses have been used to supplement genetics information for stock definition and population mixing.
- The models provide useful insights into recruitment dynamics such as predictions of high-recruitment areas or "sourcing" of recruits.

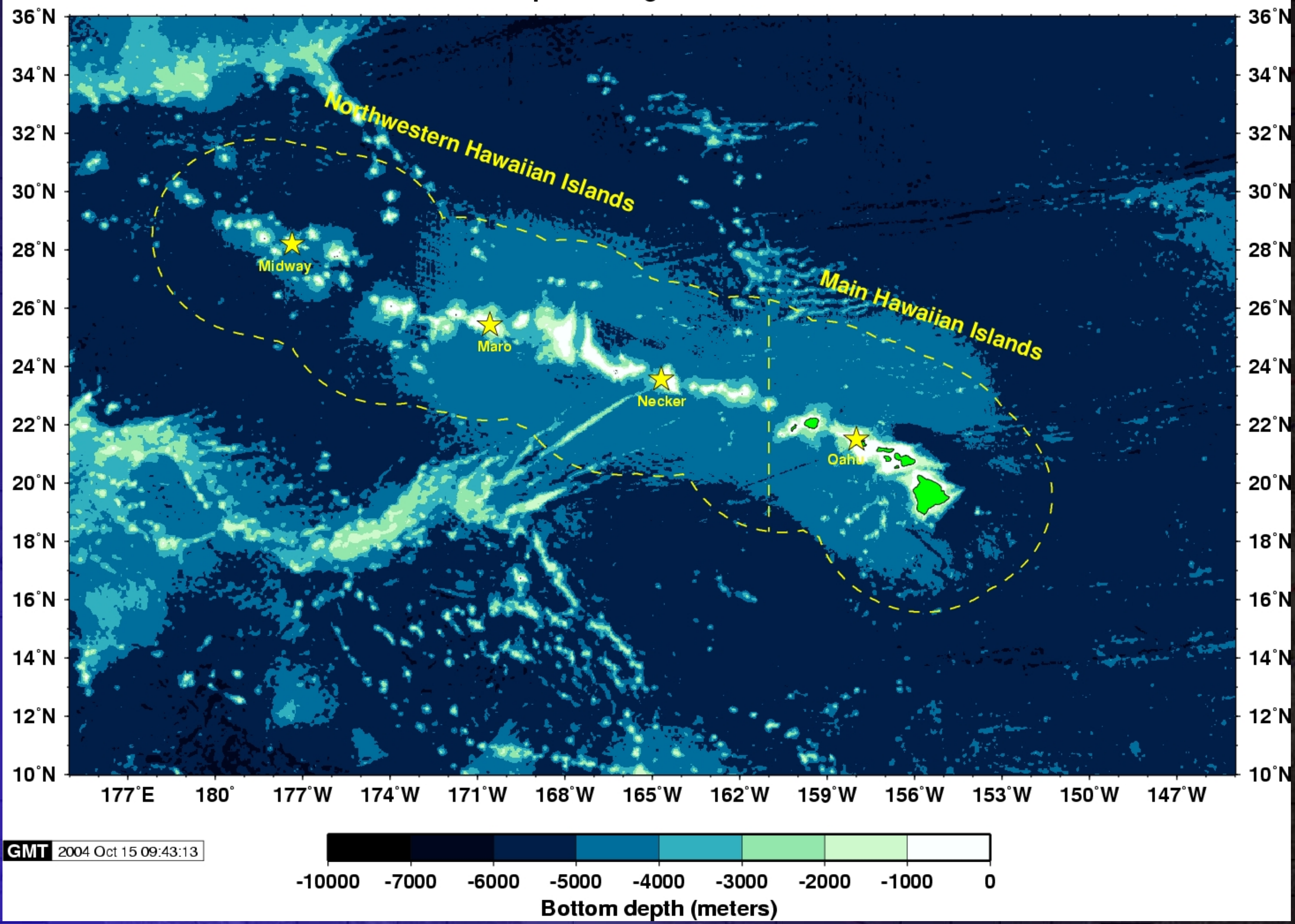
General discussion of data and methods

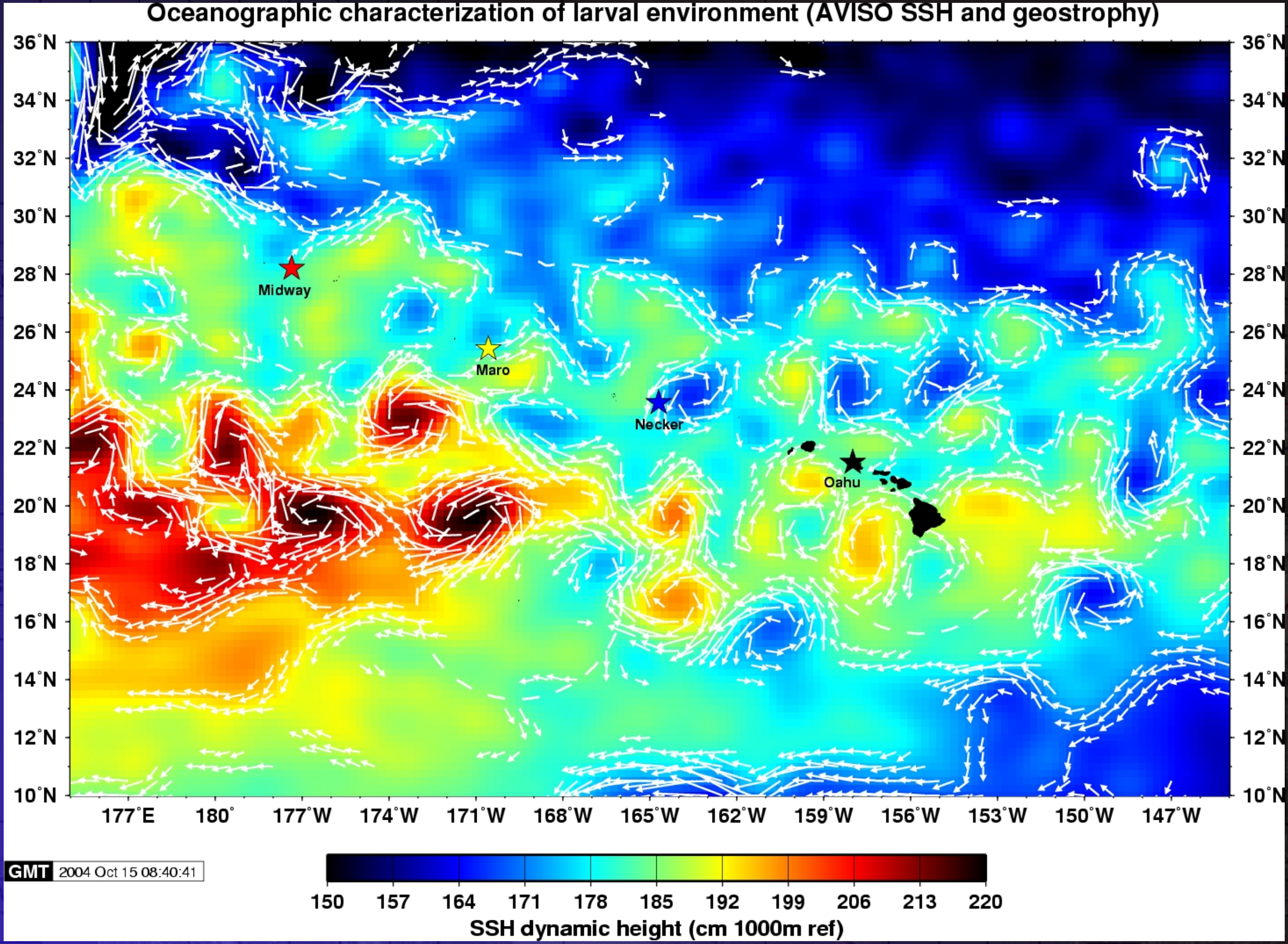
- Review of oceanographic data.
- Review of Lagrangian methodology.

Data Sources

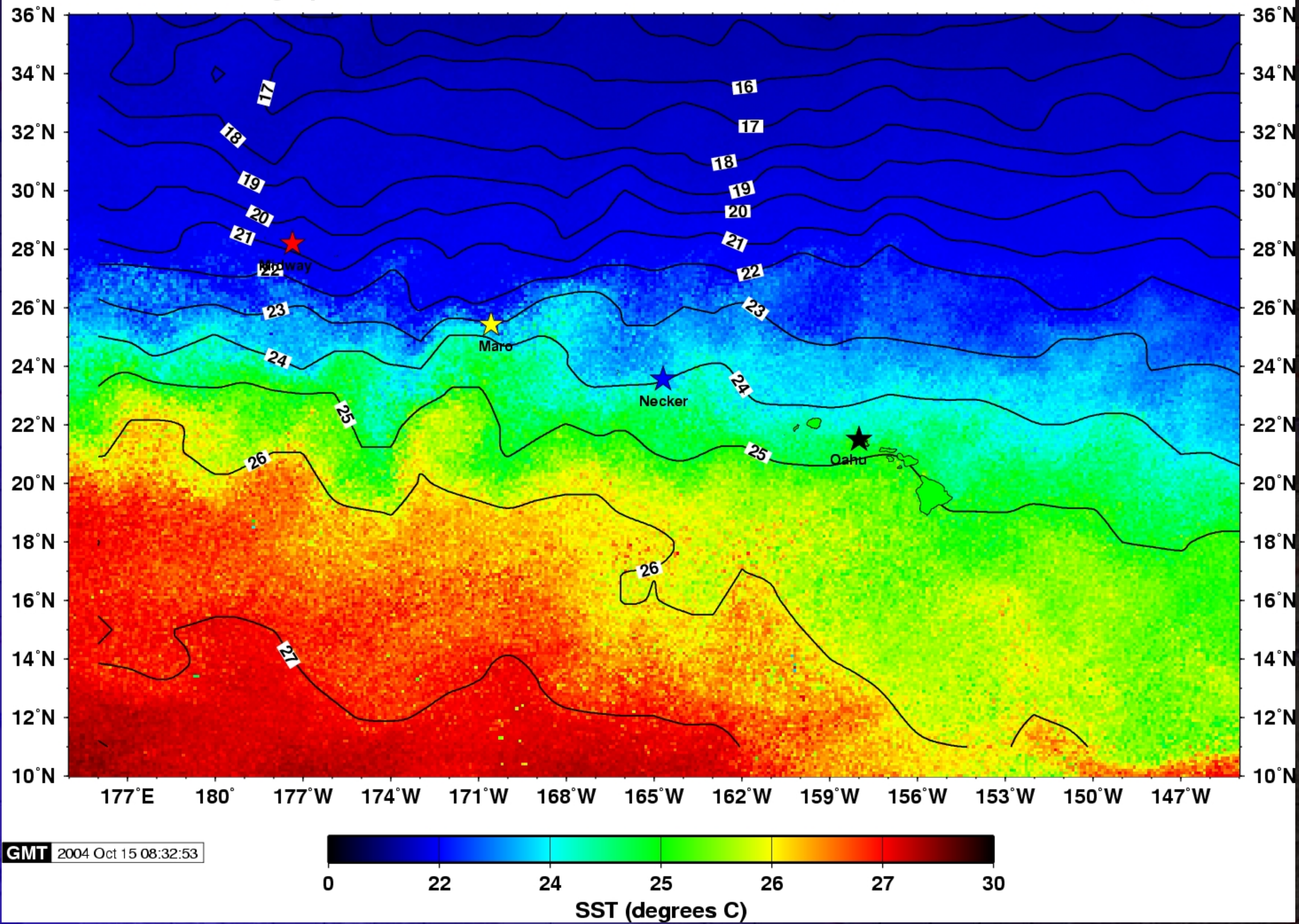
- Satellite altimetry derived geostrophic currents (Topex/POSEIDON, ERS, Jason, AVISO).
- OSCAR surface currents (NOAA).
- Naval Research Laboratory Layered Ocean Model (NLOM), Coastal Ocean Model (NCOM).
- Regional Ocean Model System (ROMS), Hybrid Coordinate Ocean Model (HYCOM).
- SST (MCSST, Pathfinder), ocean color (SeaWiFS, MODIS), winds (QuikSCAT).
- UH tidal model data.

Reference map showing larval release locations

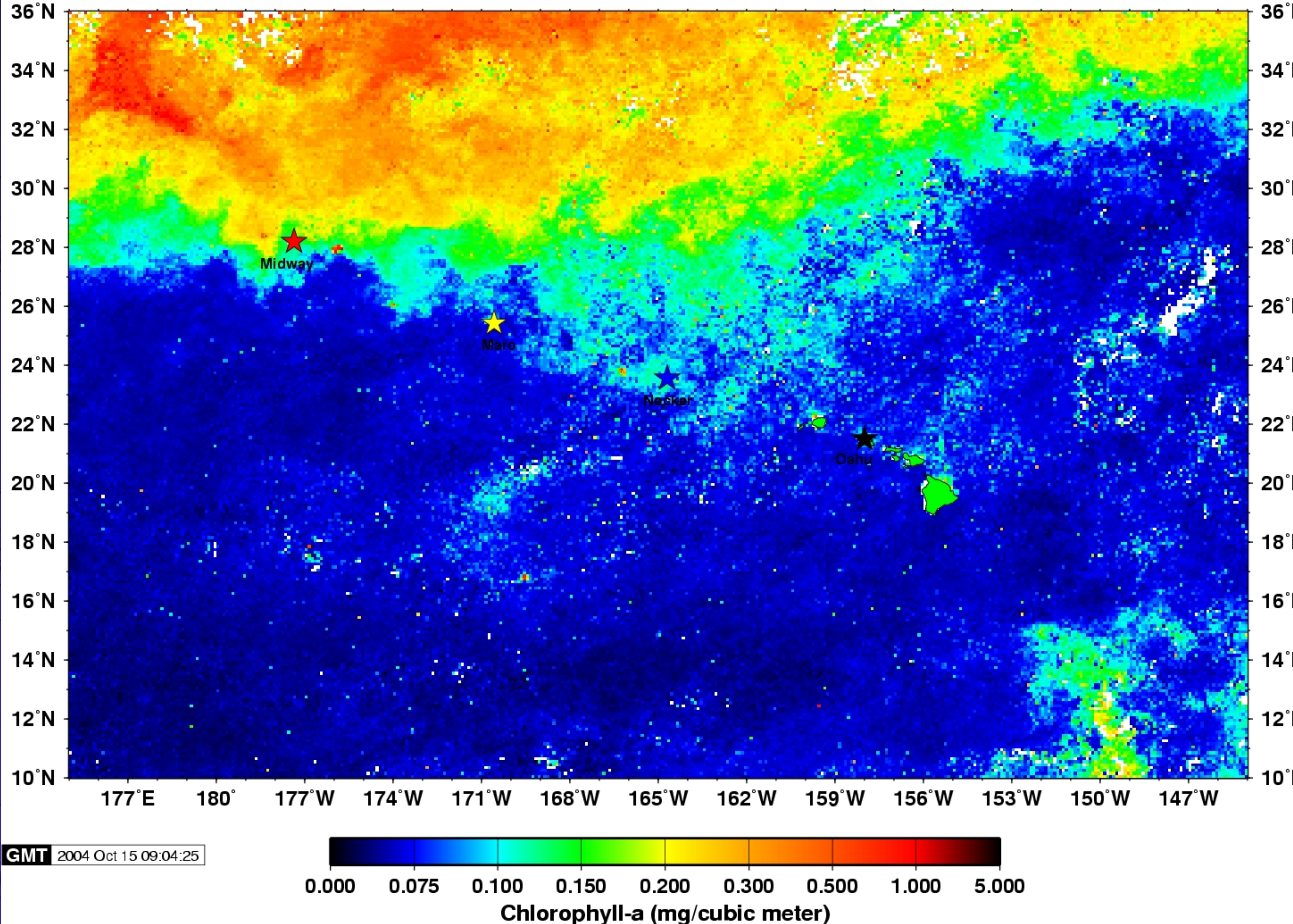


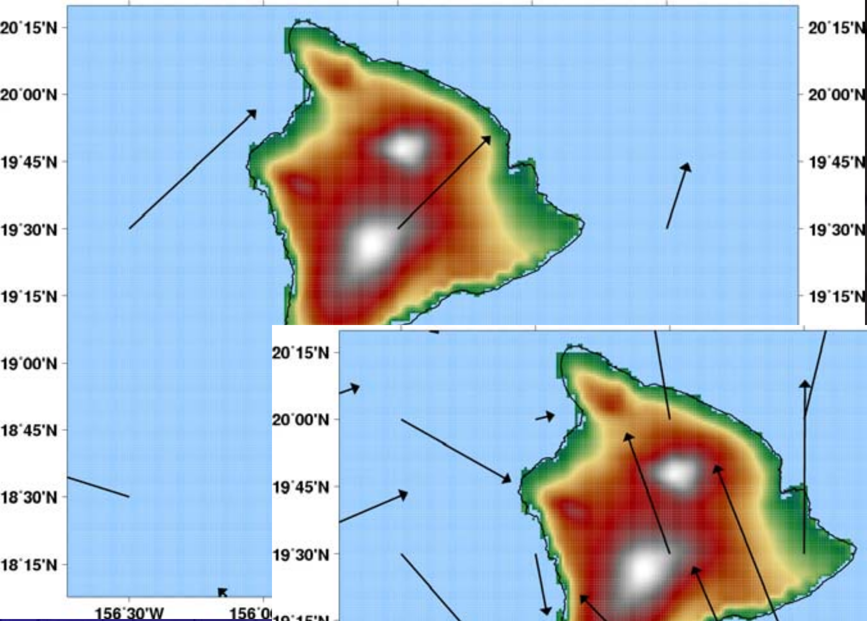

Oceanographic characterization of larval environment (AVISO SSH and geostrophy)
36°N
34°N
32°N
30°N
28°N
26°N
24°N
22°N
20°N
18°N
16°N
14°N
12°N
10°N
Midway
Maro
Necker
Oahu
177°E
180°
177°W
174°W
171°W
168°W
165°W
162°W
159°W
156°W
153°W
150°W
147°W
GMT 2004 Oct 15 08:40:41
150 157 164 171 178 185 192 199 206 213 220
SSH dynamic height (cm 1000m ref)

Oceanographic characterization of larval environment (Pathfinder AVHRR SST)

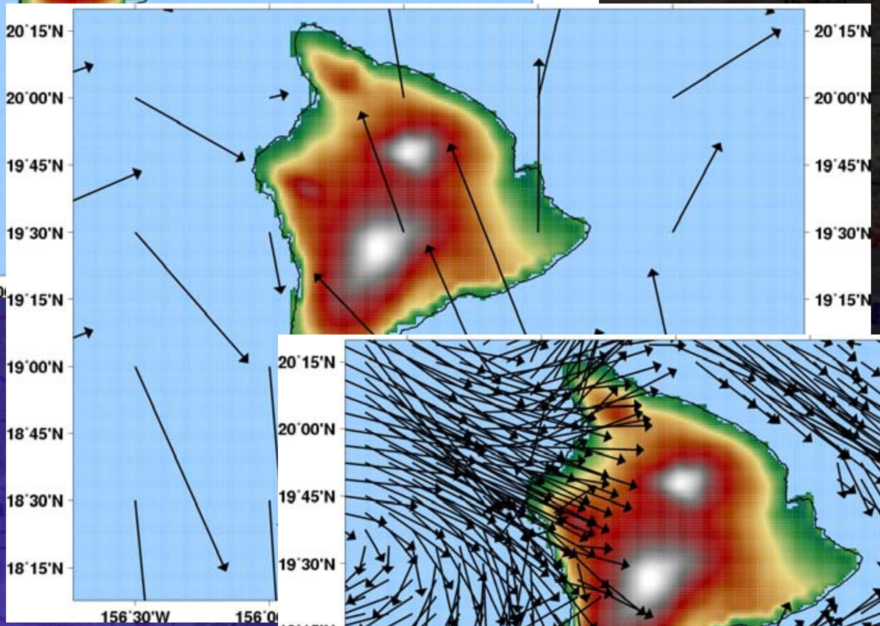


Oceanographic characterization of larval environment (SeaWiFS chlorophyll-a density)

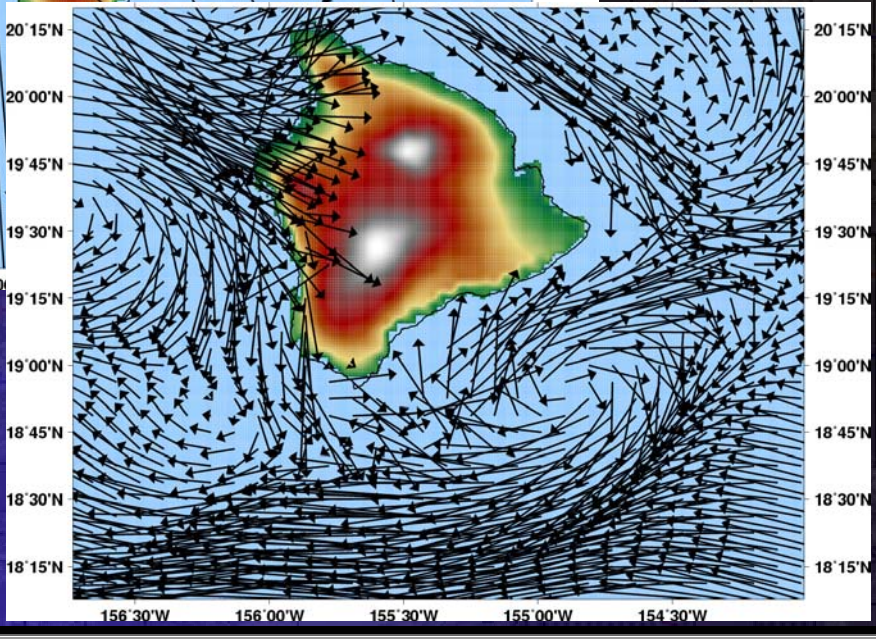




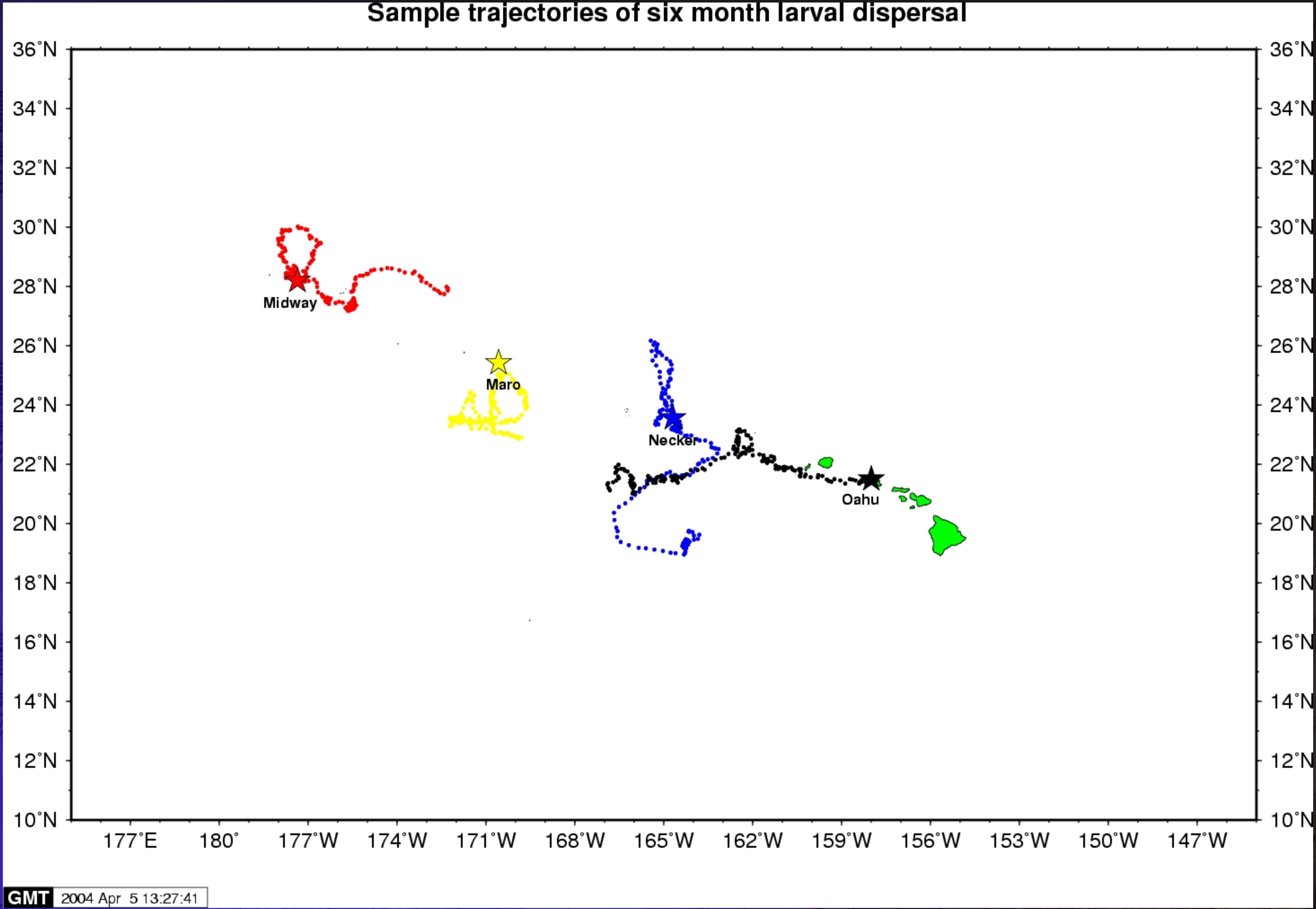
<= 1 degree OSCAR



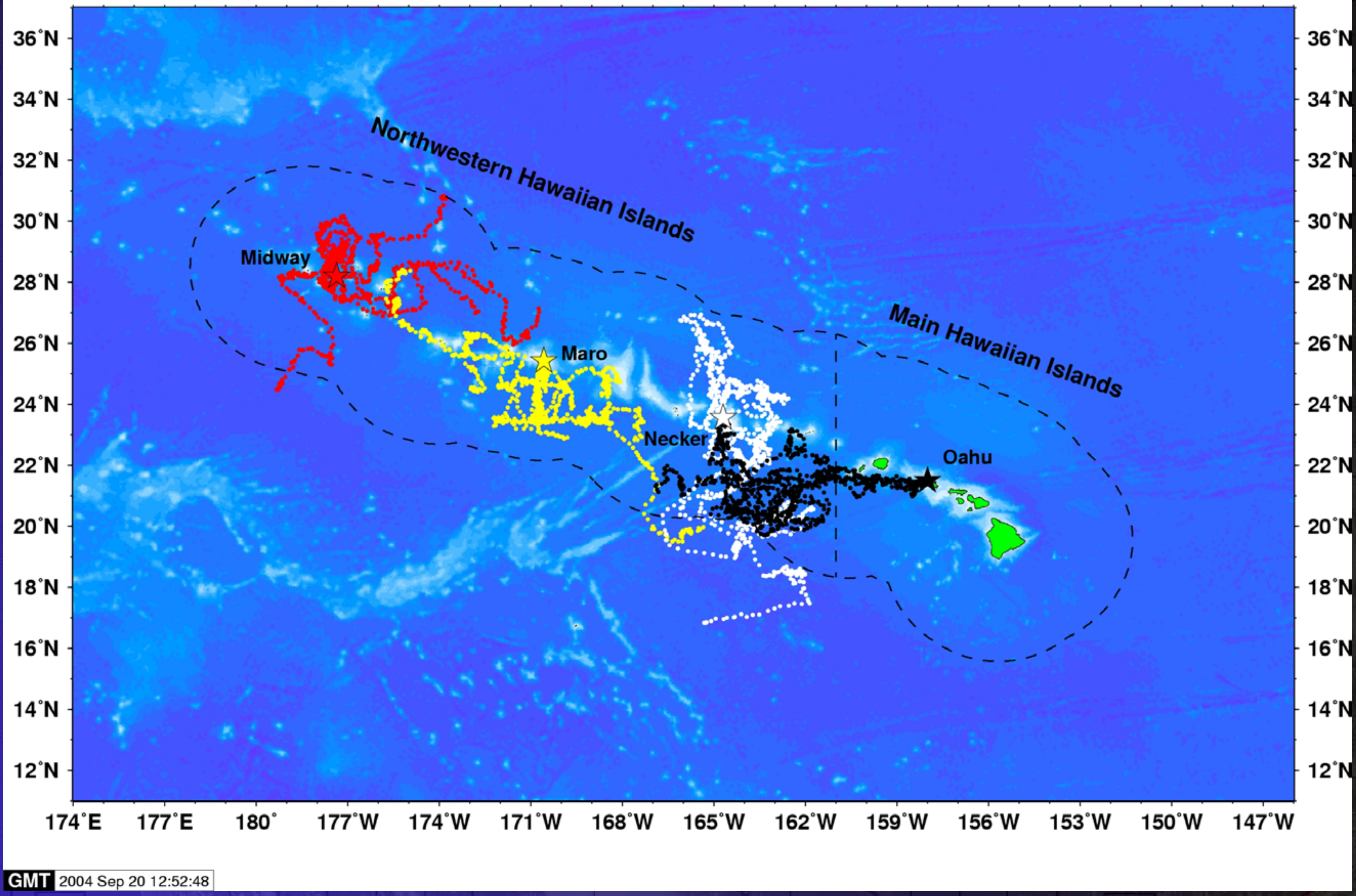
<= 0.5 degree AVISO

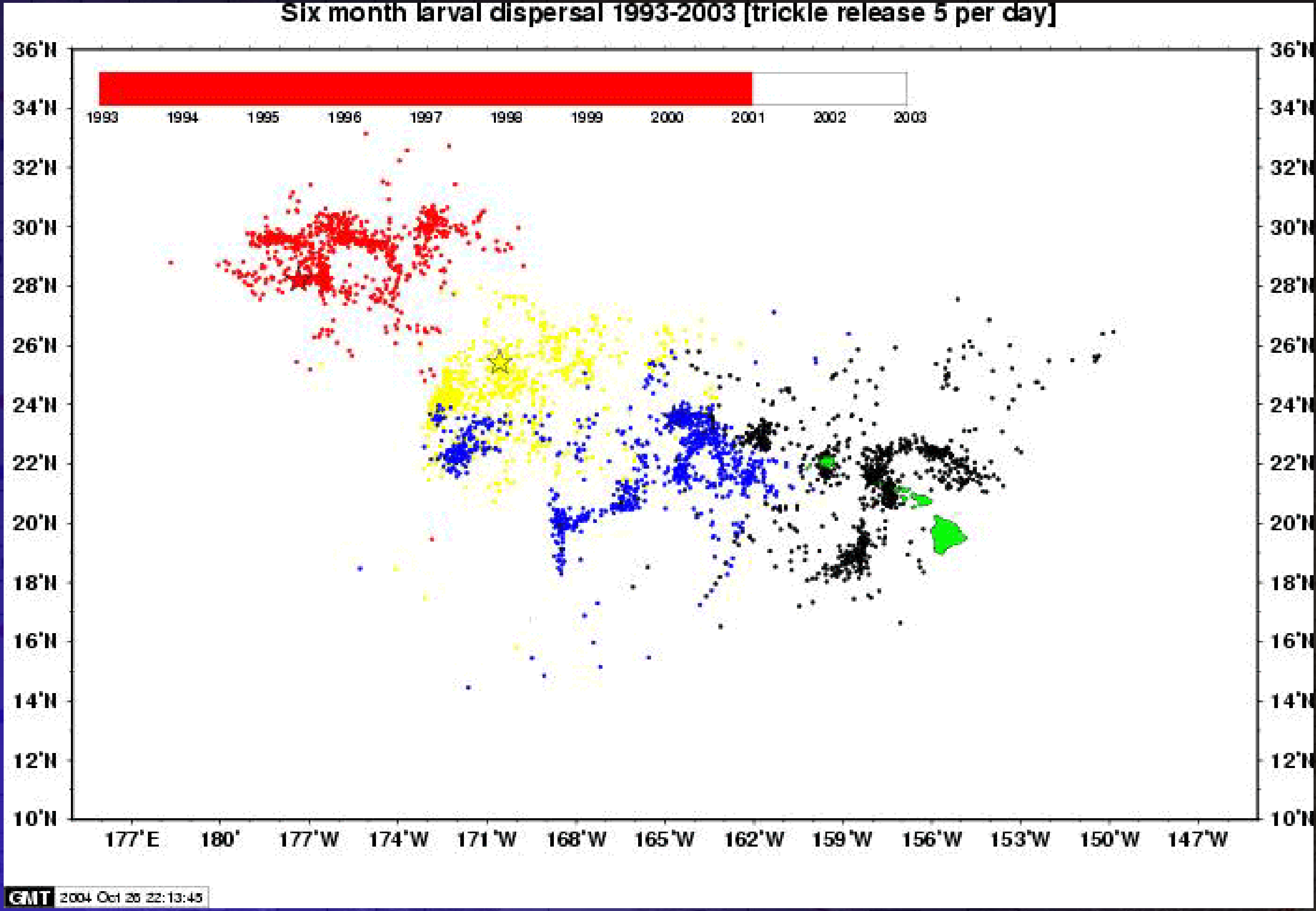


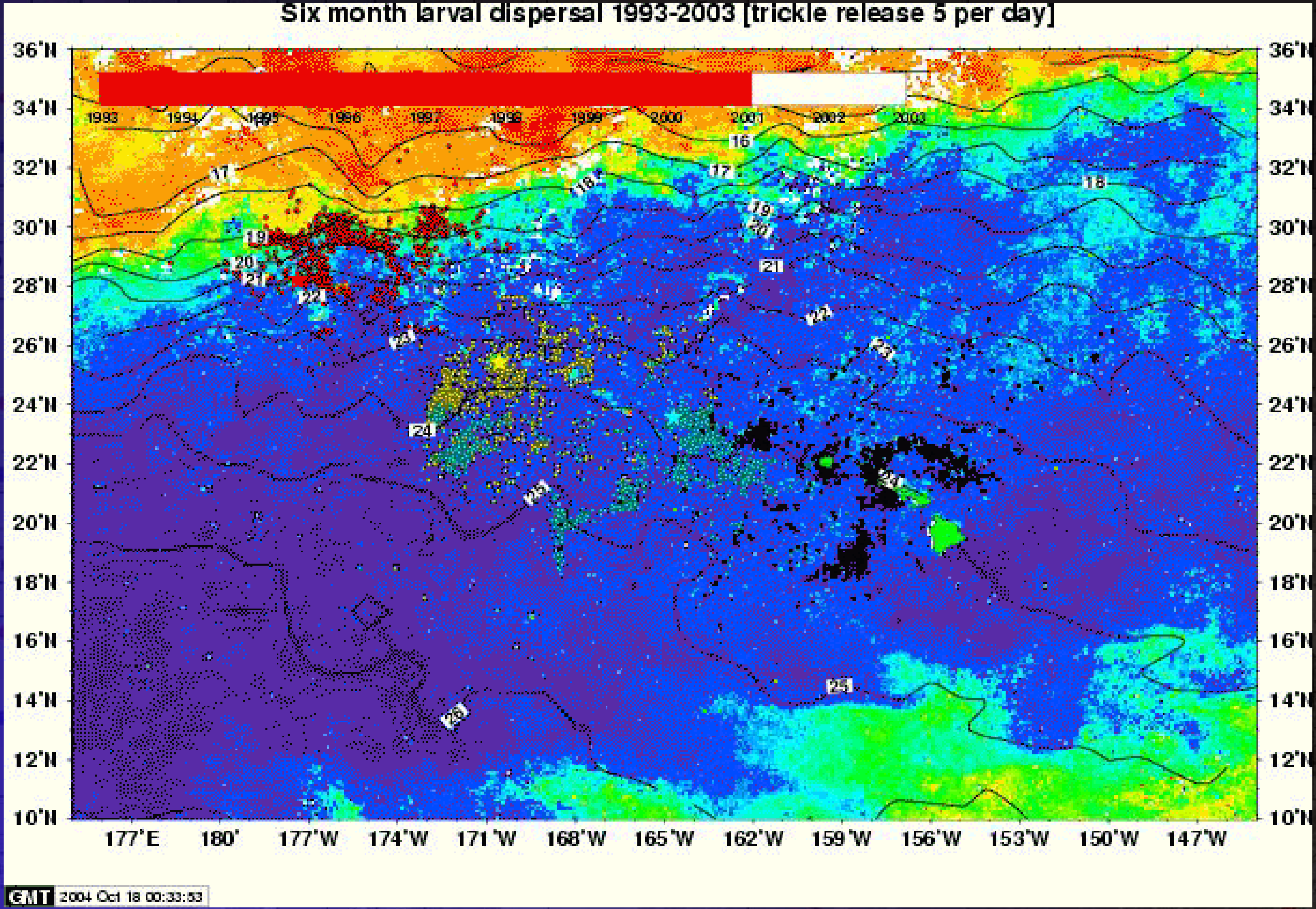
<= 1/16 degree NLOM

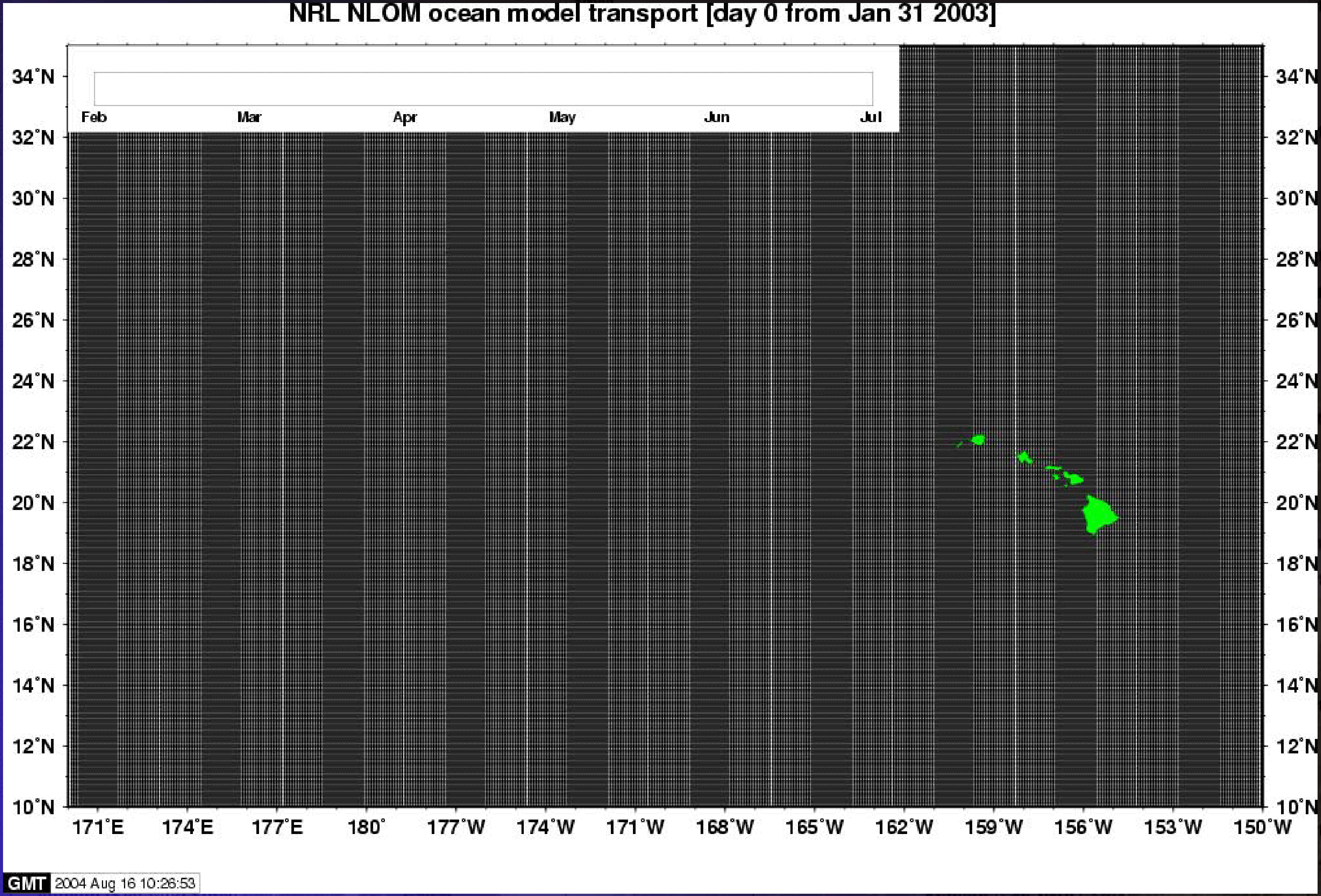

Sample trajectories of six month larval dispersal
36°N
34°N
32°N
30°N
28°N
26°N
24°N
22°N
20°N
18°N
16°N
14°N
12°N
10°N
Midway
Maro
Necker
Oahu
177°E
180°
177°W
174°W
171°W
168°W
165°W
162°W
159°W
156°W
153°W
150°W
147°W
GMT
2004 Apr 5 13:27:41

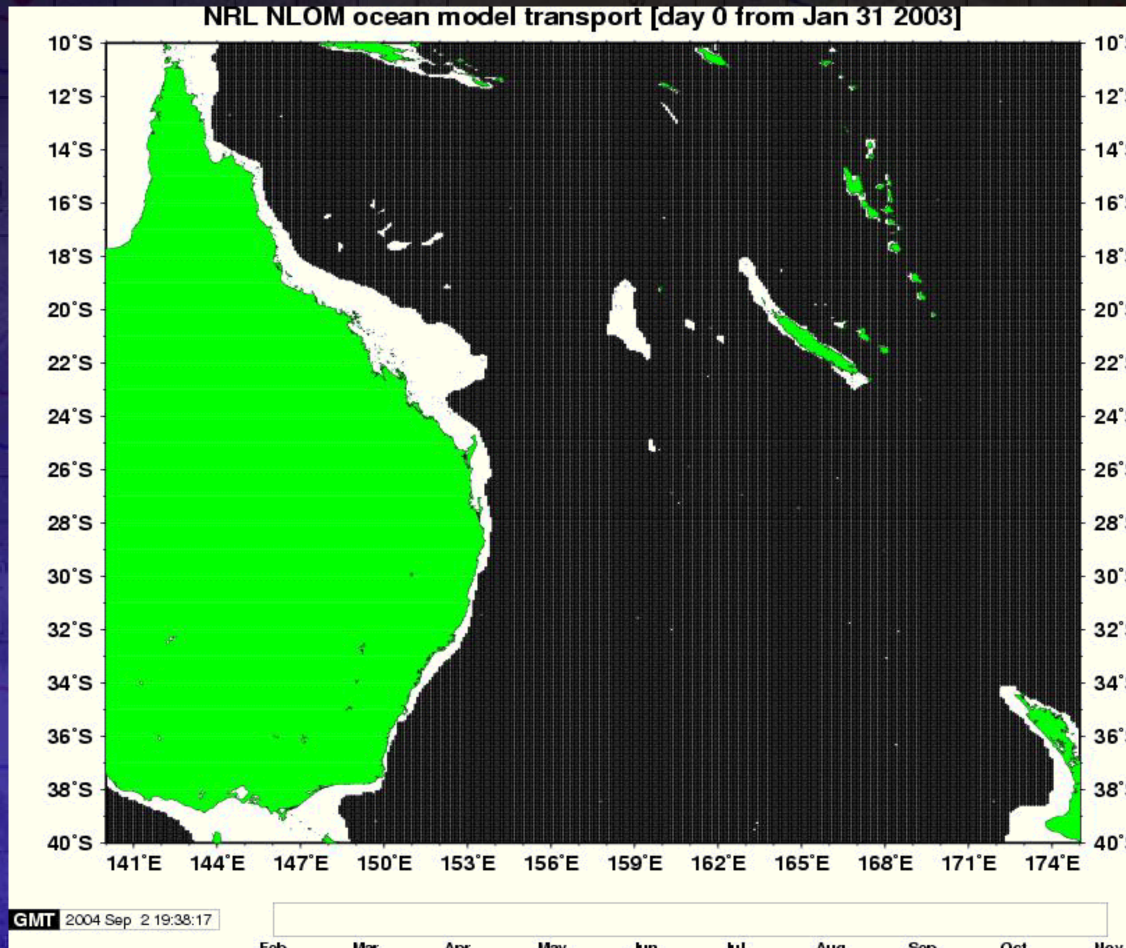
Reference map and 5 sample trajectories of 6 month transport

