Observations of Anticyclones in Hawaii using Surface Drifters

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Ph.D. Defense
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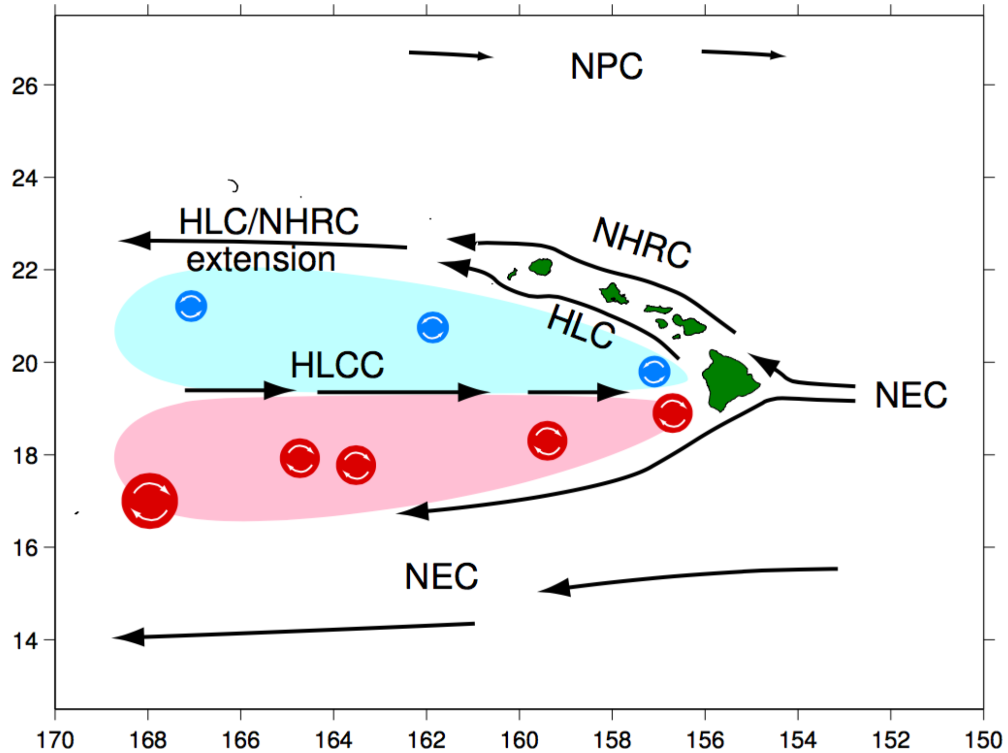
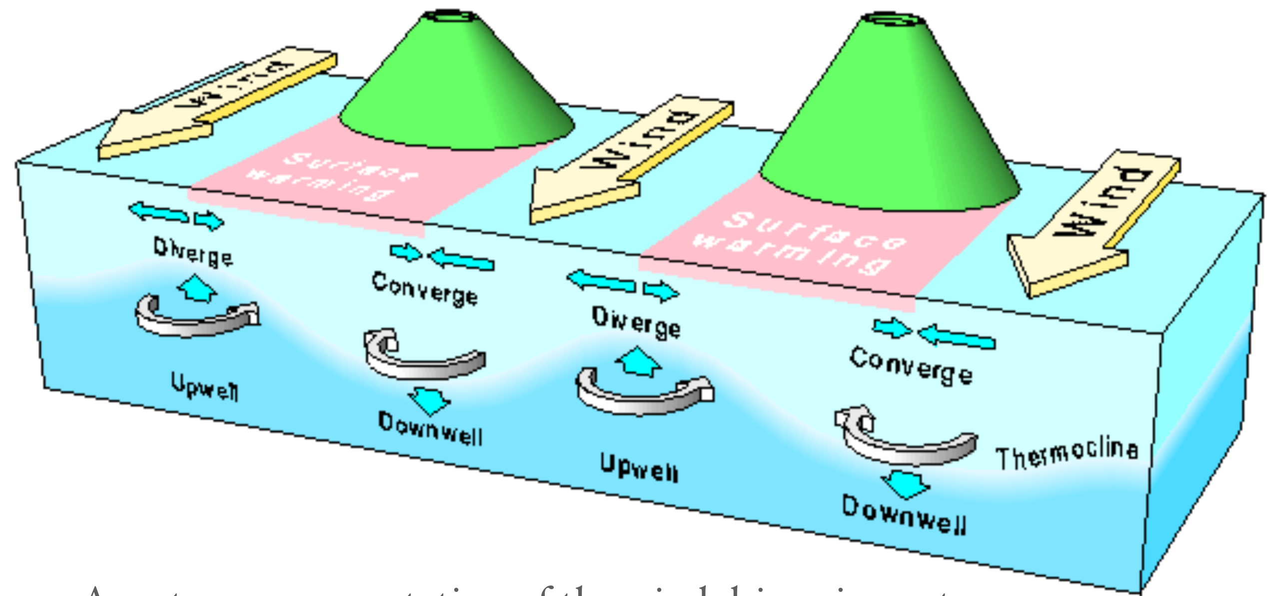
Motivation

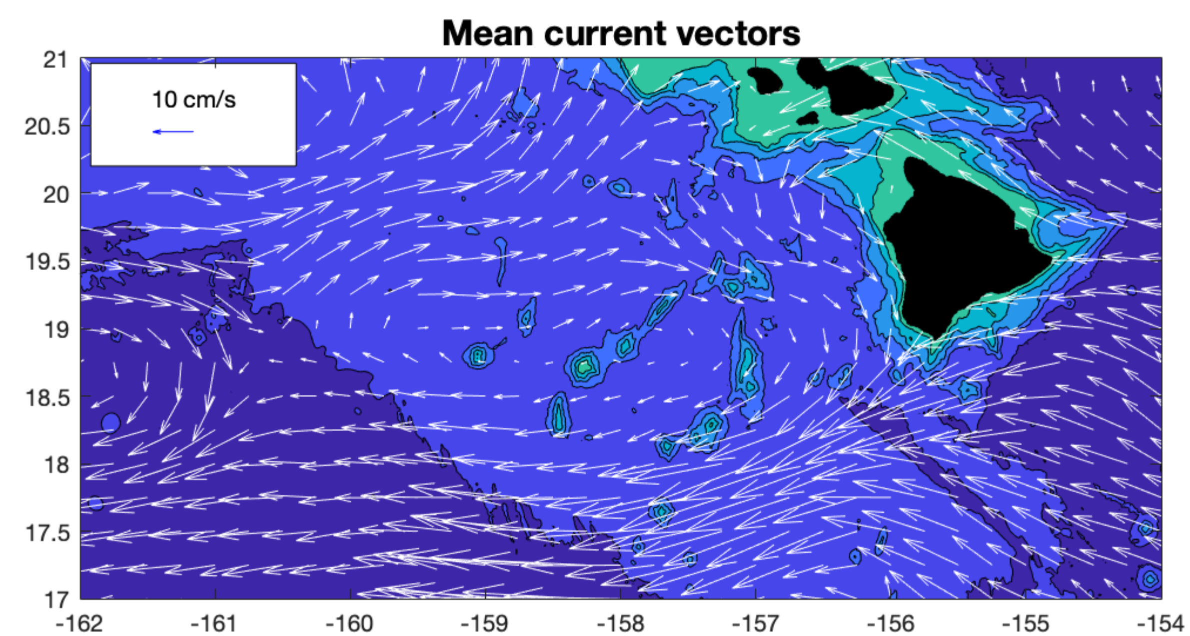


A schematic of the flow in the lee of the Hawaiian Islands. Figure from Lumpkin (1998)



A cartoon representation of the wind driven impacts on the thermocline in island lees. Figure from Ocean Atlas of Hawaii, Flament et al (1996)

- Anticyclones are observed frequently in the lee of the islands, but there has not been a recent comprehensive observational study
- What are the size, duration, and seasonality of anticyclones ivo Hawaii and Oahu?
- What are the large scale ocean and atmospheric patterns present as anticyclones evolve?



The bathymetry of South Point and associated mean currents.

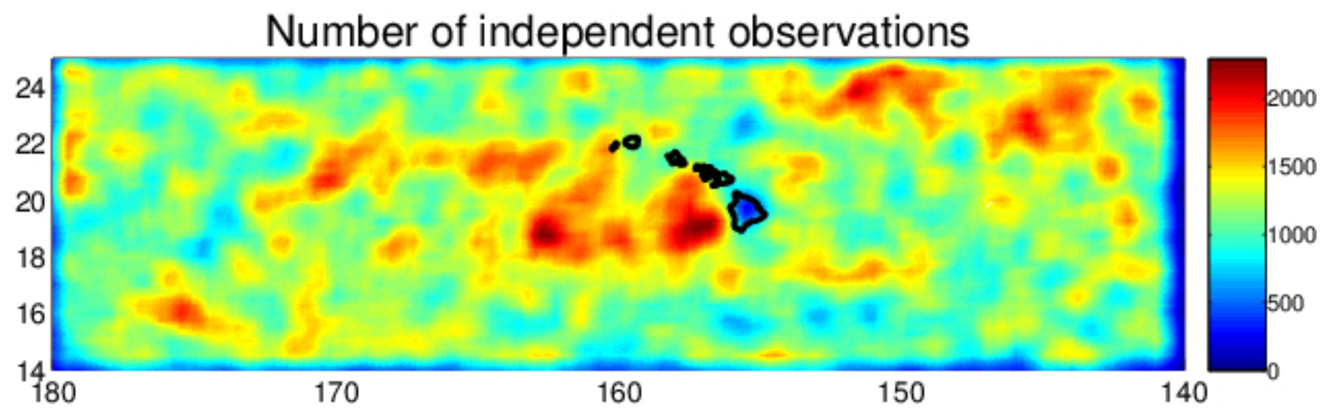
1. **Observations of Anticyclones in the Lee of Hawaii Island**

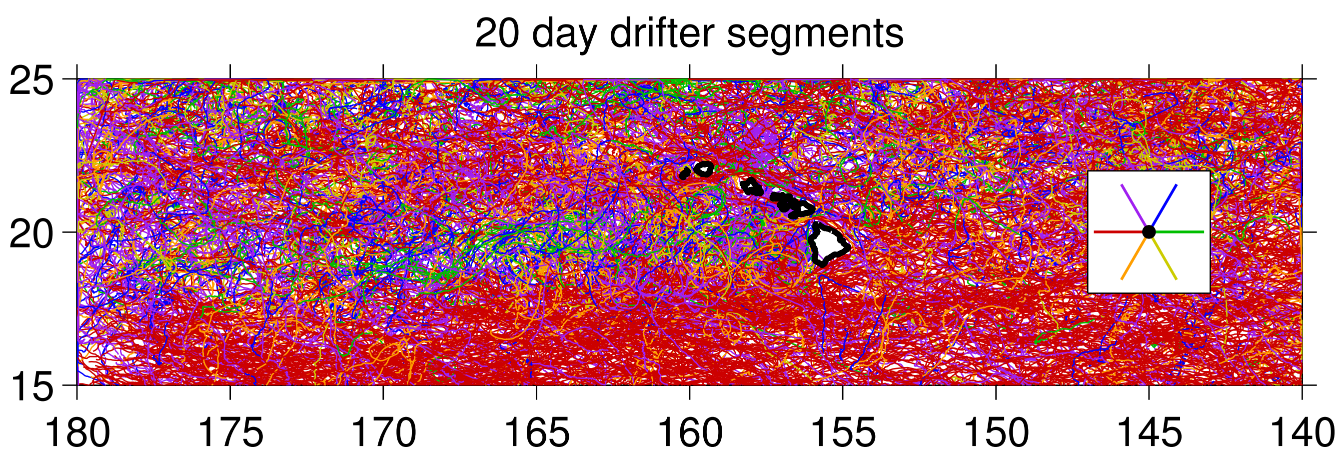
2. Drifter Statistics in West Oahu Coastal Waters: Observations of Island Lee Dynamics

3. An Estimate of Surface Drifter Leeway using Indirect Methods

4. Conclusions

Observations of Anticyclones in the Lee of Hawaii Island
Methods: Drifters



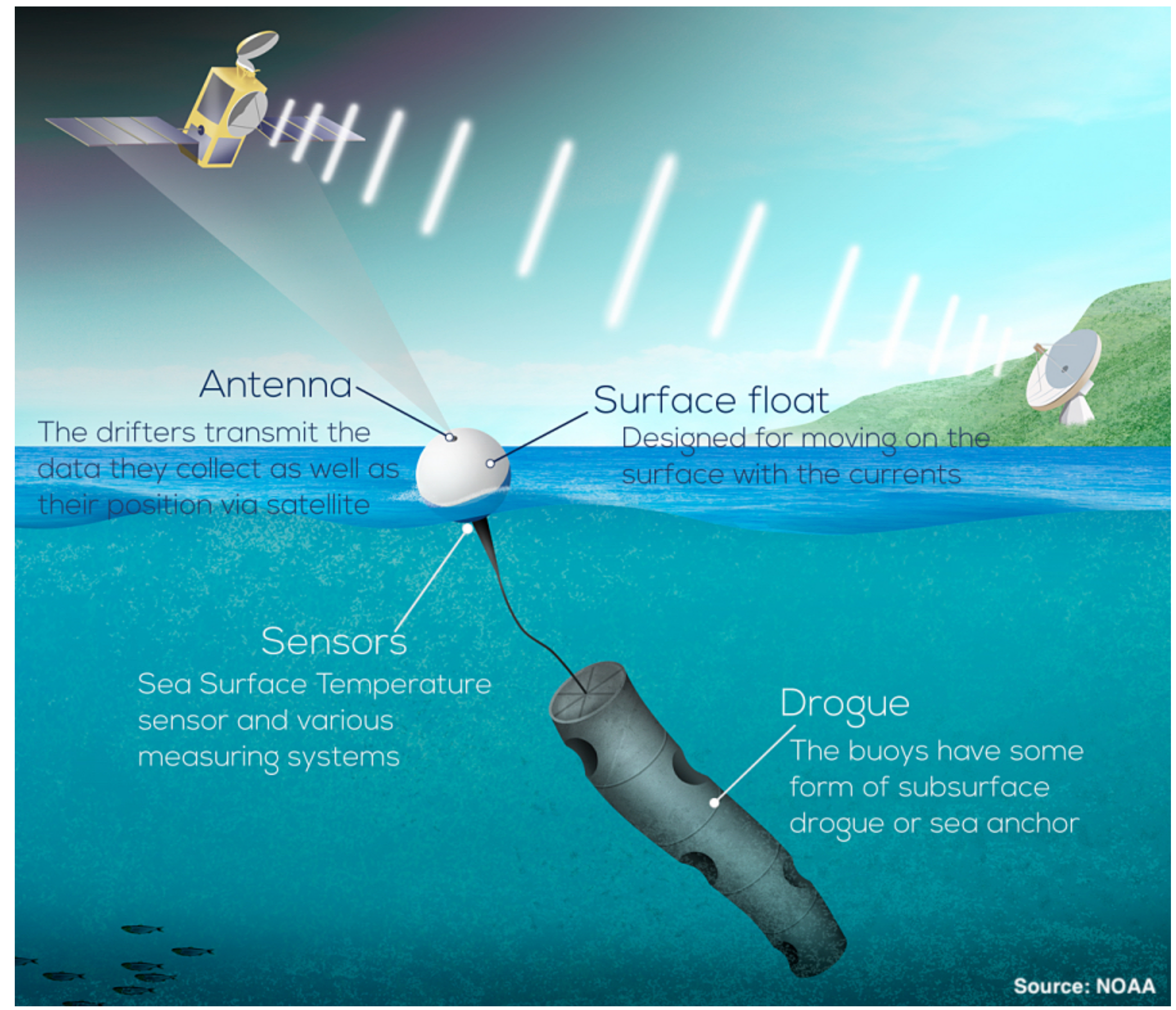


- SVP data from 1979-2016. Overall, 832 drifters passed through the region of interest.

- Highest concentration of drifters was in the lee of Hawaii.

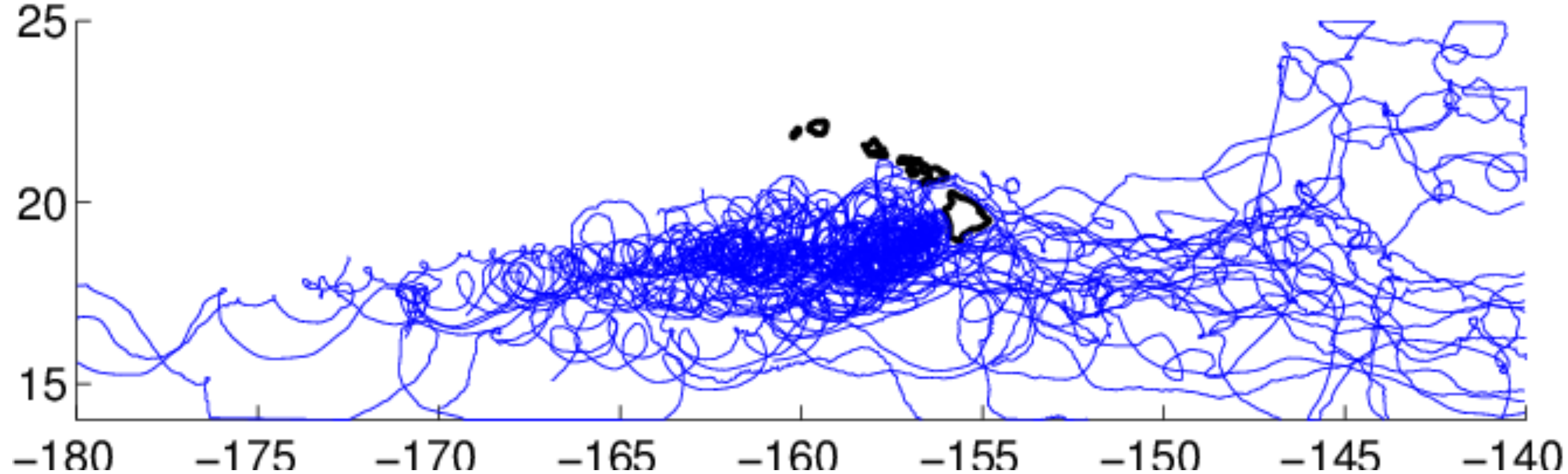
- A visual inspection of each drifter was conducted to identify anticyclonic looping trajectories.

- 25 distinct anticyclones were identified from the data.



The Surface Velocity Program (SVP) drifter, from NOAA.

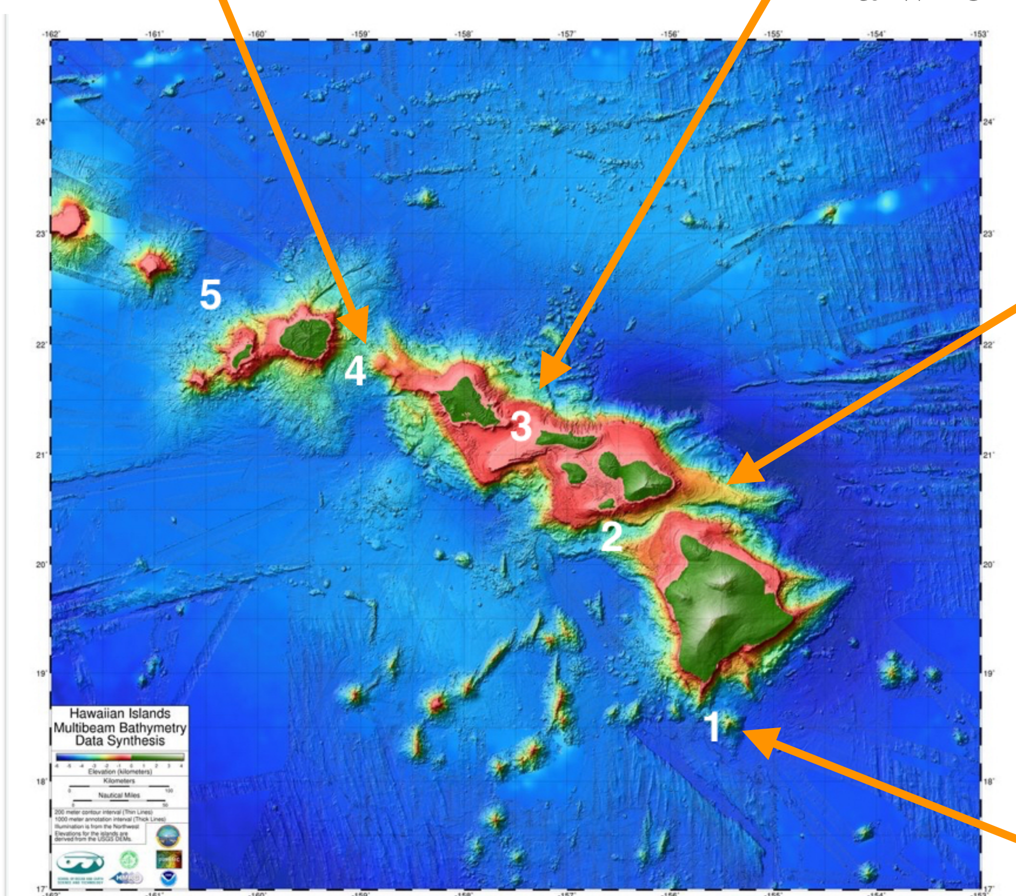
Observations of Anticyclones in the Lee of Hawaii Island
Results: Drifters