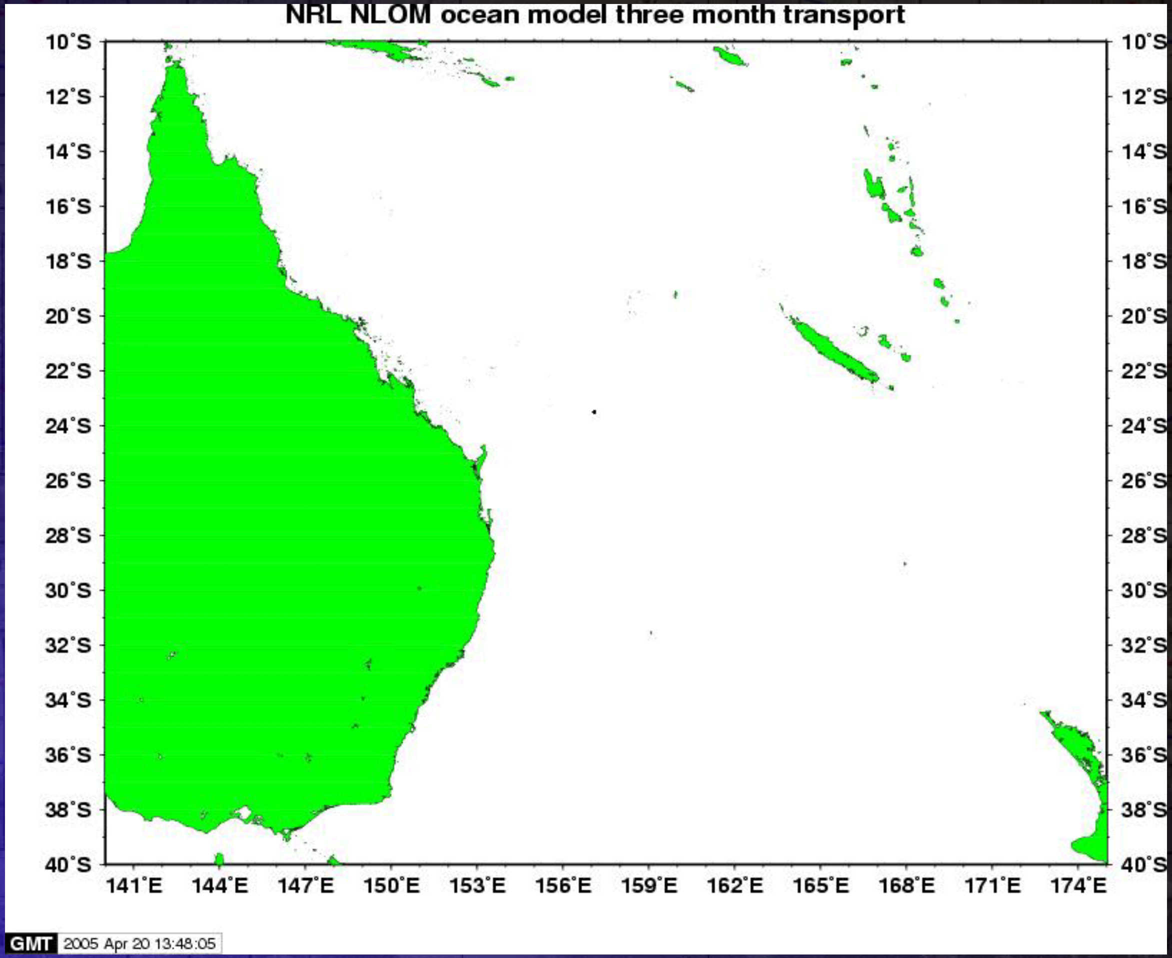



Six month larval dispersal 1993-2003 [trickle release 5 per day]
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
36°N
34°N
32°N
30°N
28°N
26°N
24°N
22°N
20°N
18°N
16°N
14°N
12°N
10°N
177°E
180°
177°W
174°W
171°W
168°W
165°W
162°W
159°W
156°W
153°W
150°W
147°W
GMT 2004 Oct 26 22:13:45

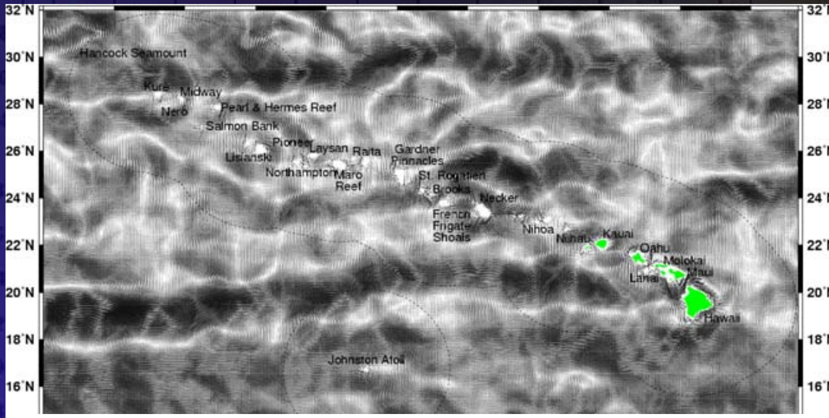

Six month larval dispersal 1993-2003 [trickle release 5 per day]
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003
36°N 34°N 32°N 30°N 28°N 26°N 24°N 22°N 20°N 18°N 16°N 14°N 12°N 10°N
177°E 180° 177°W 174°W 171°W 168°W 165°W 162°W 159°W 156°W 153°W 150°W 147°W
GMT 2004 Oct 18 00:33:53

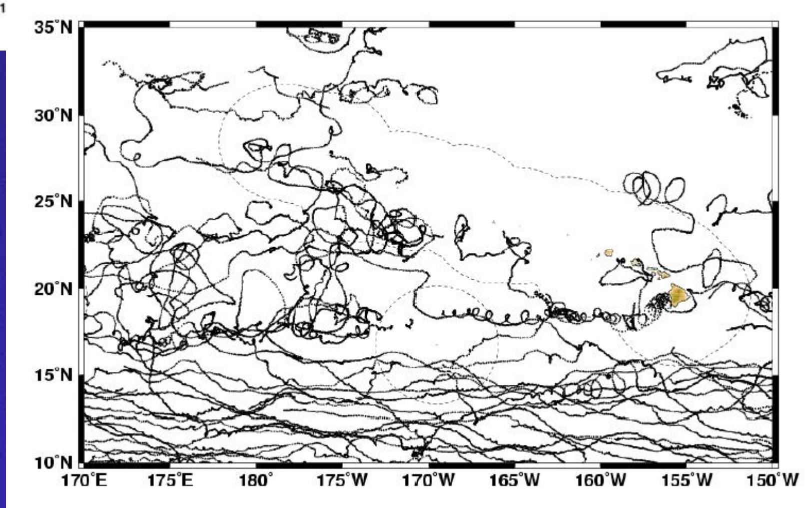

NRL NLOM ocean model transport [day 0 from Jan 31 2003]
Feb
Mar
Apr
May
Jun
Jul
34°N
32°N
30°N
28°N
26°N
24°N
22°N
20°N
18°N
16°N
14°N
12°N
10°N
171°E
174°E
177°E
180°
177°W
174°W
171°W
168°W
165°W
162°W
159°W
156°W
153°W
150°W
GMT 2004 Aug 16 10:26:53

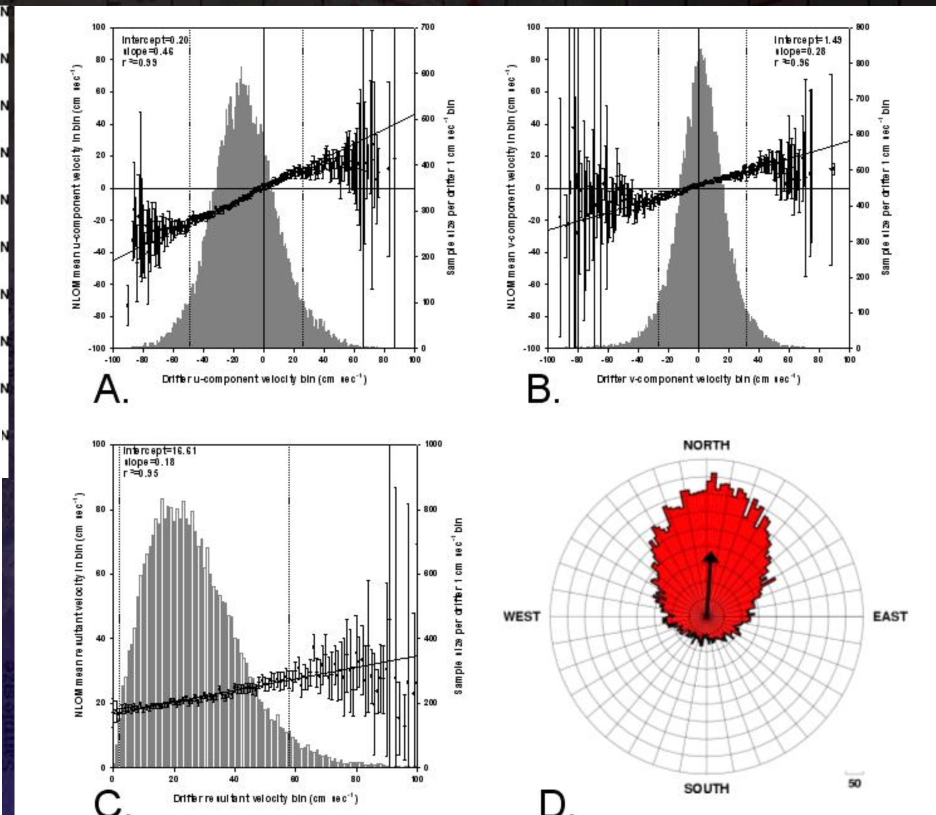

NRL NLOM ocean model transport [day 0 from Jan 31 2003]
10°S
12°S
14°S
16°S
18°S
20°S
22°S
24°S
26°S
28°S
30°S
32°S
34°S
36°S
38°S
40°S
141°E
144°E
147°E
150°E
153°E
156°E
159°E
162°E
165°E
168°E
171°E
174°E
GMT 2004 Sep 2 19:38:17
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov


NRL NLOM ocean model three month transport
10˚S
12˚S
14˚S
16˚S
18˚S
20˚S
22˚S
24˚S
26˚S
28˚S
30˚S
32˚S
34˚S
36˚S
38˚S
40˚S
141˚E
144˚E
147˚E
150˚E
153˚E
156˚E
159˚E
162˚E
165˚E
168˚E
171˚E
174˚E
GMT 2005 Apr 20 13:48:05

Naval Research Laboratory Layered Ocean Model (NLOM, 1/16th degree daily), and NOAA drifter buoys







Conclusion: Very good agreement between NLOM and drifter buoys.

Programming code

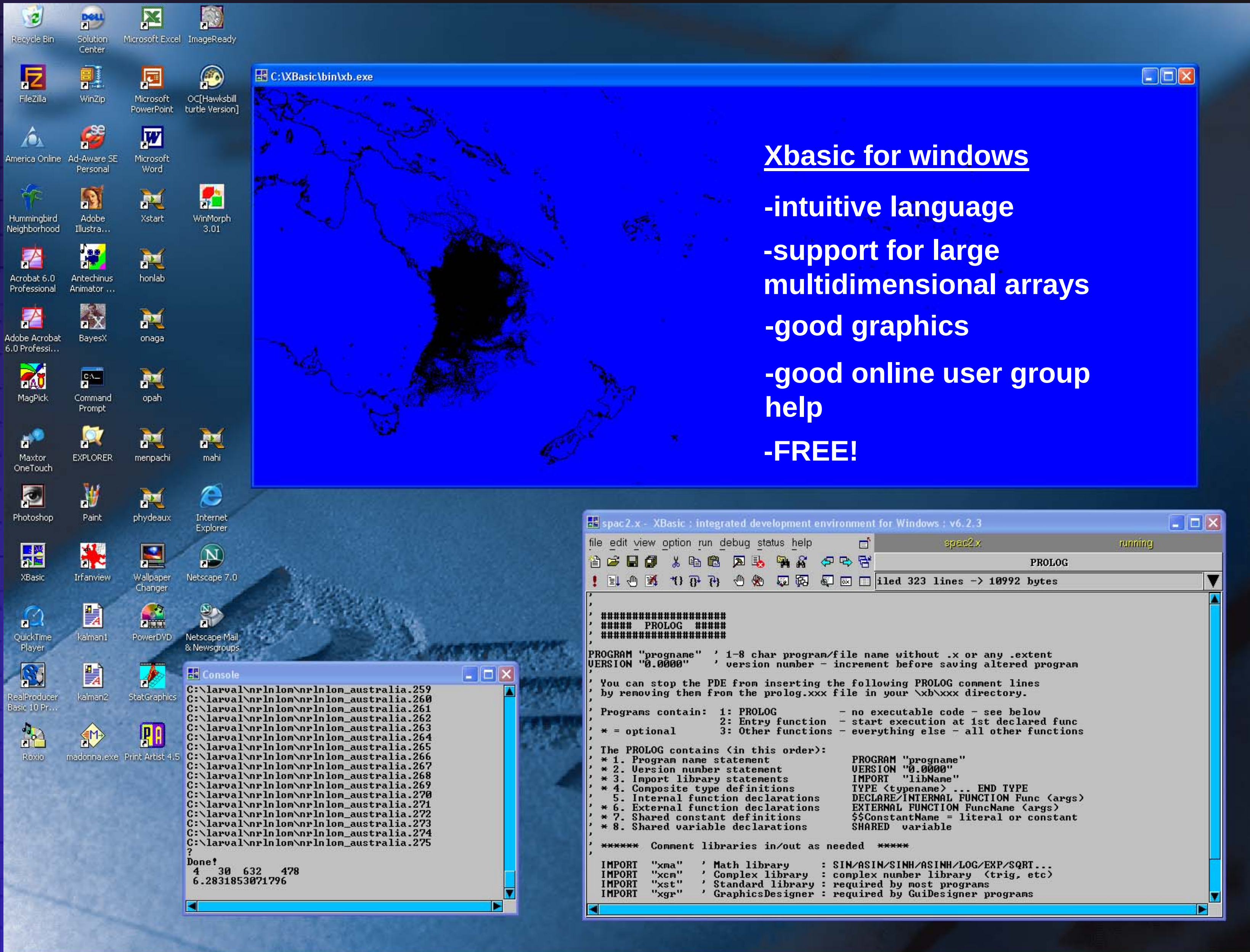
S-Plus (original) =>

QuickBasic (transitional) =>

Xbasic (present) =>

Java (future?)

Python (future?)

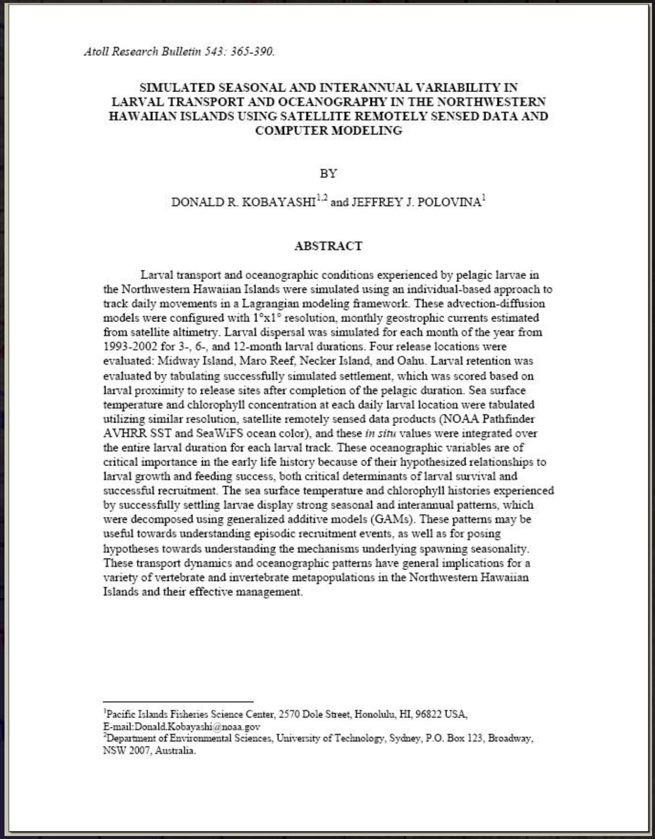

C:\XBasic\bin\xb.exe
Xbasic for windows
-intuitive language
-support for large multidimensional arrays
-good graphics
-good online user group help
-FREE!
spac2.x - XBasic : integrated development environment for Windows : v6.2.3
file edit view option run debug status help
spac2.x
running
PROLOG
iled 323 lines -> 10992 bytes
Console
C:\larval\nrlnlom\nrlnlom_australia.259
C:\larval\nrlnlom\nrlnlom_australia.275
Done!
4 30 632 478
6.2831853071796
Recycle Bin
Solution Center
Microsoft Excel
ImageReady
FileZilla
WinZip
Microsoft PowerPoint
America Online
Microsoft Word
XBasic
Photoshop
Paint
Internet Explorer
Netscape 7.0

Document presentations

- Document 1. Evaluating oceanographic conditions encountered by individual larvae.
- Document 2. Connectivity of Johnston Atoll to Hawaiian Archipelago.
- Document 3. Connectivity matrices for Hawaiian Archipelago.
- Document 4. Effects of diel vertical migration on net horizontal displacement.

First review document

- This paper examined seasonal and interannual variability in several variables related to larval survival.
- Used a long time-series of oceanographic data.
- Applied generalized additive modeling to distill simulation results.



Atoll Research Bulletin 543: 365-390.

SIMULATED SEASONAL AND INTERANNUAL VARIABILITY IN LARVAL TRANSPORT AND OCEANOGRAPHY IN THE NORTHWESTERN HAWAIIAN ISLANDS USING SATELLITE REMOTELY SENSED DATA AND COMPUTER MODELING

BY

DONALD R. KOBAYASHI[1,2] and JEFFREY J. POLOVINA[1]

ABSTRACT

Larval transport and oceanographic conditions experienced by pelagic larvae in the Northwestern Hawaiian Islands were simulated using an individual-based approach to track daily movements in a Lagrangian modeling framework. These advection-diffusion models were configured with 1°x1° resolution, monthly geostrophic currents estimated from satellite altimetry. Larval dispersal was simulated for each month of the year from 1993-2002 for 3-, 6-, and 12-month larval durations. Four release locations were evaluated: Midway Island, Maro Reef, Necker Island, and Oahu. Larval retention was evaluated by tabulating successfully simulated settlement, which was scored based on larval proximity to release sites after completion of the pelagic duration. Sea surface temperature and chlorophyll concentration at each daily larval location were tabulated utilizing similar resolution, satellite remotely sensed data products (NOAA Pathfinder AVHRR SST and SeaWiFS ocean color), and these *in situ* values were integrated over the entire larval duration for each larval track. These oceanographic variables are of critical importance in the early life history because of their hypothesized relationships to larval growth and feeding success, both critical determinants of larval survival and successful recruitment. The sea surface temperature and chlorophyll histories experienced by successfully settling larvae display strong seasonal and interannual patterns, which were decomposed using generalized additive models (GAMs). These patterns may be useful towards understanding episodic recruitment events, as well as for posing hypotheses towards understanding the mechanisms underlying spawning seasonality. These transport dynamics and oceanographic patterns have general implications for a variety of vertebrate and invertebrate metapopulations in the Northwestern Hawaiian Islands and their effective management.

[1]Pacific Islands Fisheries Science Center, 2570 Dole Street, Honolulu, HI, 96822 USA, E-mail:Donald.Kobayashi@noaa.gov
[2]Department of Environmental Sciences, University of Technology, Sydney, P.O. Box 123, Broadway, NSW 2007, Australia.

Pelagic larval ecology -- "The average fish dies in the first week of life"*

- This underscores the importance of early life history events.
- Small changes in survival can greatly benefit the population, much potential for evolutionary "fine-tuning" of reproductive strategies.
- Raises interesting questions about quantitative approaches based on, and focused on "averages"; and suggests focus should be on individuals.
- Are these very high mortalities purely stochastic or can pelagic larval success be modeled and predicted?

* Gary Sharp (1983)

Some major issues in larval mortality

- **Physical transport issues, i.e., retention and loss.**

  Variety of remotely-sensed data products and ocean circulation model output can be used to parameterize advective and diffusive processes.

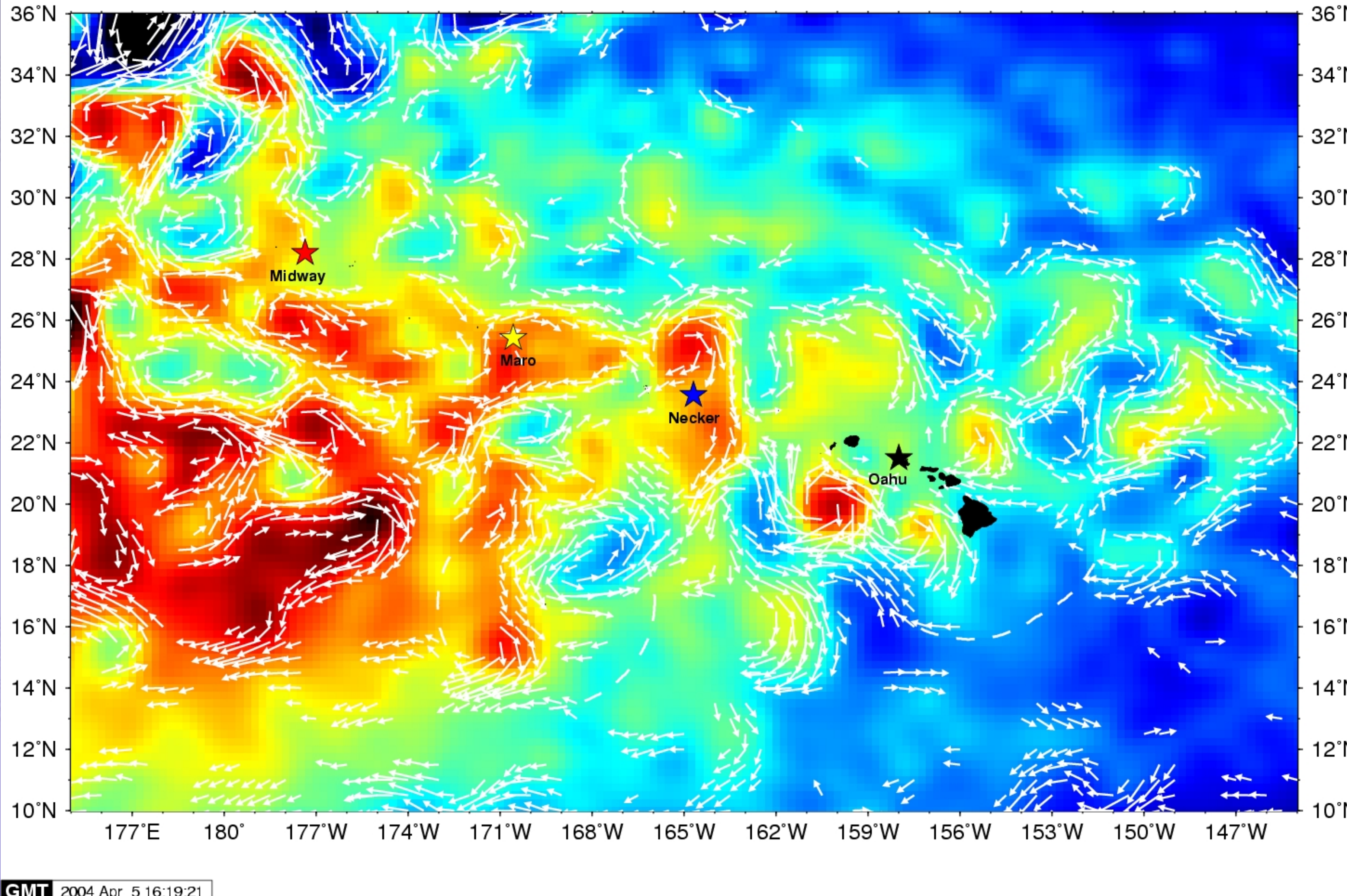
- **Growth issues, in the plankton bigger is generally better as a predator deterrent.**

  Remotely-sensed sea surface temperature (e.g., AVHRR SST) can be used as a proxy for estimating growth variability.

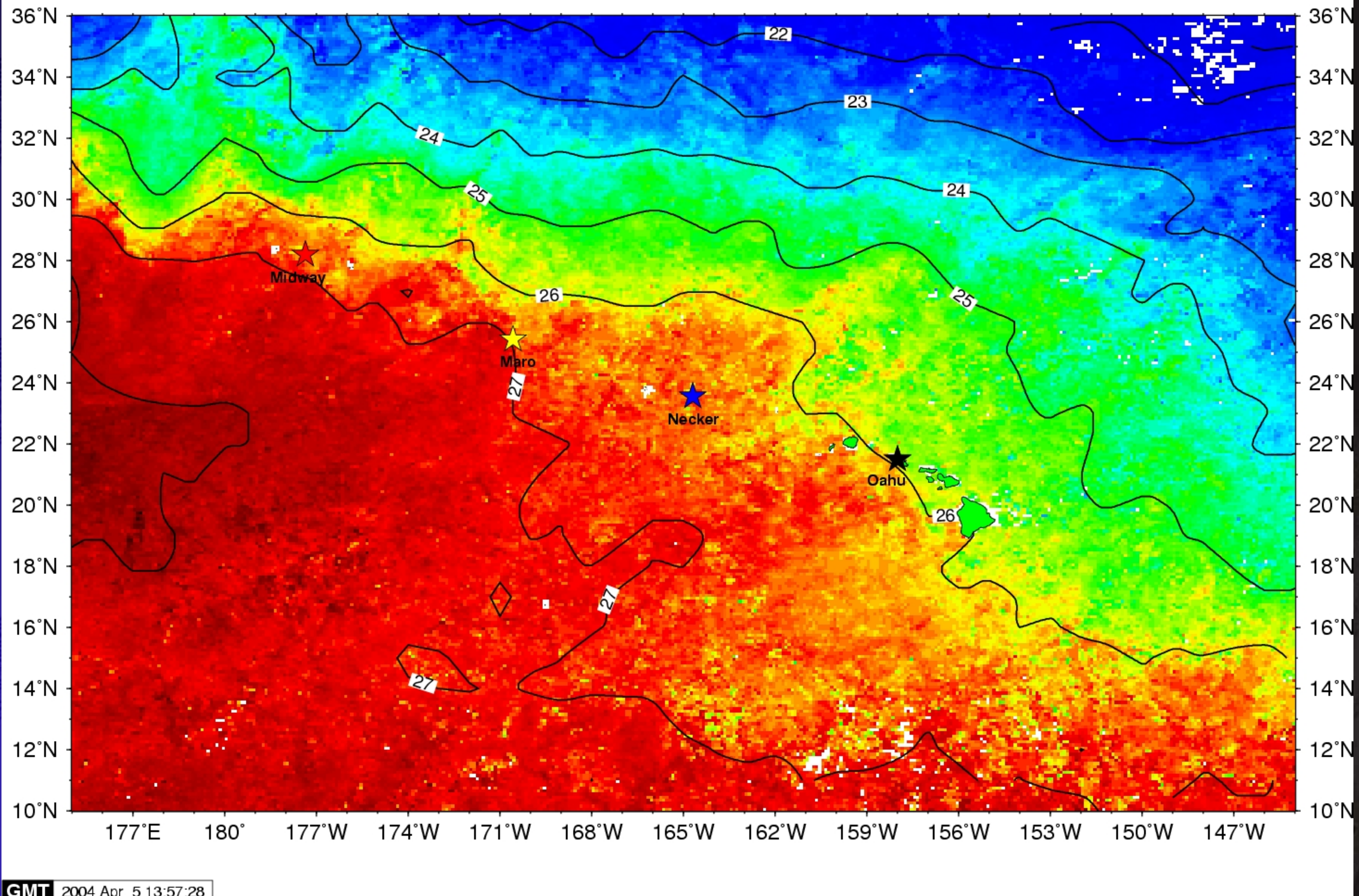
- **Food issues, quality and quantity of forage is important, e.g., Hjort's "Critical Period", Cushing's "Match-Mismatch Hypothesis", Lasker's "Stable Ocean Hypothesis".**

  Remotely-sensed Ocean color (e.g., SeaWiFS) can be used as a proxy for ocean productivity and larval food availability.

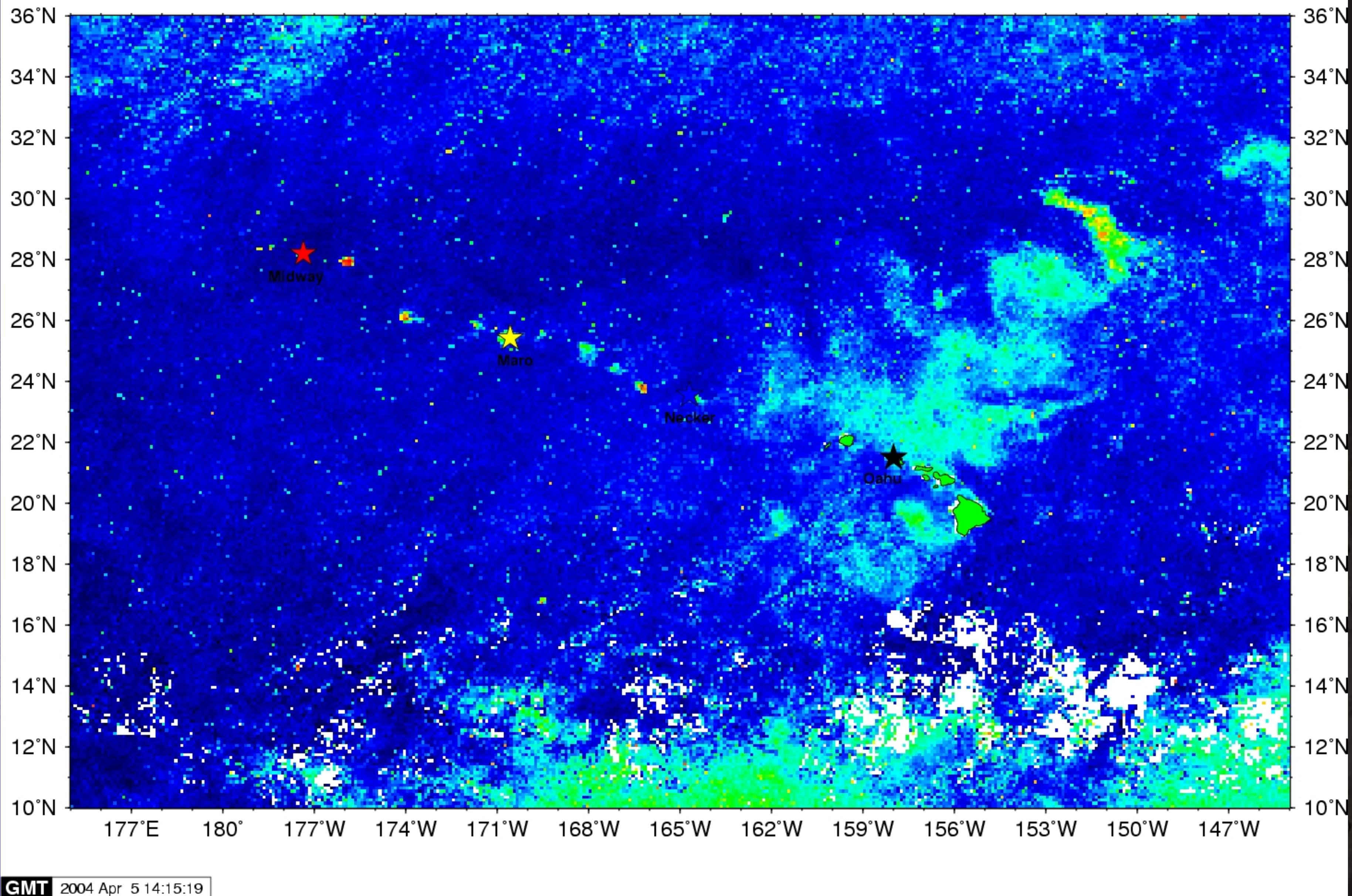
Oceanographic characterization (AVISO altimetry and geostrophic currents)



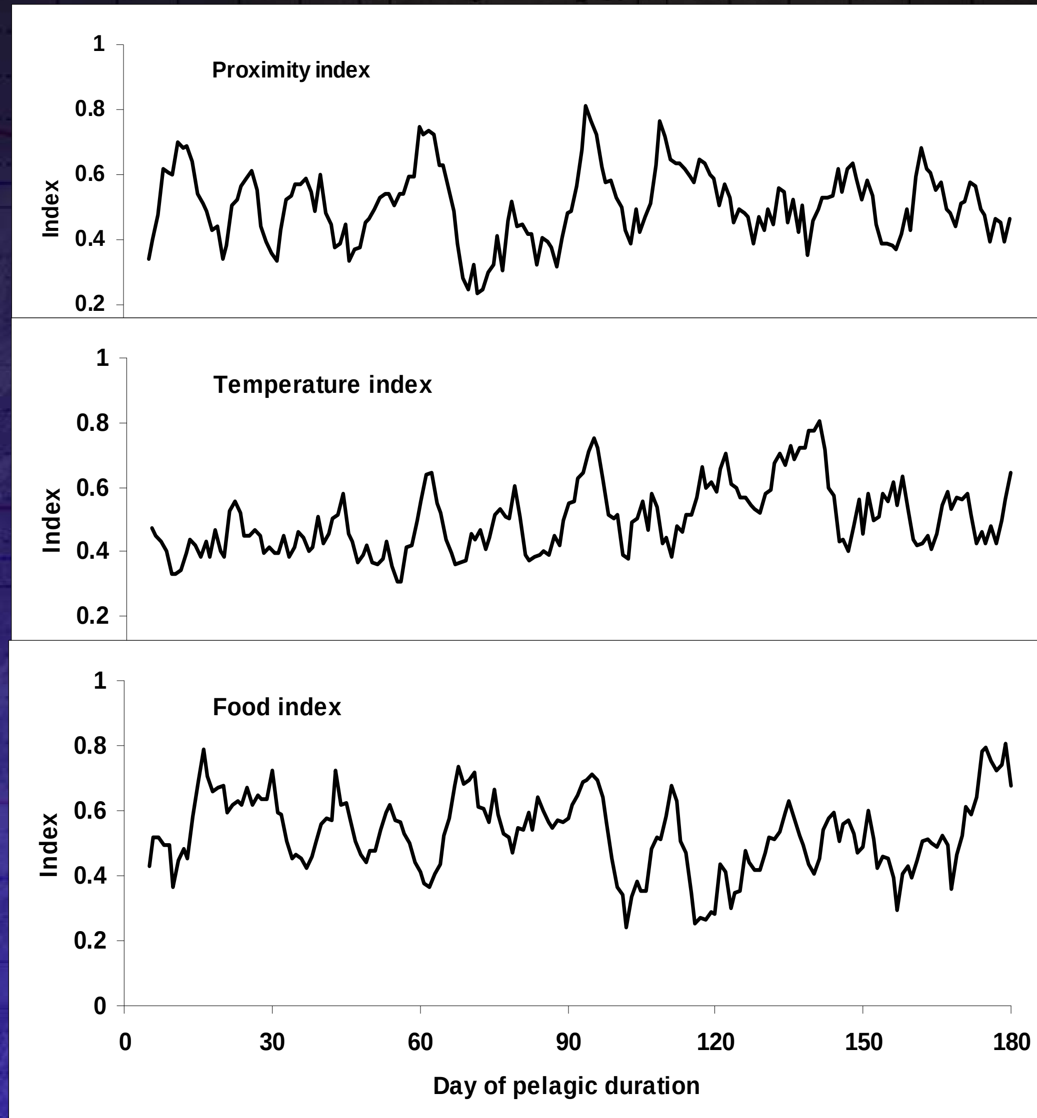
Oceanographic characterization (Pathfinder AVHRR SST)

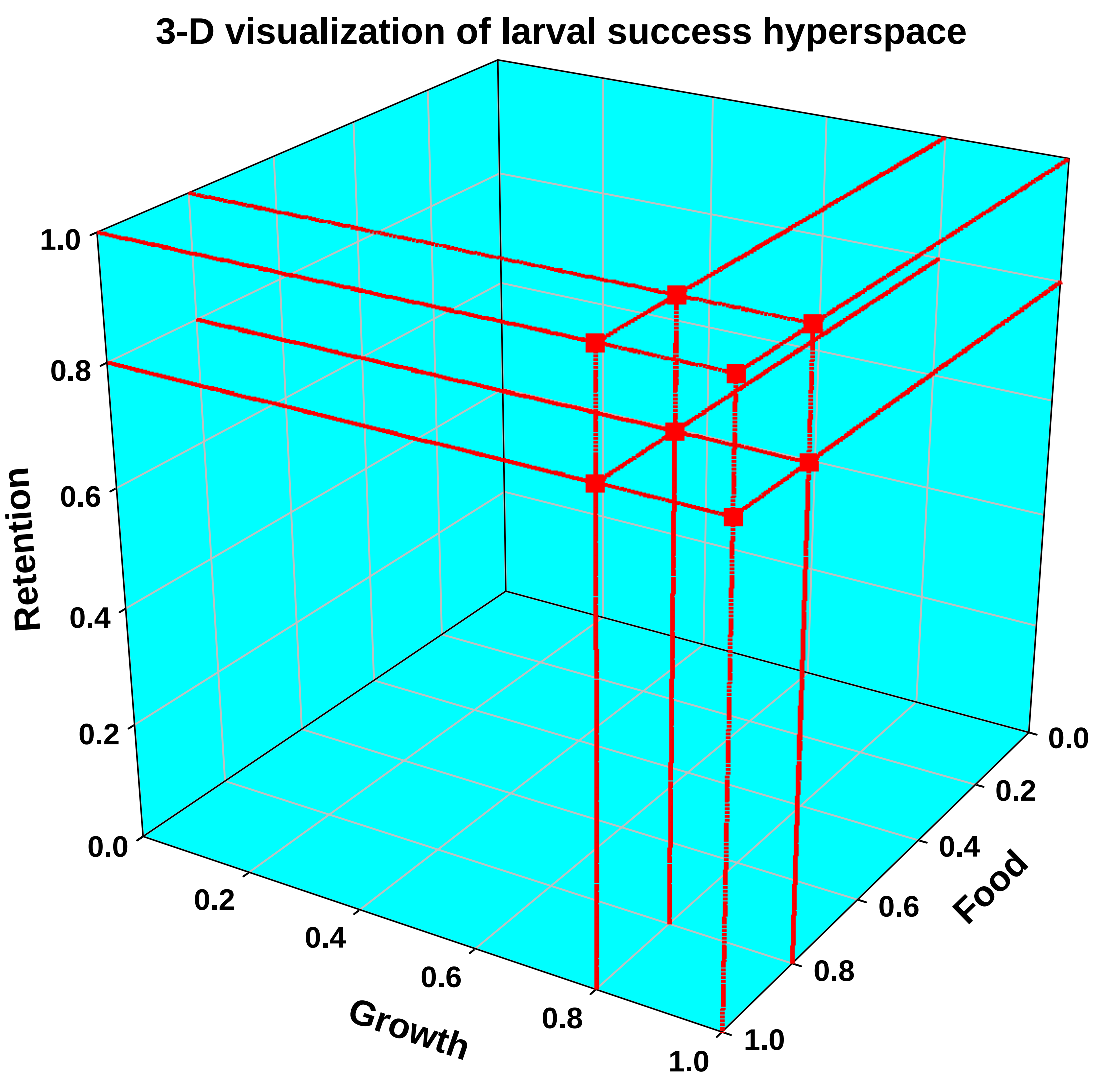


Oceanographic characterization (SeaWiFS chlorophyl density)



Track larval environmental conditions using an “individual-based” approach with integrated exposure over entire PLD




3-D visualization of larval success hyperspace
Retention
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
Growth
0.0
0.2
0.4
0.6
0.8
1.0
Food

Some of the major obstacles

- Most of the remotely-sensed data products come in many flavors and can be very difficult to "crack", particularly ocean model output data. All of the datasets utilized (currents, SST, ocean color, etc.) are time-series of high resolution spatially gridded data, extremely large files, and must be somehow "on tap" during the simulations. The computational and programming aspects of this project are potentially very time consuming.
- Appropriate statistics and analytical techniques are needed to process the anticipated voluminous output. Obviously, standard parametric techniques dealing with "averages" are not favored.