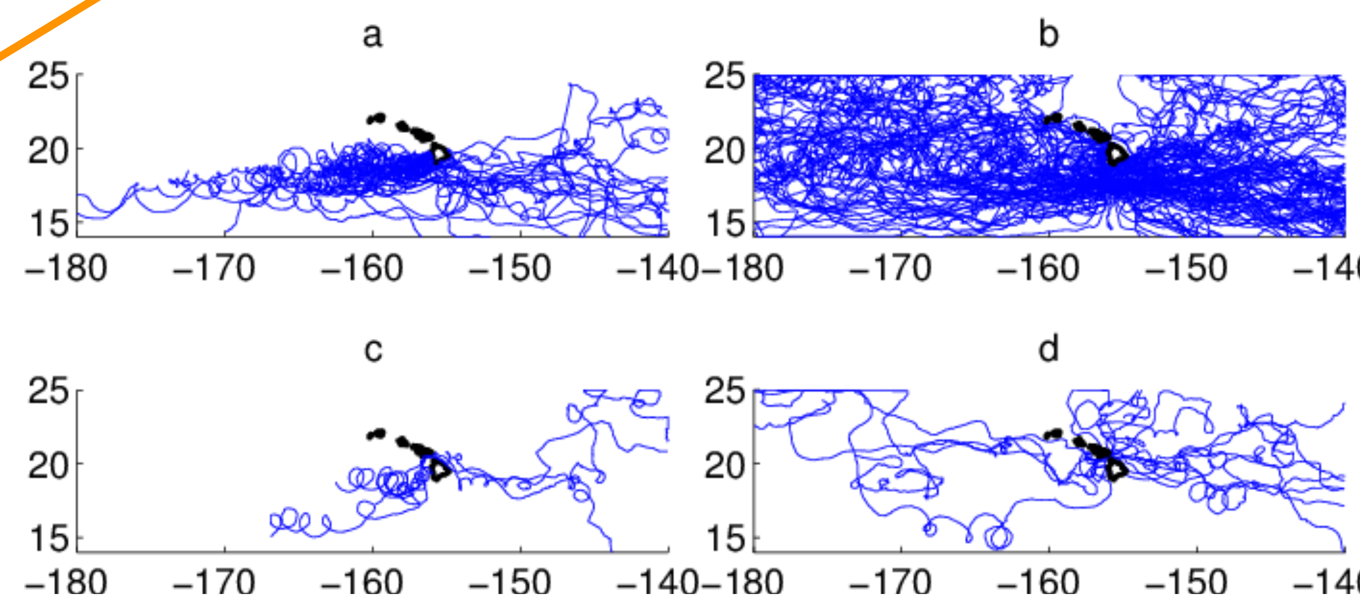


Ka`ie`ie channel

Kaiwi channel

`Alenuihāhā channel





South Point

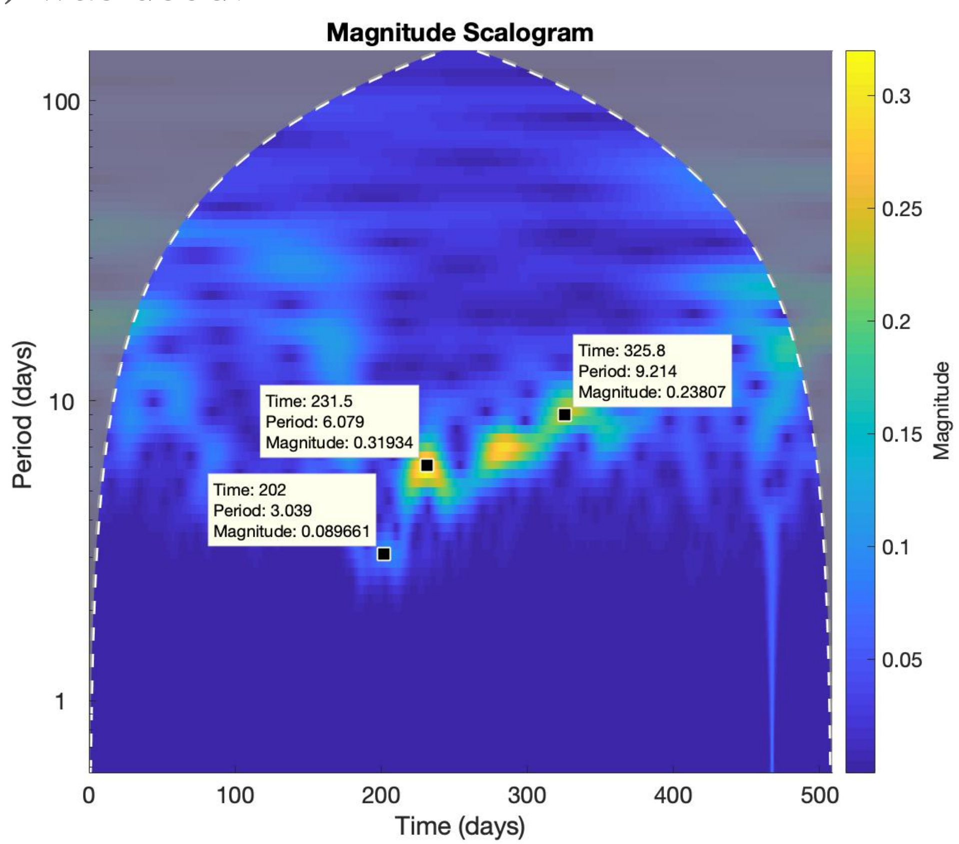
Image from Main Hawaiian Islands Multibeam Bathymetry and Backscatter Synthesis

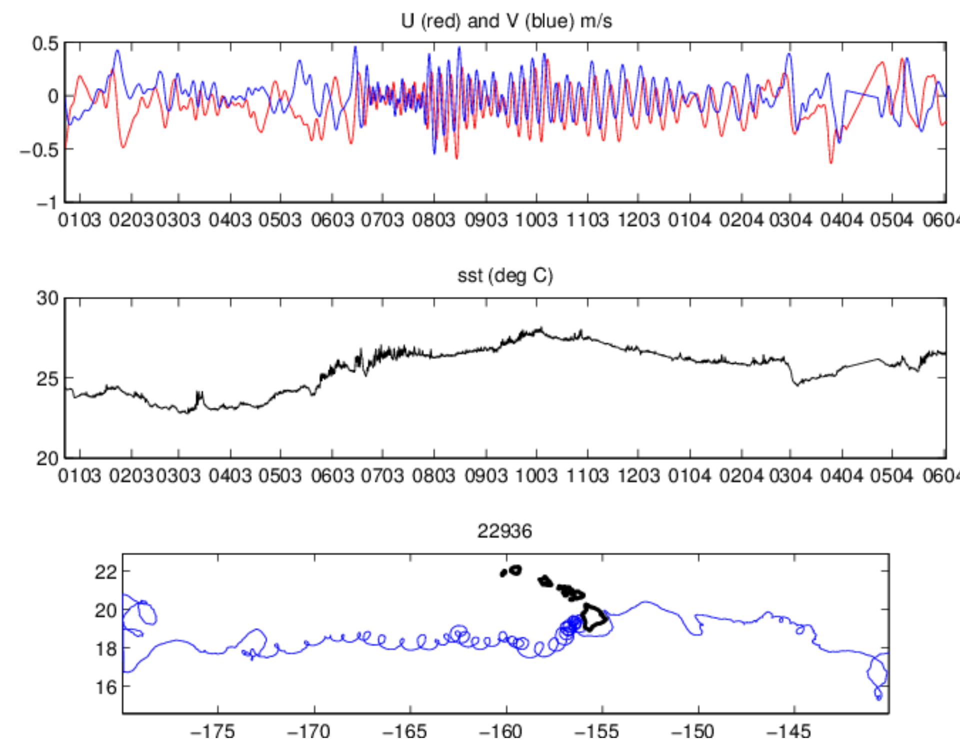
Observations of Anticyclones in the Lee of Hawaii Island
Methods: Drifters

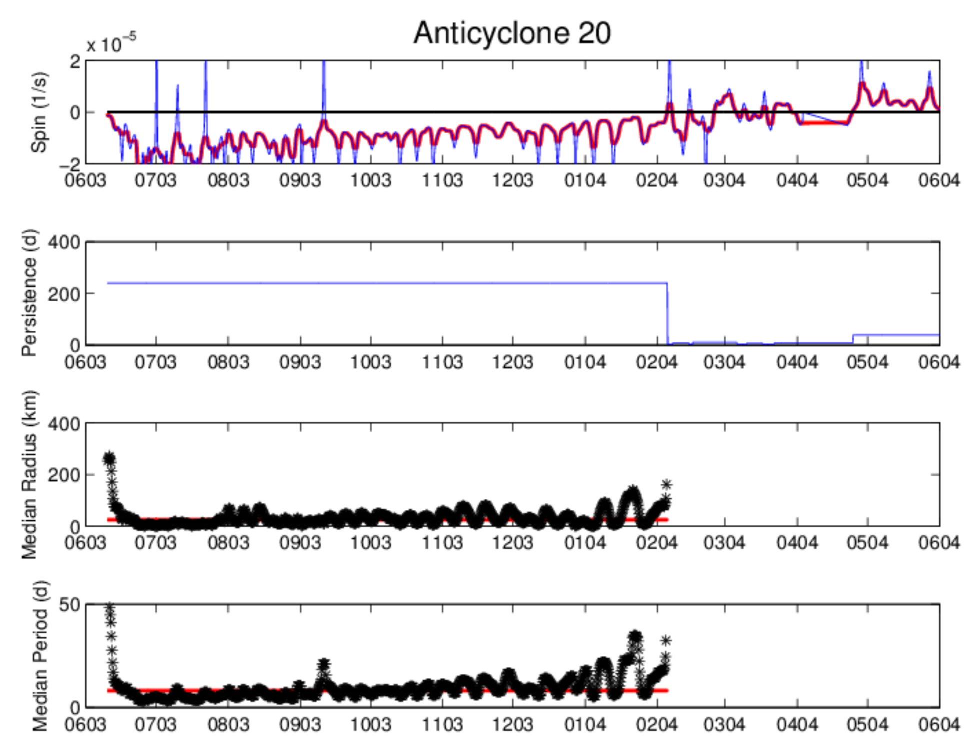
- Once an anticyclone was identified, its period and radius were calculated following methods from Lumpkin (2016):

$$P = \frac{2\pi}{|\Omega|}, R = \frac{\sqrt{2EKE}}{|\Omega|} \text{ where } \Omega = \frac{\langle u'dv' - v'du' \rangle}{(2\Delta t EKE)}$$

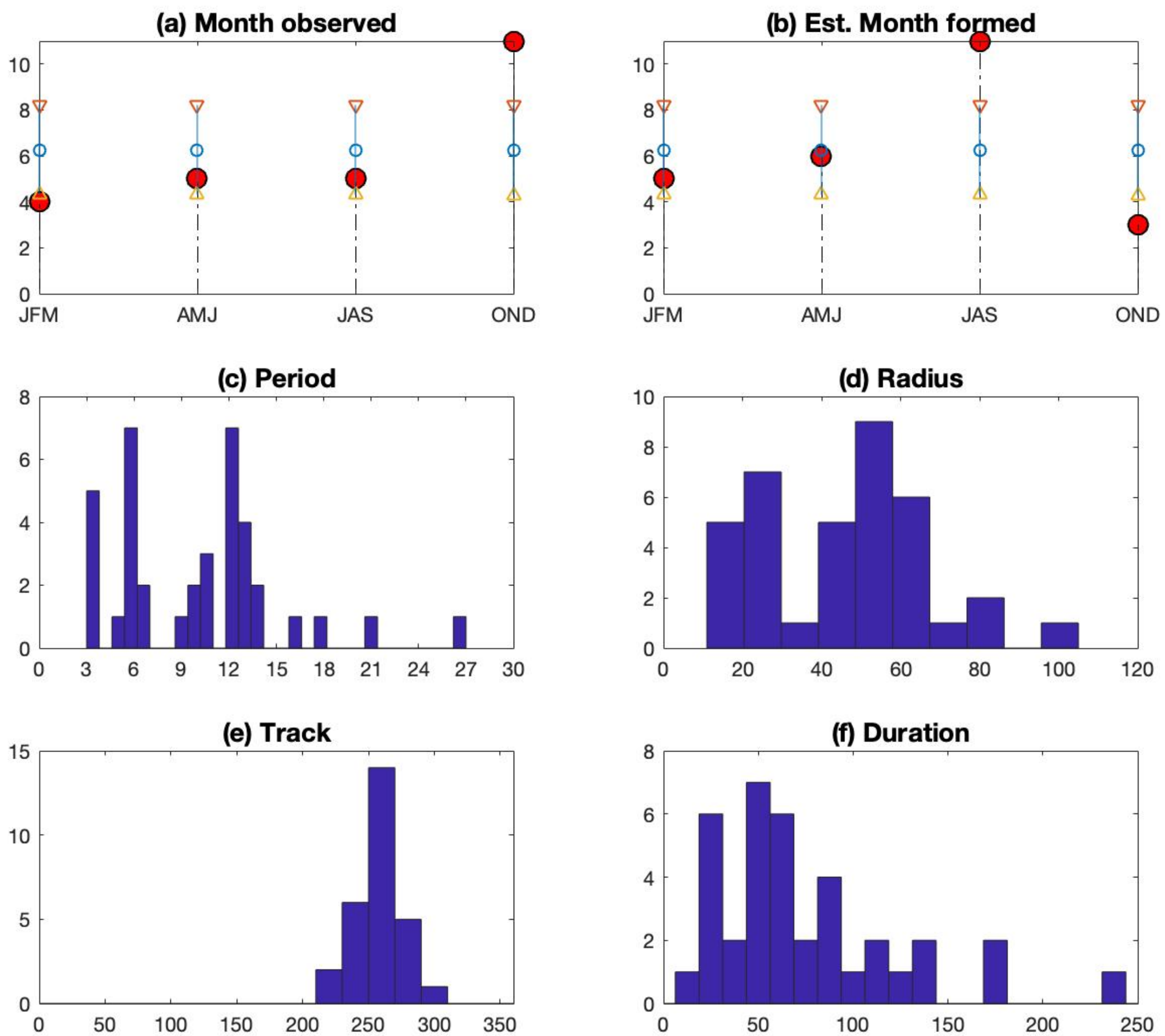
- However, where vortex merging was observed, the method of calculating period and radius using spin was less effective. In order to see subtle transitions in period over time, a continuous wavelet transform (CWT) was used:







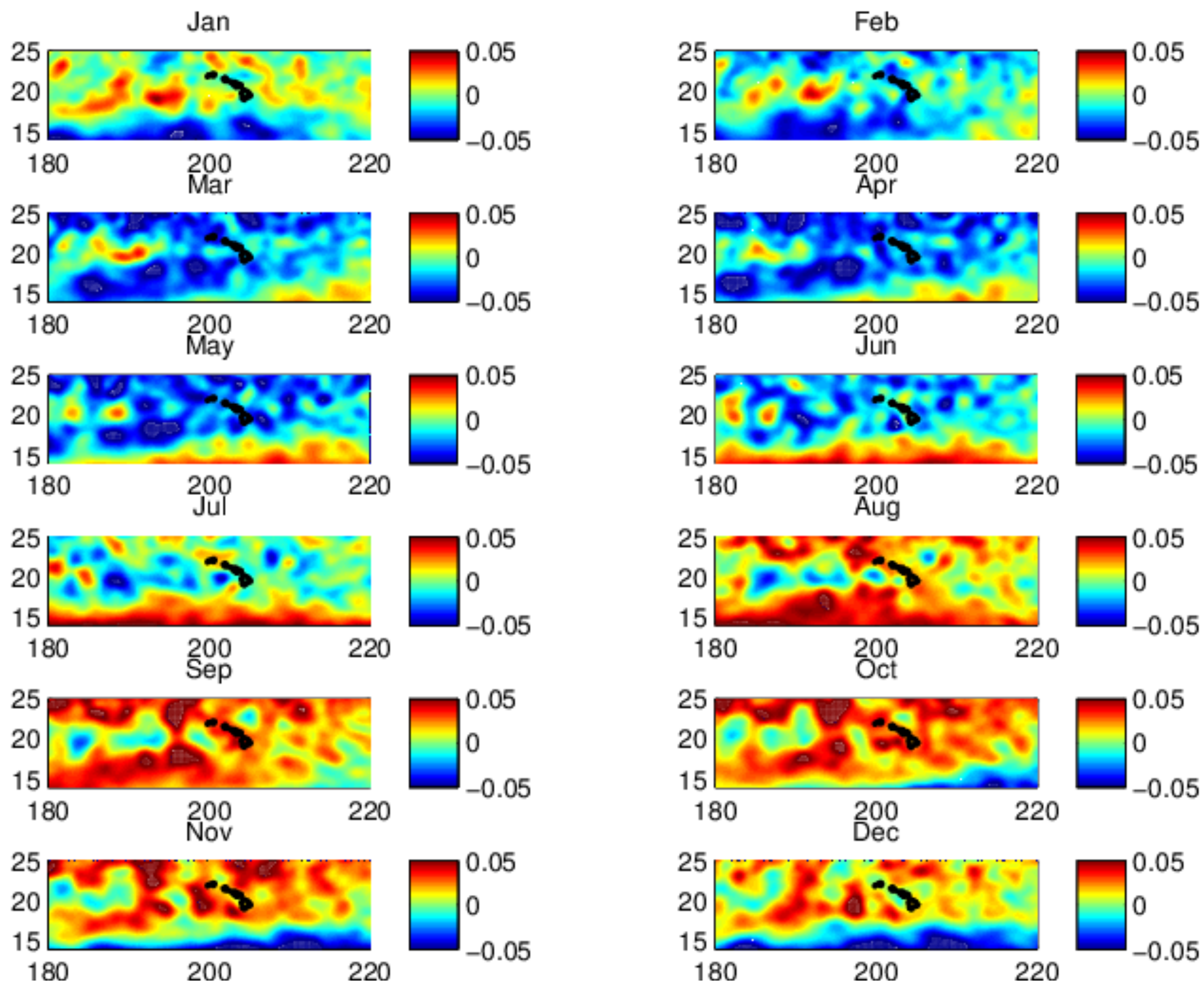
Observations of Anticyclones in the Lee of Hawaii Island
Results: Drifters



	Median	Mean	Standard Deviation
Period (d)	11	10.7	±5.2
Radius (km)	52.5	46.9	±22.1
Month	8	7.4	±3
Track (°T)	264	260	±19.2
Distance (km)	350	556	±434.3
Persistence (d)	63.3	75.5	±49.9

- Anticyclones formed most often in summer months (July-September)
- Lowest anticyclone formation in Fall months (October - December).
- Followed very narrow track away from islands.

Observations of Anticyclones in the Lee of Hawaii Island
Results: Satellite Data - SLA



- Strongest positive SLA in lee region during summer and fall months (up to 10cm in summer)

Observations of Anticyclones in the Lee of Hawaii Island
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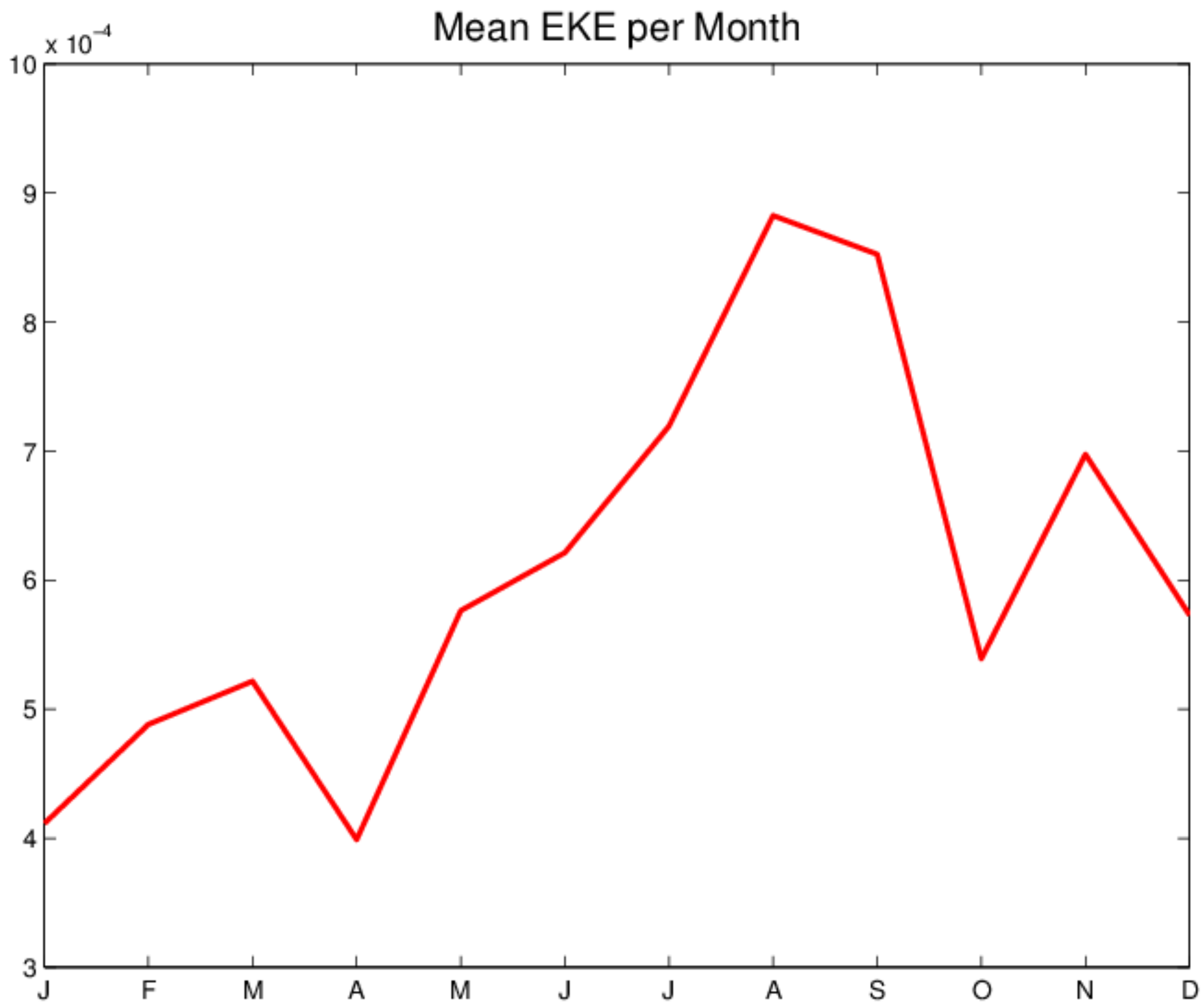

- Strongest positive SLA in lee region during summer and fall months (up to 10cm in summer)