Model parameterization

Larval distribution is a function of:

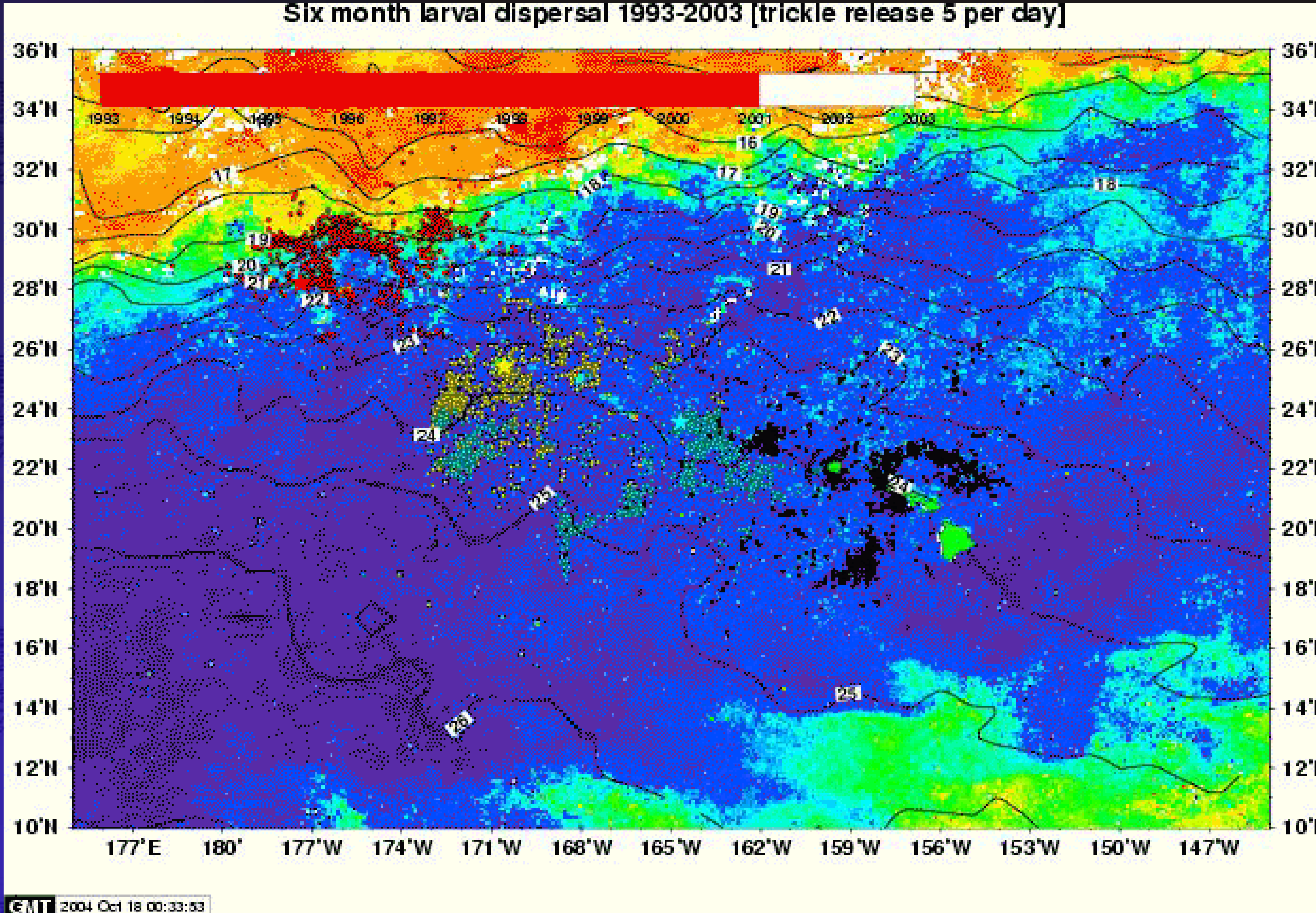
- **Production processes (adult spawning time, location, and amount).**
- **Dispersal processes (current patterns, thermal environment, food availability, and larval behavior).**

Adult spawning seasonality

- **Many aquatic organisms release their propagules in a seasonal pattern.**
- **Timing of spawning may be related to optimal survival of propagules, i.e., spawn when the larval habitat is most favorable.**
- **Three aspects of the larval environment will be examined with respect to seasonality (transport/loss, temperature, and chlorophyll-a).**

Advection-diffusion model with environmental fields

- Larval transport modeled in a lagrangian (individual-based) approach using satellite altimetry derived geostrophic flow fields (TOPEX/Poseidon/Jason).
- Integrated exposure of individual larvae to temperature using remotely sensed SST (Pathfinder).
- Integrated exposure of individual larvae to chlorophyll-a using remotely sensed ocean color (SeaWiFS).
- 5000 releases from each combination of:
  - 4 spawning locations (Midway, Maro, Necker, Oahu)
  - 11 spawning years (1993-2003)
  - 12 spawning months (January-December)
  - 3 pelagic larval durations (3, 6, 12 months)



Pacific Islands Fisheries Science Center

Ecosystems and Oceanography Division

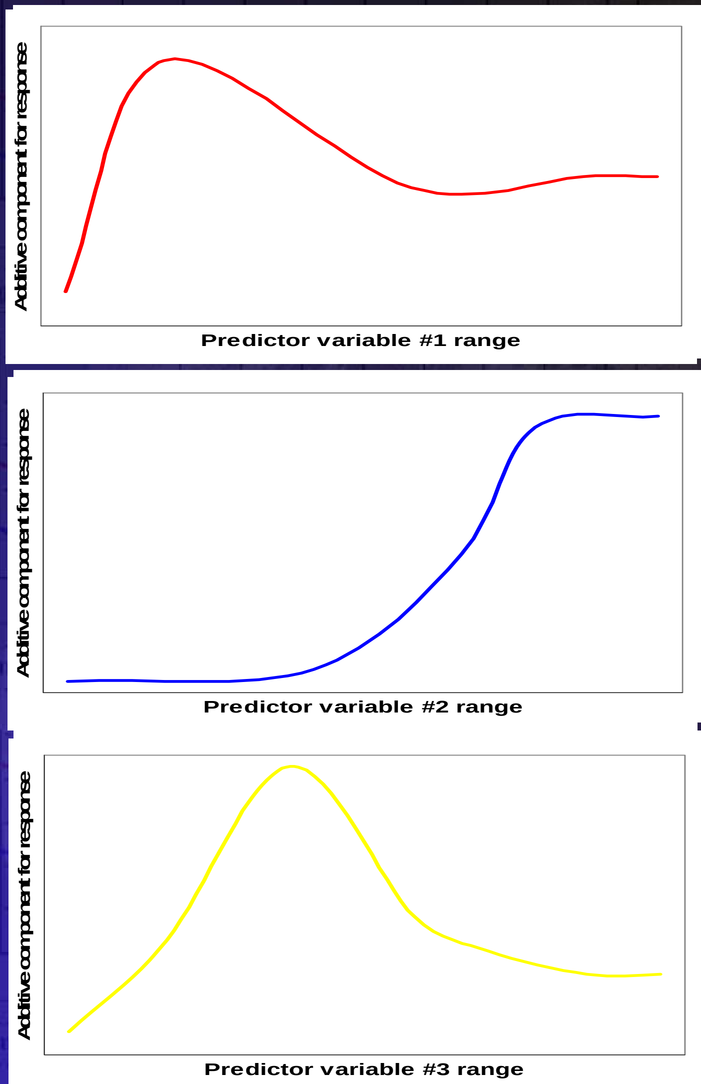
Pago Pago Room, Imin Center

May 19-22, 2008

Data capture and analysis

- For each combination of 5000 releases, the following data were recorded:
  - Number of larvae retained at release site.
  - Number of larvae reaching Oahu.
  - Number of larvae not reaching any of the 4 sites.
  - Integrated SST exposure of retained larvae.
  - Integrated chlorophyll-a exposure of retained larvae.
- The time-series or integrated encounter history cannot be simply proxied by any other means! (sequence, duration, etc.)
- Generalized additive models (GAMs) were used to identify correlative factors for each of the above.

Generalized Additive Models (GAMs)



Simple linear models attempt to parameterize the underlying processes with functions constrained by certain assumptions of linearity and/or symmetry.

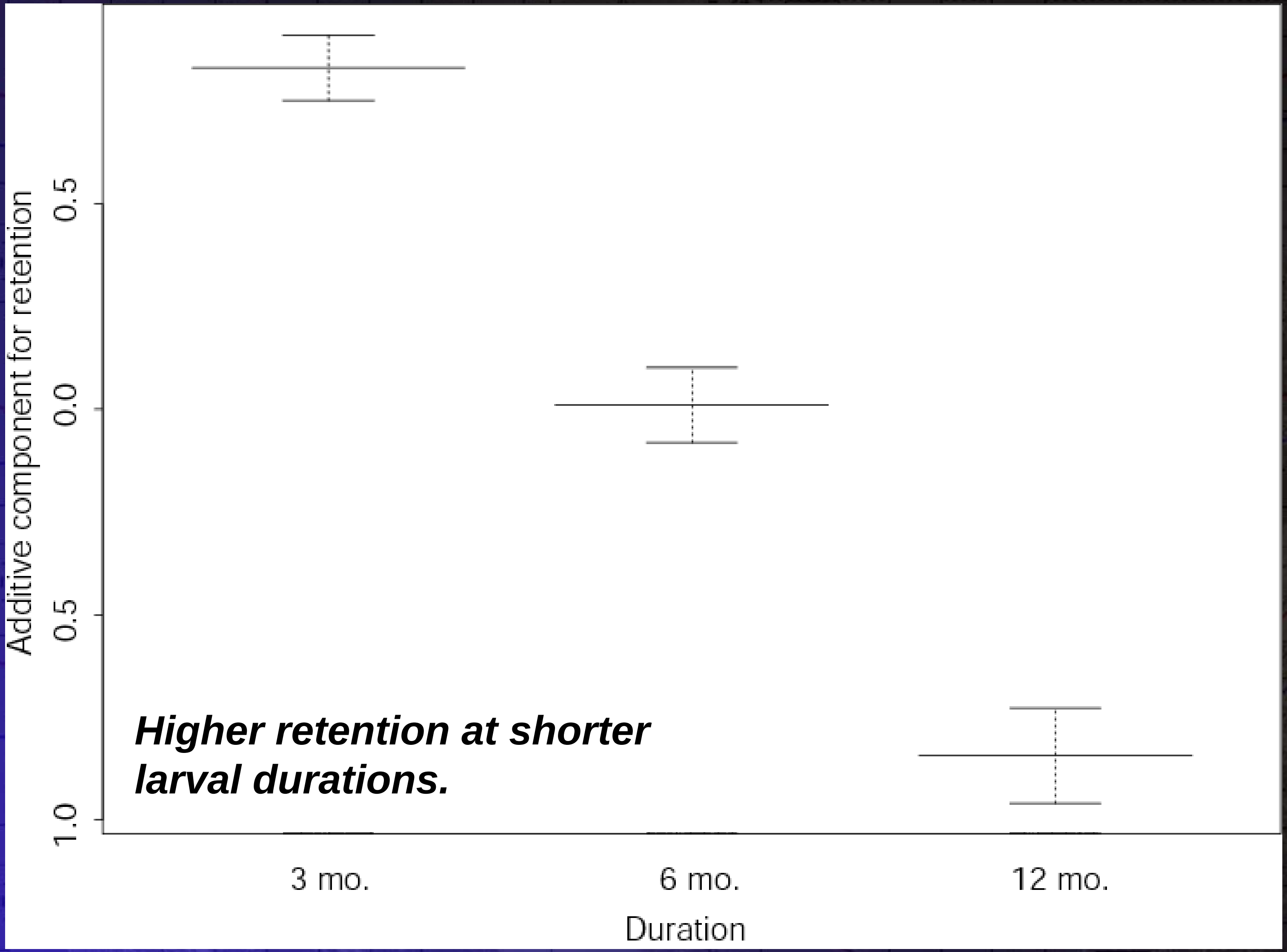
GAMs offer flexible shape functions for the additive components and can be linear if the data warrants.

GAMs can accommodate a wide variety of continuous or discrete data for both heuristic and predictive purposes.

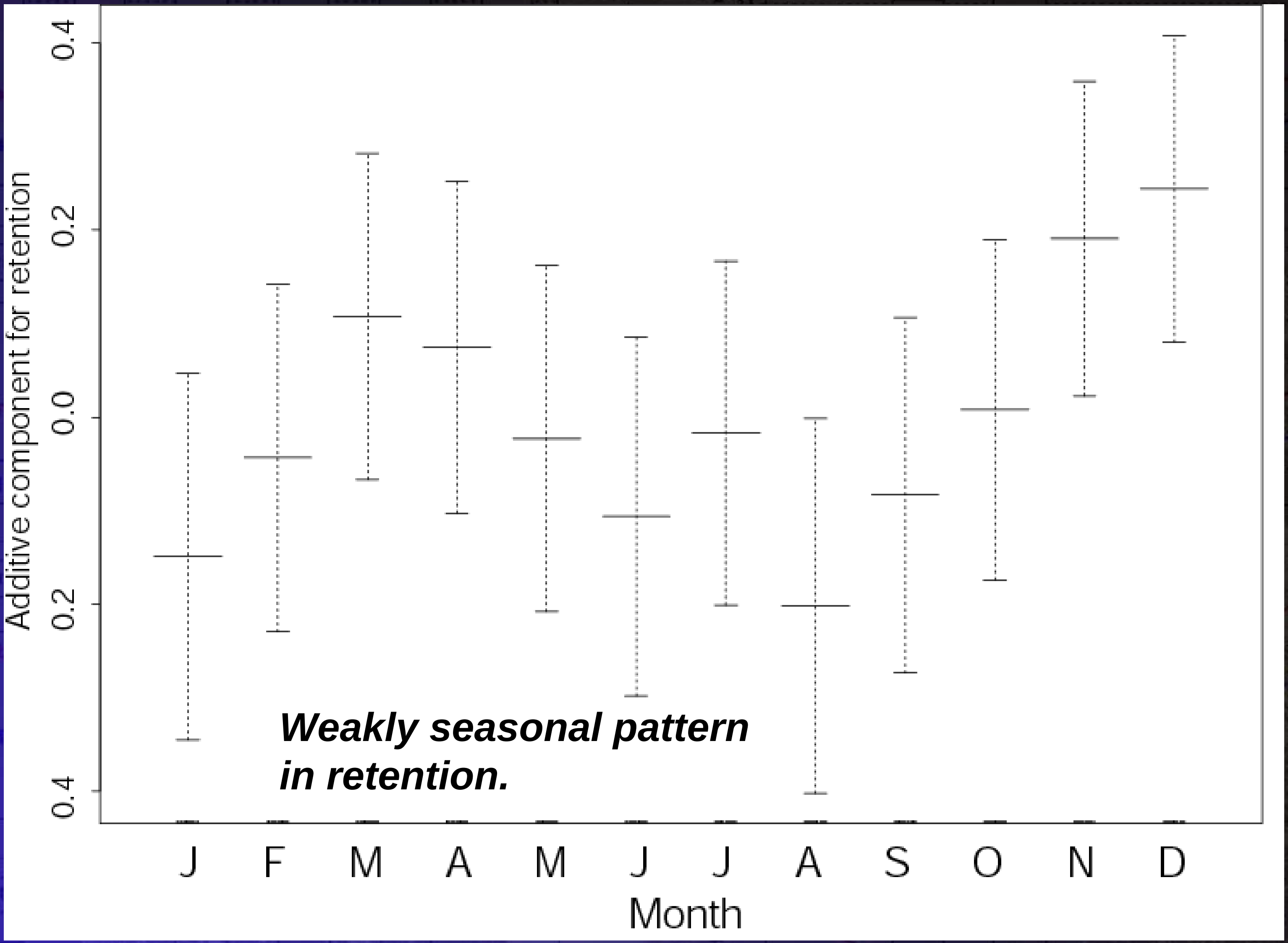
Summary of generalized additive models (GAMs) performed

Response variables:	Predictor variables:
Larval retention, Larval settlement at Oahu, Larval non-settlement, SST history of retained larvae, Chlorophyll-a history of retained larvae	Year, Month, Site, Duration

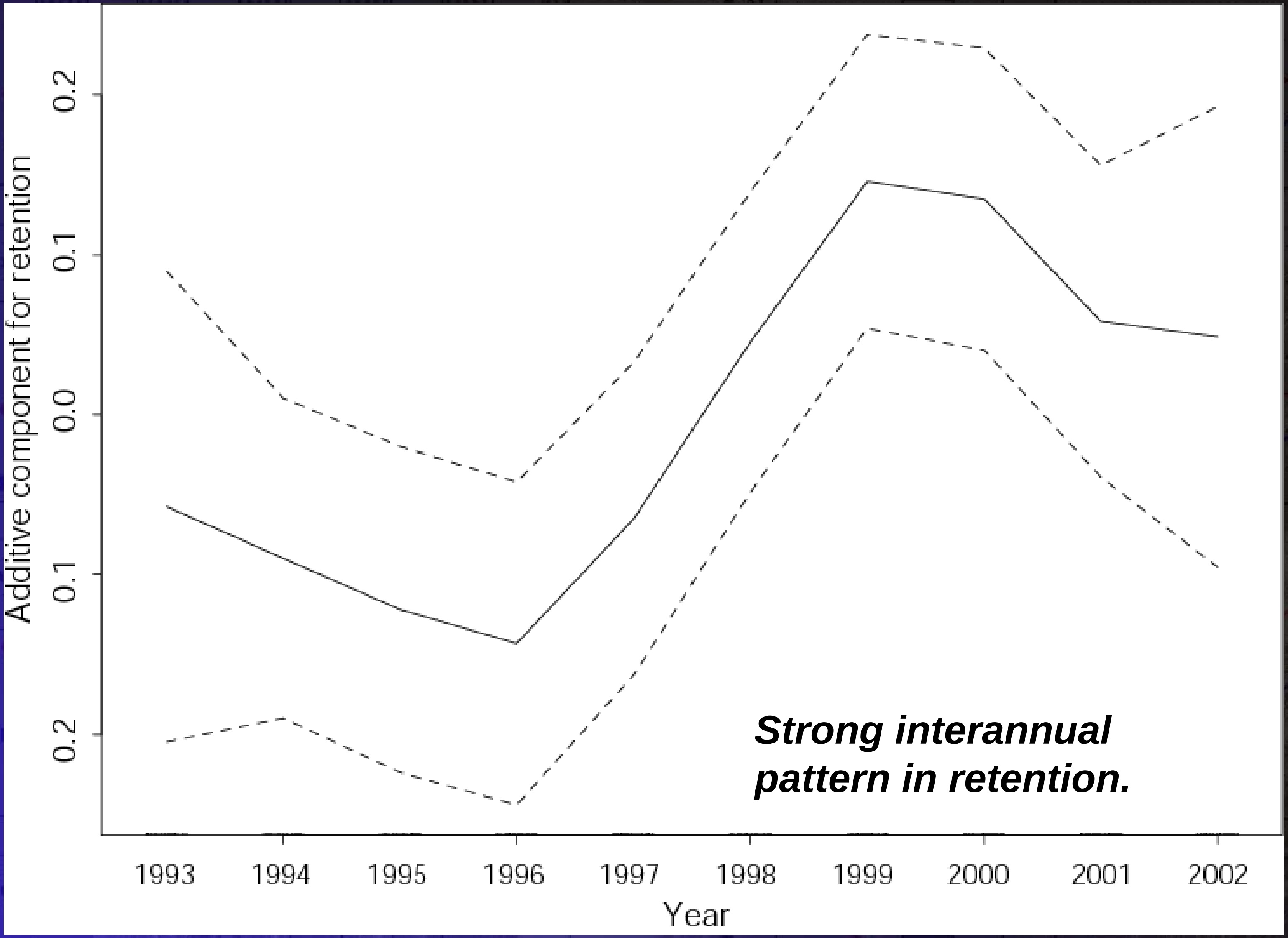
Larval Retention – Effect of Pelagic Duration



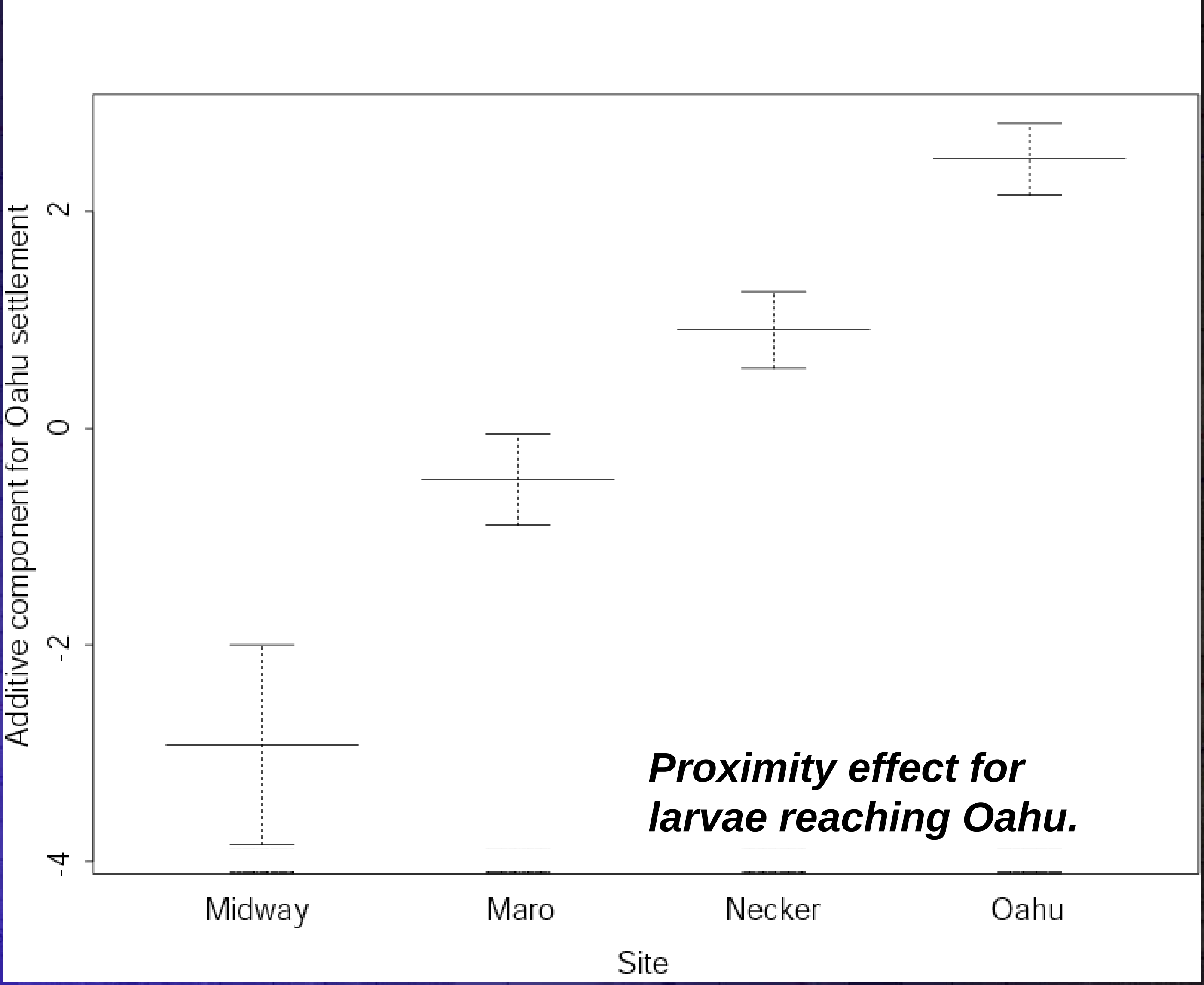
Larval Retention – Effect of Month



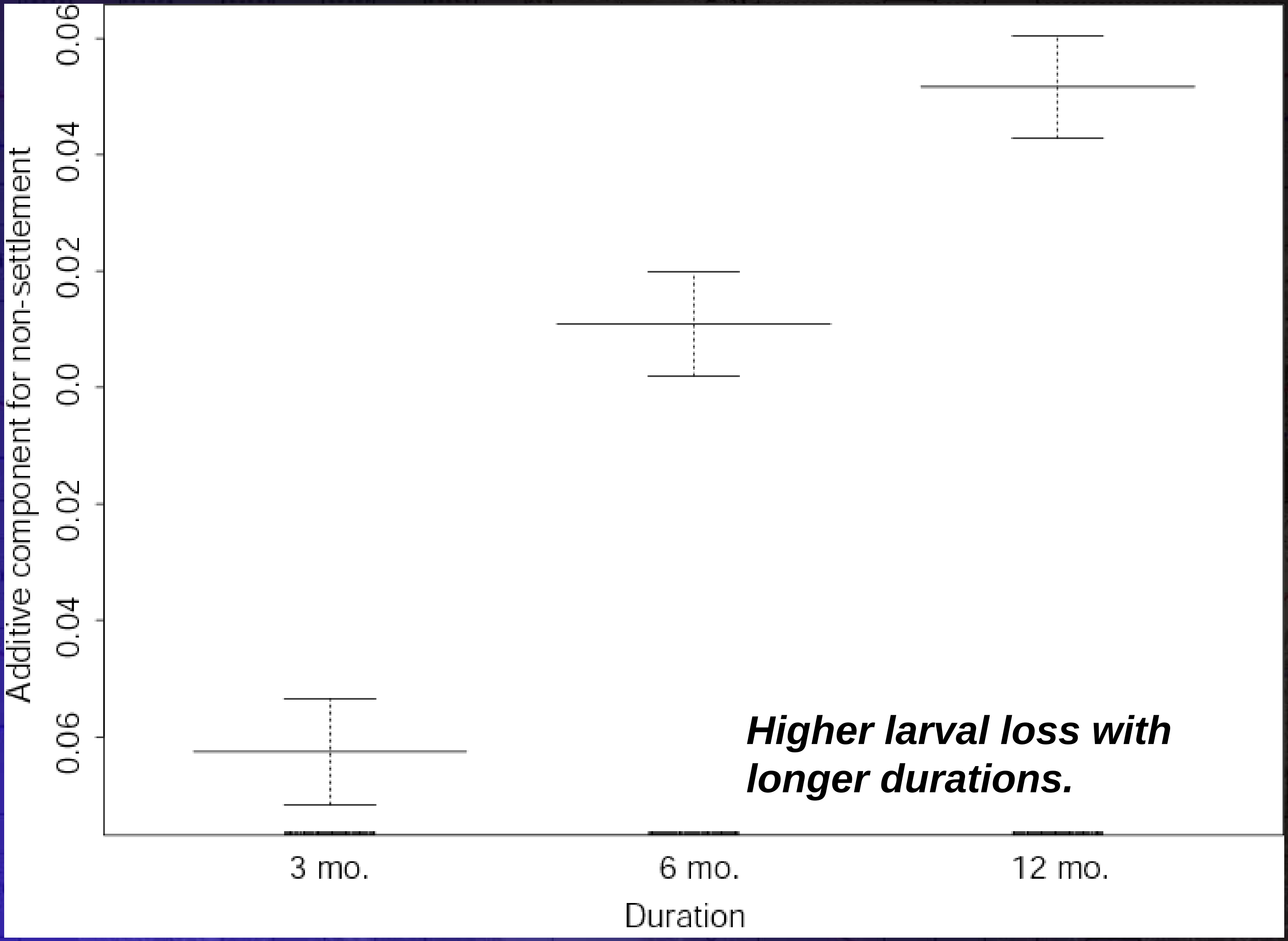
Larval Retention – Effect of Year



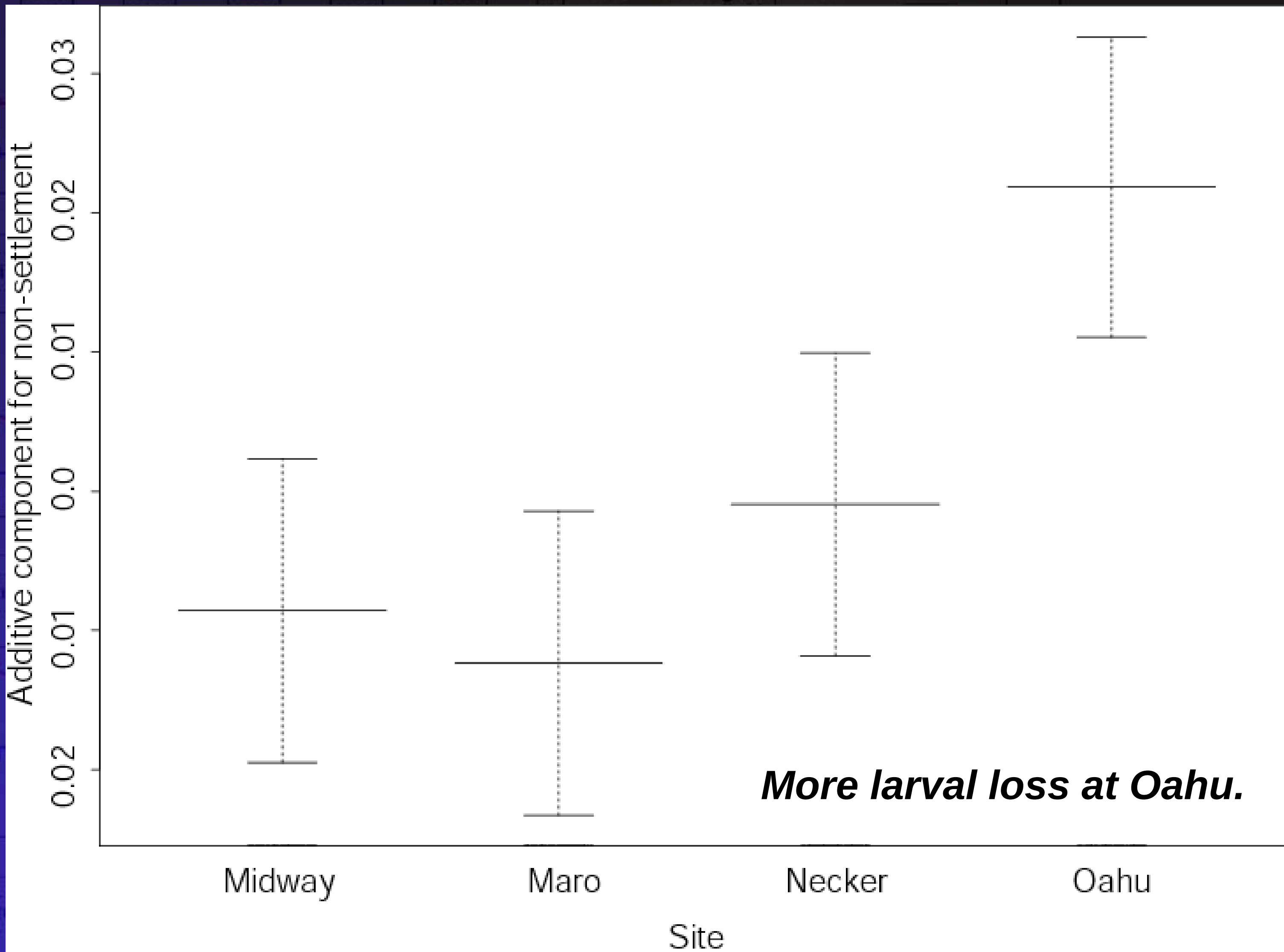
Larval settlement at Oahu – Effect of Site



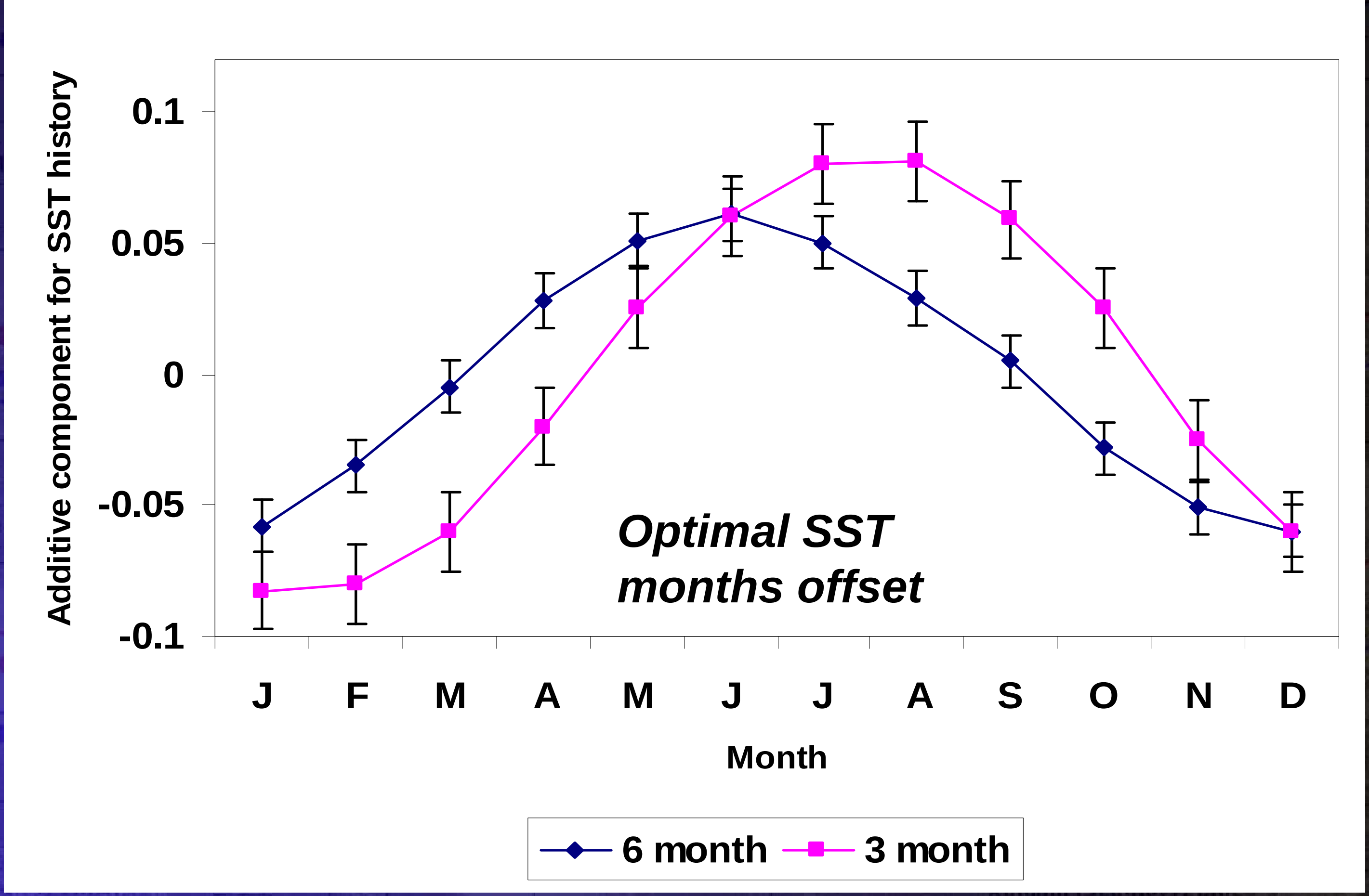
Larval loss – Effect of Pelagic Duration



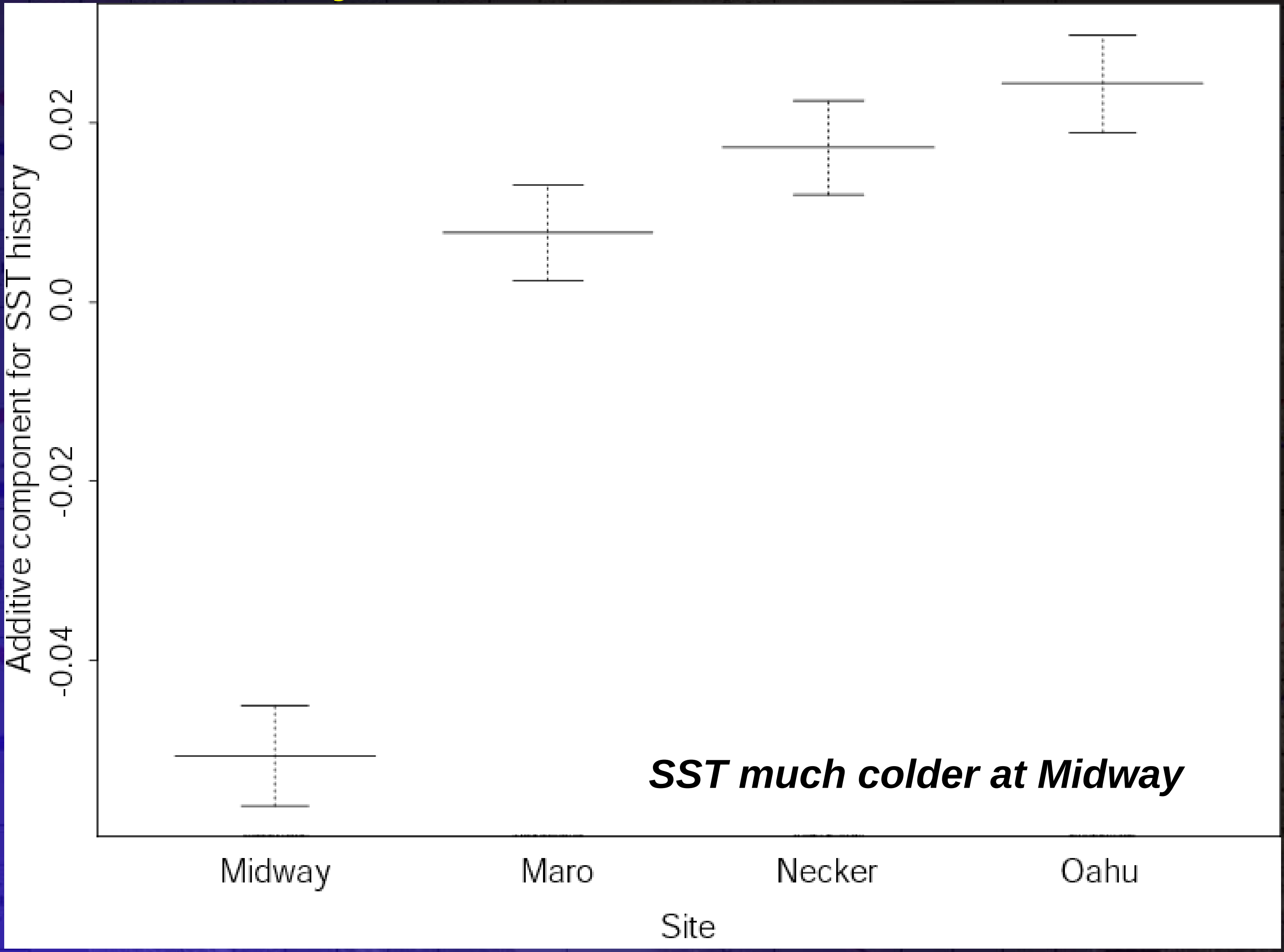
Larval loss – Effect of Site



SST History of 3 & 6 Month Retained Larvae – Effect of Month



SST History of Retained Larvae – Effect of Site



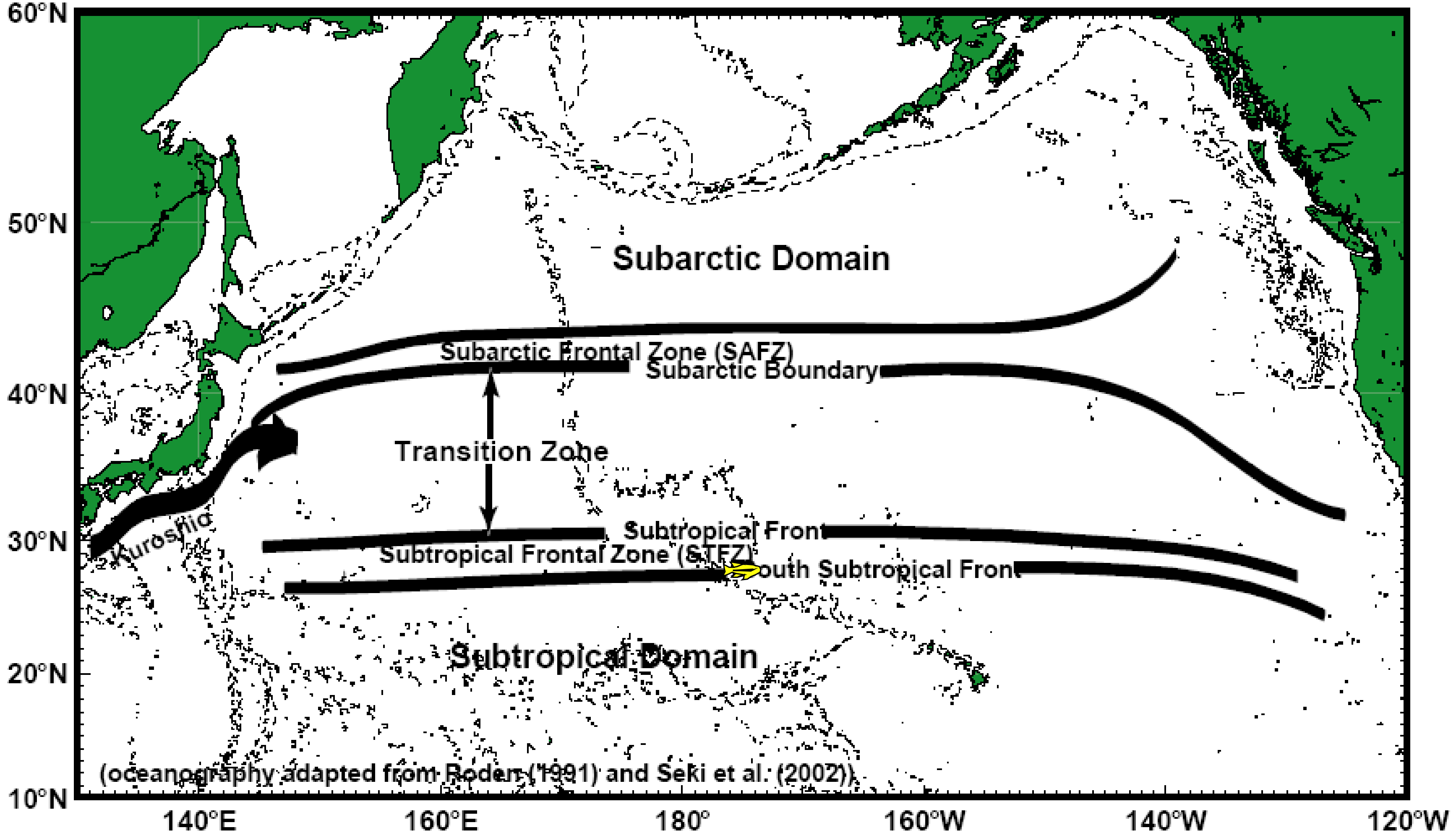
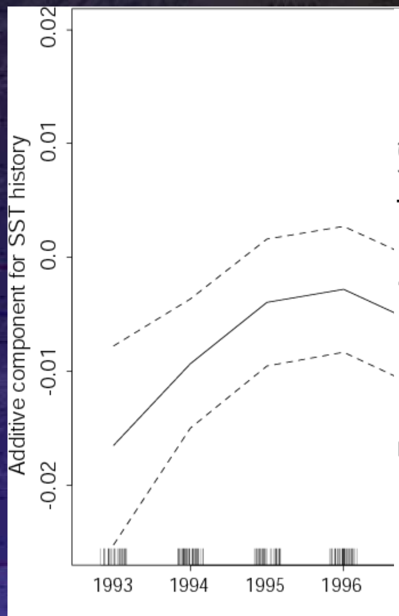
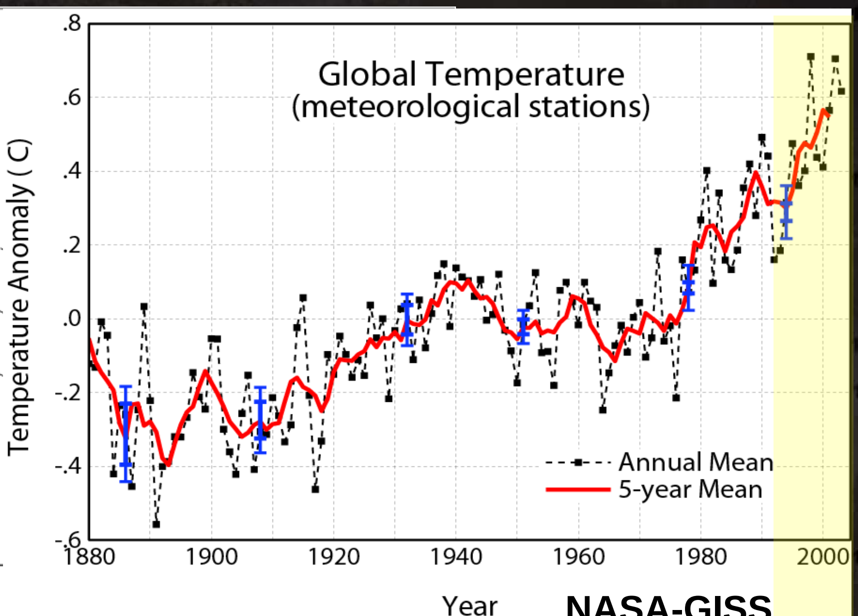


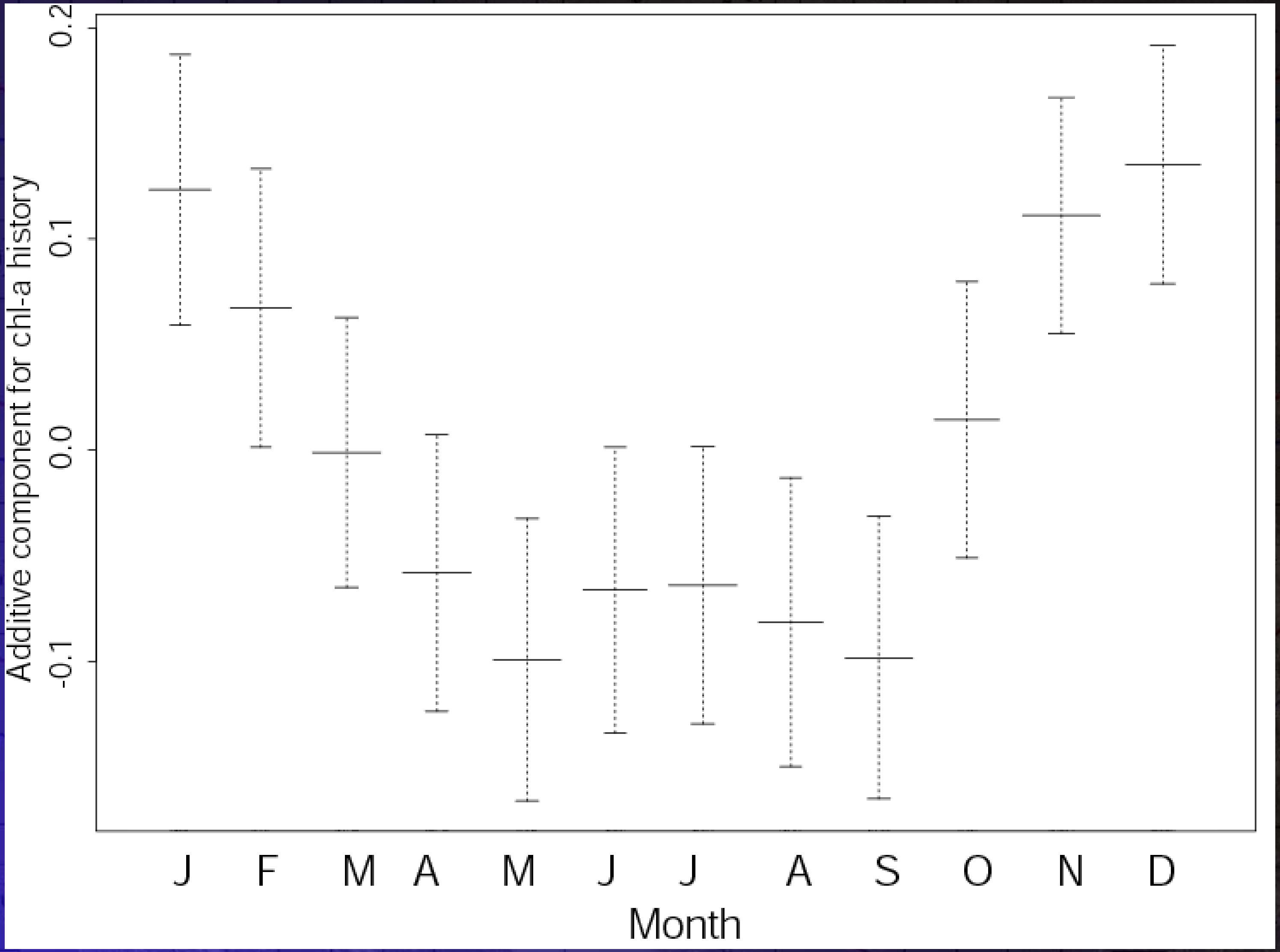
FIGURE 126 SCHEMATIC REPRESENTAITON OF THE NORTH PACIFIC TRANSITION ZONE AND ITS RELATION TO THE MAJOR FEATURES OF THE NORTH PACIFIC OCEAN.

SST History of Retained Larvae – Effect of Year

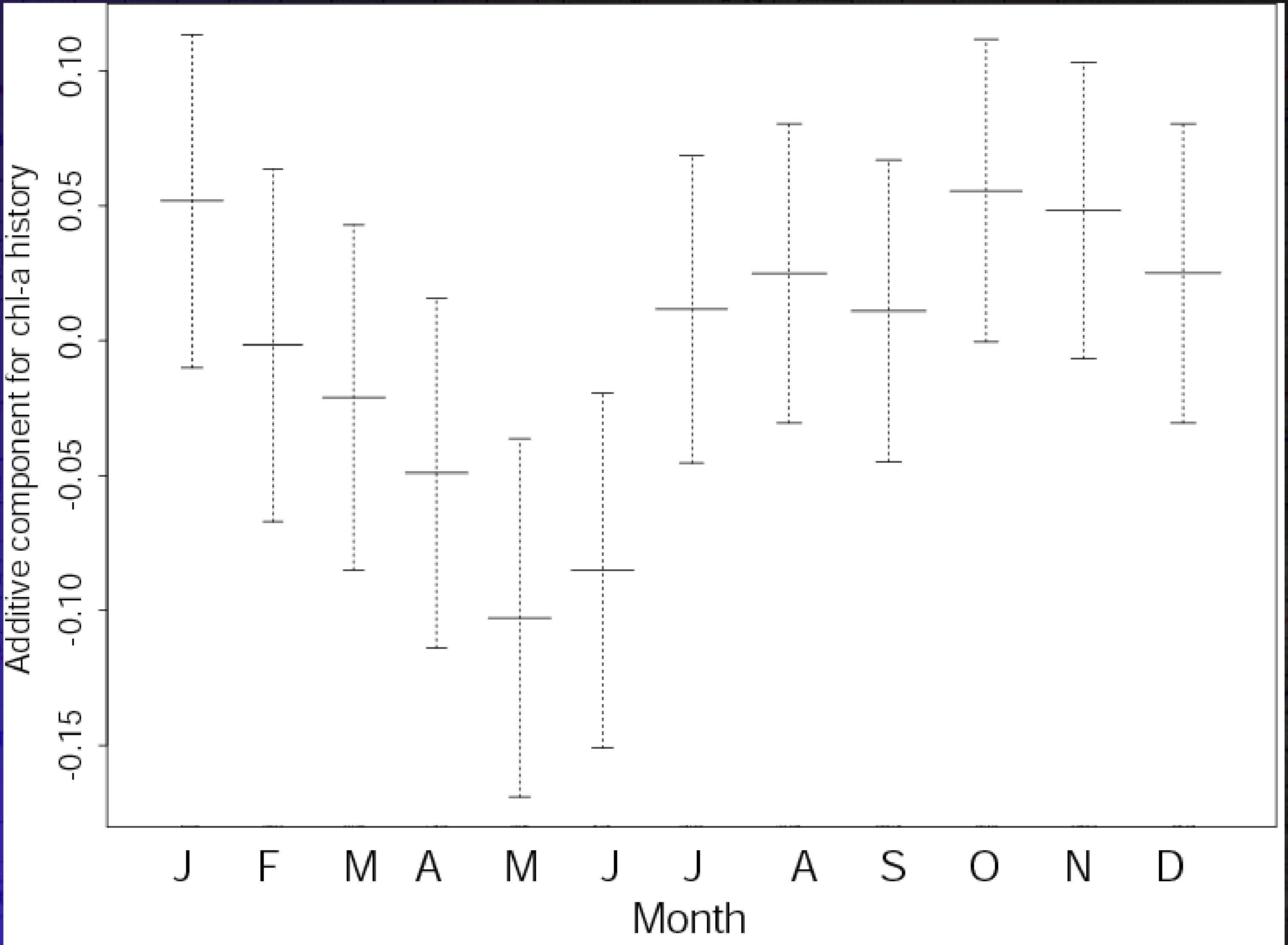




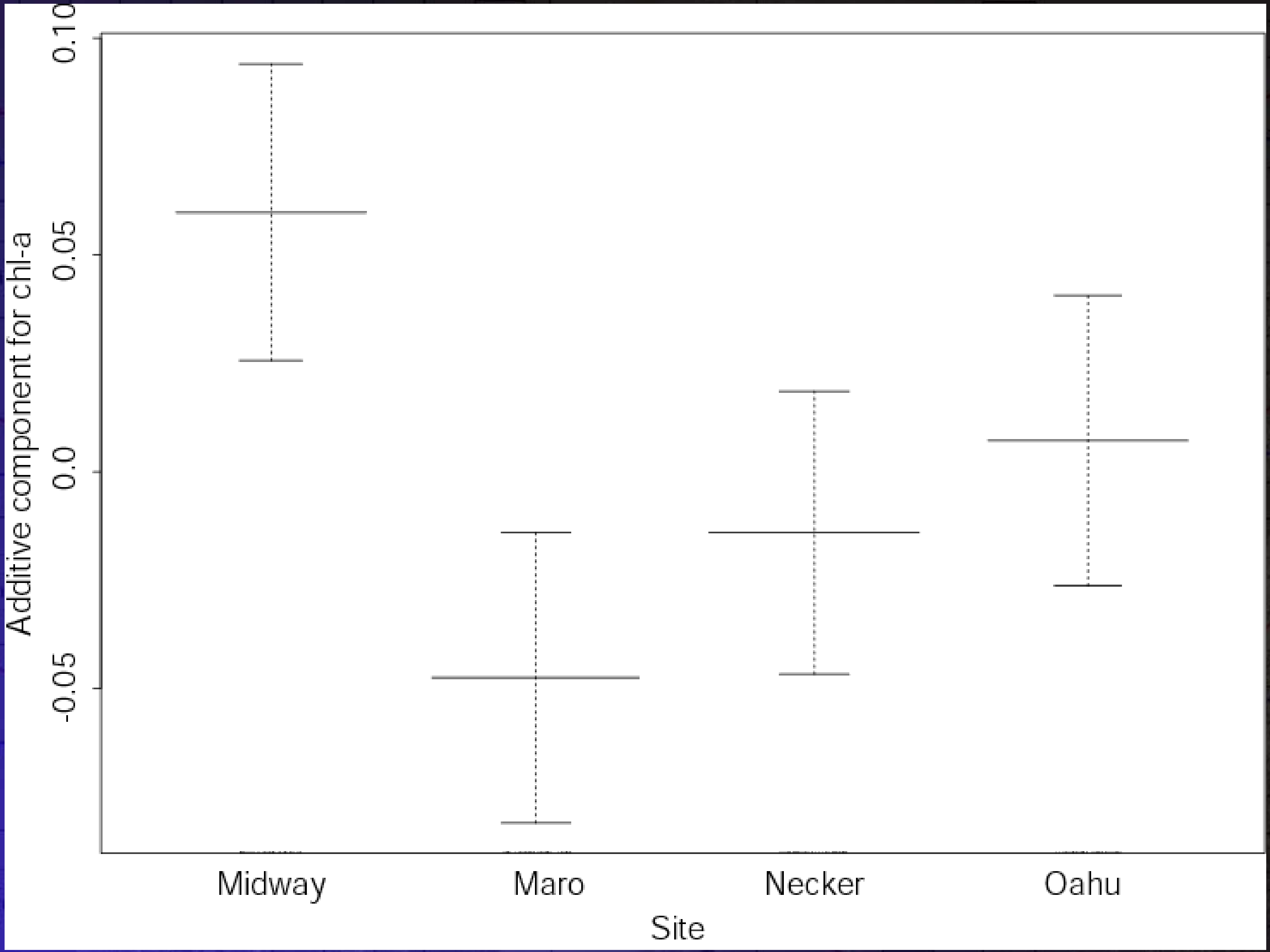
Chl-a History of 3 month Retained Larvae – Effect of Month



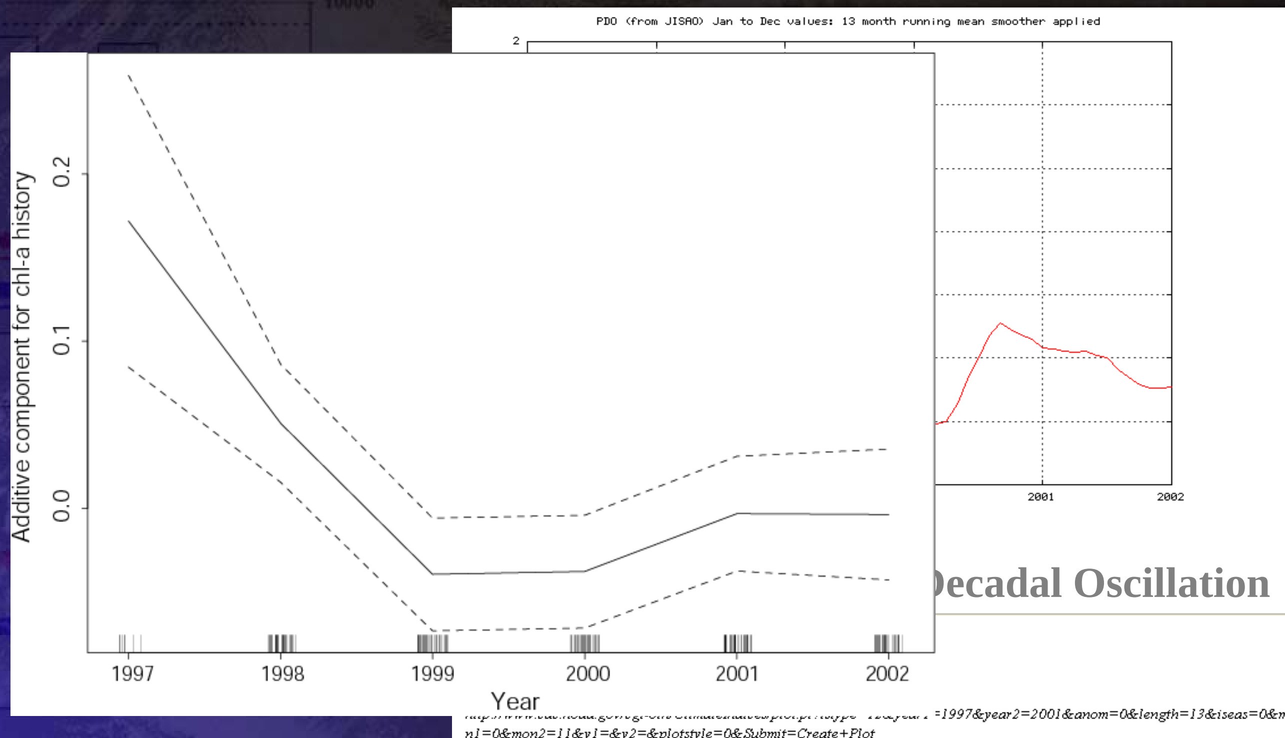
Chl-a History of 6 month Retained Larvae – Effect of Month

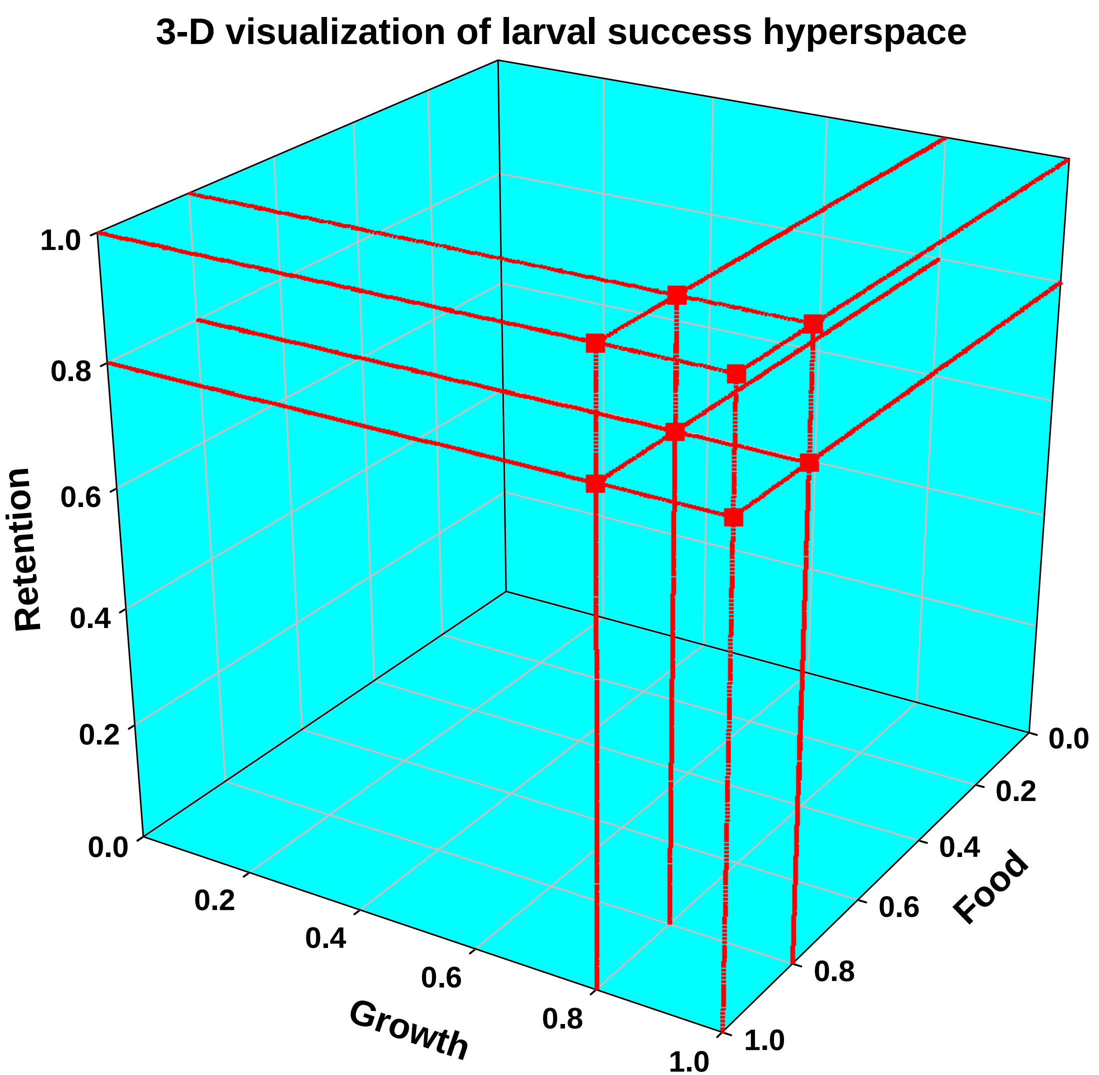


Chl-a History of Retained Larvae – Effect of Site



Chl-a History of Retained Larvae – Effect of Year





3-D visualization of larval success hyperspace
Retention
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
Growth
0.0
0.2
0.4
0.6
0.8
1.0
Food

Conclusions

- **Larval retention, transport, and potential non-settlement were found to be strongly related to pelagic duration, spawning location, and seasonal & interannual effects.**
- **SST history was strongly seasonal with May-August peaks, also strong spawning site relationships and interannual effects. There were exceptionally low values at Midway, and a trend of increasing values to the south.**
- **Chlorophyll-a history was strongly seasonal with April-August lows, also strong spawning site relationships and interannual effects. There were exceptionally high values at Midway, and a trend of increasing values to the south.**
- **Midway was strongly impacted in both SST and chlorophyll-a histories by its proximity to the South Subtropical Front, with markedly reduced SST and elevated chlorophyll-a.**

Second review document

- This paper examined potential larval transport corridors between Johnston Atoll and the Hawaiian Archipelago.
- Used a year (2003) of Navy NLOM data.
- Corroborated findings from field surveys and genetic analyses.

Coral Reefs (2006) 25: 407–417
DOI 10.1007/s00338-006-0118-5

REPORT

Donald R. Kobayashi

Colonization of the Hawaiian Archipelago via Johnston Atoll: a characterization of oceanographic transport corridors for pelagic larvae using computer simulation

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Abstract Larval transport between Johnston Atoll and the Hawaiian Archipelago was examined using computer simulation and high-resolution ocean current data. The effects of pelagic larval duration and spawning seasonality on long-distance transport and local retention were examined using a Lagrangian, individual-based approach. Retention around Johnston Atoll appeared to be low, and there appeared to be seasonal effects on both retention and dispersal. Potential larval transport corridors between Johnston Atoll and the Hawaiian Archipelago were charted. One corridor connects Johnston Atoll with the middle portion of the Hawaiian Archipelago in the vicinity of French Frigate Shoals. Another corridor connects Johnston Atoll with the lower inhabited islands in the vicinity of Kauai. Transport appears to be related to the subtropical countercurrent and the Hawaiian Lee countercurrent, both located to the west of the archipelago and flowing to the east. A new analytical tool, termed CONREC–IRC is presented for the quantification of spatial patterns.

Keywords Oceanography · Settlement · Recruitment · Metapopulation · Dispersal · Retention

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D. R. Kobayashi
Department of Environmental Sciences, University of Technology, Sydney, P.O. Box 123, Broadway, NSW 2007, Australia

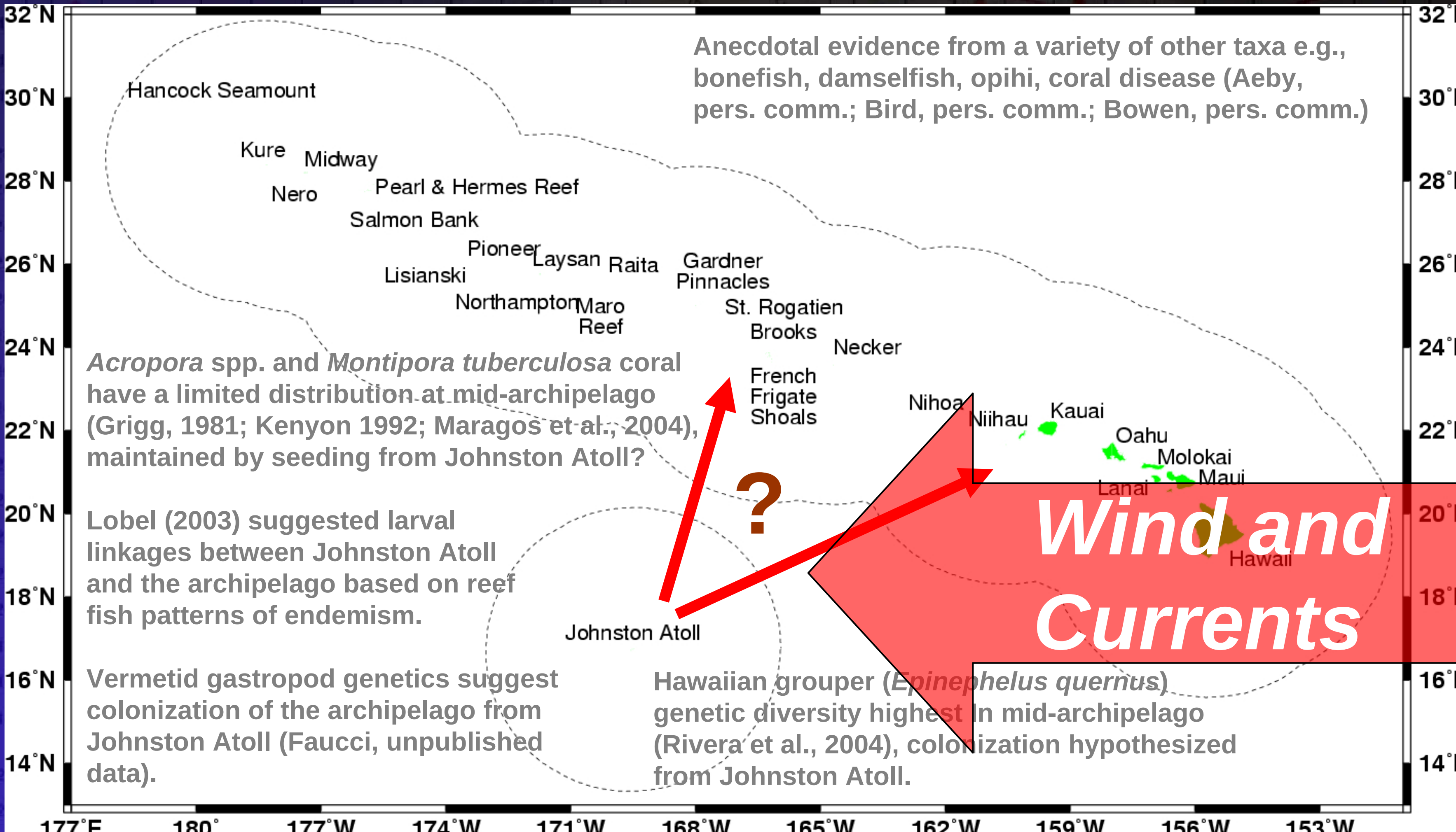
D. R. Kobayashi (✉)
Pacific Islands Fisheries Science Center, 2570 Dole Street, Honolulu, HI 96822, USA
E-mail: Donald.Kobayashi@noaa.gov
Tel.: +1-808-9835394
Fax: +1-808-9832902

Introduction

Johnston Atoll is an extremely isolated coral atoll at 16°45′N, 169°31′W, approximately 1,325 km southwest of the Hawaiian Island of Oahu (Fig. 1). The nearest island, French Frigate Shoals, in the middle of the Hawaiian Archipelago, is 865 km to the north–north-east, and Kingman Reef in the northernmost portion of the Line Islands is 1,385 km to the southeast. The fauna of Johnston Atoll is relatively well documented (e.g., Kosaki et al. 1991; Lobel 2003), with biogeographic ties to both the Hawaiian Islands and the Line Islands (Springer 1982; Robertson et al. 2004; Mundy 2005), and has a relatively low rate of endemism.

Several, recent scientific findings across a wide group of taxa have given rise to compelling evidence that Johnston Atoll is a stepping stone to species colonization in the Hawaiian Archipelago. A genetics study of the Hawaiian grouper, *Epinephelus quernus*, has shown that the greatest genetic diversity of this species occurs in the middle of the Hawaiian Archipelago (Rivera et al. 2004). Based on this spatial pattern, it was hypothesized that *E. quernus* colonized the archipelago via Johnston Atoll and subsequently radiated to the north and south portions of the archipelago. Corals of the genus *Acropora* in and around the Hawaiian Archipelago have been the subject of extensive biogeographic study (Grigg 1981; Grigg et al. 1981). Despite the ability of *Acropora* to reproduce in the Hawaiian Archipelago (Kenyon 1992), it is thought that *Acropora* initially arrived and may be primarily maintained by long-distance larval transport from Johnston Atoll. This is based on the distribution and abundance of adult colonies. These spatial patterns and likely colonization routes are also exhibited by other coral species, such as *Montipora tuberculosa* (Maragos et al. 2004). Recent genetics work on vermetid gastropods has also yielded evidence of a Johnston Atoll link for the colonization pathway of these species (Faucci, personal communication). These findings suggest that

Johnston Atoll



Anecdotal evidence from a variety of other taxa e.g., bonefish, damselfish, opihi, coral disease (Aeby, pers. comm.; Bird, pers. comm.; Bowen, pers. comm.)

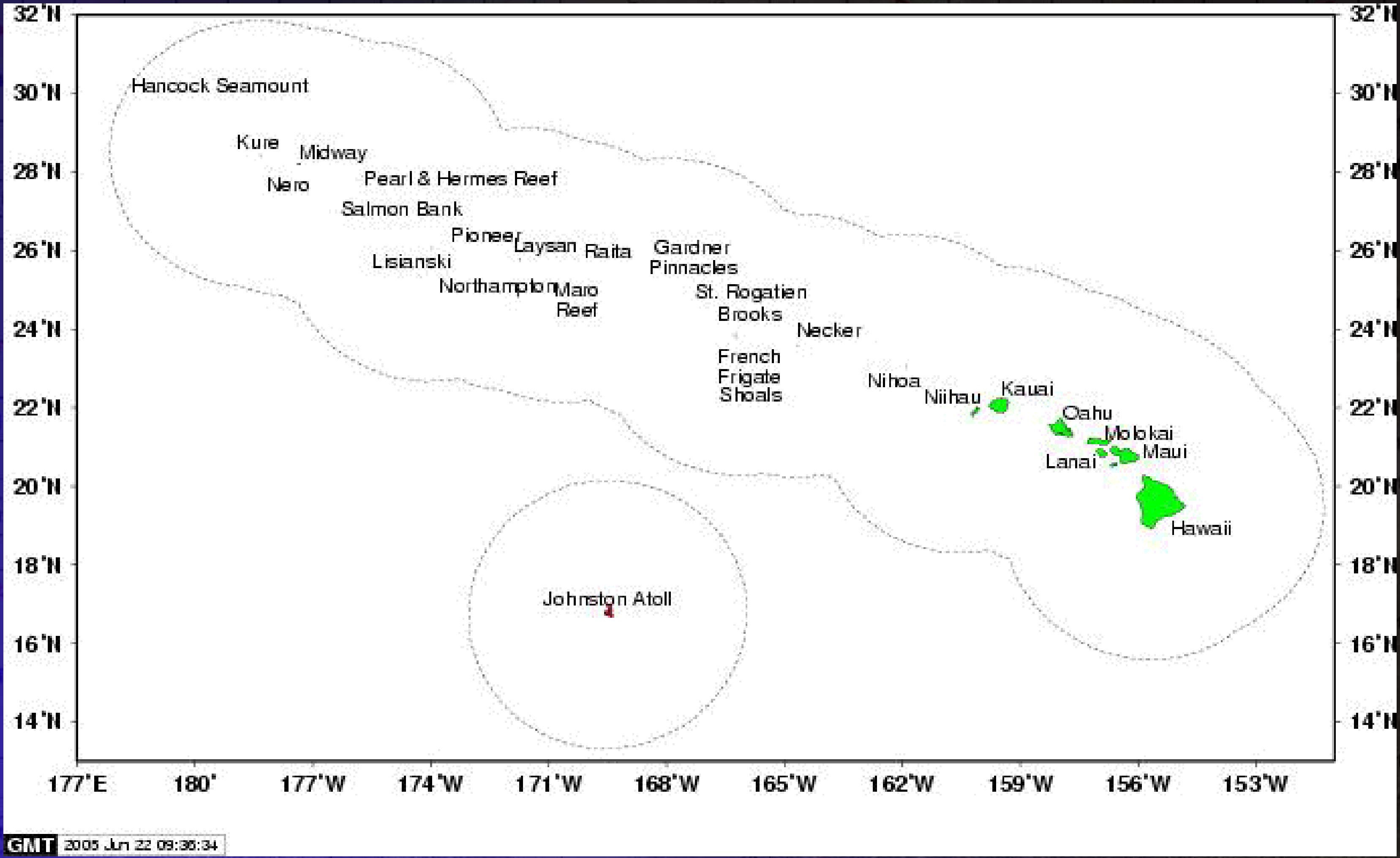
Acropora spp. and *Montipora tuberculosa* coral have a limited distribution at mid-archipelago (Grigg, 1981; Kenyon 1992; Maragos et al., 2004), maintained by seeding from Johnston Atoll?

Lobel (2003) suggested larval linkages between Johnston Atoll and the archipelago based on reef fish patterns of endemism.

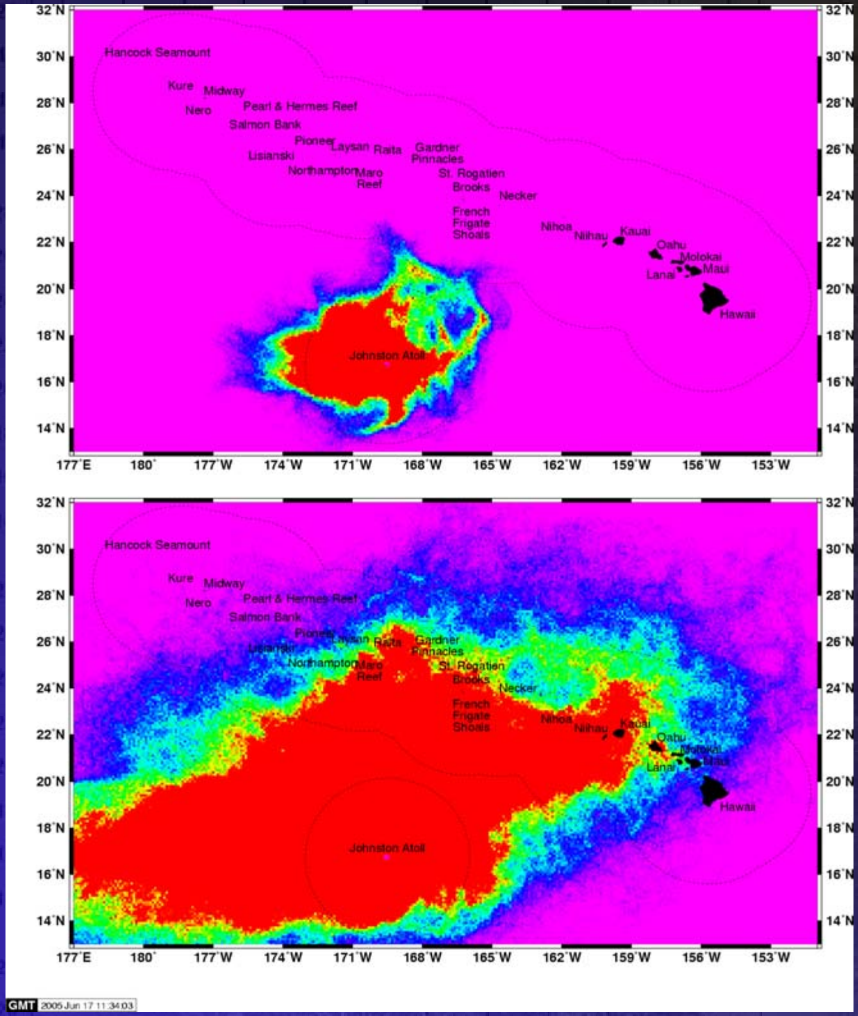
Vermetid gastropod genetics suggest colonization of the archipelago from Johnston Atoll (Faucci, unpublished data).

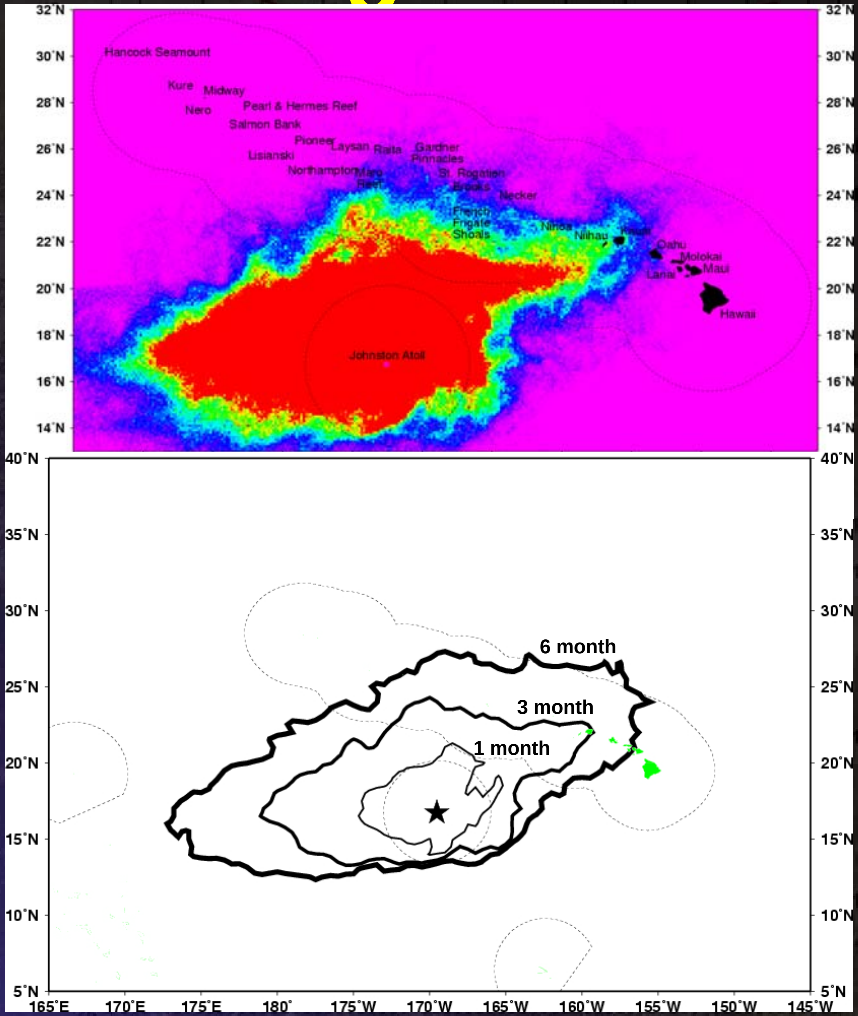
Hawaiian grouper (*Epinephelus quernus*) genetic diversity highest in mid-archipelago (Rivera et al., 2004), colonization hypothesized from Johnston Atoll.

Johnston Atoll

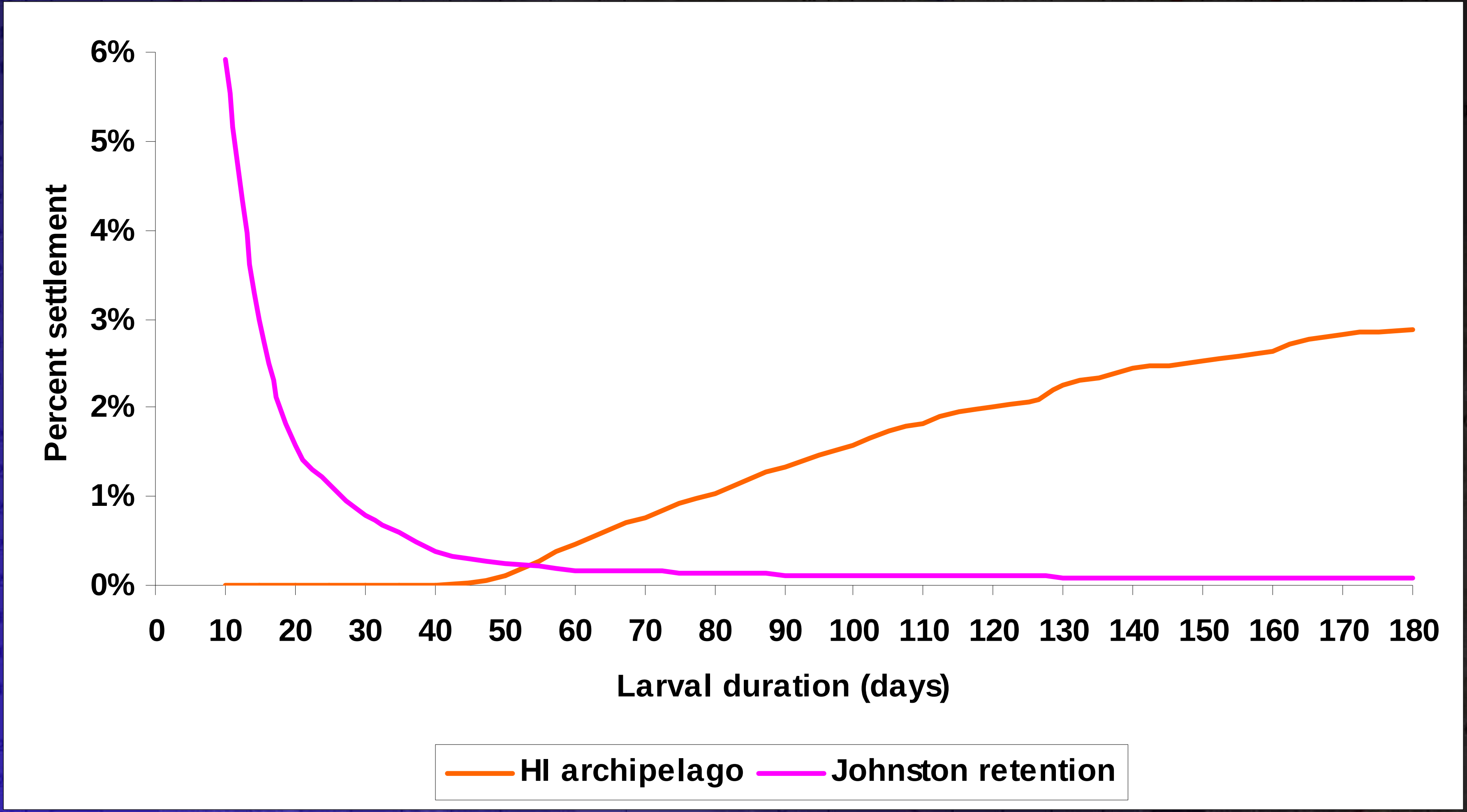


1, 3, 6 month durations, "larval containment regions"

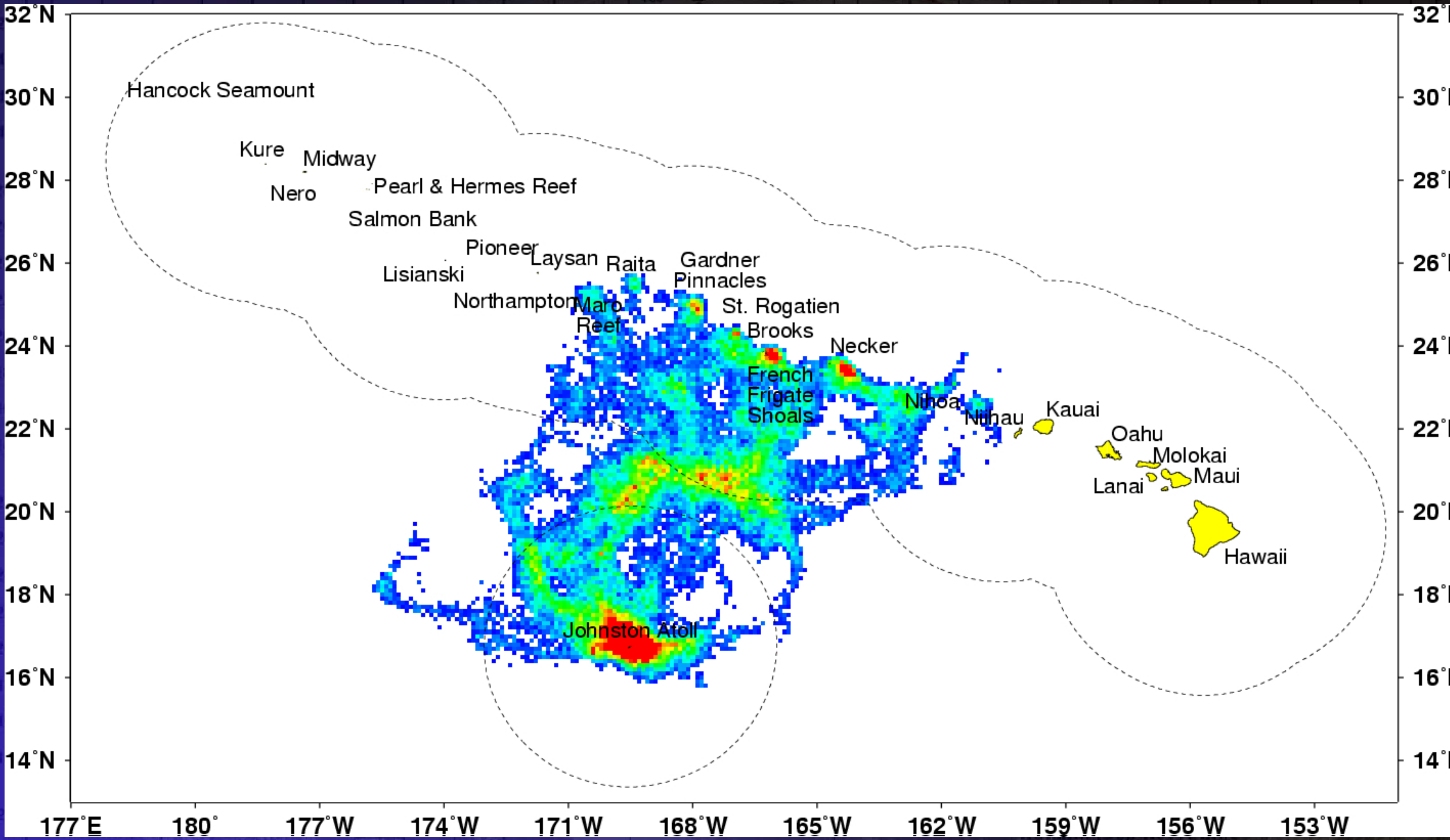




Transport and retention as a function of larval duration

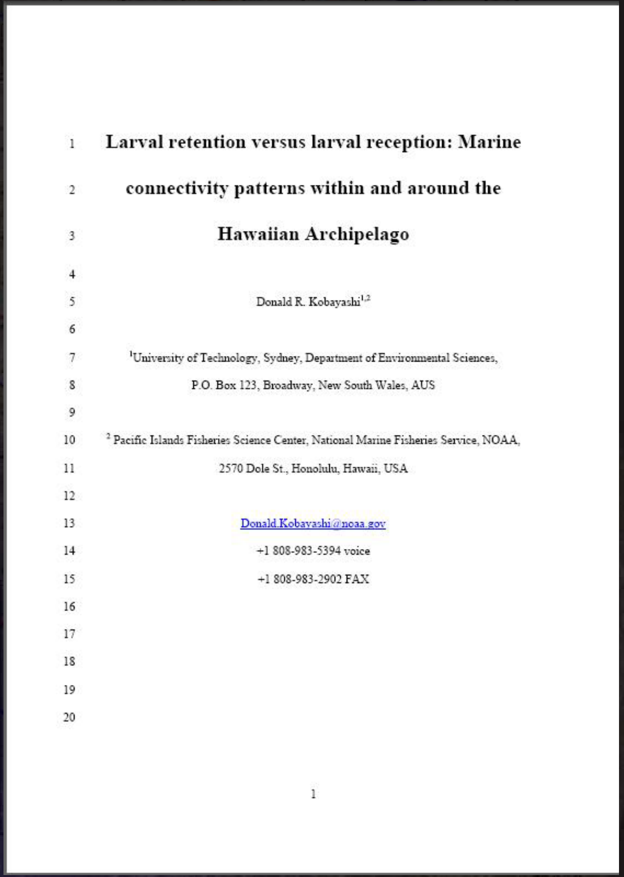


North and South "Corridors"



Third review document

- This paper examined connectivity across all major geographic strata in the Hawaiian Archipelago.
- Used a year (2003) of Navy NLOM data.
- Undergoing revision from Marine Ecology Progress Series reviewer comments.