- Highest EKE in JAS

Observations of Anticyclones in the Lee of Hawaii Island
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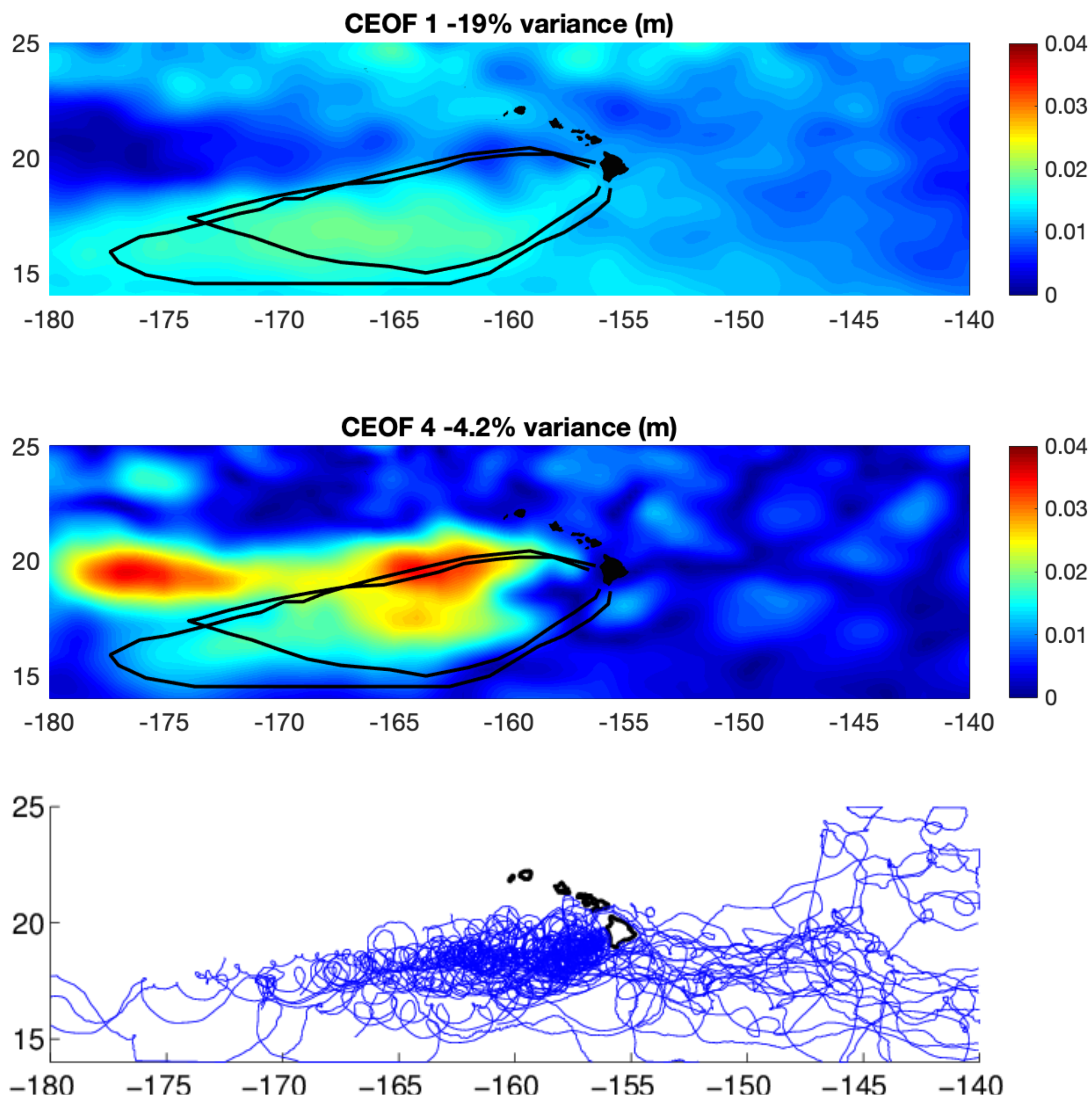
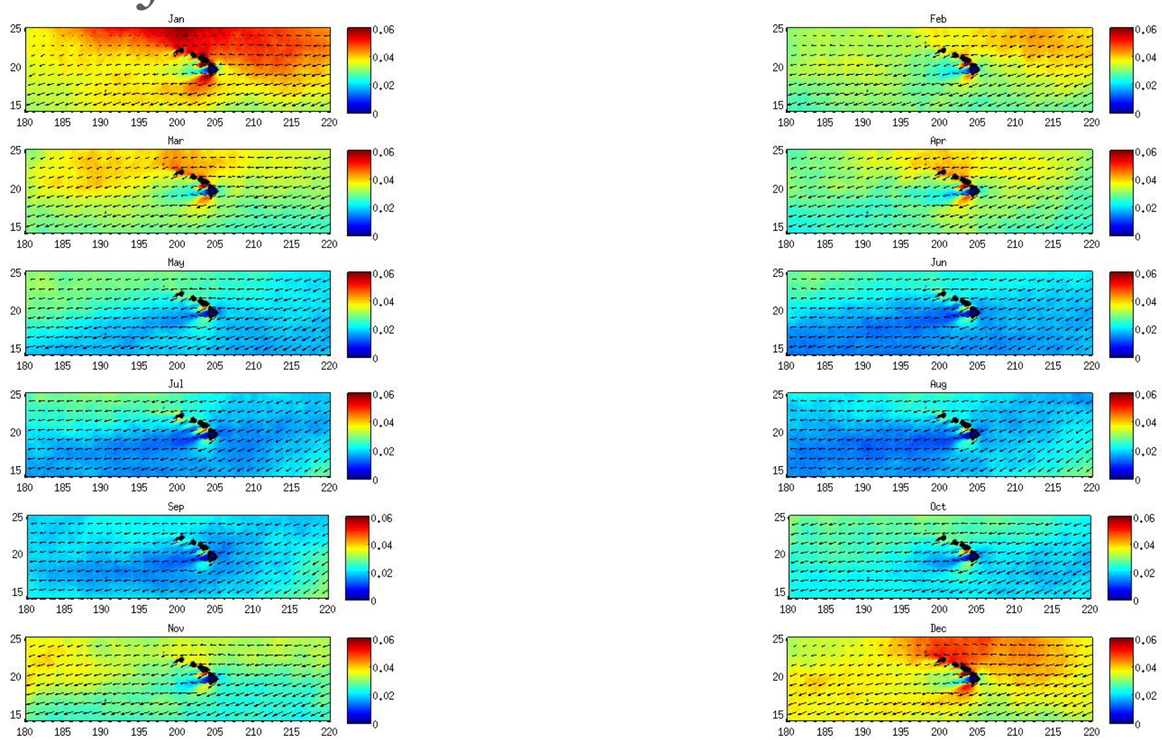


- Strongest positive SLA in lee region during summer and fall months (up to 10cm in summer)
- Highest EKE in JAS
- CEOF analysis shows four main modes. Mode 1 is annual cycle, Modes 2/3 are inter-annual, Mode 4 is 100 day period.
- Mode 4 has two regions of high sla variability in lee region, one in line with HLCC, one weaker one in line with anticyclonic vector.

Observations of Anticyclones in the Lee of Hawaii Island
Methods: Satellite Data - Wind

Jan　　Feb

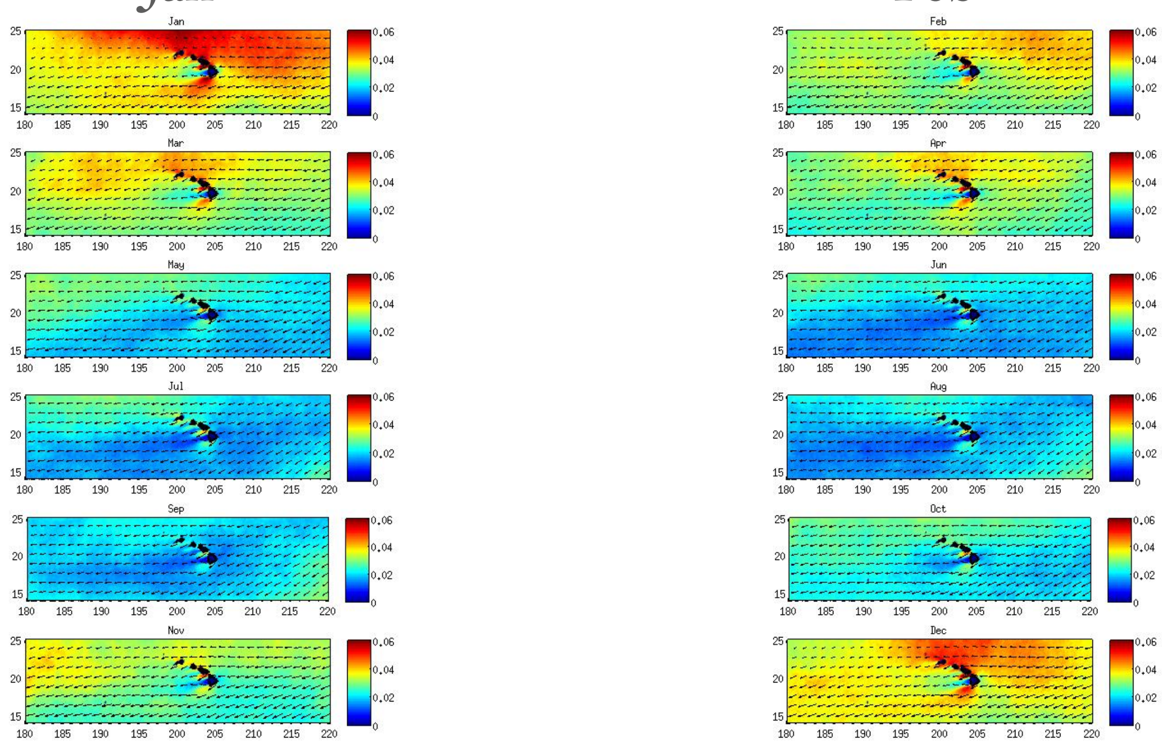


Nov　　Dec

Observations of Anticyclones in the Lee of Hawaii Island
Methods: Satellite Data - Wind

- Strongest wind stress in winter months, but gusty with highest occurrence of Kona winds.

Jan Feb



Nov Dec

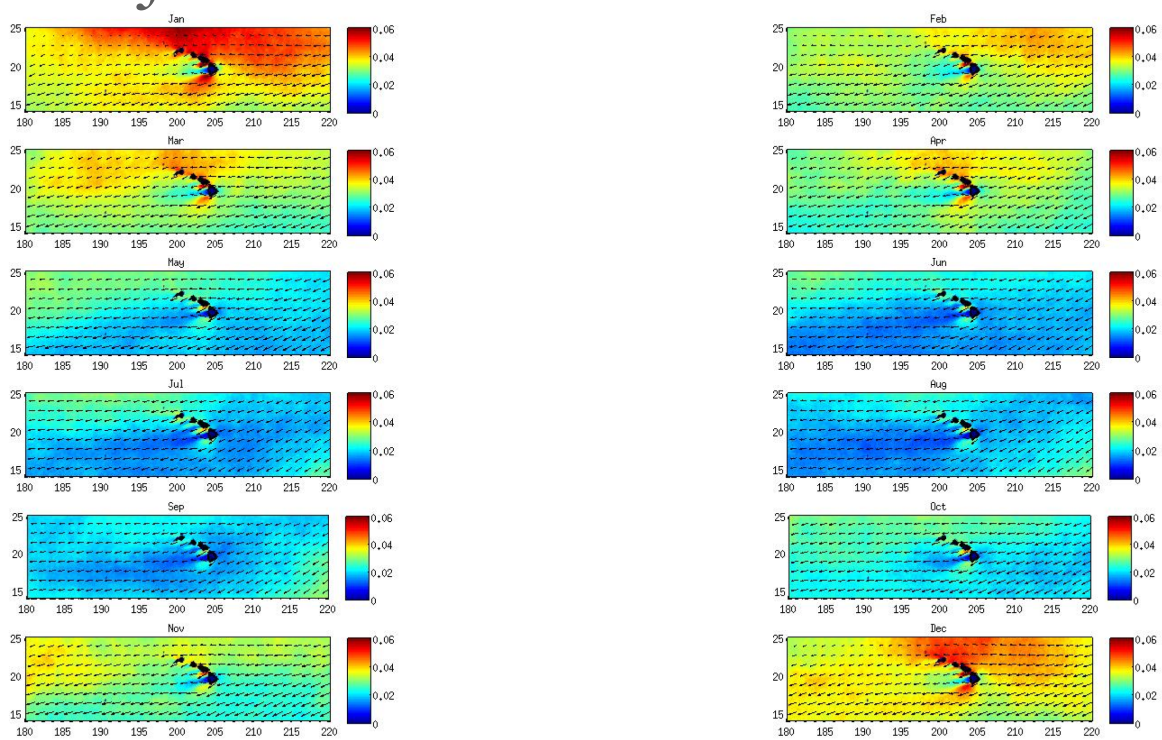
Observations of Anticyclones in the Lee of Hawaii Island
Methods: Satellite Data - Wind

- Strongest wind stress in winter months, but gusty with highest occurrence of Kona winds.