Larval retention versus larval reception: Marine connectivity patterns within and around the Hawaiian Archipelago

Donald R. Kobayashi[1,2]

[1]University of Technology, Sydney, Department of Environmental Sciences, P.O. Box 123, Broadway, New South Wales, AUS

[2] Pacific Islands Fisheries Science Center, National Marine Fisheries Service, NOAA, 2570 Dole St., Honolulu, Hawaii, USA

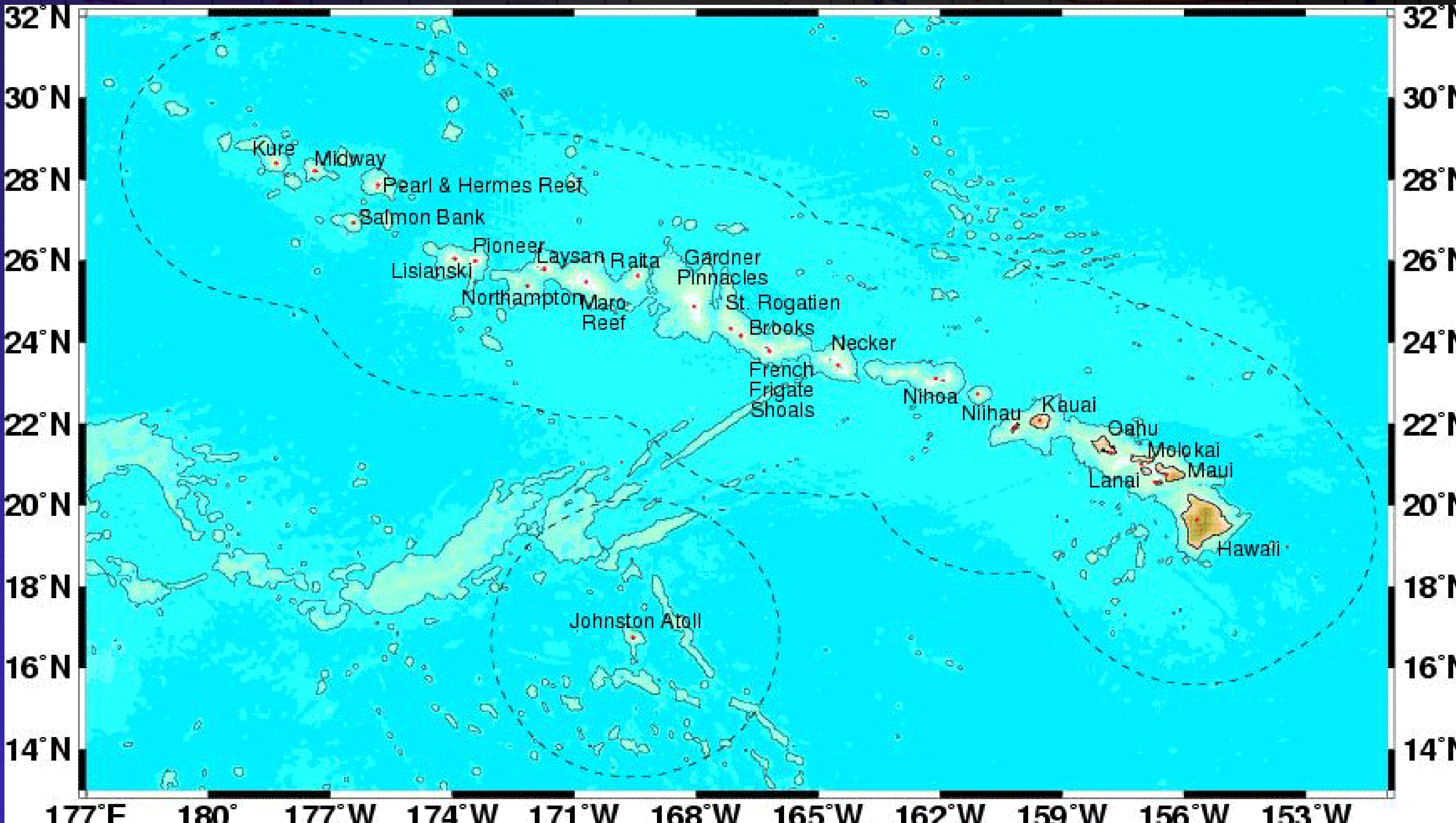
Donald.Kobayashi@noaa.gov

+1 808-983-5394 voice

+1 808-983-2902 FAX

1

Archipelagic connectivity



Recent Modeling Approach

- **Lagrangian, individual-based, stochastic modeling framework.**
  - **Parameterized by spawning location, spawning timing, and pelagic larval duration (PLD).**
- **Naval Research Laboratory Layered Ocean Model (NLOM).**
  - **Daily, 1/16th degree latitude/longitude resolution.**

Connectivity Analysis

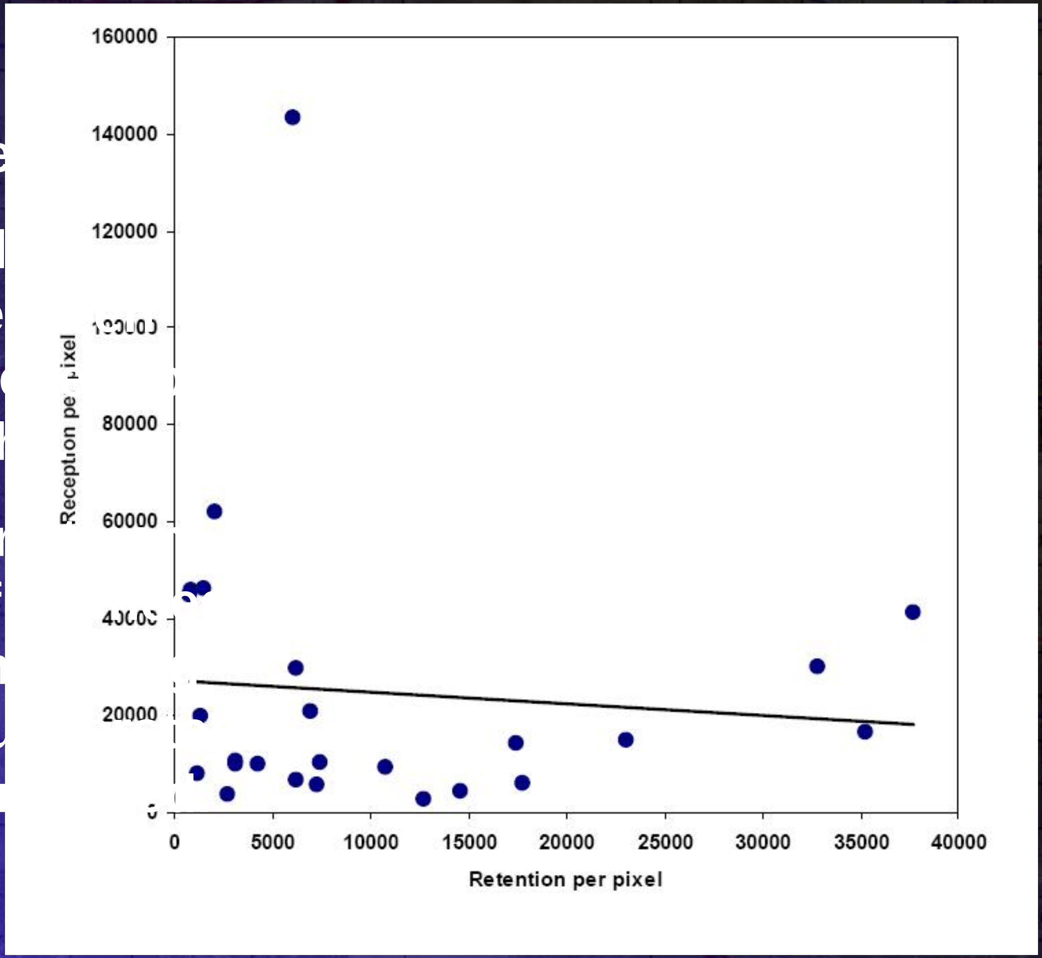
Index #	Location	Longitude E	Latitude N	2' pixels 0-100m	Total releases	Total retention	Retention per release	Total reception	Total settlement	Settlement per pixel
1	Kure	181.66	28.41	11	2409000	30747	1.28%	38426	69173	6288
2	Midway	182.62	28.21	9	1971000	38579	1.96%	89336	127915	14213
3	Pearl & Hermes	184.17	27.86	24	5256000	176189	3.35%	131800	307989	12833
4	Salmon	183.57	26.93	2	438000	3072	0.70%	92505	95577	47789
5	Lisianski	186.07	26.05	24	5256000	258803	4.92%	217695	476498	19854
6	Pioneer	186.57	26.00	29	6351000	91598	1.44%	288039	379637	13091
7	Laysan	188.26	25.82	27	5913000	189576	3.21%	556023	745599	27615
8	Northampton	187.85	25.38	4	876000	24289	2.77%	572478	596767	149192
9	Maro	189.30	25.48	91	19929000	1335332	6.70%	400380	1735712	19074
10	Raita	190.57	25.64	14	3066000	88058	2.87%	414671	502729	35909
11	Gardner	191.96	24.88	143	31317000	1822490	5.82%	363624	2186114	15288
12	St. Rogatien	192.86	24.33	19	4161000	26880	0.65%	375485	402365	21177
13	Brooks	193.10	24.16	5	1095000	10549	0.96%	308981	319530	63906
14	French Frigate Shoals	193.80	23.79	51	11169000	319006	2.86%	343052	662058	12982
15	Necker	195.50	23.44	66	14454000	1176951	8.14%	399529	1576480	23886
16	Nihoa	197.89	23.11	37	8103000	277273	3.42%	377511	654784	17697
17	Middle	198.93	22.73	3	657000	2593	0.39%	137013	139606	46535
18	Niihau	199.84	21.91	21	4599000	67025	1.46%	220240	287265	13679
19	Kauai	200.45	22.09	36	7884000	628720	7.97%	504455	1133175	31477
20	Oahu	202.21	21.28	92	20148000	2125237	10.55%	1373999	3499236	38035
21	Molokai	202.95	21.01	84	18396000	2759697	15.00%	2521814	5281511	62875
22	Lanai	203.28	20.57	4	876000	3399	0.39%	178743	182142	45536
23	Maui	203.58	20.76	63	13797000	2378704	17.24%	2601584	4980288	79052
24	Hawaii	204.32	19.64	99	21681000	3490738	16.10%	1628482	5119220	51709
25	Johnston	190.45	16.75	1	219000	1241	0.57%	7850	9091	9091

Decoupled Retention and Reception

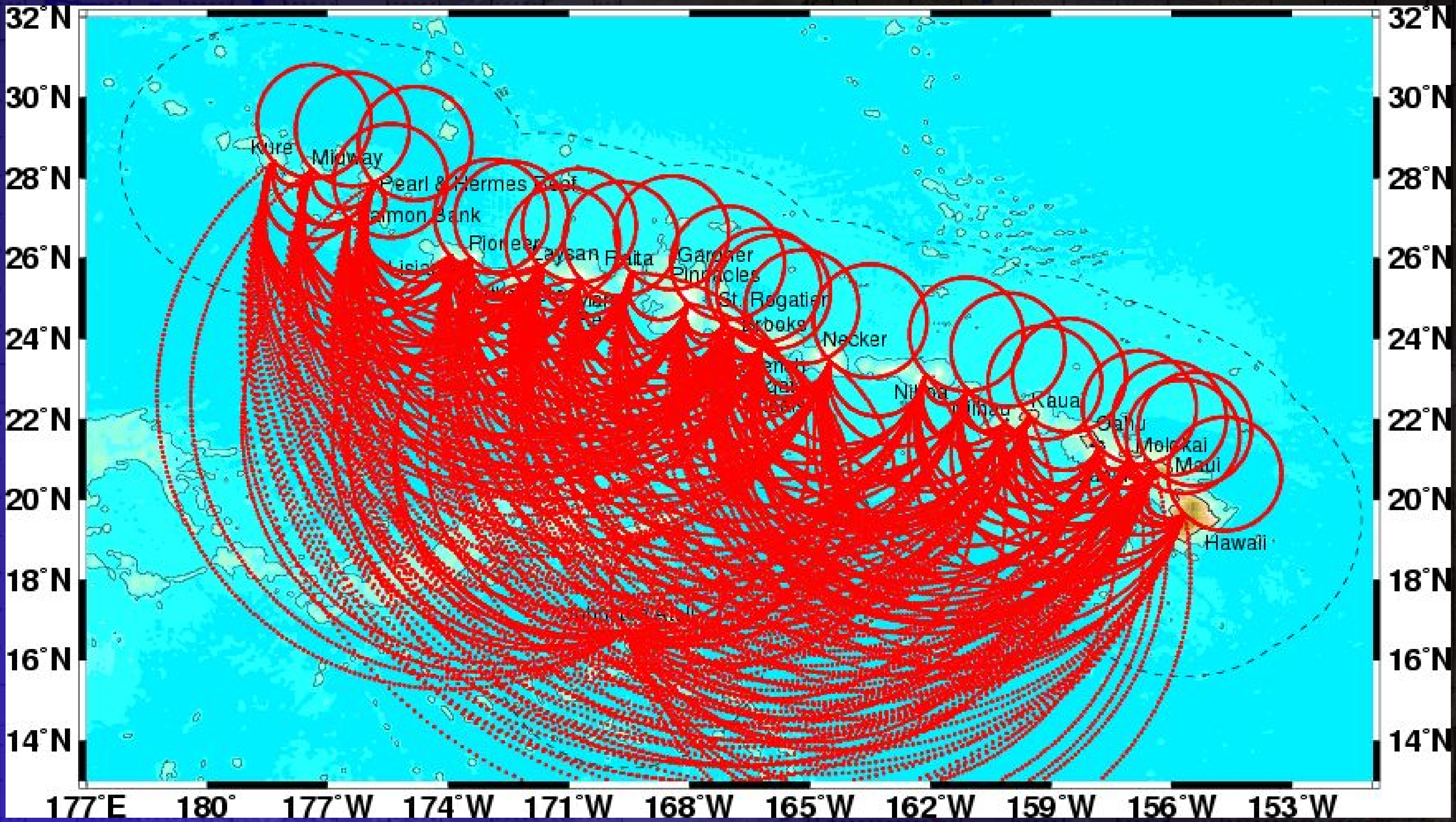
Interpre

The lack of a cl relationship be retention and r most noteworth

Settlement/recr studies in the f "source" the in larvae to fully u the dynamics i



Can we examine the strength of each of these connections?



Appendix Table 1A. Dispersal kernel matrix for 15 day PLD. Each cell represents probability of a larva leaving source location and arriving at sink location using 2003-2004 NLOM daily currents. Highlighted diagonal cells represent natal retention.

Source

Sink	Kure	Midway	Pearl & Hermes	Salmon	Lisianski	Pioneer	Laysan	Northampton	Maro	Raita	Gardner	St Rogatien	Brooks	French Frigate Shoals	Necker	Nihoa	Middle	Niihau	Kauai	Oahu	Molokai	Lanai	Maui	Hawaii	Johnston
Kure	0.043	0.019	0.001	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Midway	0.033	0.078	0.011	0.026	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pearl & Hermes	0.003	0.011	0.128	0.018	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Salmon	0.000	0.006	0.024	0.022	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Lisianski	0.000	0.000	0.000	0.004	0.201	0.046	0.001	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pioneer	0.000	0.000	0.000	0.001	0.095	0.051	0.013	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Laysan	0.000	0.000	0.000	0.000	0.002	0.024	0.118	0.073	0.048	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Northampton	0.000	0.000	0.000	0.000	0.009	0.040	0.057	0.104	0.030	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Maro	0.000	0.000	0.000	0.000	0.000	0.006	0.032	0.034	0.250	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Raita	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.011	0.122	0.012	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gardner	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.018	0.224	0.018	0.012	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
St Rogatien	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.021	0.025	0.024	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Brooks	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.010	0.036	0.043	0.011	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
French Frigate Shoals	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.029	0.045	0.131	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Necker	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.005	0.033	0.326	0.017	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Nihoa	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.132	0.035	0.010	0.003	0.000	0.000	0.000	0.000	0.000	0.000
Middle	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.011	0.014	0.004	0.000	0.000	0.000	0.000	0.000	0.000
Niihau	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.018	0.061	0.034	0.001	0.000	0.000	0.000	0.000	0.000
Kauai	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.102	0.306	0.007	0.000	0.000	0.000	0.000	0.000
Oahu	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.015	0.344	0.084	0.028	0.008	0.002	0.000
Molokai	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.147	0.463	0.136	0.128	0.005	0.000
Lanai	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.009	0.013	0.010	0.002	0.000
Maui	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.017	0.152	0.240	0.502	0.044	0.000
Hawaii	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.024	0.146	0.064	0.384	0.000
Johnston	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.024
Lost	0.921	0.886	0.836	0.925	0.691	0.833	0.777	0.762	0.660	0.826	0.727	0.888	0.871	0.818	0.657	0.833	0.910	0.810	0.638	0.468	0.268	0.436	0.288	0.563	0.976

Source/sink dynamics and NWHI Monument

A. 30 day PLD.
Probability of what reaches sink came from source.

Sink \ Source	MHI	NWHI	Johnston
MHI	0.99	0.01	0.00
NWHI	0.02	0.98	0.00
Johnston	0.00	0.00	1.00
Lost	0.34	0.66	0.00

B. 90 day PLD.
Probability of what reaches sink came from source.

Sink \ Source	MHI	NWHI	Johnston
MHI	0.95	0.05	0.00
NWHI	0.04	0.96	0.00
Johnston	0.26	0.72	0.02
Lost	0.39	0.61	0.00

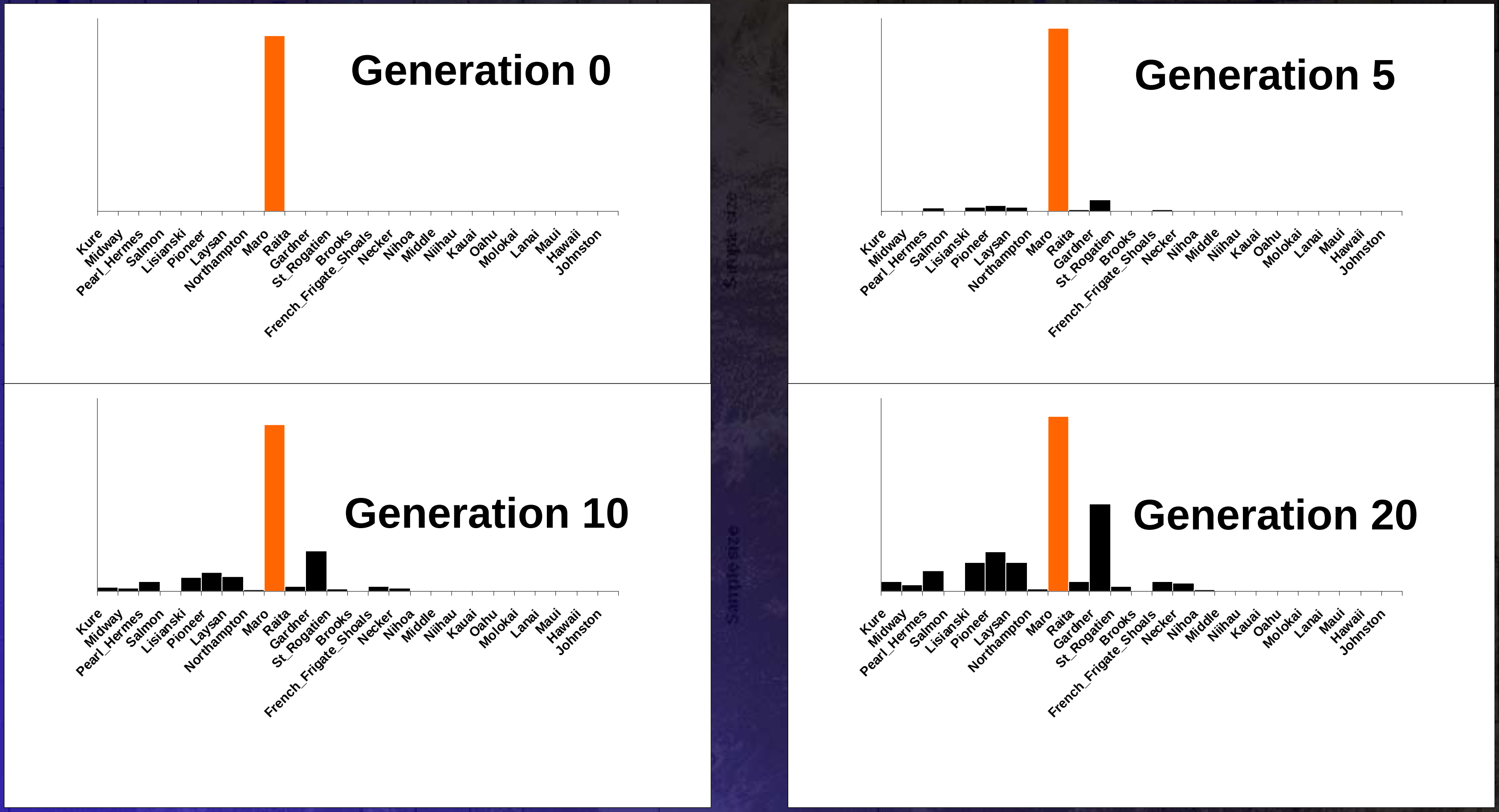
C. 180 day PLD.
Probability of what reaches sink came from source.

Sink \ Source	MHI	NWHI	Johnston
MHI	0.83	0.17	0.00
NWHI	0.07	0.93	0.00
Johnston	0.56	0.44	0.00
Lost	0.41	0.59	0.00

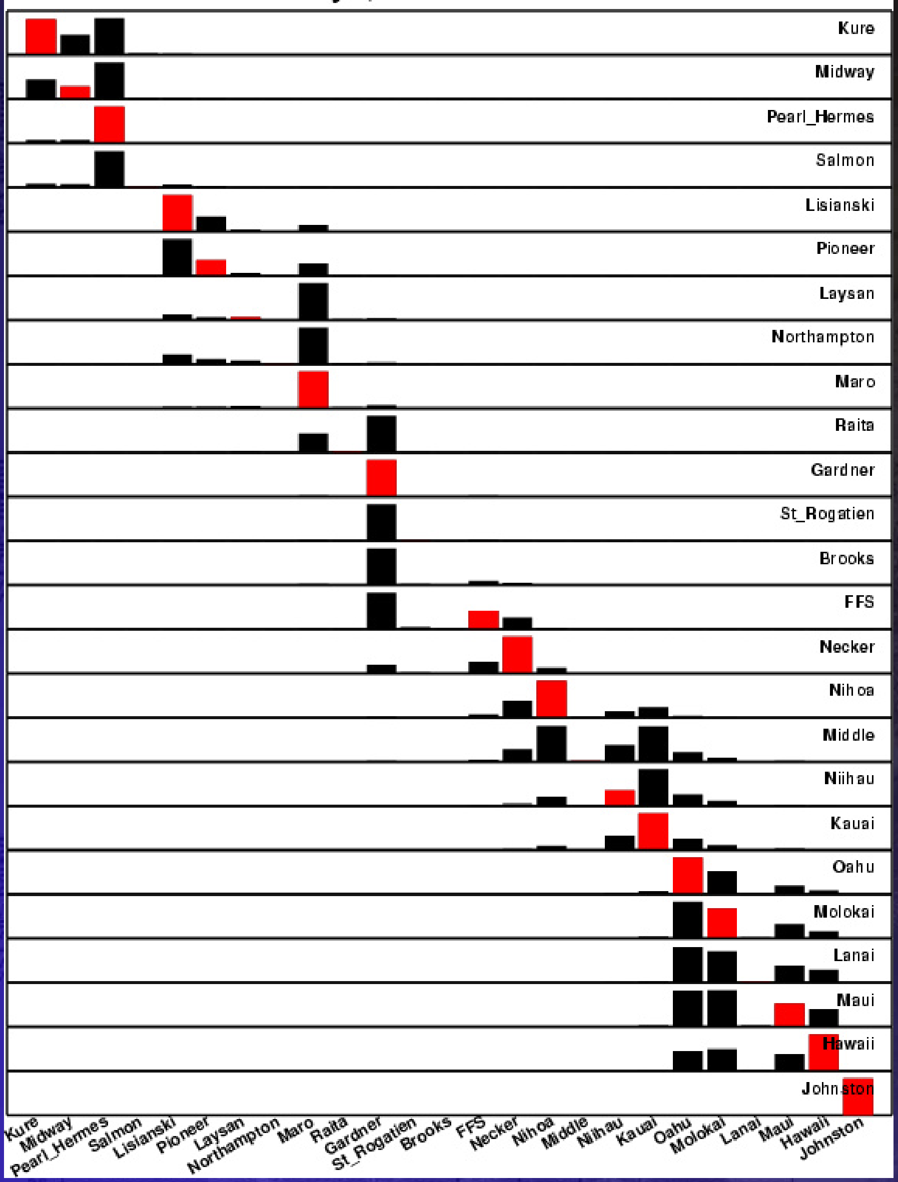
Metapopulation structure

- The next series of slides examine the breakdown of “source” components at various “sink” sites, assuming the dispersal dynamics just presented, merged into a simple multi-generation computer simulation, starting from a purely “native” population.
- Maro Reef, 6 month PLD, for example:

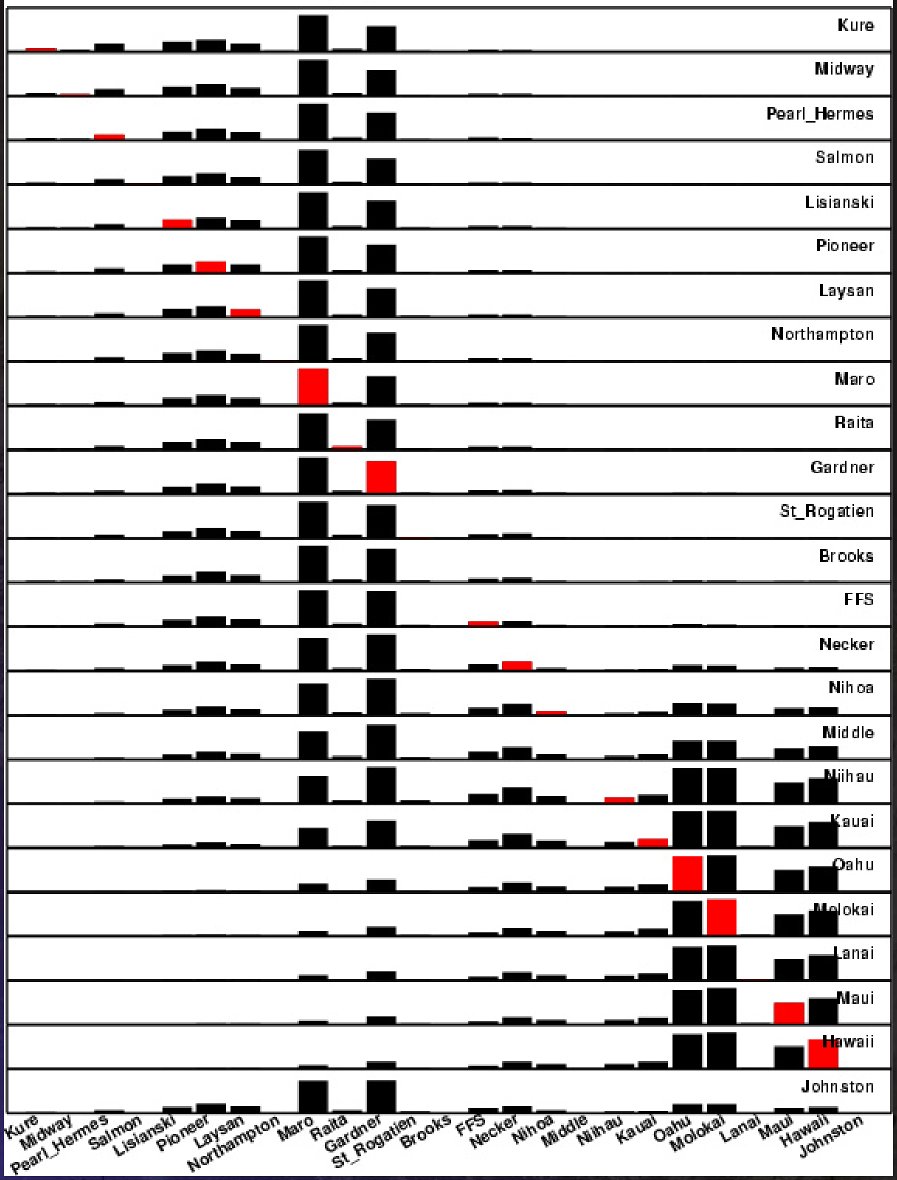
Example snapshots at various points in generation time at Maro Reef



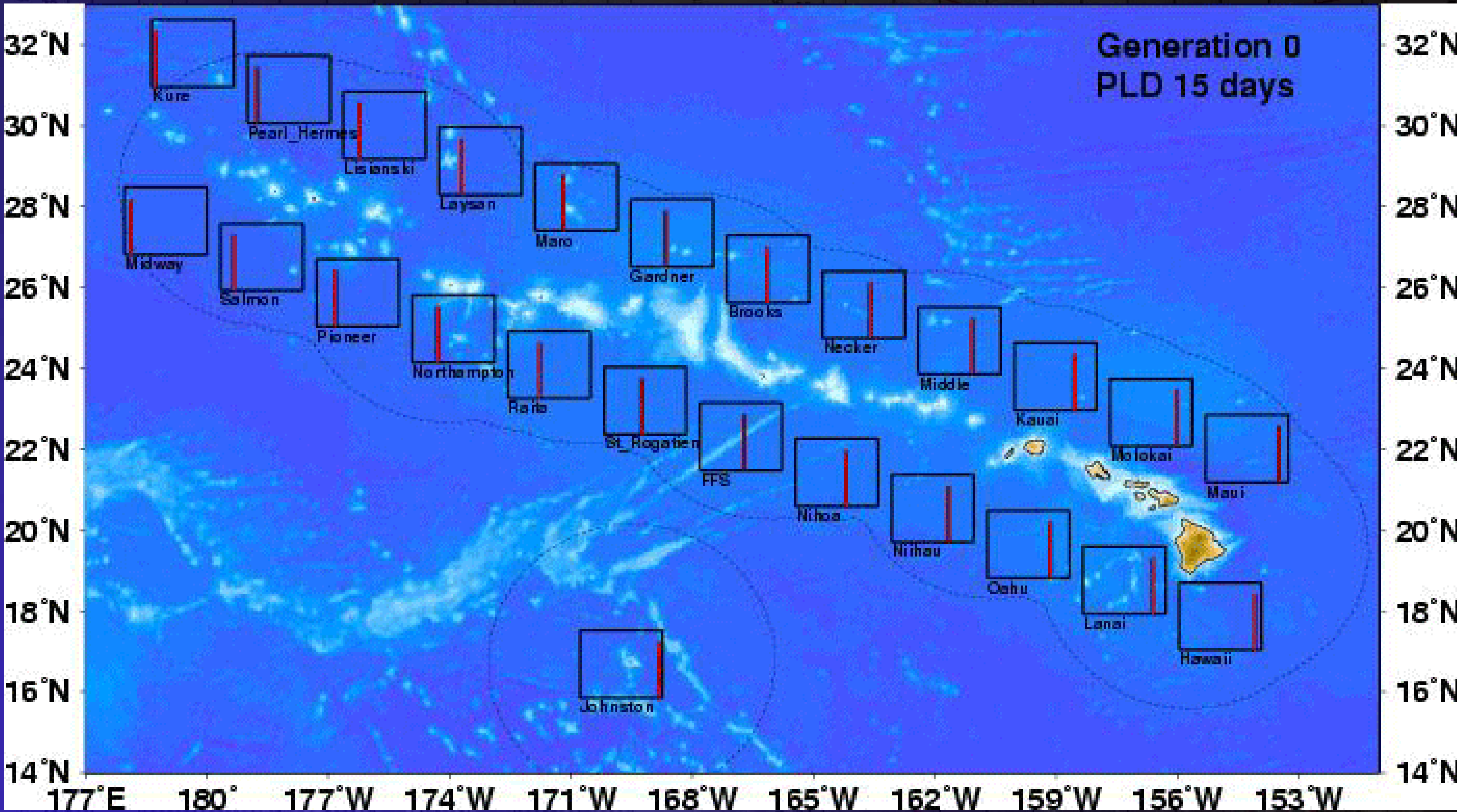
PLD 15 days, Generation 1000



PLD 90 days, Generation 1000



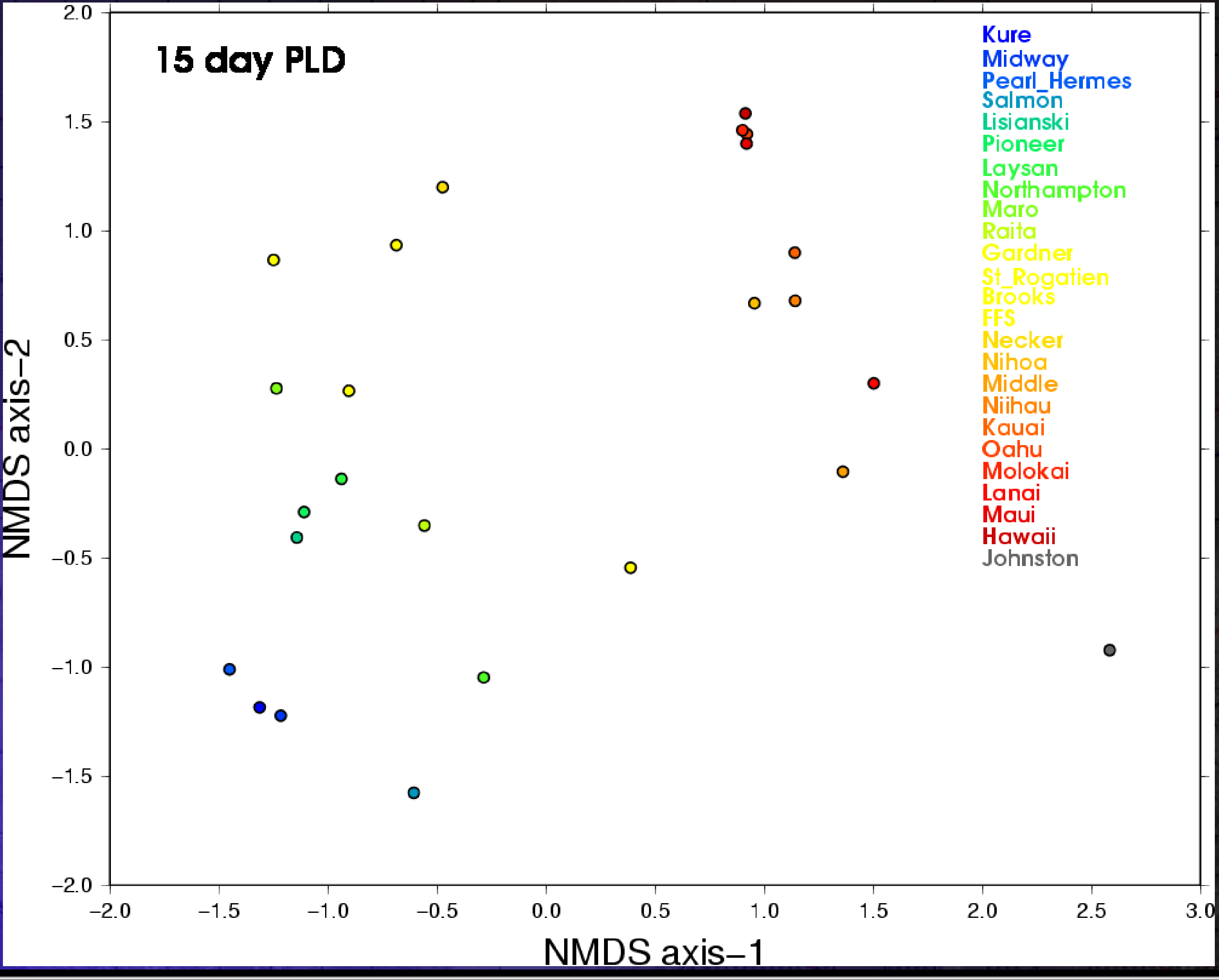
Metapopulation Simulation



Distillation of results

- Ordination techniques, such as nonmetric multidimensional scaling (NMDS) is a useful technique to group data and identify meaningful dimensions for further examination.
- Next plot shows NMDS results from metapopulation structure.
- Highlights the importance of PLD and starts to delineate spatial affinities.

Nonmetric multidimensional scaling (NMDS)



Archipelagic connectivity summary, future work, and collaborators

- New insights into the early life-history of insular species are becoming available using computer simulation and oceanographic data.
- This will help towards understanding connectivity, metapopulation dynamics, and the utility of marine protected areas. Such knowledge will improve management and stock assessment.
- Future work will focus heavily on partnerships for ground-truthing various model predictions.
- Collaboration with other PIFSC research divisions, UH/HIMB geneticists, oceanographers, and Australian researchers.

Fourth review document

- This manuscript examined the effect of diel vertical migration on horizontal transport.
- Used a long time series of AVISO altimetry-derived geostrophic currents and OSCAR surface currents.
- Undergoing revision from Pacific Science reviewer comments.

Running head: Larval transport modeling

Natal retention mediated by diel vertical migration:
Larval transport modeling in the Hawaiian Archipelago
with layered current fields[1]

Donald R. Kobayashi[2]
Dept. of Environmental Sciences, University of Technology, Sydney
P.O. Box 123, Broadway, New South Wales, 2007, Australia

[1]Manuscript accepted xxx-xxx-xx

[2]Present address:
NOAA Fisheries, Pacific Islands Fisheries Science Center
2570 Dole Street, Honolulu, Hawaii, 96822, USA

Donald.Kobayashi@noaa.gov
+1 808-983-5394 voice
+1 808-983-2902 FAX

Keywords: Recruitment; Settlement; Metapopulation; Connectivity; Simulation

1

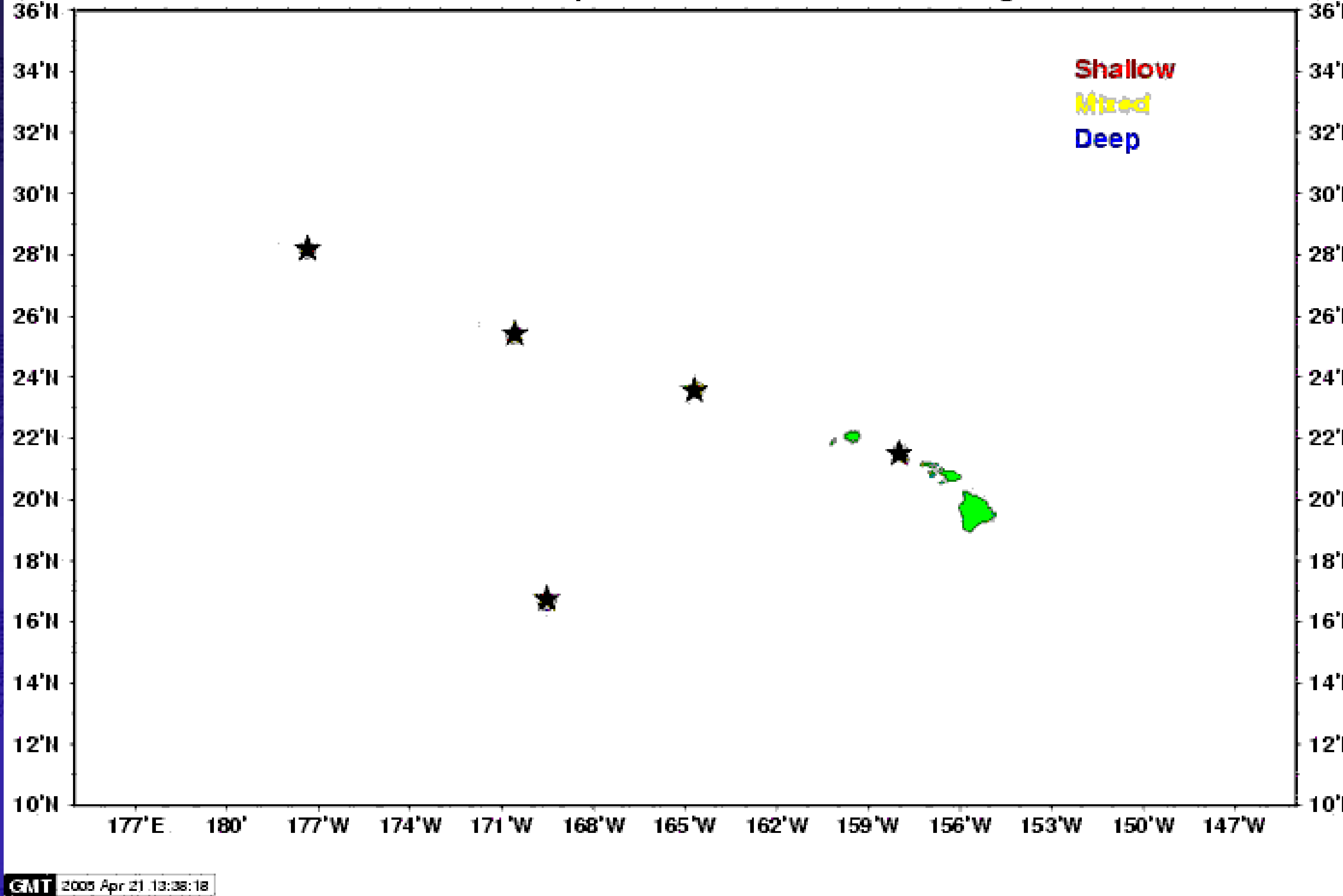
Vertical migration manuscript

- Historically, movement models have been 2-dimensional, examining areal transport.
- Incorporate vertical migration by allowing differential exposure to either surface (OSCAR) or deep currents (AVISO).
- Evaluate range from either all shallow to all deep, with 3 intermediate strategies.
- Examine many sites, months, years, and PLDs.
- Similar analysis with GAMs.

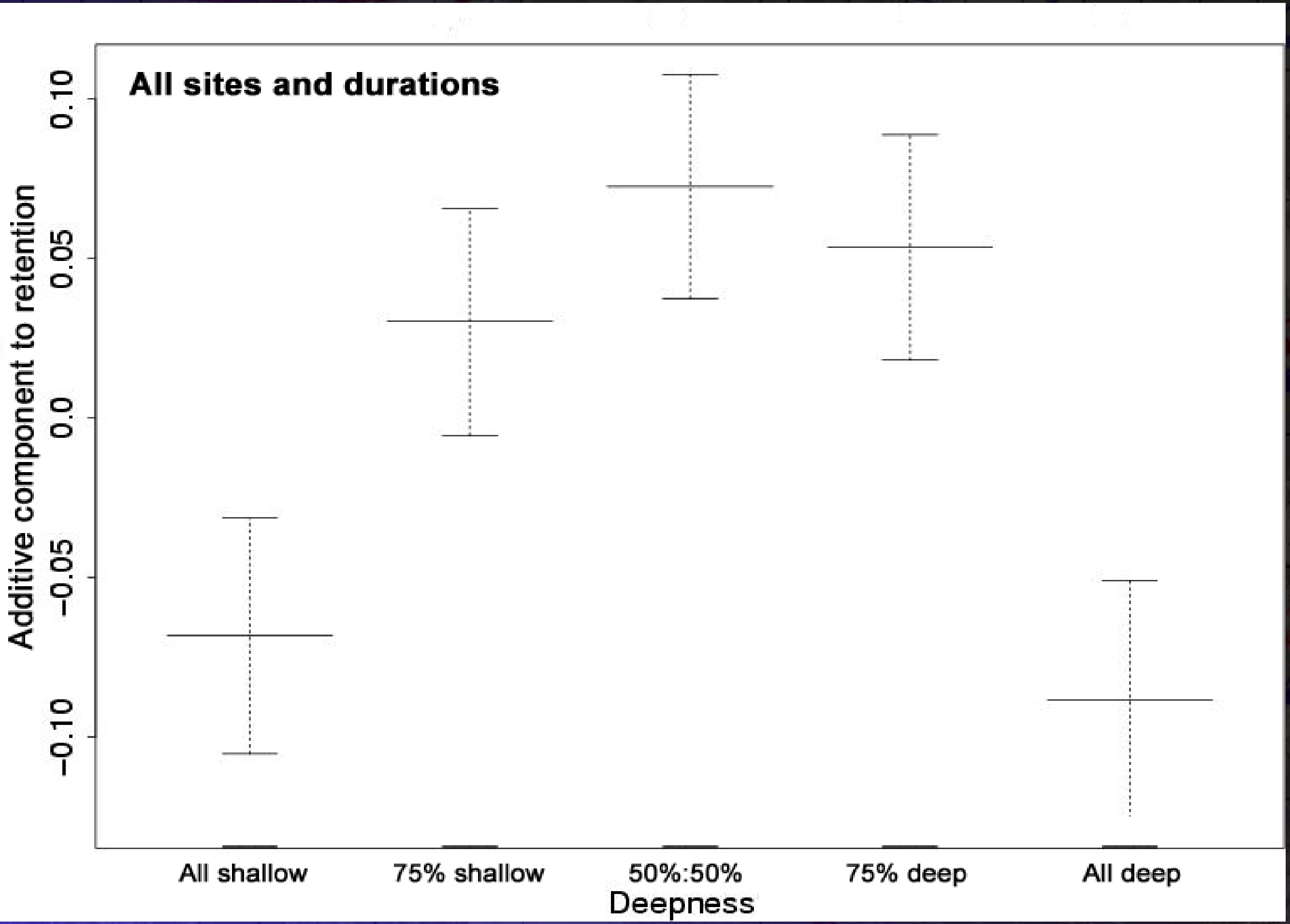
Diel vertical migration behavior

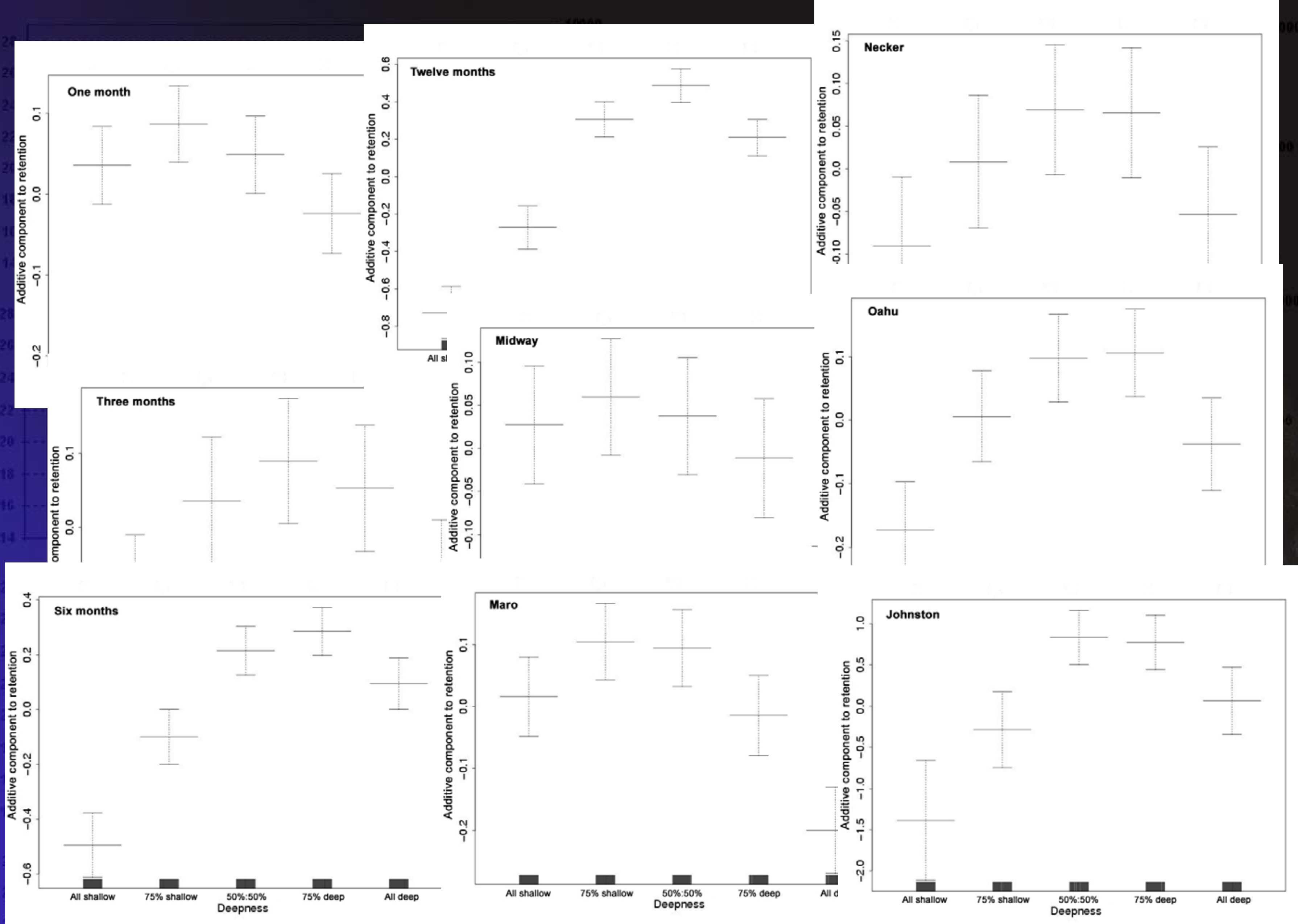
- **In the next slide we will see a single run for demonstration purposes, with 3 color-coded levels.**
- **Red denotes surface larvae.**
- **Blue denotes deep larvae.**
- **Yellow denotes a mixed tactic of 50% in surface/deep.**
- **This is a single run for 3 month duration mid-2002.**

Three month larval dispersal with differential vertical migration

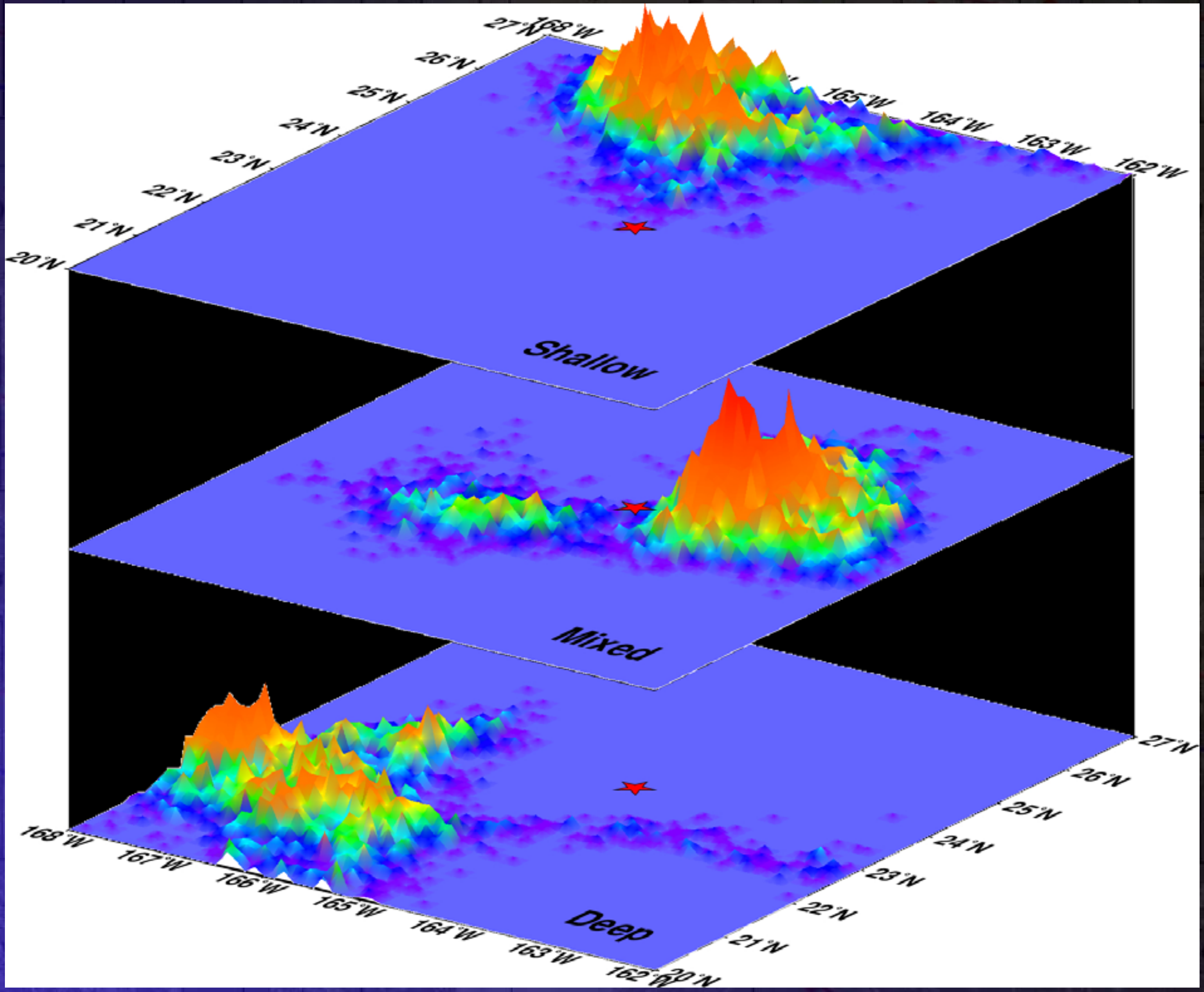


GAM to evaluate effect of DVM on retention




One month
Three months
Six months
Twelve months
Midway
Maro
Necker
Oahu
Johnston
Additive component to retention
All shallow
75% shallow
50%:50%
75% deep
All deep
Deepness

Example Distribution



Vertical migration conclusions & future

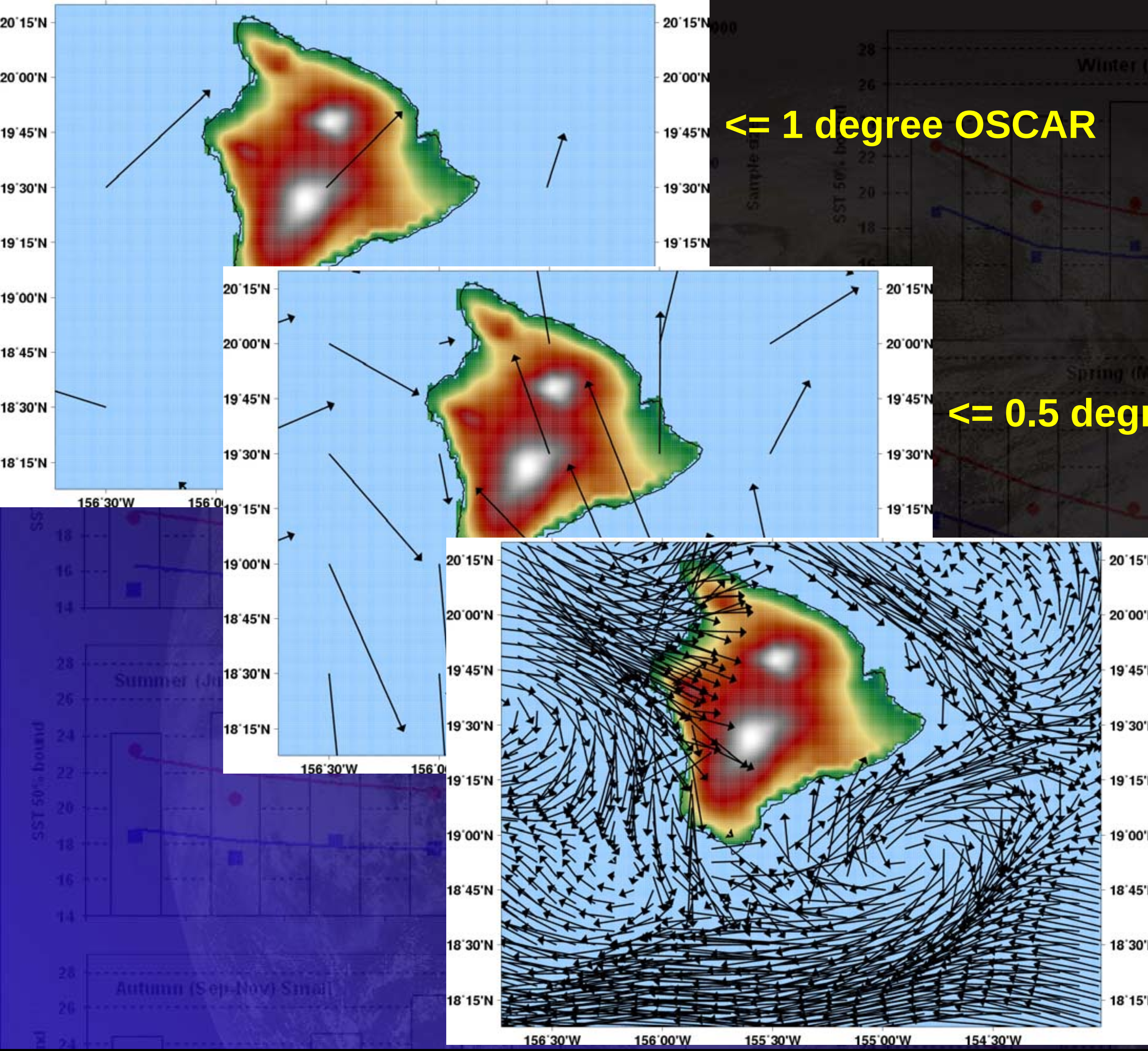
- Vertical movement behavior was found to be an important factor for retention.
- Intermediate levels of shallow/deep were found to be optimal.
- This finding was robust with respect to location, pelagic larval duration, year, and month.
- Incorporate daily NCOM with 18 layers (upper 100m) for finer resolution model.
- Incorporate the environmental fields as done in earlier work.
- Revise manuscript for Pacific Science.

Ongoing and future research initiatives

- Explore newer circulation model data.
- Comparison of models (e.g., NLOM vs. NCOM) .
- Evaluate eddy diffusivity coefficient.
- Improve boundary behavior.
- Incorporate behavior – orientation & swimming.
- Port code to Java and/or Python.
- Development of connectivity web interface for resource managers.

Explore newer circulation model data

- Navy Coastal Ocean Model (NCOM)*
- Tidal model (UH)*
- ROMS
- HYCOM

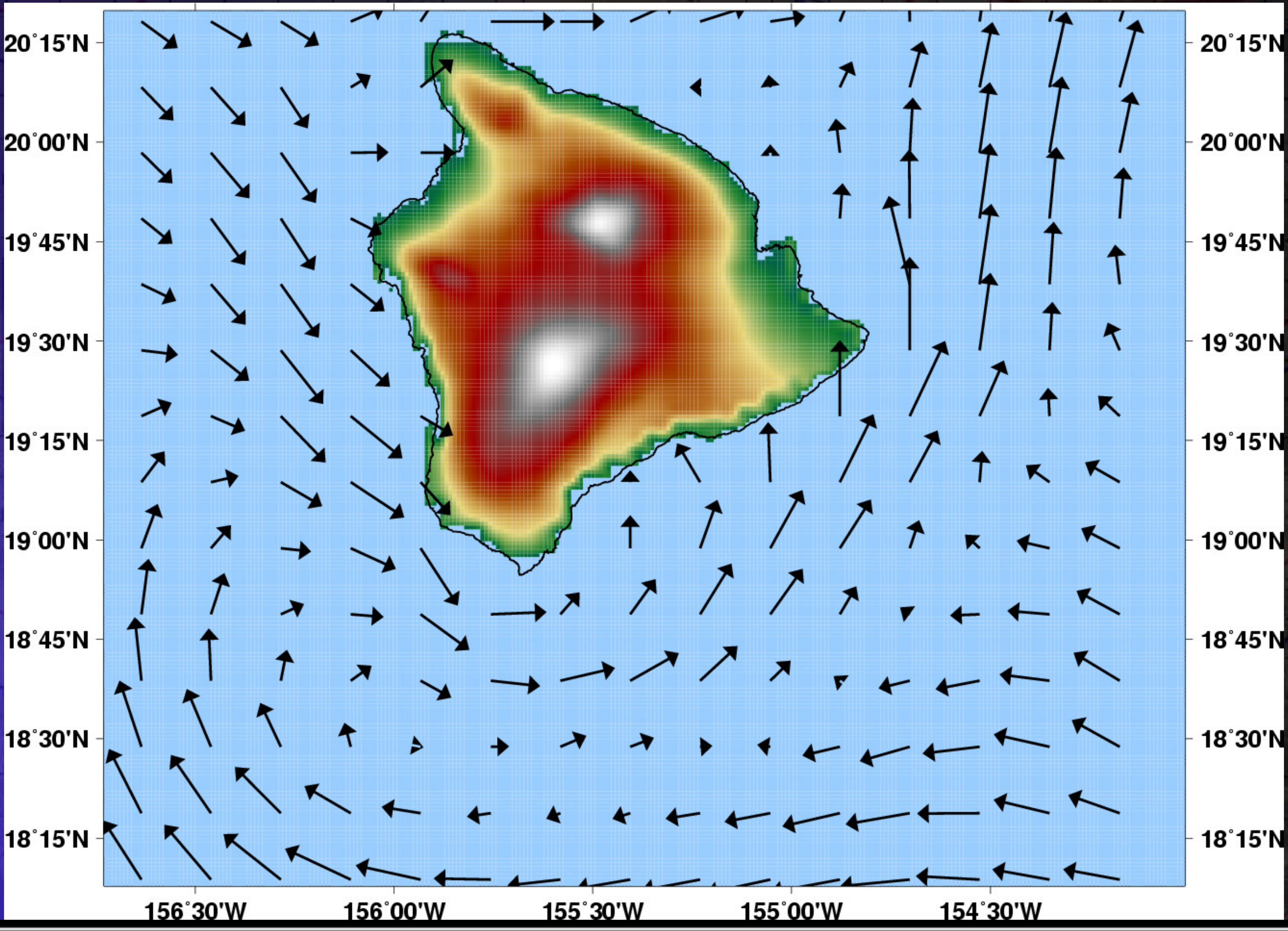


<= 1 degree OSCAR

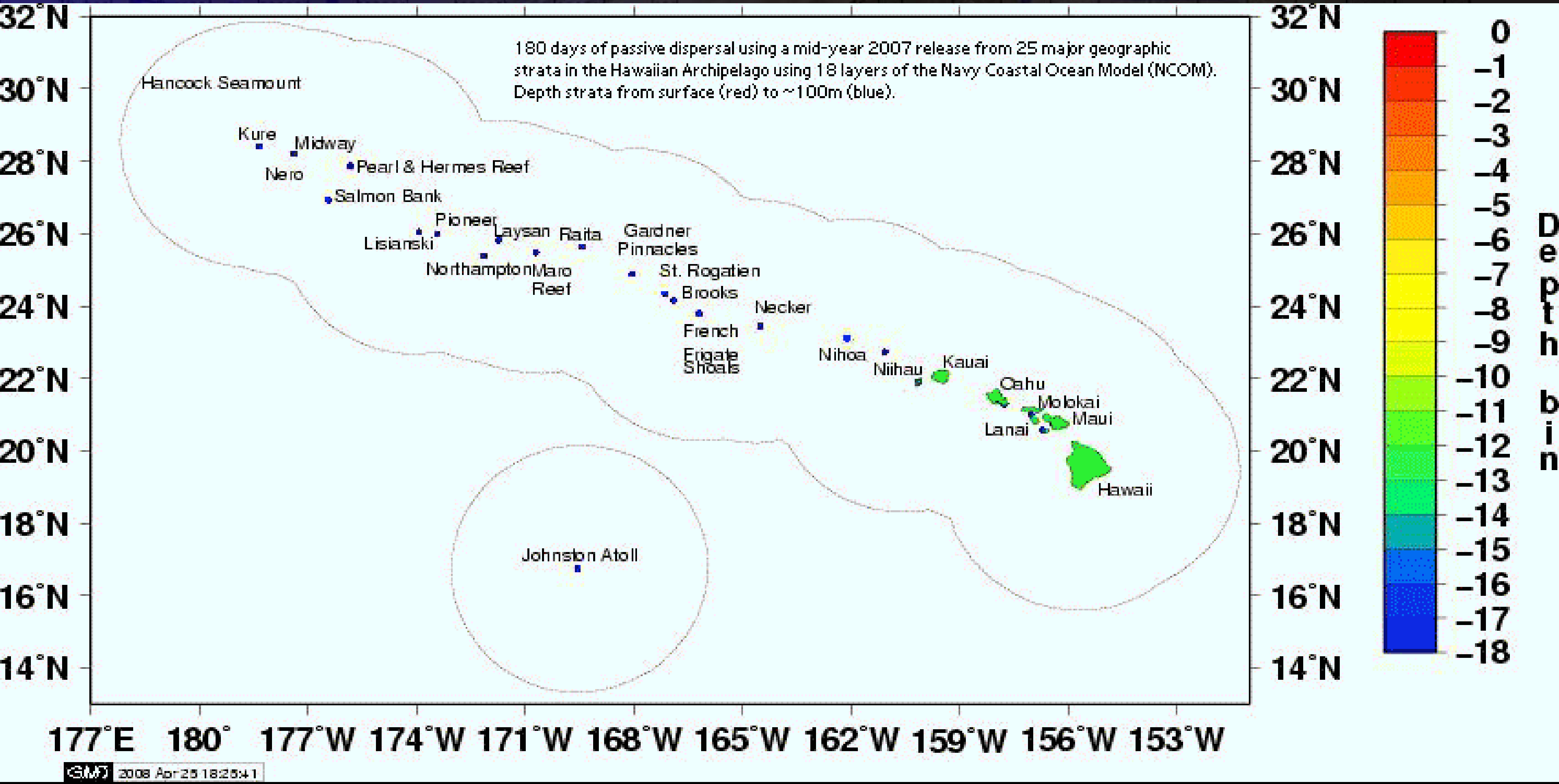
<= 0.5 degree AVISO

<= 1/16 degree NLOM

NCOM model, daily, 0.1 degree, 18 layers in upper 100m

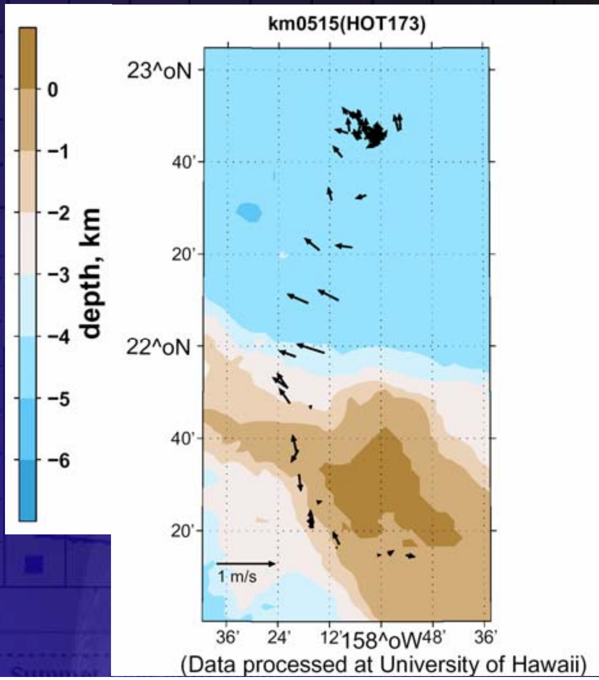


Example of NCOM transport using vertical layers



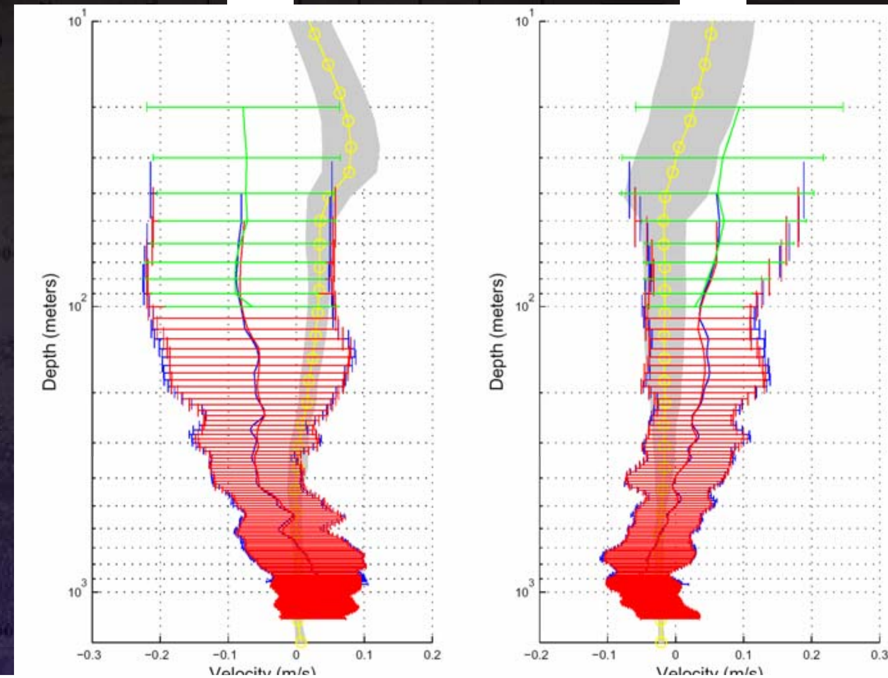
Compare NCOM to Sta. ALOHA data

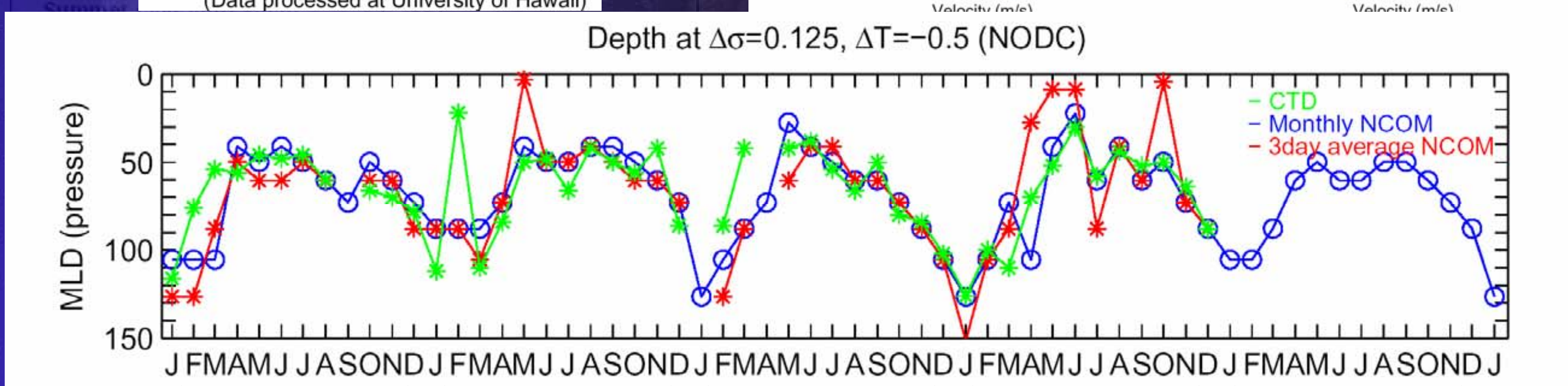
(Dr. Sachiko Yoshida, UH IPRC)



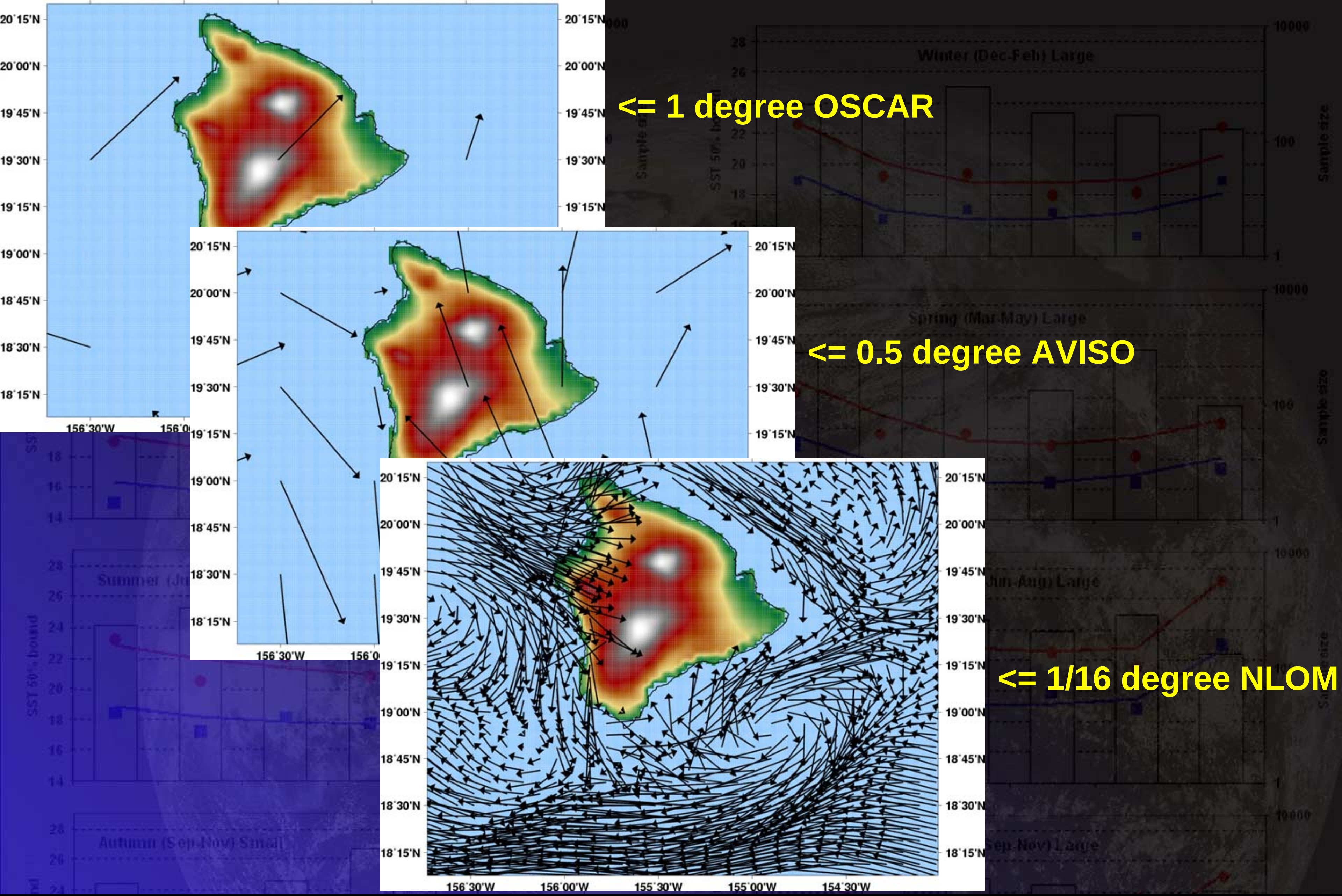
Zonal Velocity (m/s)

Meridional Velocity (m/s)

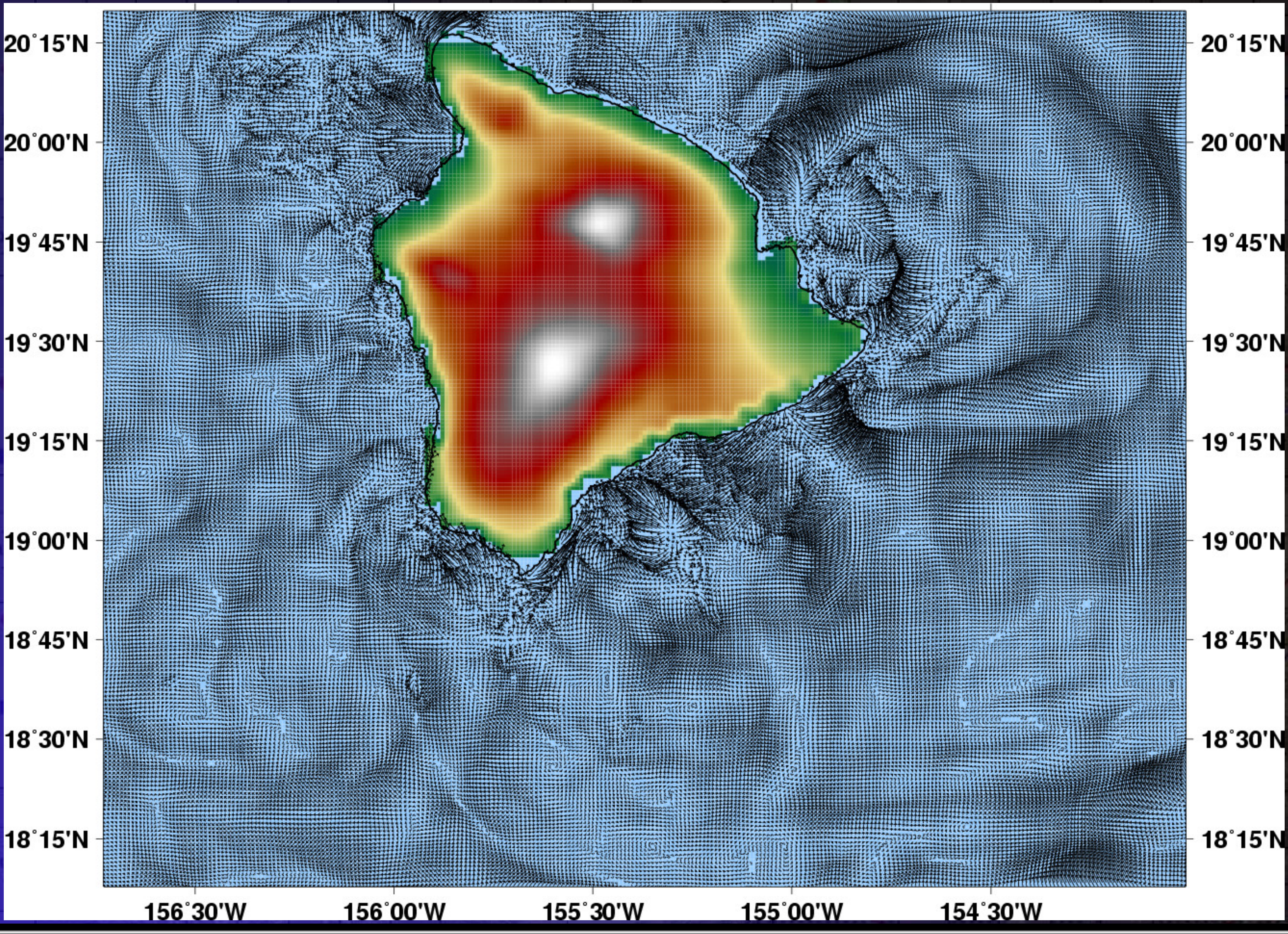




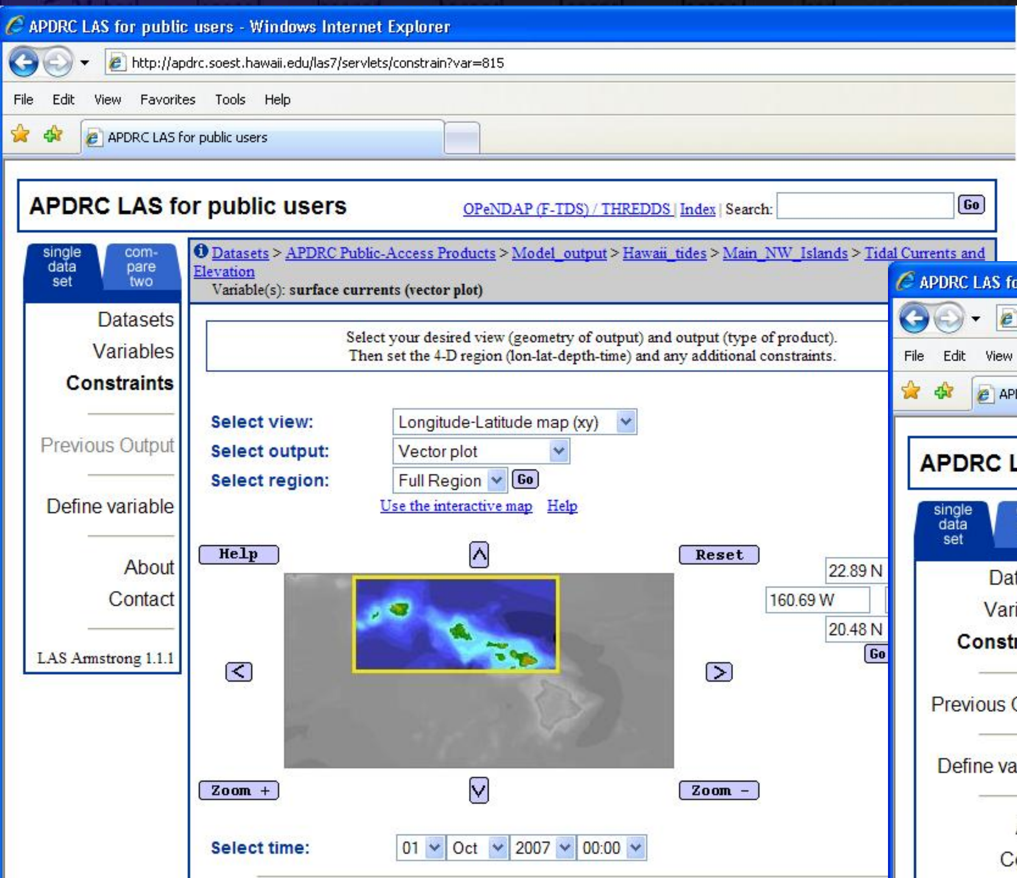
2003 2004 2005 2006 2007

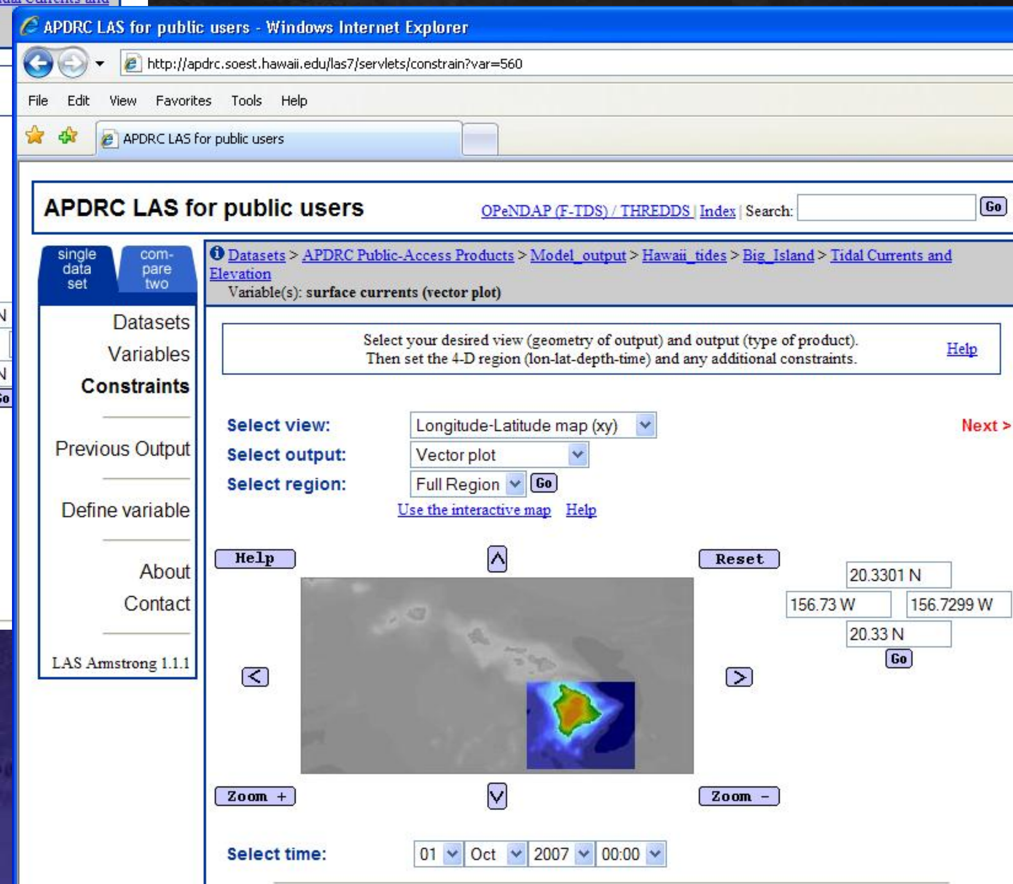

<= 1 degree OSCAR
<= 0.5 degree AVISO
<= 1/16 degree NLOM
20°15'N
20°00'N
19°45'N
19°30'N
19°15'N
19°00'N
18°45'N
18°30'N
18°15'N
156°30'W
156°00'W
155°30'W
155°00'W
154°30'W

UH tidal model, hourly, 0.01 degree, 3 layers



UH tide model presently in 2 spatial domains

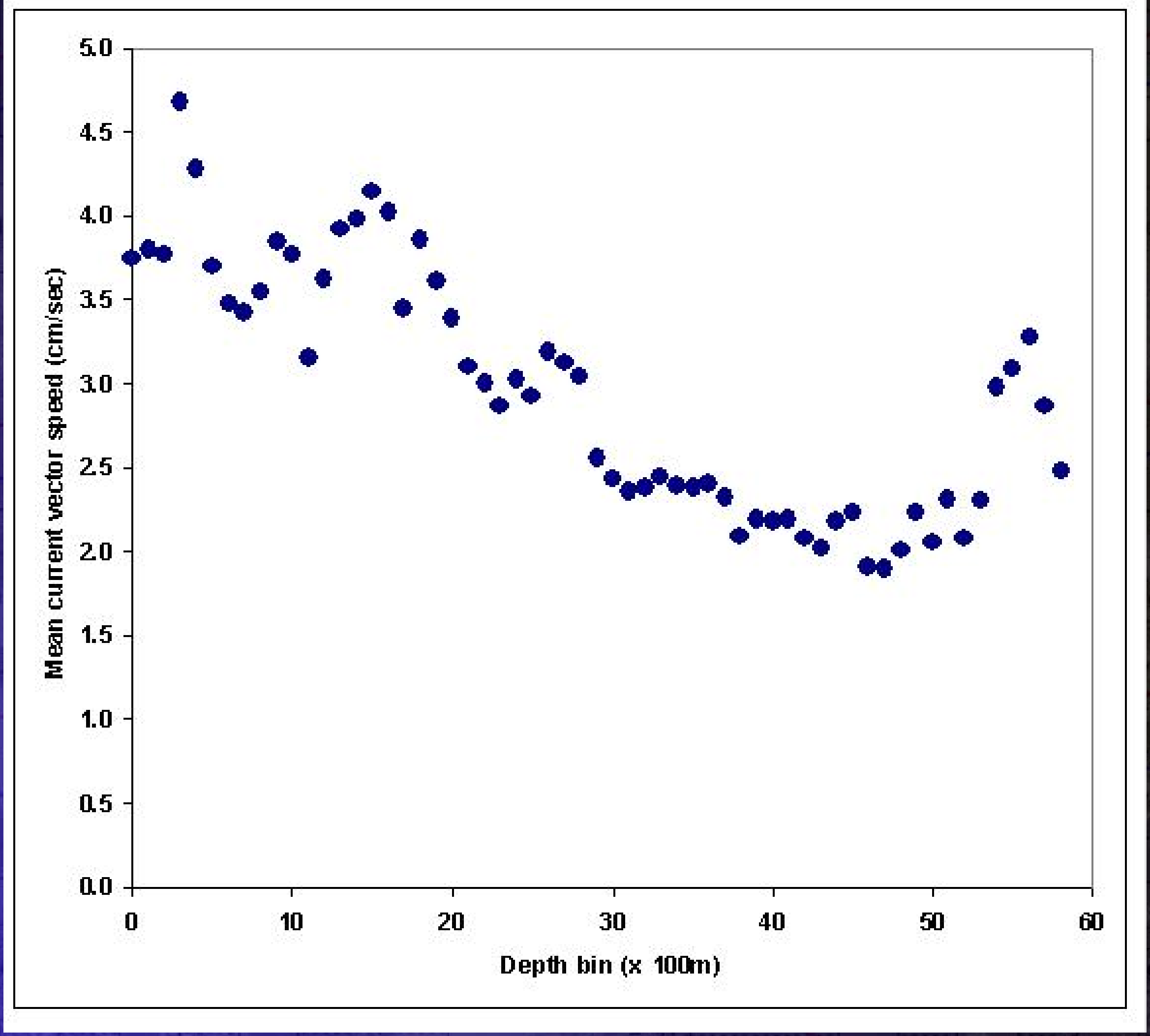




Merging NCOM and tidal model

- One goal of the upcoming year, related to possible CAMEO proposal, is to merge the 2 products.
- This would allow simultaneous utilization of good flow fields both offshore and nearshore for any single trajectory.
- The superimposition would likely involve a taper/weight function to allow smooth transition.
- This has not been accomplished yet...