- Most consistent winds in summer (smallest standard deviation)

Jan

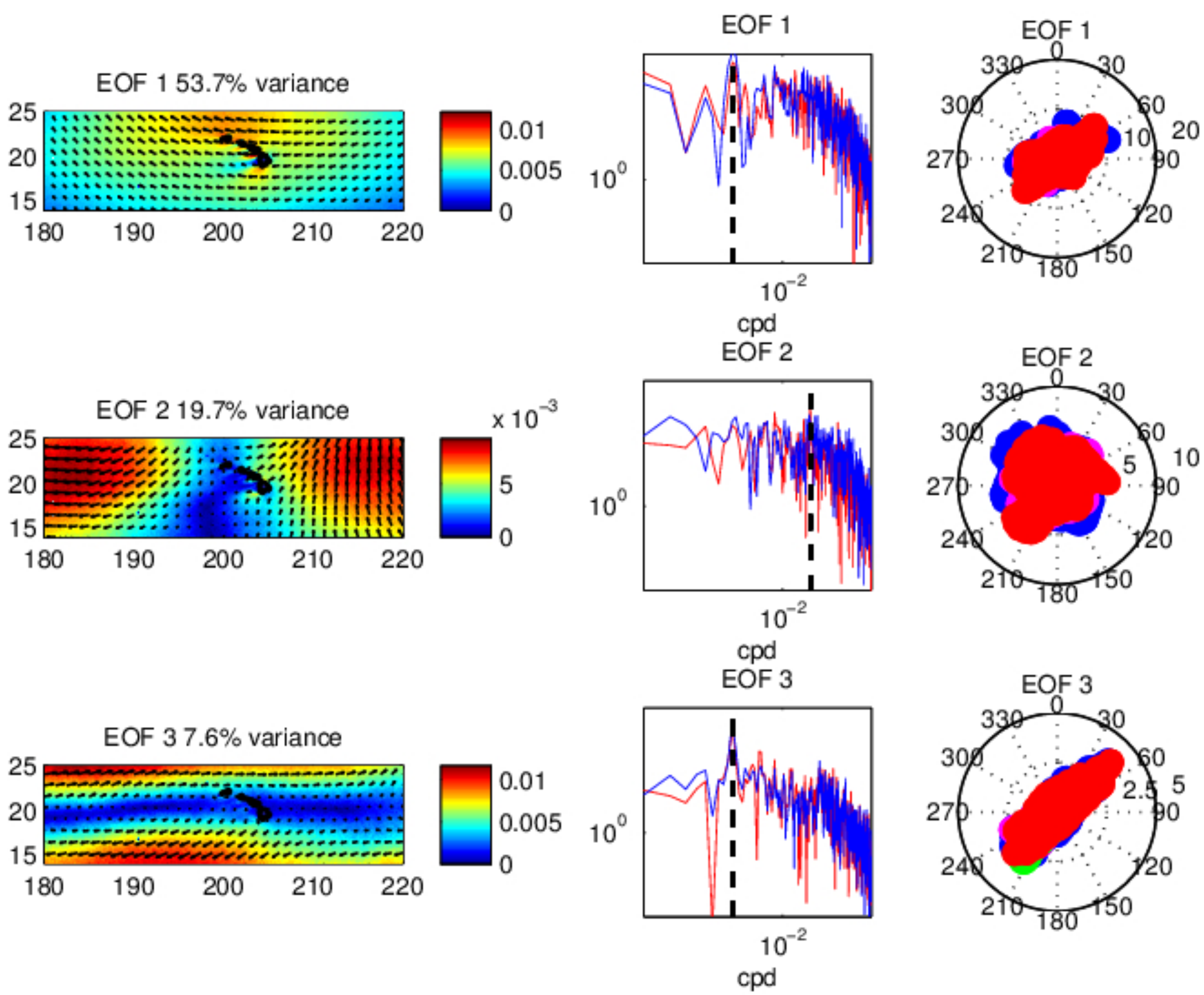
Feb



Nov

Dec

Observations of Anticyclones in the Lee of Hawaii Island
Methods: Satellite Data - Wind



- Strongest wind stress in winter months, but gusty with highest occurrence of Kona winds.
- Most consistent winds in summer (smallest standard deviation)
- EOF analysis shows three main modes. Mode 1 and 3 have strong seasonal cycle.
- Mode 2 has a dominant period of 50 days.

Observations of Anticyclones in the Lee of Hawaii Island
Conclusions

* Formation of anticyclones (from drifter data) most common during summer months.

* Compares well to satellite data results. During summer months, EKE calculated from SLA in lee of islands is greatest, as well as largest strongest lee SLA signals.

* Peak NE trade winds (aka most consistent) occur during summer months, with lowest number of Kona wind days.

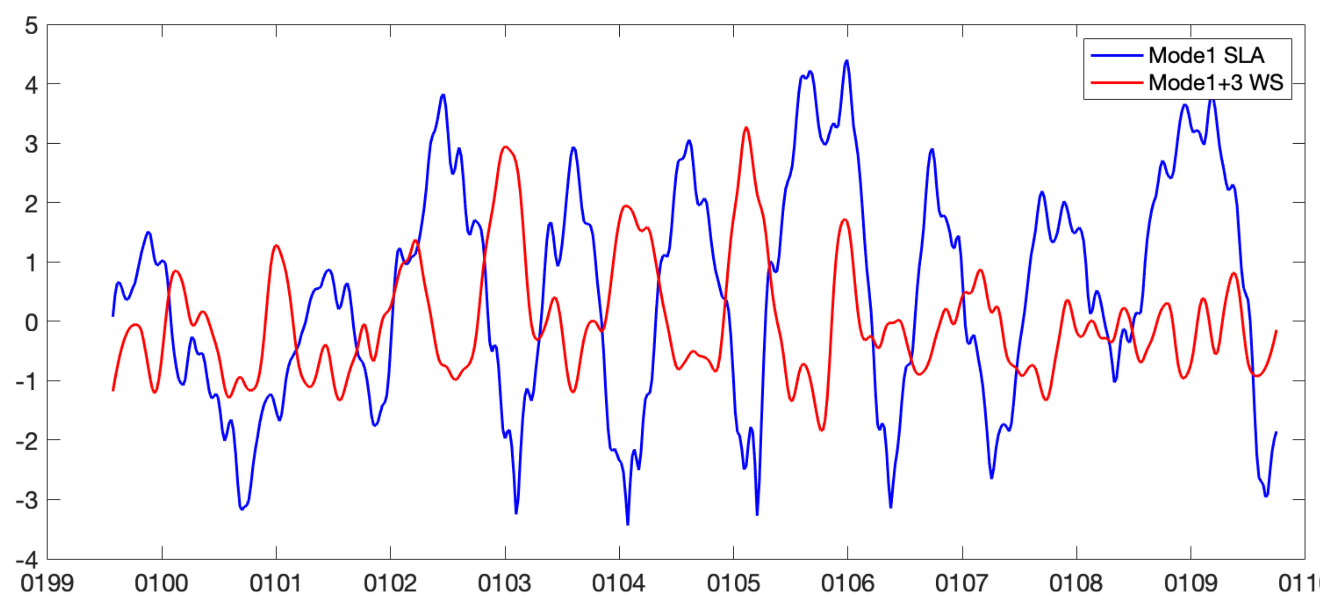
* In winter, winds are gustier, but less consistent and this results in the shortest westward extent of the Ekman pumping zone off of South Point.

* Cyclonic zone was non-existent in drifter data. Only three cyclones were observed, one of which passed well south of the island chain. The other two were close in to the island of Hawaii.

Observations of Anticyclones in the Lee of Hawaii Island
Conclusions

* Both Wind Stress and SLA have annual cycles in EOF results. The pattern in the annual SLA mode matches the observed anticyclonic sector south of Hawaii.

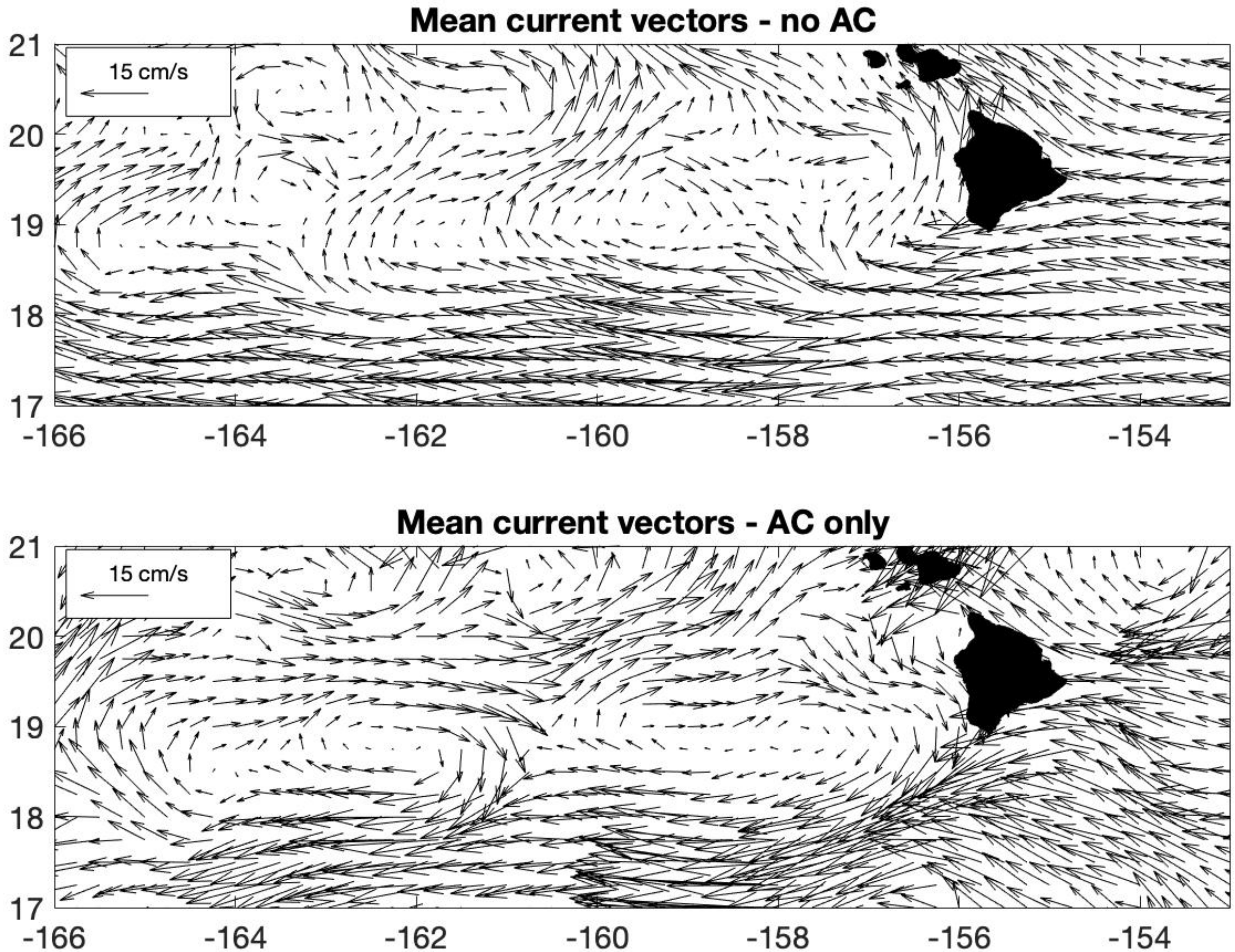
* The time series of the annual wind stress modes (combined 1 and 3) has a periodic correlation with the SLA annual mode, with a 6 month lag delay.



* There is no noticeable correlation between the 50 day wind stress signal in Mode 2 and the 100 day SLA signal seen in Mode 4. What causes the 100 day SLA signal is still unanswered.

* Wind forcing of anticyclonic zone likely at an annual cycle with strongest formation in summer months. Due to a lack of data for NEC strength off of South Point, current shear's contribution to anticyclone formation cannot be quantified. But NEC is stronger off South Point during anticyclones.