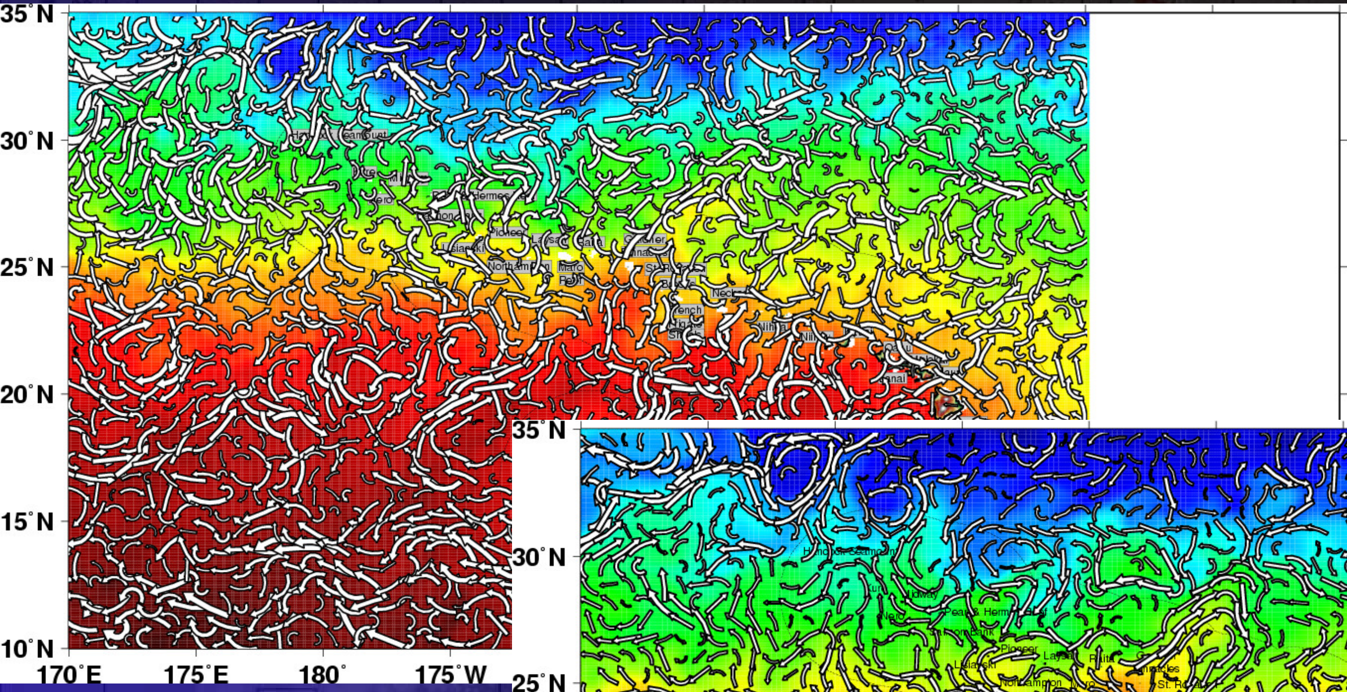
Average tidal flow as function of depth



Model comparison

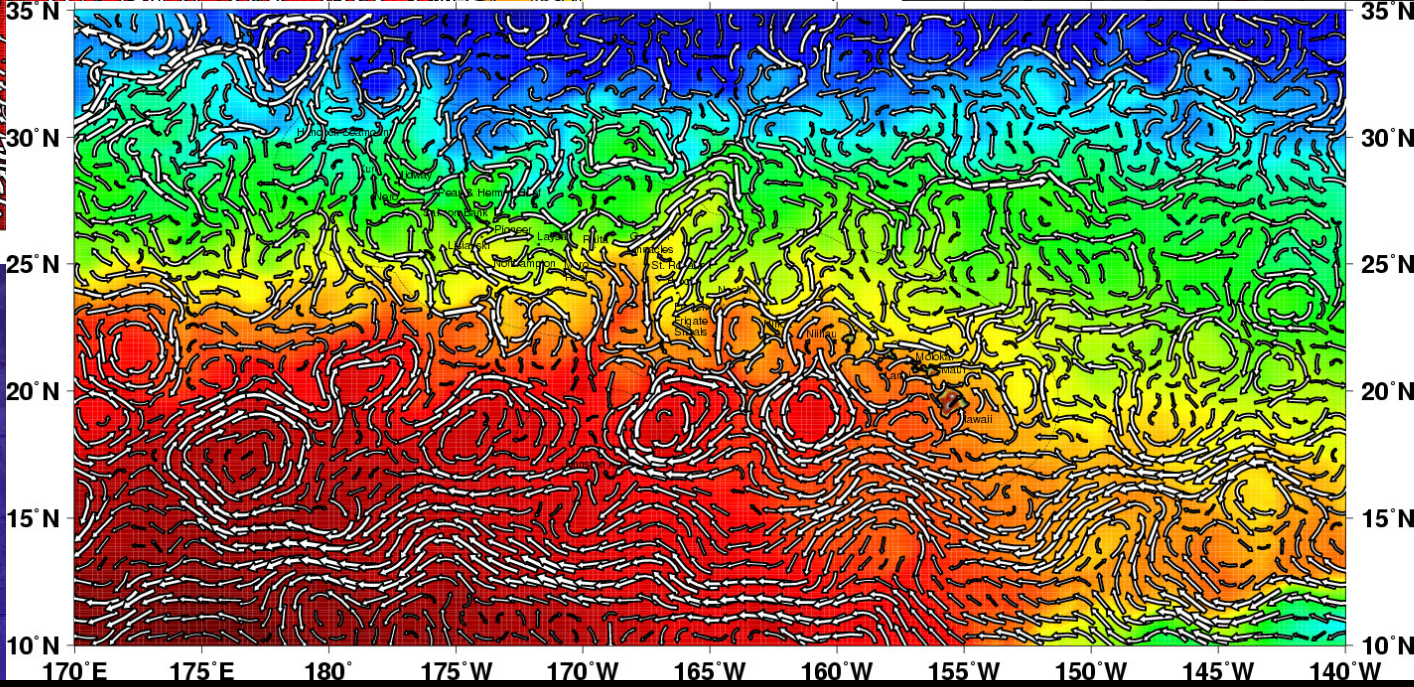
- Johnston Atoll and connectivity analysis utilized 2003 NLOM data.
- NCOM is more readily available now, with vertical layers.
- Comparison is not complete, but some preliminary findings.

NLOM and NCOM current fields

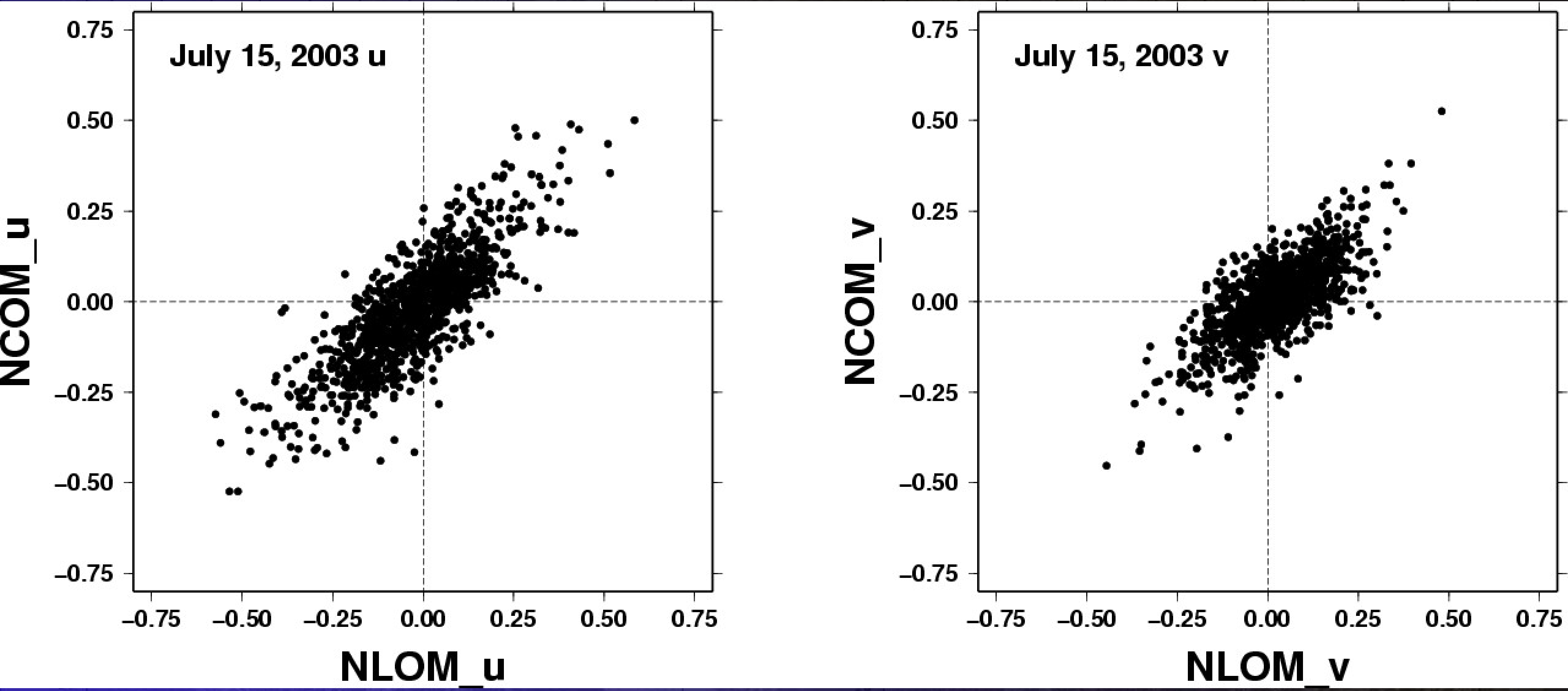


<= NLOM

NCOM =>



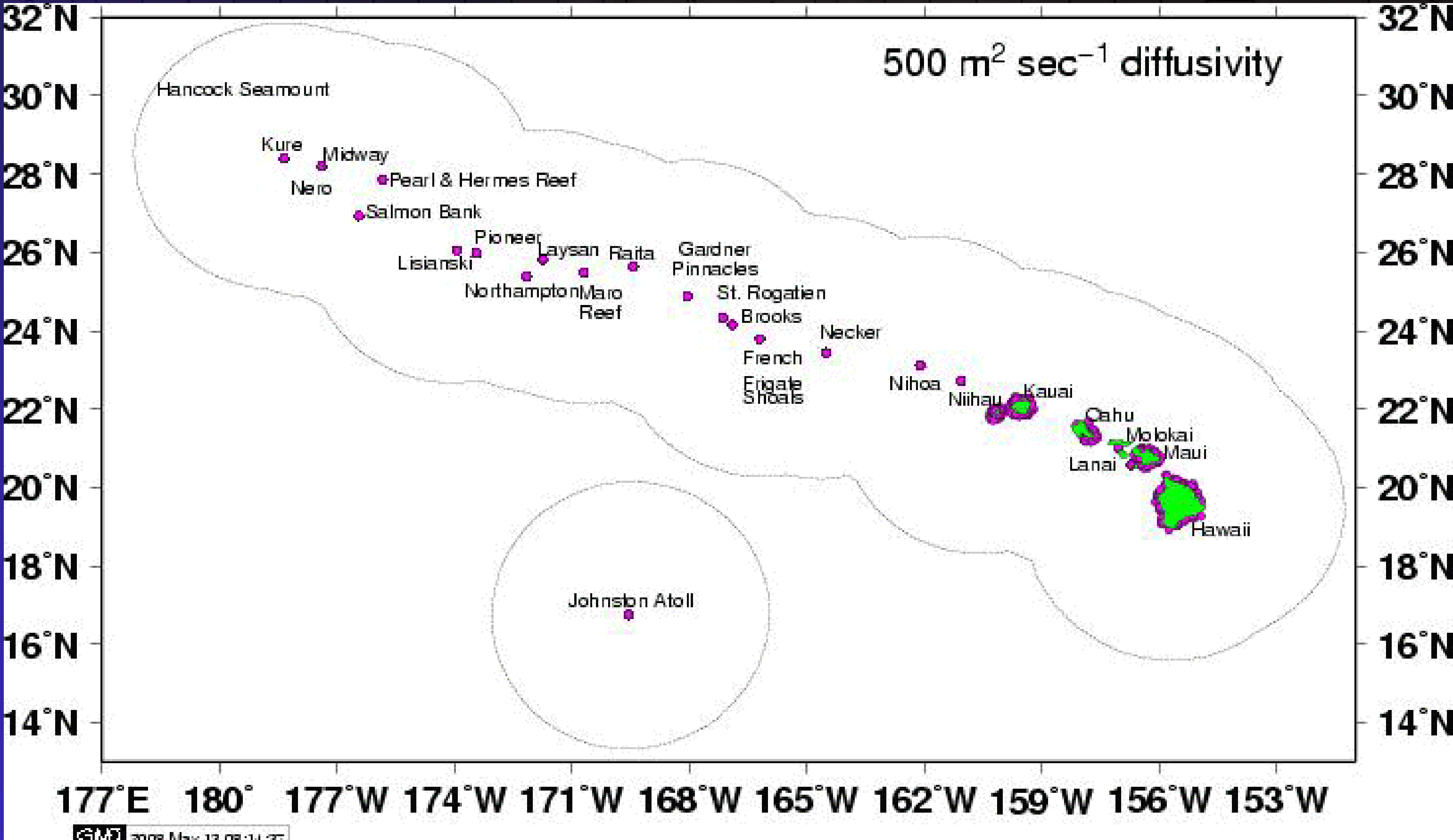
“Snapshot” comparison of NLOM and NCOM

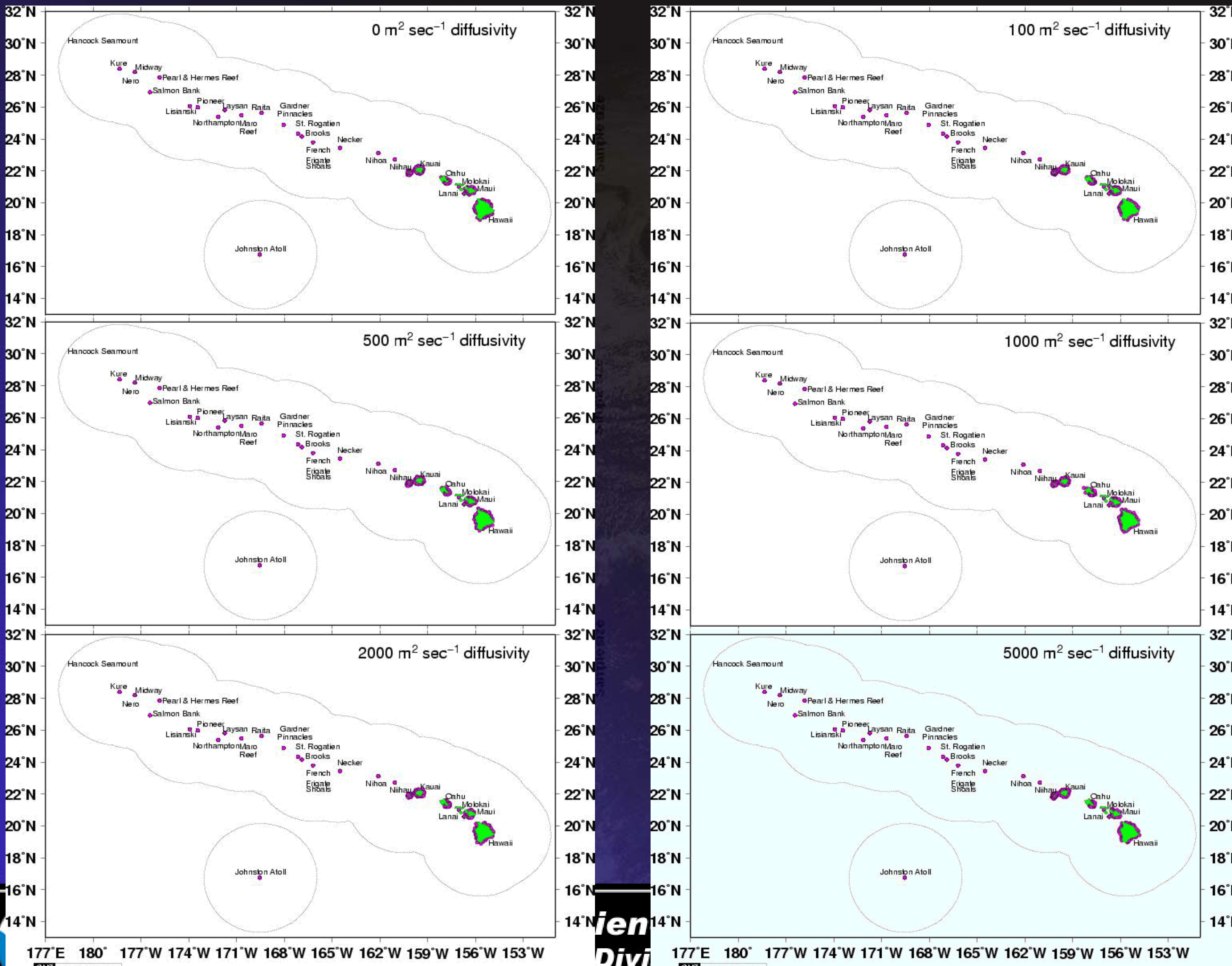


Eddy diffusivity coefficient

- This parameter determines how a cluster of particles slowly disperse independent of currents.
- Presently using same 500 m^2 sec^{-1} as utilized in Polovina et al. (1999), which was tuned to larval lobster catch distributions.
- Refinement of this critical parameter and sensitivity analyses are needed.

Perform simulations with variable eddy diffusivity




0 m^2 sec^{-1} diffusivity
100 m^2 sec^{-1} diffusivity
500 m^2 sec^{-1} diffusivity
1000 m^2 sec^{-1} diffusivity
2000 m^2 sec^{-1} diffusivity
5000 m^2 sec^{-1} diffusivity
Hancock Seamount
Kure
Midway
Nero
Pearl & Hermes Reef
Salmon Bank
Pioneer
Lisianski
Laysan
Raita
Gardner Pinnacles
Northampton
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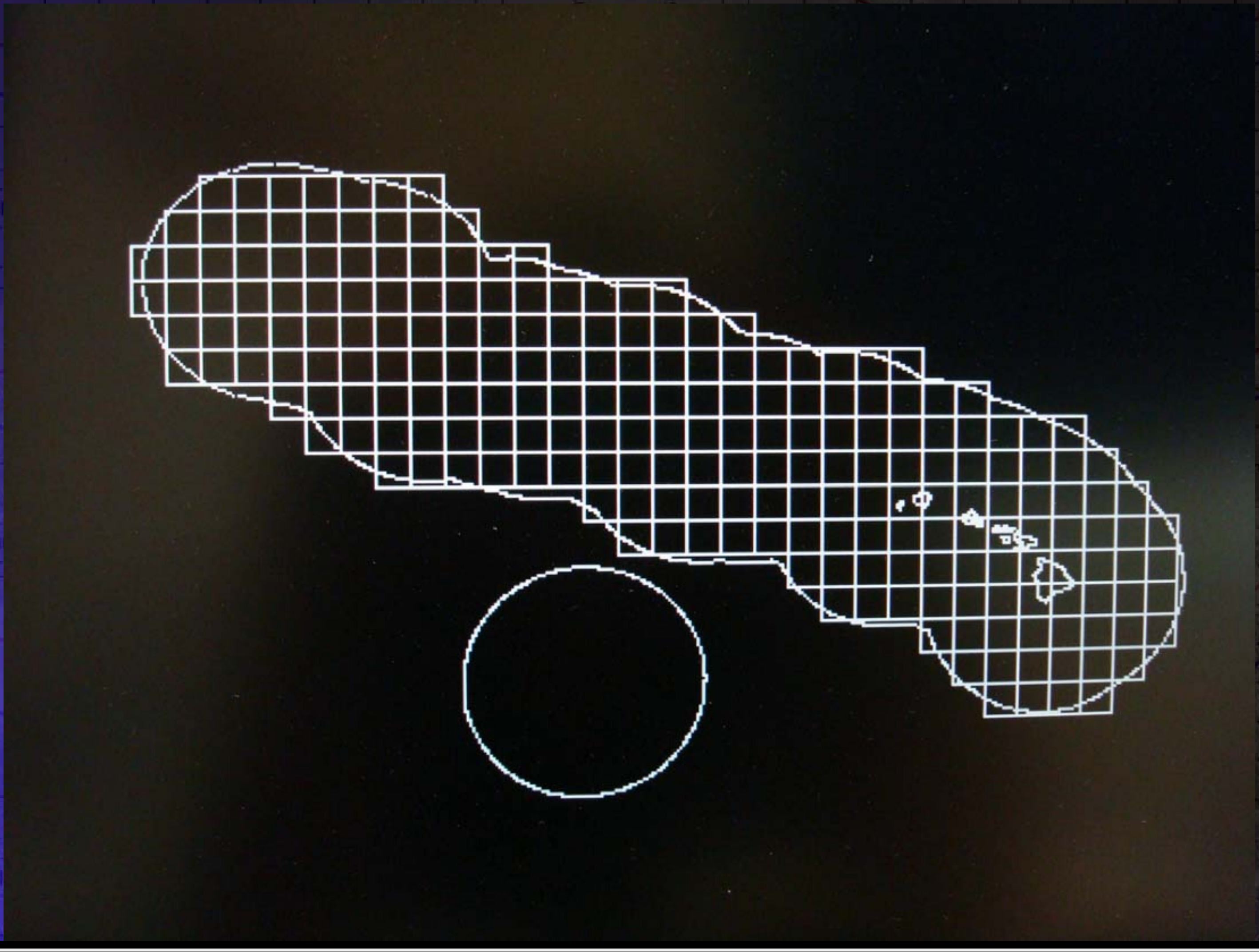
French Frigate Shoals
Nihoa
Niihau
Kauai
Oahu
Molokai
Maui
Lanai
Hawaii
Johnston Atoll
32°N
30°N
28°N
26°N
24°N
22°N
20°N
18°N
16°N
14°N
177°E 180° 177°W 174°W 171°W 168°W 165°W 162°W 159°W 156°W 153°W

Boundary behavior

- Earlier simulations ignored boundaries or simplified complex shapes into a series of squares or circles which are easier to deal with computationally.
- Recent improvements utilize an algorithm which analytically determines if a Cartesian point is within a specified polygon.

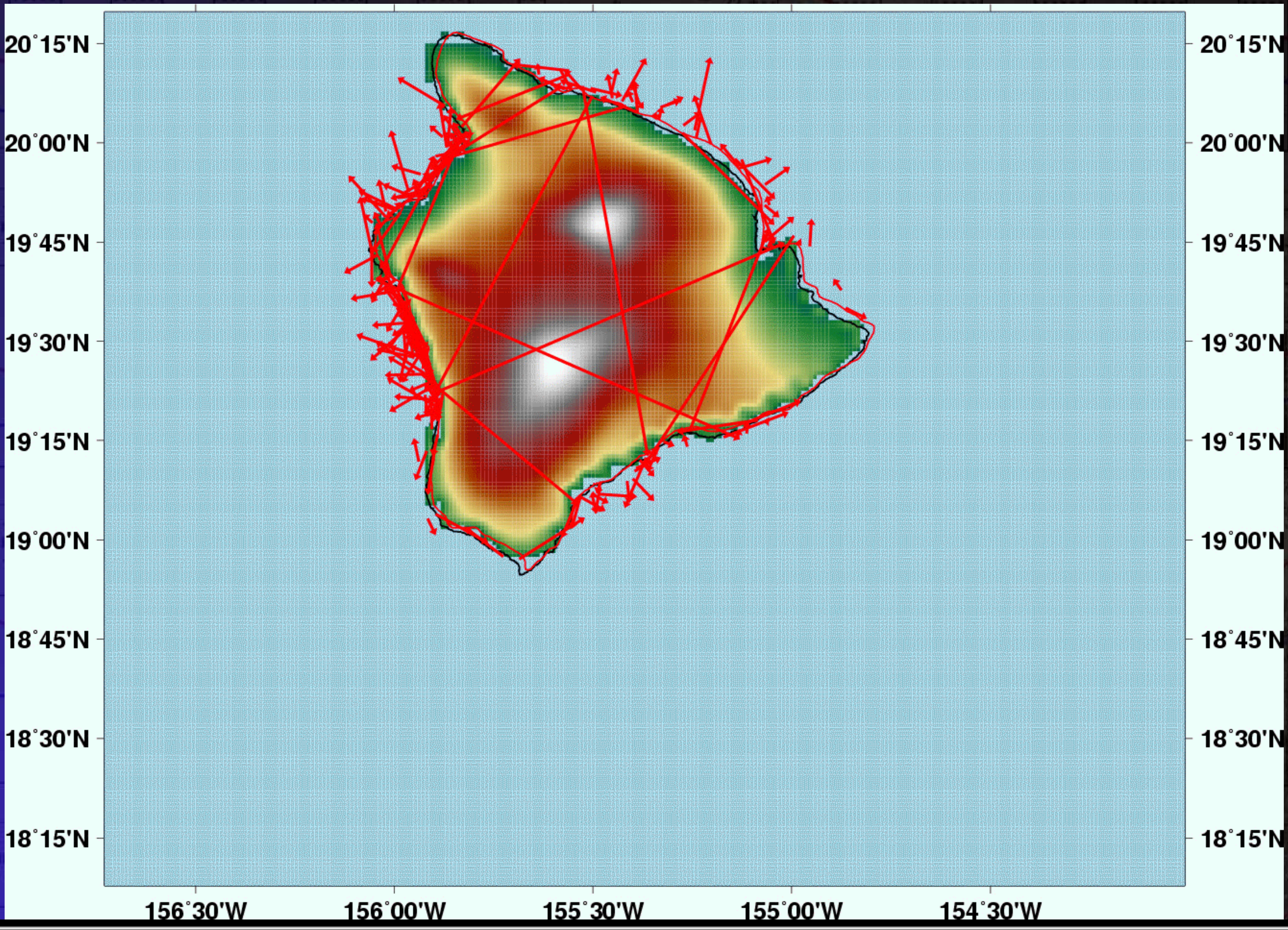
EEZ example using squares



Algorithm to determine if Cartesian point is within a polygon

- 1030 REM *****GIVEN A CLOSED CONTOUR (POLYGON) DEFINED BY THE NC POINTS WHOSE
- 1040 REM COORDINATES ARE IN VECTORS CX AND CY, THIS SUBROUTINE DETERMINES
- 1050 REM WHICH OF THE N WEIGHTED POINTS IN VECTORS X AND Y ARE ENCLOSED BY
- 1060 REM THE CONTOUR.
- 1070 REM THE VECTOR zkey IS RETURNED WITH A ZERO IN EACH ELEMENT CORRESPONDING
- 1080 REM (BY INDEX) TO AN ELEMENT IN (X,Y) THAT IS NOT ENCLOSED, AND A ONE
- 1090 REM CORRESPONDING TO EACH ELEMENT THAT IS ENCLOSED.
- 1100 REM .....THE WEIGHTS ASSIGNED EACH POINT ARE SUPPLIED IN VECTOR W.
- 1110 REM THE SUM OF WEIGHTS ENCLOSED IS RETURNED IN WINC. THE NUMBER OF POINTS
- 1120 REM ENCLOSED IS RETURNED IN NINC.
- 1130 REM .....THE ALGORITHM REQUIRES THAT THE CONTOUR BE CLOSED, AND THAT
- 1140 REM THE FIRST AND LAST POINTS OF THE CONTOUR VECTOR BE IDENTICAL.
- 1150 REM .....VECTOR zkey MUST BE DIMENSIONED AT LEAST N IN THE MAIN PROGRAM.
- 1160 REM *****
- 1170 REM VERSION OF JAN 24, 1987
- 1180 REM *****
- 1190 REM dim x(1), y(1), w(1), zkey(1), cx(1), cy(1)
- 1200 REM .....INITIALIZE
- 1210 LET ninc = 0
- 1220 LET winc = 0
- 1230 REM .....FIND MAX AND MIN COORDINATES OF CONTOUR
- 1240 LET xmax = cx(1)
- 1250 LET xmin = cx(1)
- 1260 LET ymax = cy(1)
- 1270 LET ymin = cy(1)
- 1280 FOR i = 1 TO nc
- 1290 LET xt = cx(i)
- 1300 IF (xt - xmax) <= 0 THEN GOTO 1340 ELSE GOTO 1310
- 1310 REM Fortran Statement number 1010
- 1320 LET xmax = xt
- 1330 GOTO

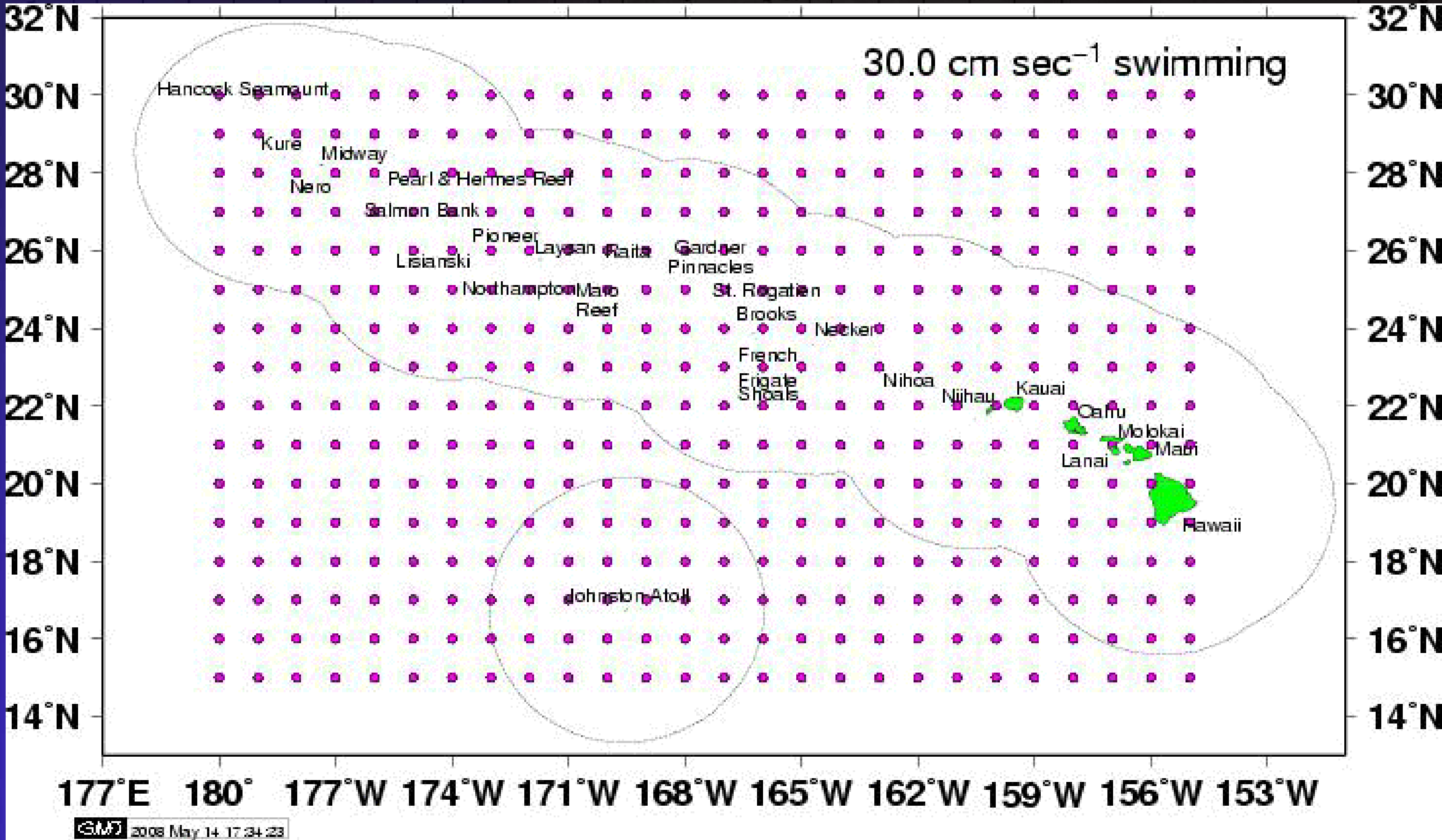
Testing algorithm

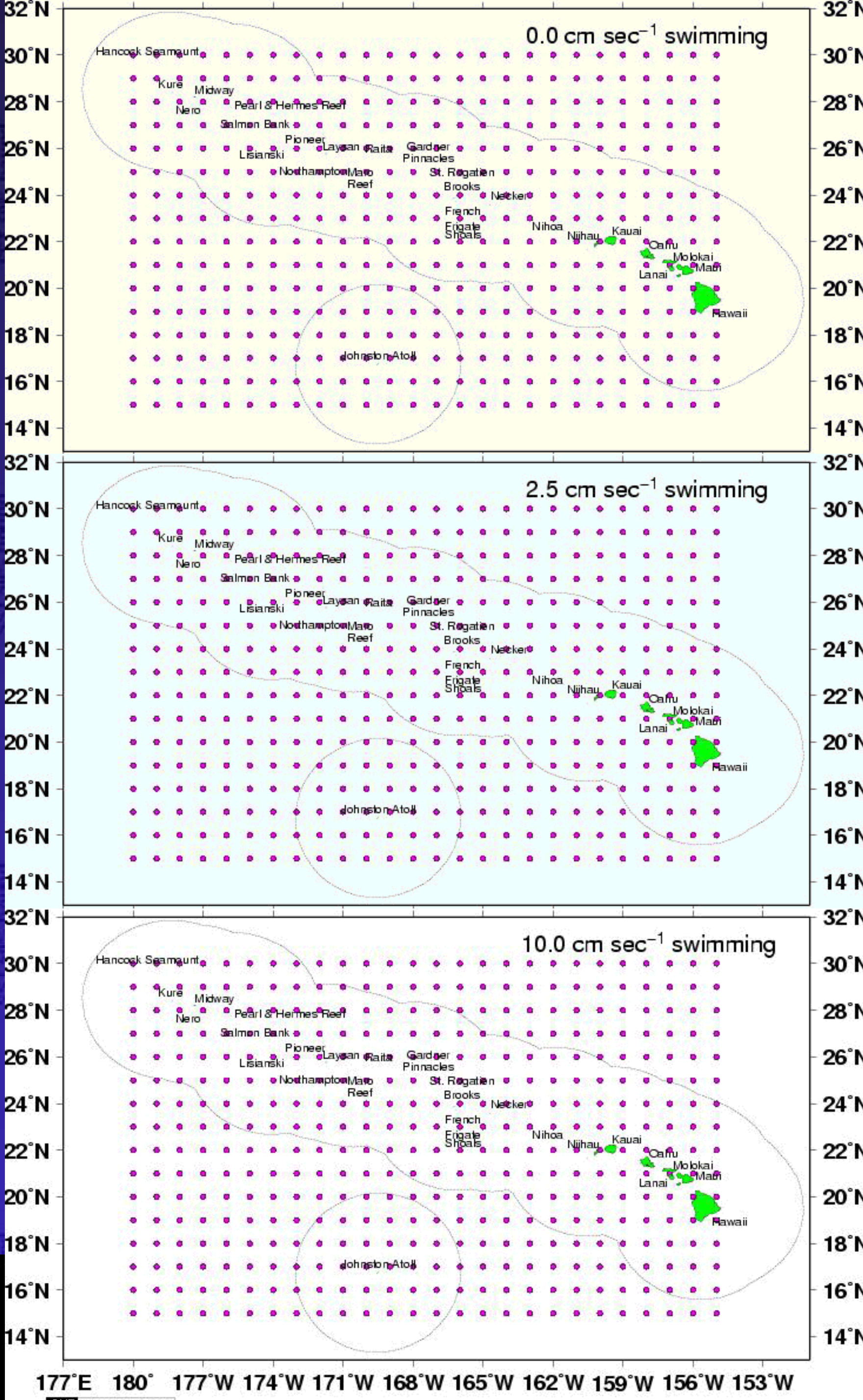


Swimming behavior

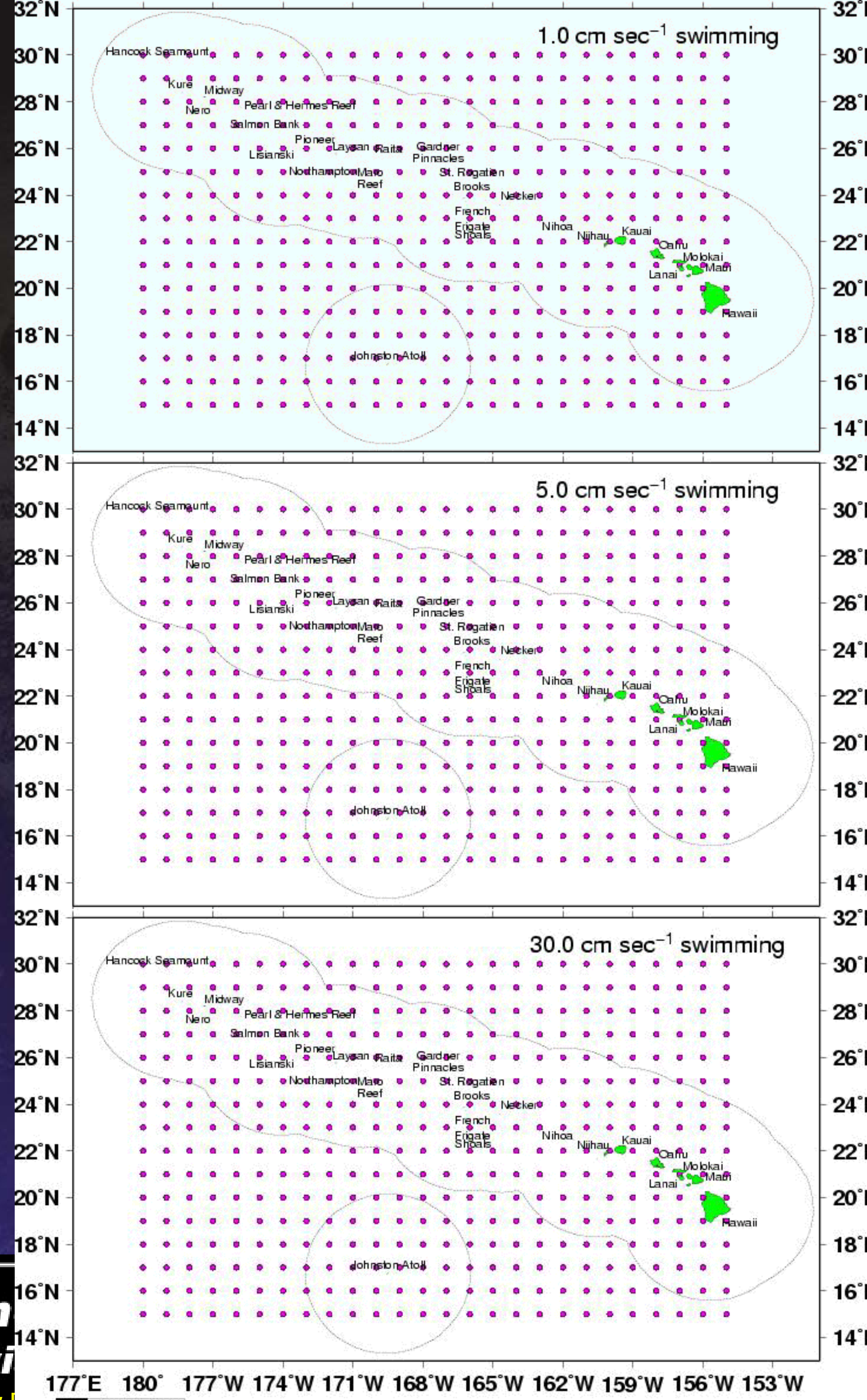
- Examine several levels of swimming behavior (0-30 cm/sec).
- Orientation towards "nearest" habitat, not necessarily "natal" habitat.
- Operationally, loop through list of habitat pixels, find closest, calculate vector components, updated every time step.
- This following work is preliminary and ongoing…

Test of swimming behavior algorithm





0.0 cm sec^{-1} swimming
2.5 cm sec^{-1} swimming
10.0 cm sec^{-1} swimming
Hancock Seamount
Kure
Midway
Nero
Pearl & Hermes Reef
Salmon Bank
Pioneer
Lisianski
Laysan
Raita
Gardner Pinnacles
Northampton
Maro Reef
St. Rogatien
Brooks
Necker
French Frigate Shoals
Nihoa
Niihau
Kauai
Oahu
Molokai
Maui
Lanai
Hawaii
Johnston Atoll
32°N 30°N 28°N 26°N 24°N 22°N 20°N 18°N 16°N 14°N
177°E 180° 177°W 174°W 171°W 168°W 165°W 162°W 159°W 156°W 153°W
GMT 2008 May 14 17:34:21



1.0 cm sec^{-1} swimming
5.0 cm sec^{-1} swimming
30.0 cm sec^{-1} swimming
Hancock Seamount
Kure
Midway
Nero
Pearl & Hermes Reef
Salmon Bank
Pioneer
Lisianski
Laysan
Raita
Gardner Pinnacles
Northampton
Maro Reef
St. Rogatien
Brooks
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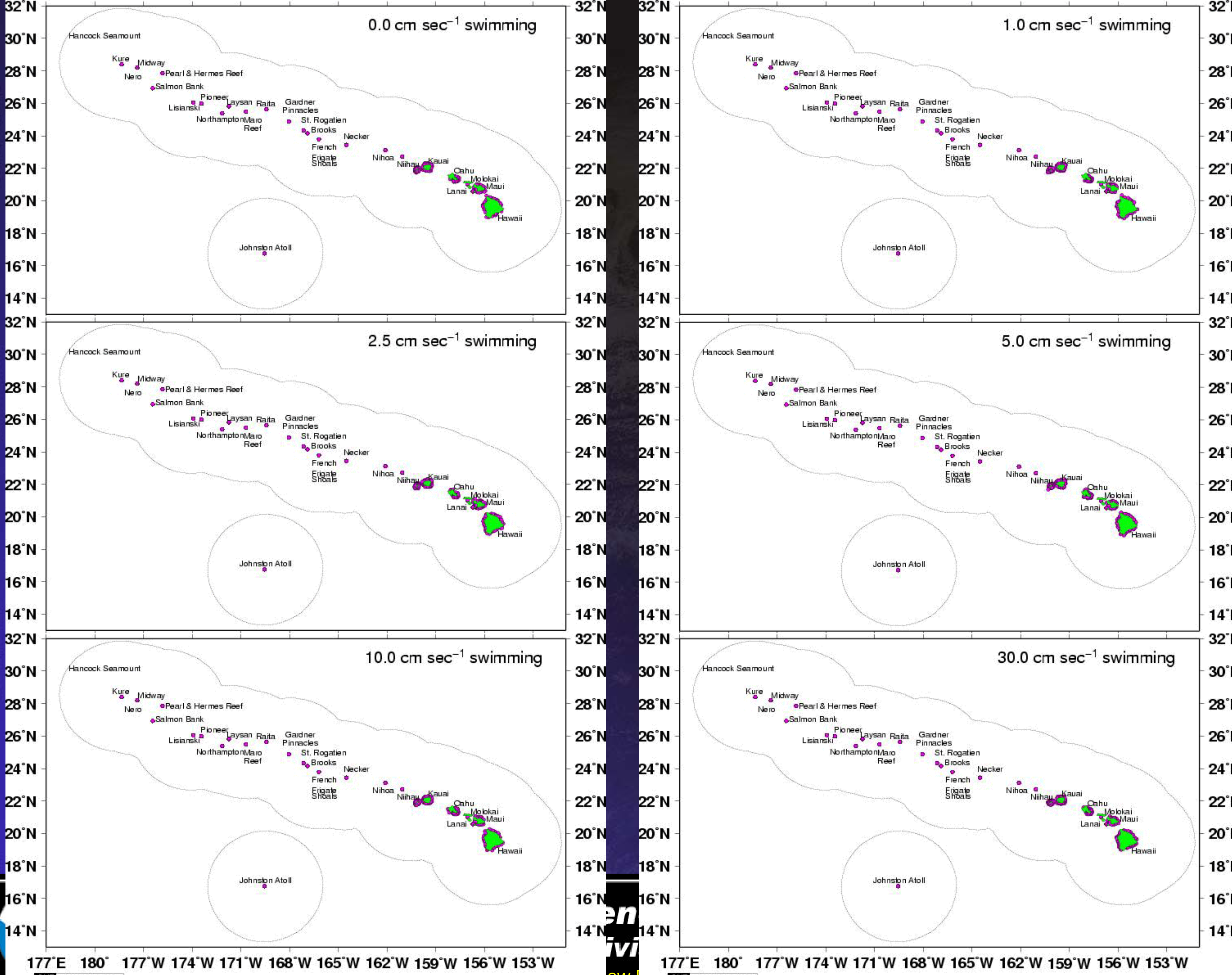
Kauai
Oahu
Molokai
Maui
Lanai
Hawaii
Johnston Atoll
32°N 30°N 28°N 26°N 24°N 22°N 20°N 18°N 16°N 14°N
177°E 180° 177°W 174°W 171°W 168°W 165°W 162°W 159°W 156°W 153°W
GMT 2008 May 14 17:34:23



0.0 cm sec^{-1} swimming
1.0 cm sec^{-1} swimming
2.5 cm sec^{-1} swimming
5.0 cm sec^{-1} swimming
10.0 cm sec^{-1} swimming
30.0 cm sec^{-1} swimming
Hancock Seamount
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Nihoa
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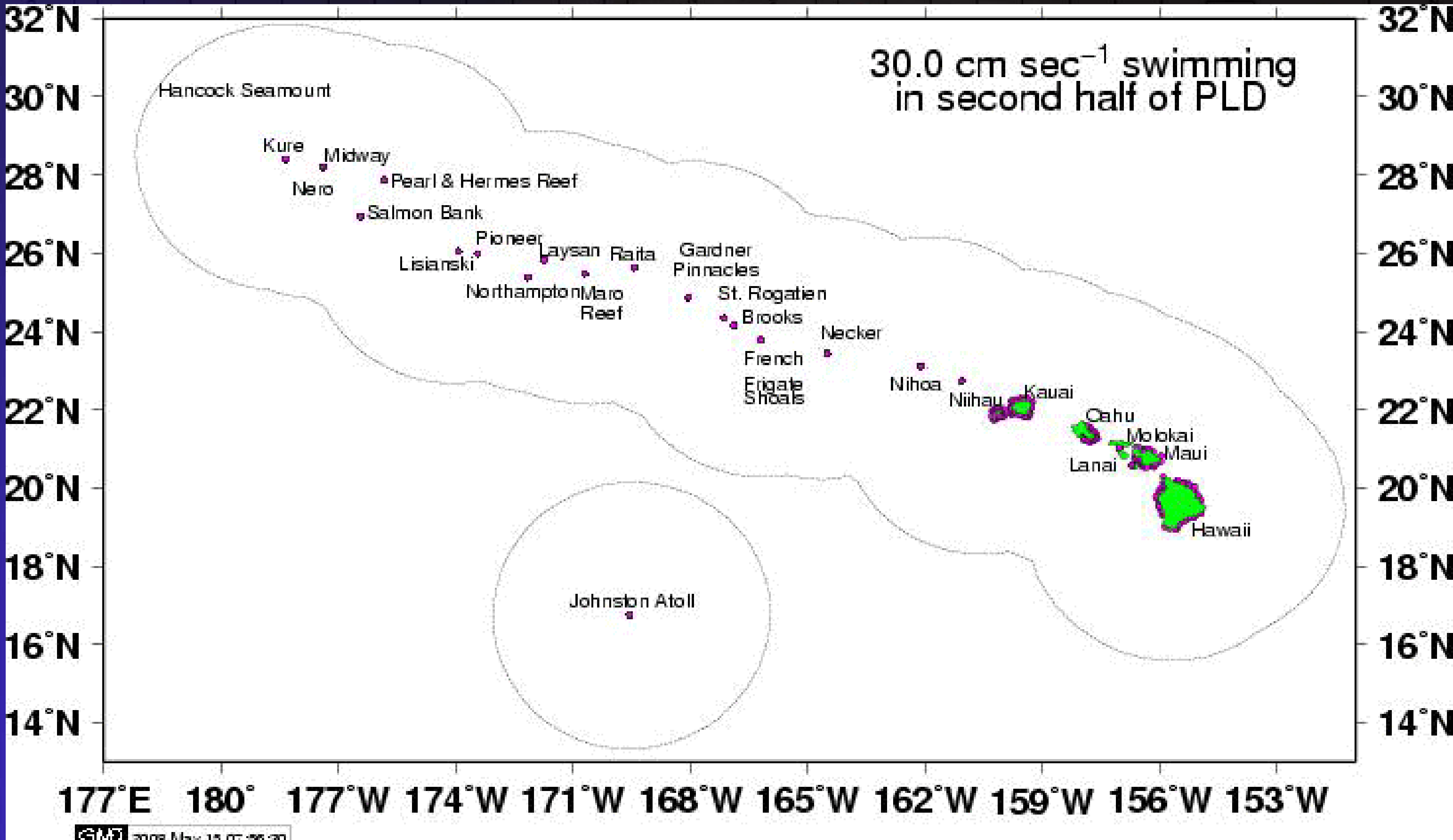
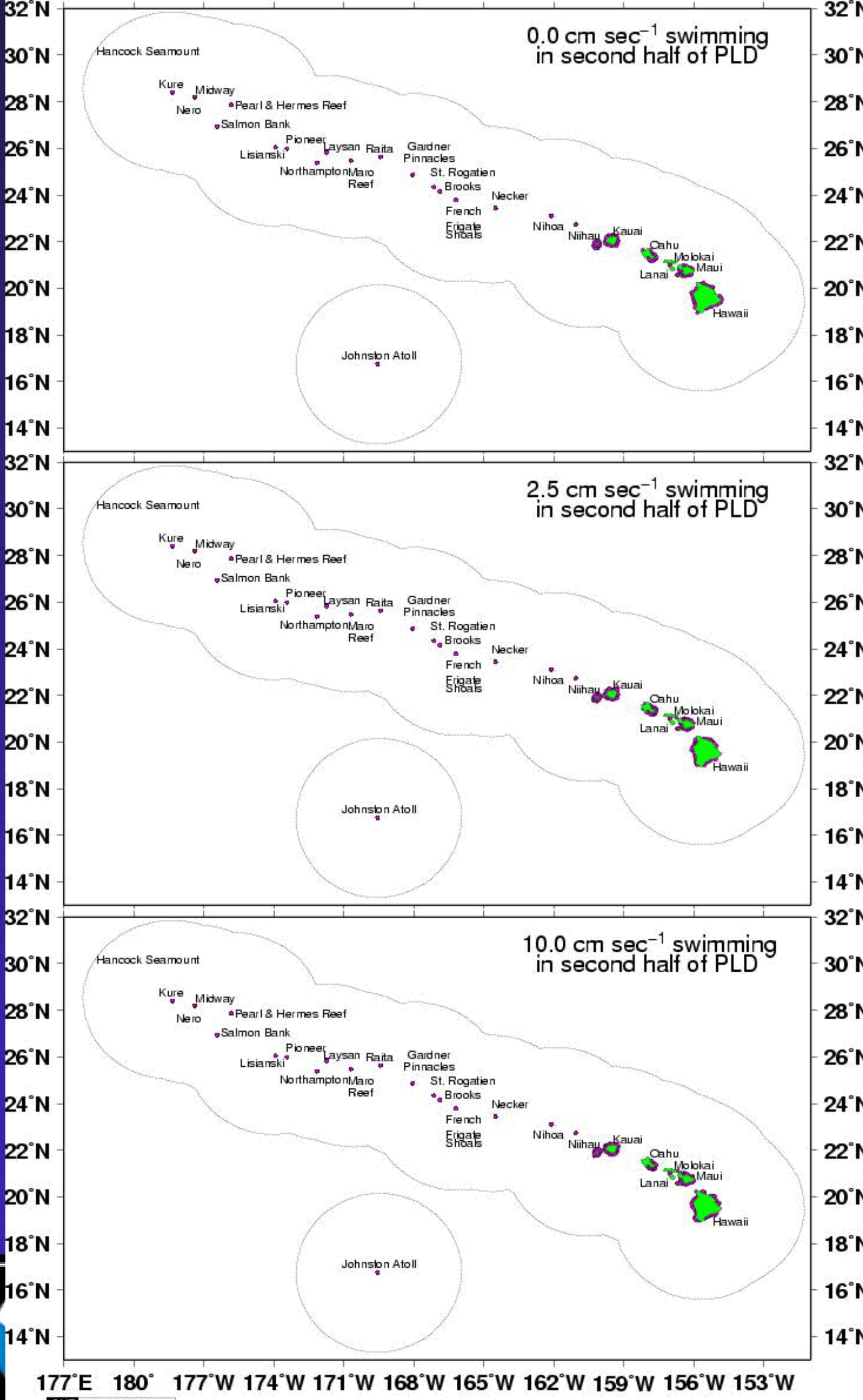
Kauai
Oahu
Molokai
Maui
Lanai
Hawaii
Johnston Atoll
32°N 30°N 28°N 26°N 24°N 22°N 20°N 18°N 16°N 14°N
177°E 180° 177°W 174°W 171°W 168°W 165°W 162°W 159°W 156°W 153°W
GMT 2008 May 14 12:42:05
GMT 2008 May 14 12:42:06

Swimming behavior activated in later stages of PLD (e.g. preflexion to postflexion fish larvae)




0.0 cm sec^{-1} swimming in second half of PLD
2.5 cm sec^{-1} swimming in second half of PLD
10.0 cm sec^{-1} swimming in second half of PLD
Hancock Seamount
Kure
Midway
Nero
Pearl & Hermes Reef
Salmon Bank
Pioneer
Lisianski
Laysan
Raita
Gardner Pinnacles
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Lanai
Hawaii
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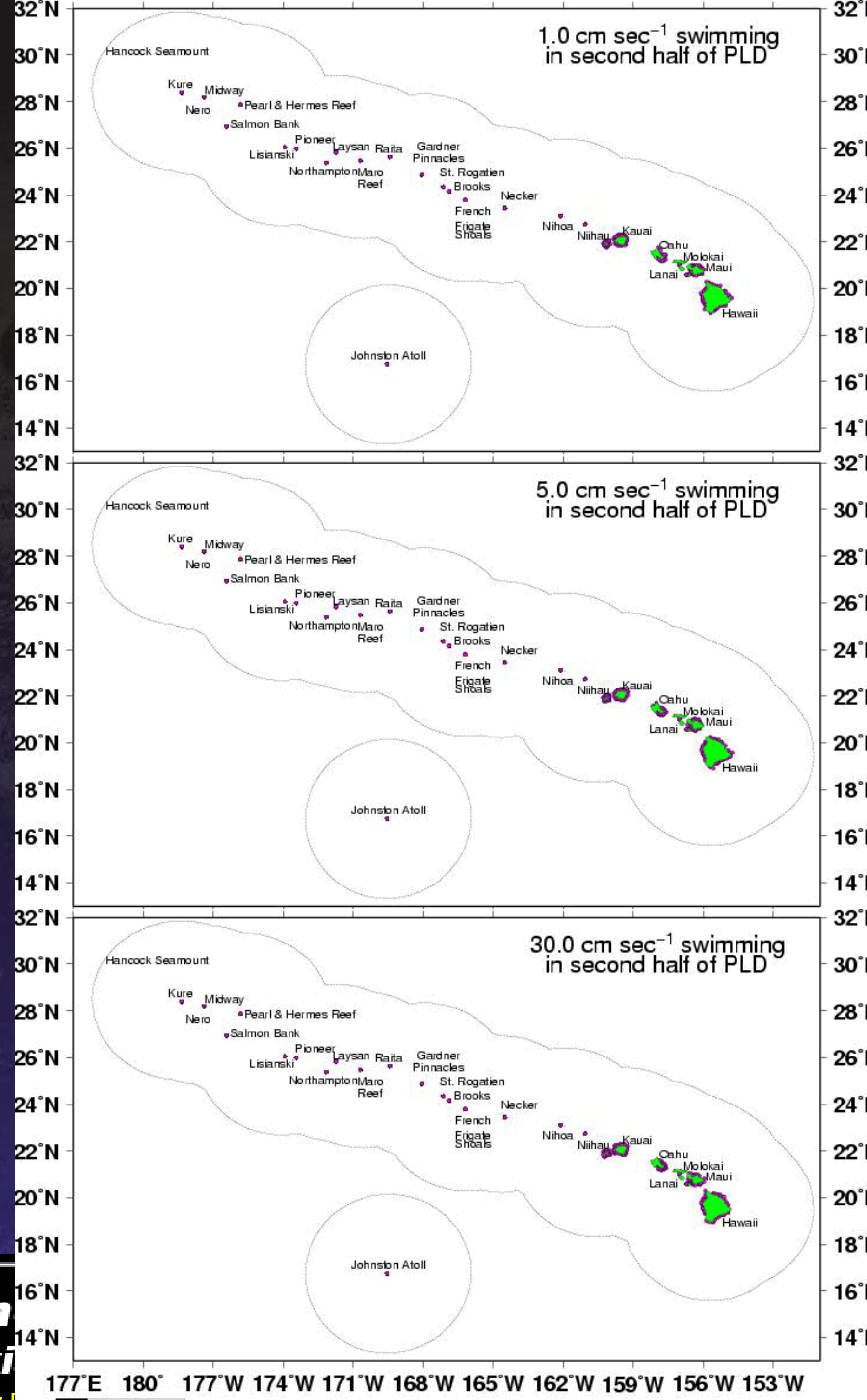
177°E 180° 177°W 174°W 171°W 168°W 165°W 162°W 159°W 156°W 153°W
2008 May 15 07:56:29

1.0 cm sec^{-1} swimming in second half of PLD
5.0 cm sec^{-1} swimming in second half of PLD
30.0 cm sec^{-1} swimming in second half of PLD
Hancock Seamount
Kure
Midway
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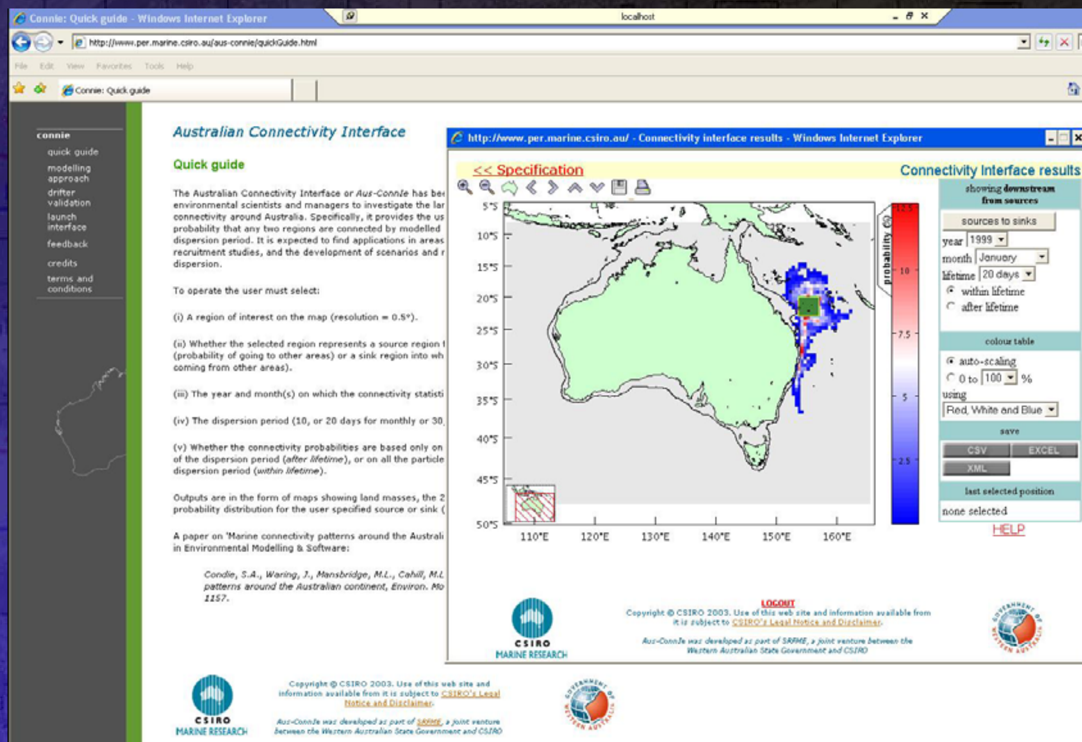
177°E 180° 177°W 174°W 171°W 168°W 165°W 162°W 159°W 156°W 153°W
2008 May 15 07:56:30

Connectivity web interface

- CSIRO product at:

http://www.per.marine.csiro.au/aus-connie/



Connectivity Interface splash page - Windows Internet Explorer

http://www.per.marine.csiro.au/aus-connie/

File Edit View Favorites Tools Help

Connectivity Interface splash page

Australian Connectivity Interface

CSIRO MARINE RESEARCH SRFME GOVERNMENT OF WESTERN AUSTRALIA

Scott Condie, Jim Mansbridge, Madeleine Cahill
CSIRO Marine Reseach, Hobart, Tasmania.

Jason Waring , Irshad Nainar
CSIRO Marine Research, Perth, Western Australia.

PLEASE ENTER

Done Internet

Connie: Quick guide - Windows Internet Explorer

http://www.per.marine.csiro.au/aus-connie/quickGuide.html

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Connie: Quick guide

connie

- quick guide
- modelling approach
- drifter validation
- launch interface
- feedback
- credits
- terms and conditions

Australian Connectivity Interface

Quick guide

The Australian Connectivity Interface or *Aus-ConnIe* has been developed as a tool for environmental scientists and managers to investigate the large-scale patterns of spatial connectivity around Australia. Specifically, it provides the user with an estimate of the probability that any two regions are connected by modelled ocean circulation over a specified dispersion period. It is expected to find applications in areas such as larval dispersion and recruitment studies, and the development of scenarios and risk assessments for contaminant dispersion.

To operate the user must select:

(i) A region of interest on the map (resolution = 0.5°).

(ii) Whether the selected region represents a source region from which particles disperse (probability of going to other areas) or a sink region into which particles arrive (probability of coming from other areas).

(iii) The year and month(s) on which the connectivity statistics will be based.

(iv) The dispersion period (10, or 20 days for monthly or 30, 40, 60 or 80 days for quarterly).

(v) Whether the connectivity probabilities are based only on the particle distribution at the end of the dispersion period (*after lifetime*), or on all the particle distributions that occur over the dispersion period (*within lifetime*).

Outputs are in the form of maps showing land masses, the 200 m depth contour, and the probability distribution for the user specified source or sink (resolution = 0.5°)."

A paper on 'Marine connectivity patterns around the Australian continent' has been published in Environmental Modelling & Software:

Condie, S.A., Waring, J., Mansbridge, M.L., Cahill, M.L., 2005, Marine connectivity patterns around the Australian continent, Environ. Model. & Softw. 20, 1149-1157.

CSIRO MARINE RESEARCH

Aus-ConnIe was developed as part of SRFME, a joint venture between the Western Australian State Government and CSIRO

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http://www.per.marine.csiro.au/ - Aus-ConnIe login - Windows Internet Explorer

Welcome to the Aus-ConnIe login

ANONYMOUS LOGIN (unable to save definition masks, etc)

The *Aus-ConnIe* connectivity patterns are derived from current fields estimated by Satellite Altimetry and Modelled Wind fields. As such, users should treat the results with some caution. *Aus-ConnIe* is not intended, and should not be used, to replace detailed local monitoring and/or modelling studies in assessing the risks associated with new developments or other marine activities. Use of this web site and information available from it is subject to CSIRO's Legal Notice and Disclaimer.

Yes I agree and wish to continue | No I wish to exit

OR ...

REGISTERED USER LOGIN

User authentication

Please type your ConnIe username and password

Username:

Password:

Login

If you don't have an account then please register. If you have forgotten either your username or password then please send an e-mail to the ConnIe help desk.

CSIRO MARINE RESEARCH

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(v) Whether the connectivity probabilities are based only on of the dispersion period (*after lifetime*), or on all the particle dispersion period (*within lifetime*).

Outputs are in the form of maps showing land masses, the 2 probability distribution for the user specified source or sink (

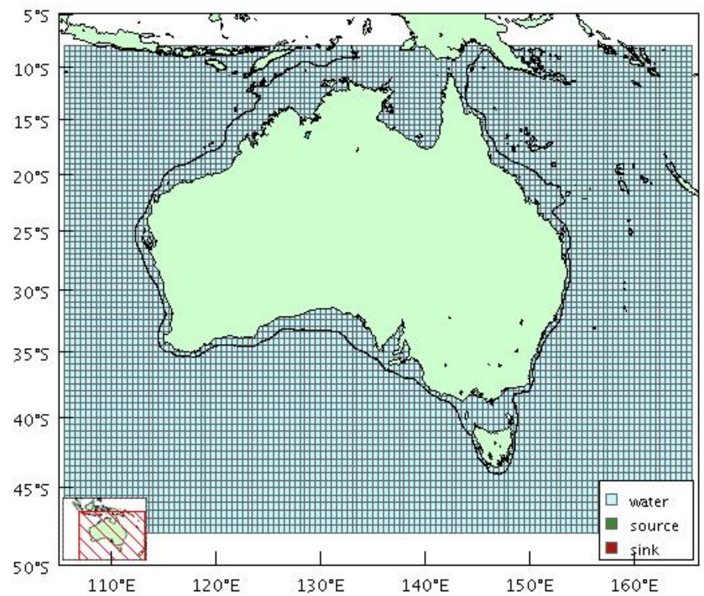
A paper on 'Marine connectivity patterns around the Australi in Environmental Modelling & Software:

> *Condie, S.A., Waring, J., Mansbridge, M.L., Cahill, M.L patterns around the Australian continent, Environ. Mo 1157.*

http://www.per.marine.csiro.au/ - Connectivity interface specification - Windows Internet Explorer

Connectivity Interface specification

Results >>



select cells

sweep/click grid to select:
- Source
- Sink
- Clear

clear all cells

statistics

year 1995

month January

lifetime 10 days

- within lifetime
- after lifetime

definitions

load

perth

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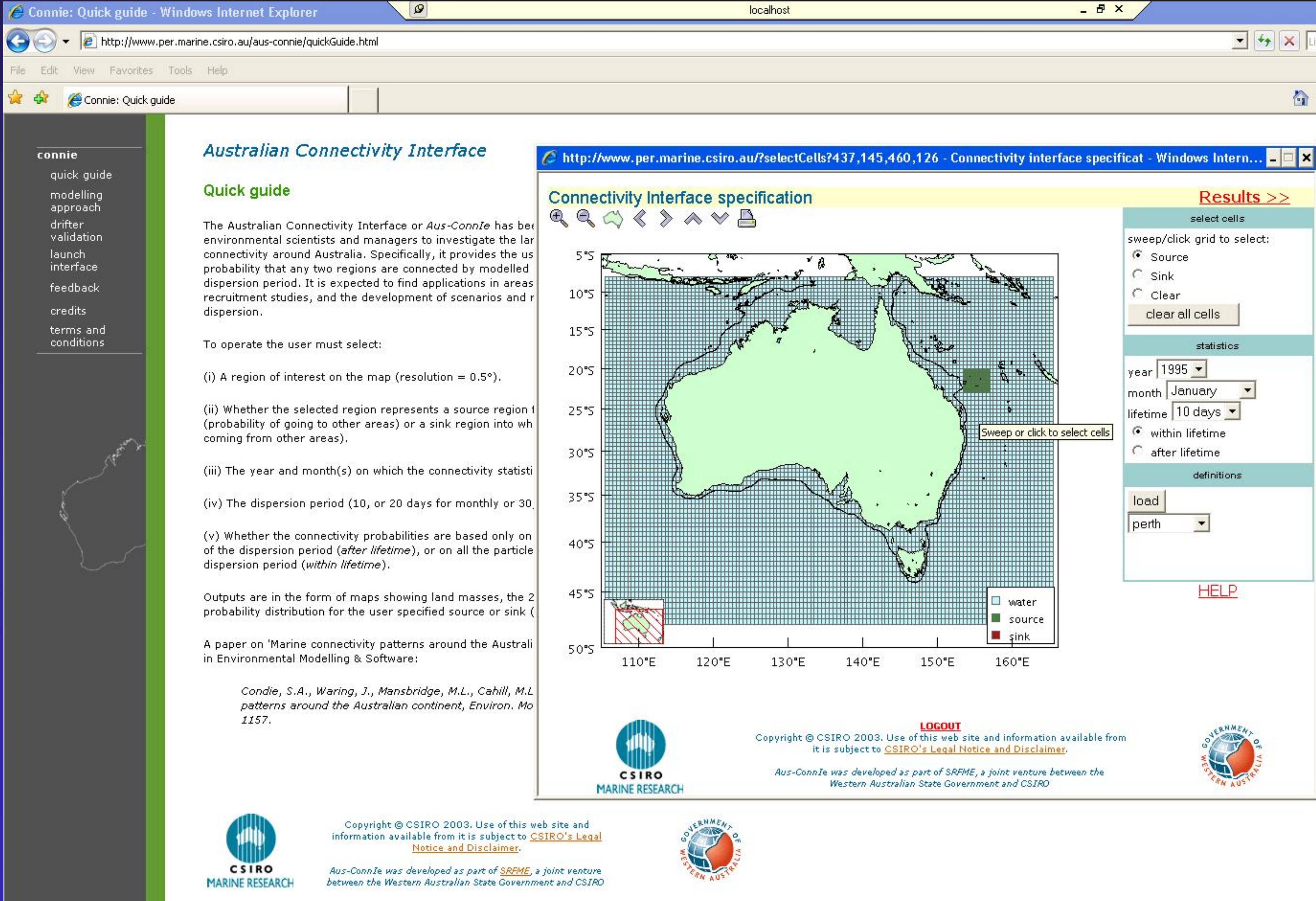
Connie: Quick guide - Windows Internet Explorer
http://www.per.marine.csiro.au/aus-connie/quickGuide.html
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Australian Connectivity Interface
Quick guide
The Australian Connectivity Interface or Aus-ConnIe has bee
environmental scientists and managers to investigate the lar
connectivity around Australia. Specifically, it provides the us
probability that any two regions are connected by modelled
dispersion period. It is expected to find applications in areas
recruitment studies, and the development of scenarios and r
dispersion.
To operate the user must select:
(i) A region of interest on the map (resolution = 0.5°).
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Sweep or click to select cells
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sink
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sweep/click grid to select:
Source
Sink
Clear
clear all cells
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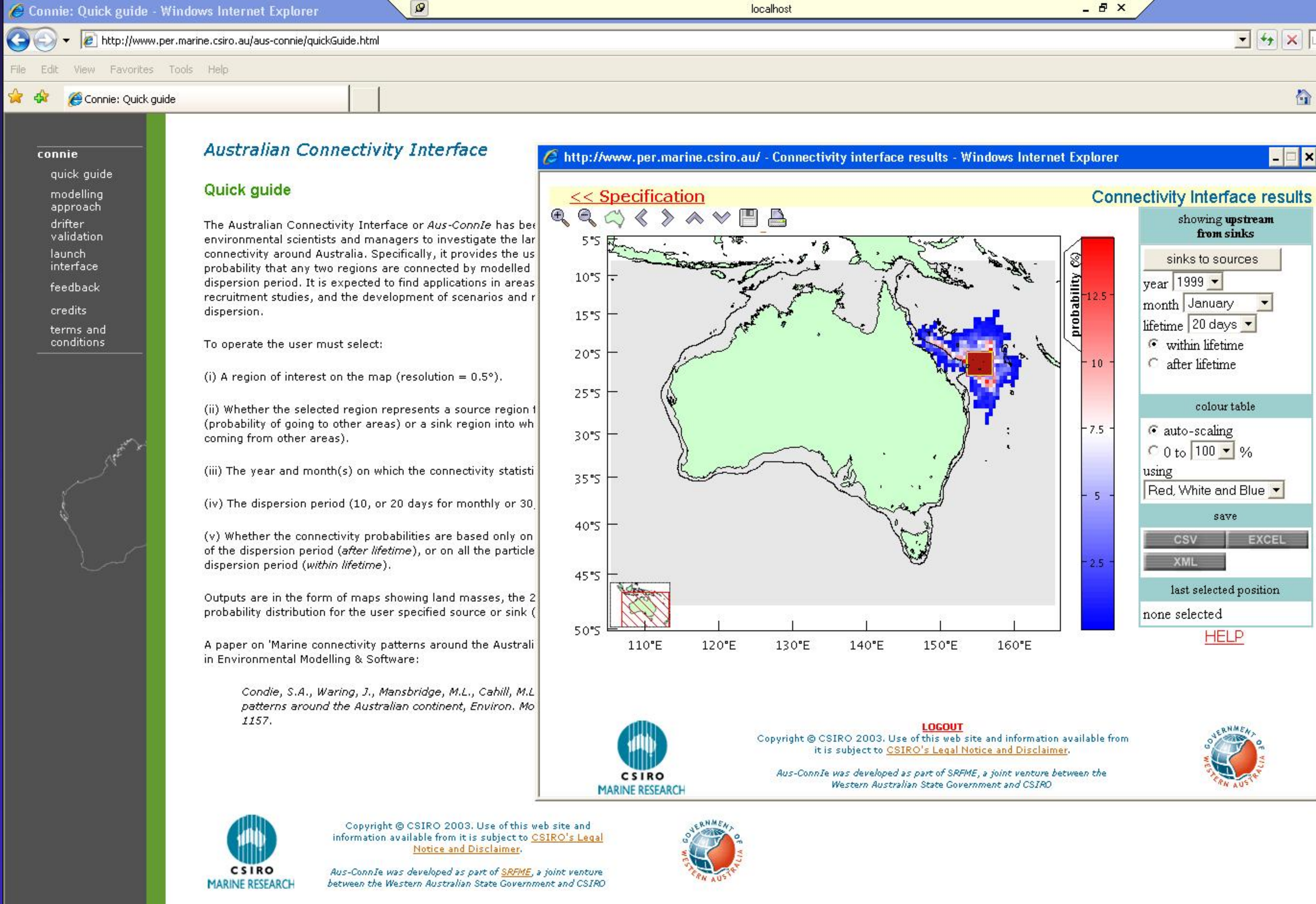
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showing upstream from sinks
sinks to sources
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month January
lifetime 20 days
within lifetime
after lifetime
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auto-scaling
0 to 100 %
using
Red, White and Blue
save
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EXCEL
XML
last selected position
none selected
HELP
probability (%)
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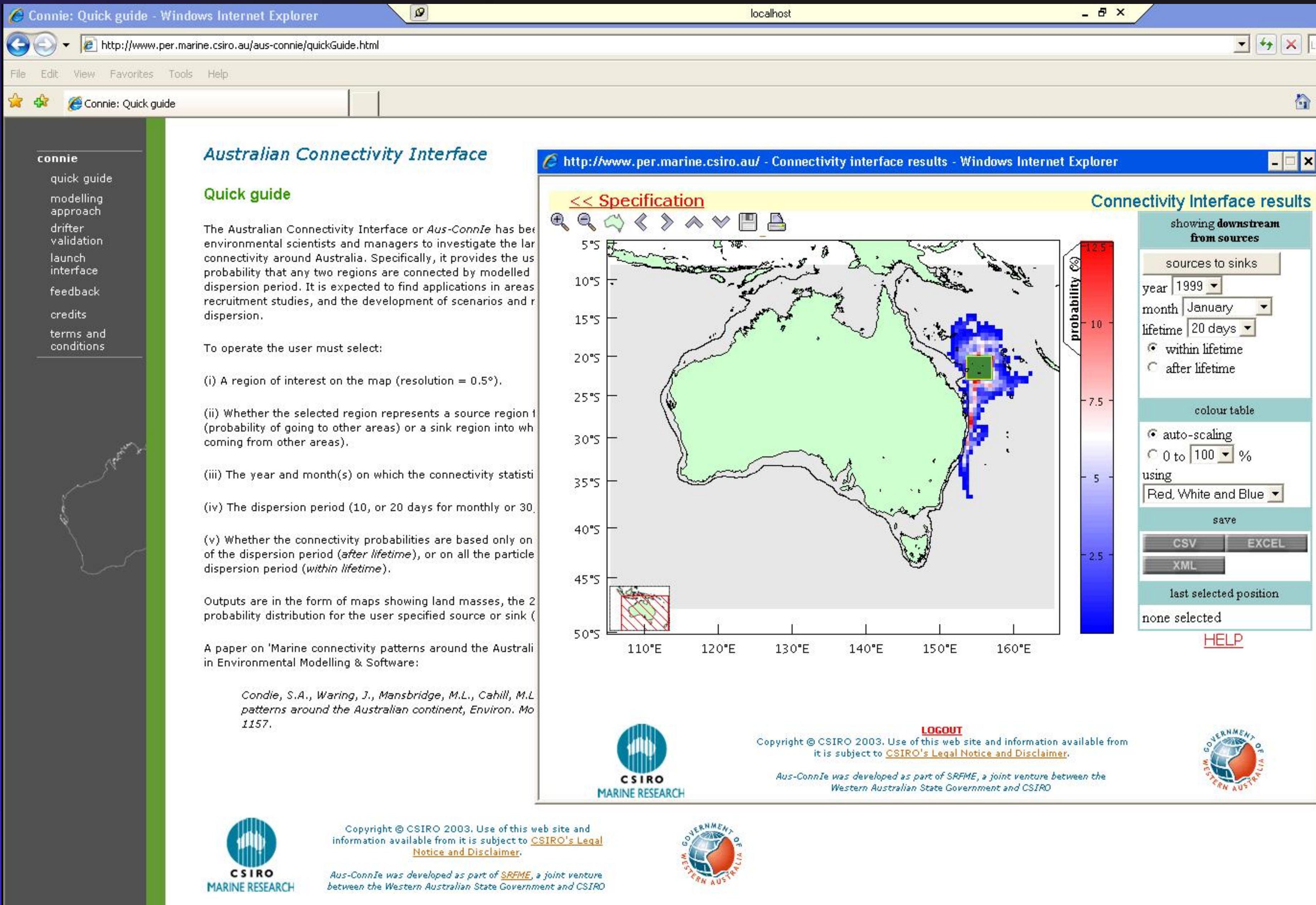
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Connie: Modelling approach

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Australian Connectivity Interface

Modelling approach

The currents were estimated from satellite derived sealevel and modelled wind fields using the methodology described by Griffin et al. (2001). Dispersion patterns associated with the circulation were measured by individually tracking a large numbers of neutrally buoyant particles distributed throughout the water column and moving with the currents.

Particles followed complex paths, which were sensitive to their initial location. This suggested the need for a statistical description of the dispersion results based on large numbers of particle trajectories. The statistical description provides the probability of any two regions within the domain being connected by the prevailing circulation within a specified dispersion period.

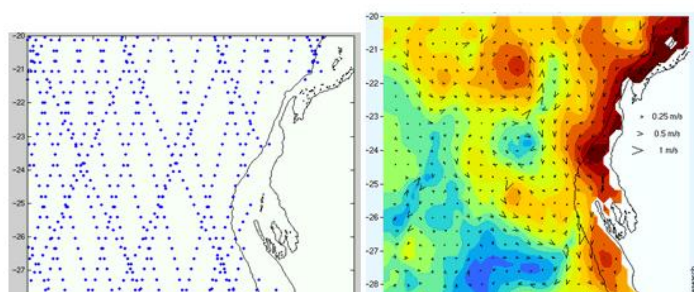
Sealevel estimates

Sealevel fields were required to estimate the large-scale current patterns around Australia (i.e. geostrophic currents). The sealevel at each location consists of a long-term mean component plus short-term fluctuations or anomalies.

Data on sealevel anomalies were collected from a number of sources:

(i) Altimeter data from the Topex/Poseidon satellite (9.9 day cycle).
(ii) Altimeter data from the ERS satellite (35 day cycle).
(iii) Tide-gauges around the Australian coastline.

An example of the effective spatial resolution of the combined Topex/Poseidon and ERS satellites is indicated in Figure 1 for a region off northwestern Australia. The coastal tide-gauge data was interpolated along the coastline to achieve a comparable resolution.
The long-term mean sealevel field was calculated from the mean ocean density field. This density field is based on historical temperature and salinity measurements from the NODC World Ocean Atlas 1994 hydrographic data, and CSIRO RV Franklin, RV Southern Surveyor and SRV Aurora Australis hydrographic data (Dunn and Ridgway 2002, Ridgway et al. 2002).
A time series of sealevel fields has been derived by optimally interpolating data from the coastal tide-gauges and two altimeters onto a 0.2° latitude-longitude grid, then adding it to the mean sealevel field (Bretherton et al. 1976, Le Traon 1990, Cahill and Condie 2001). The final sealevel fields were archived at five-day intervals over the period January 1995 to December 1999.



Development for Hawaiian Archipelago

- Dr. James Potemra (University of Hawaii, SOEST, IPRC), Dr. Scott Condie (CSIRO), and myself are in the process of developing a similar product for the Hawaiian Archipelago.
- This may be part of a CAMEO proposal.