Observations of Anticyclones in the Lee of Hawaii Island
Results: Currents near South Point



1. Observations of Anticyclones in the Lee of Hawaii Island

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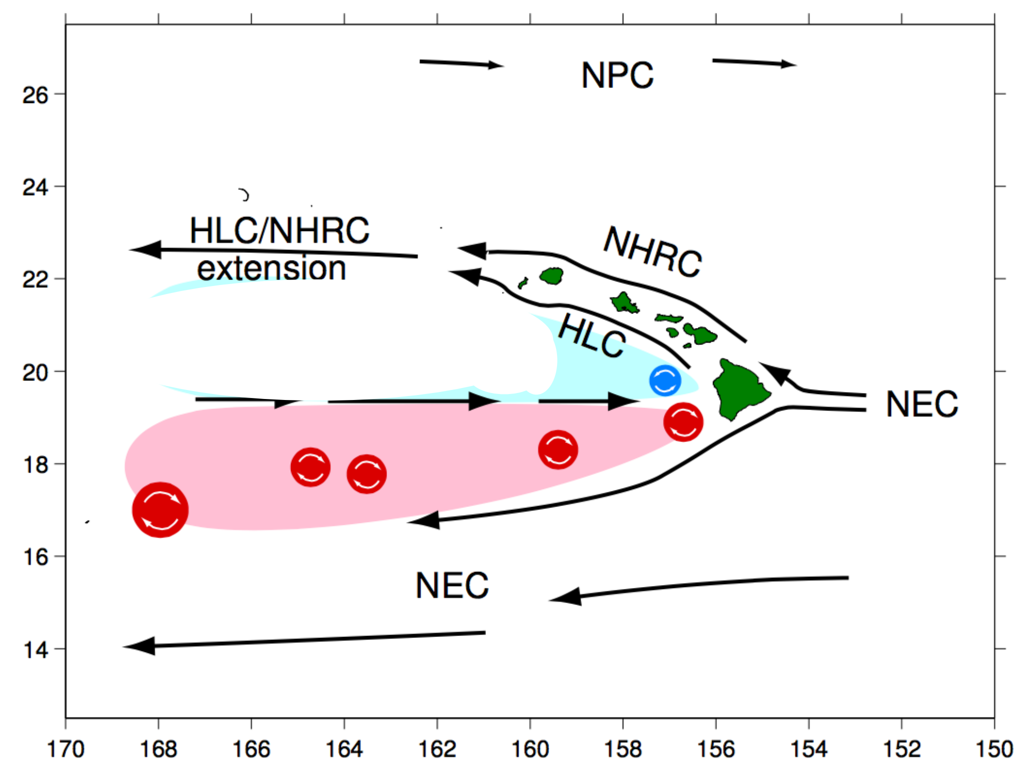
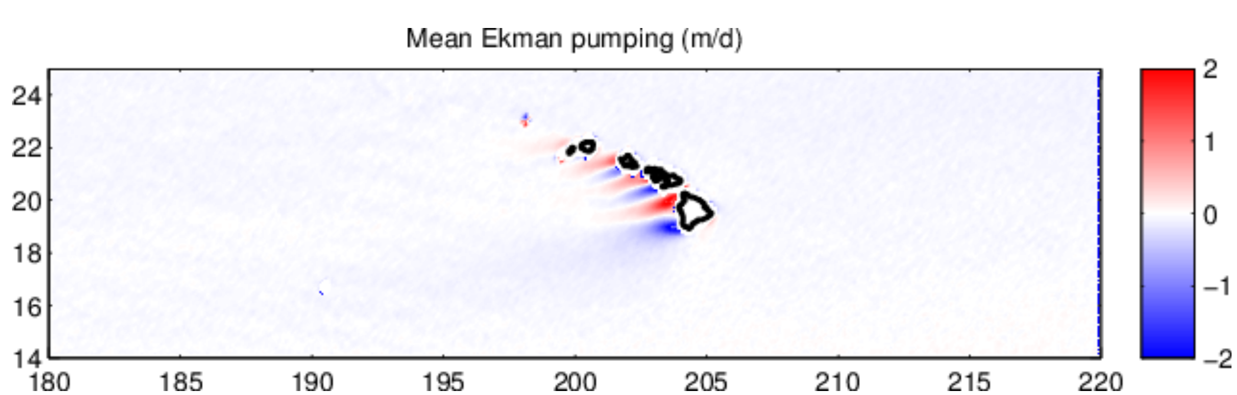
Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
Introduction



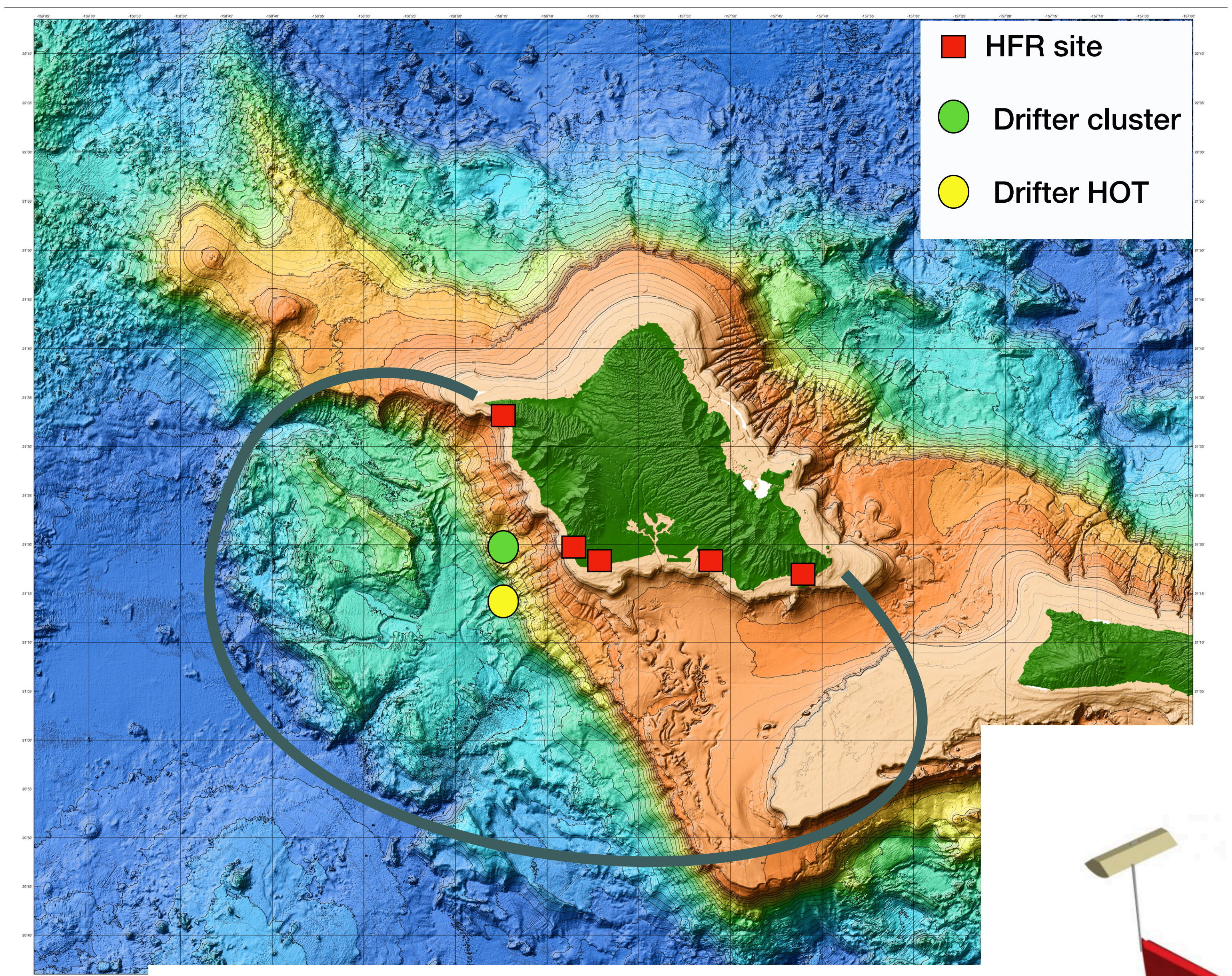
A schematic of the flow in the lee of the Hawaiian Islands. Modified from Lumpkin (1998) to reflect reduced cyclonic sector extent.

- Anticyclones were observed in lee of island of Hawaii creating a well defined sector.
- Are they also consistent in lee of other islands? There have been previous observations of individual anticyclones off Oahu (Chavanne et al, 2010).
- Is the cyclonic sector visible in other islands?

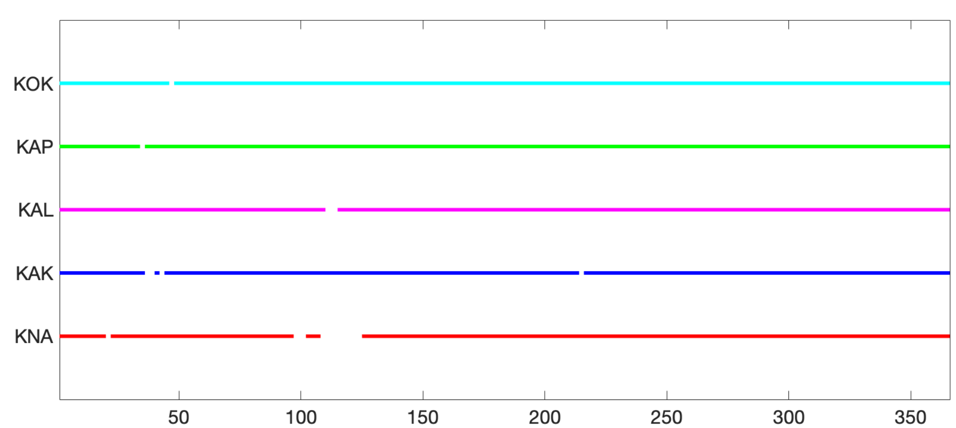


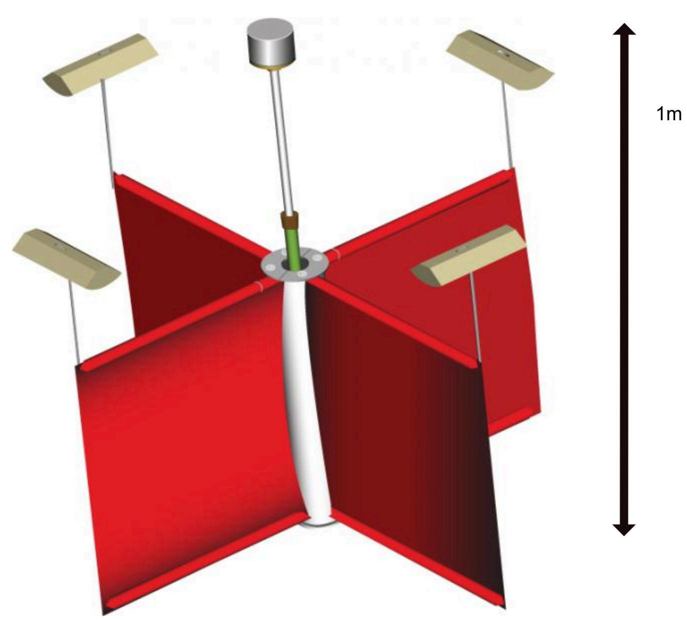
- Wind stress curl dipoles and the resultant Ekman pumping are visible off both Oahu and Maui.
- What does the island lee look like in this region? HFR availability on Oahu made looking into this possible.

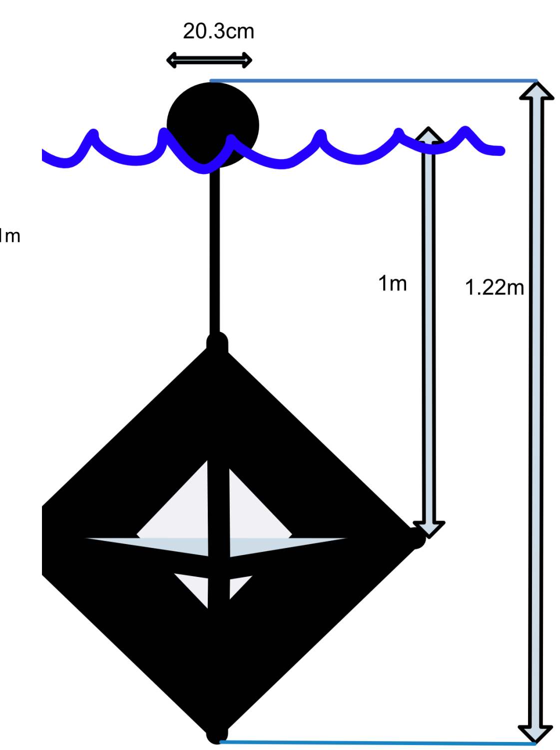
Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
Methods



- 5 High Frequency Radar sites covering south and west coasts of Oahu.
- 75 CODE style drifters
- 9 Microstar style drifters
- Repeated deployments at Station Kahe
- One Cluster deployment of 9 each.







Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
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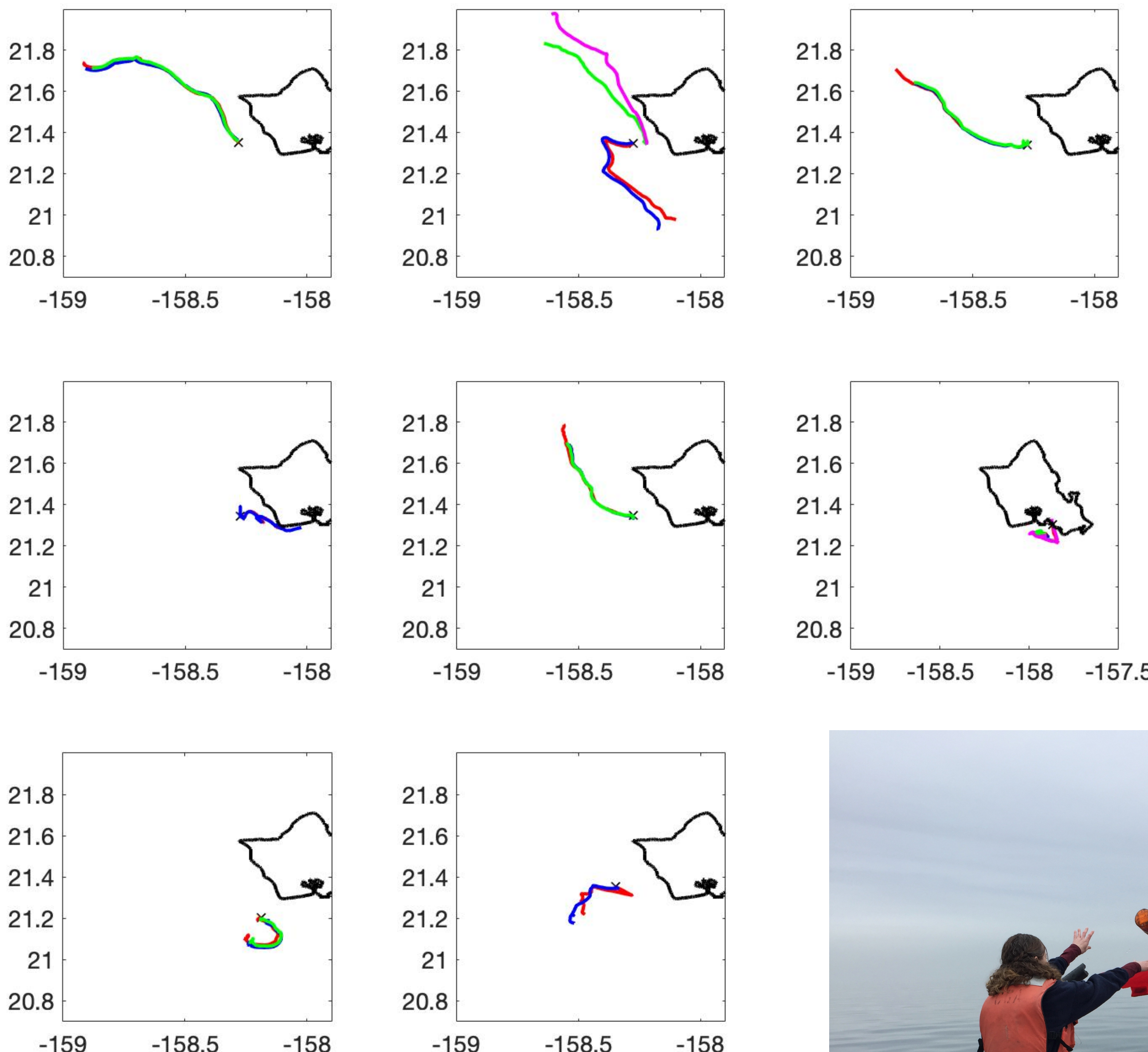
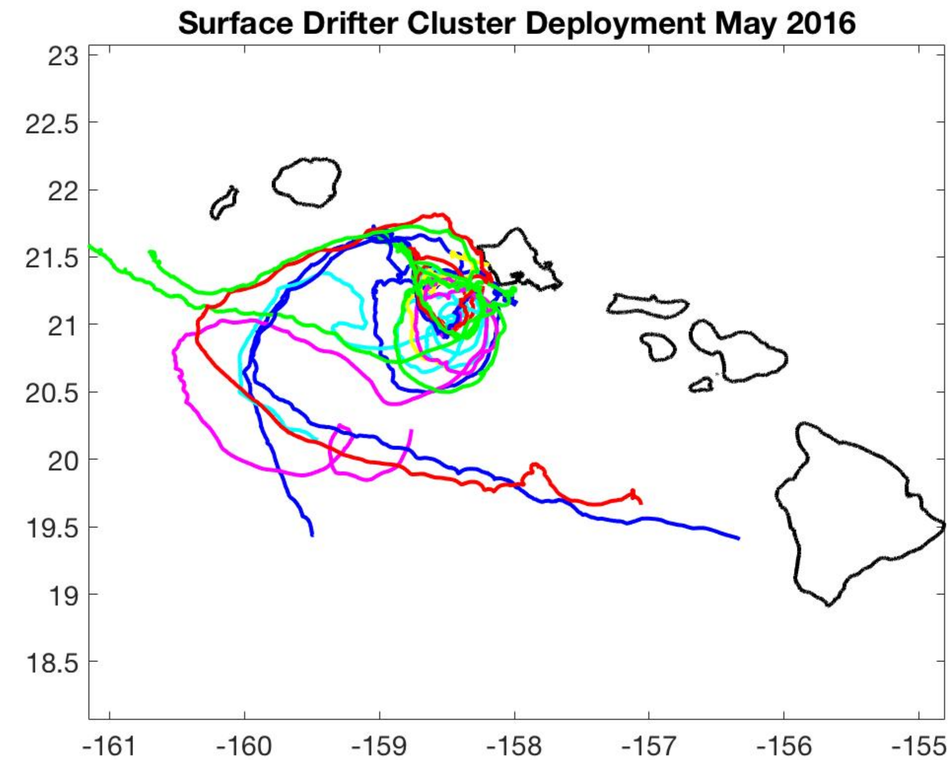
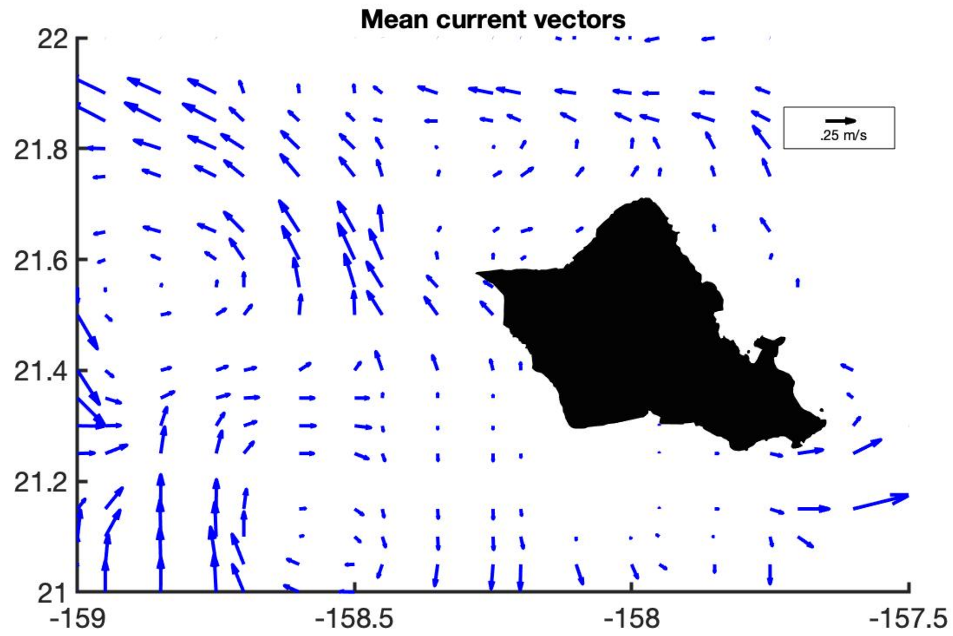
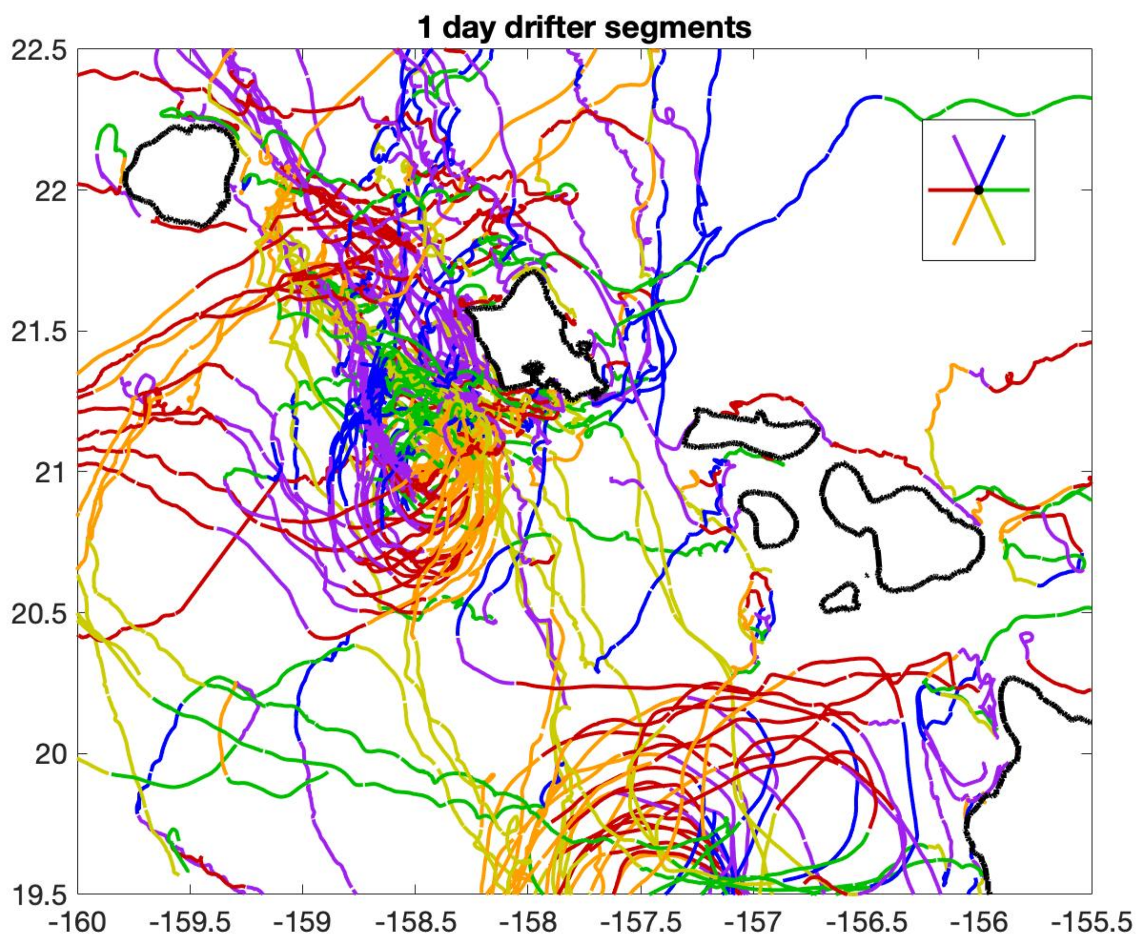




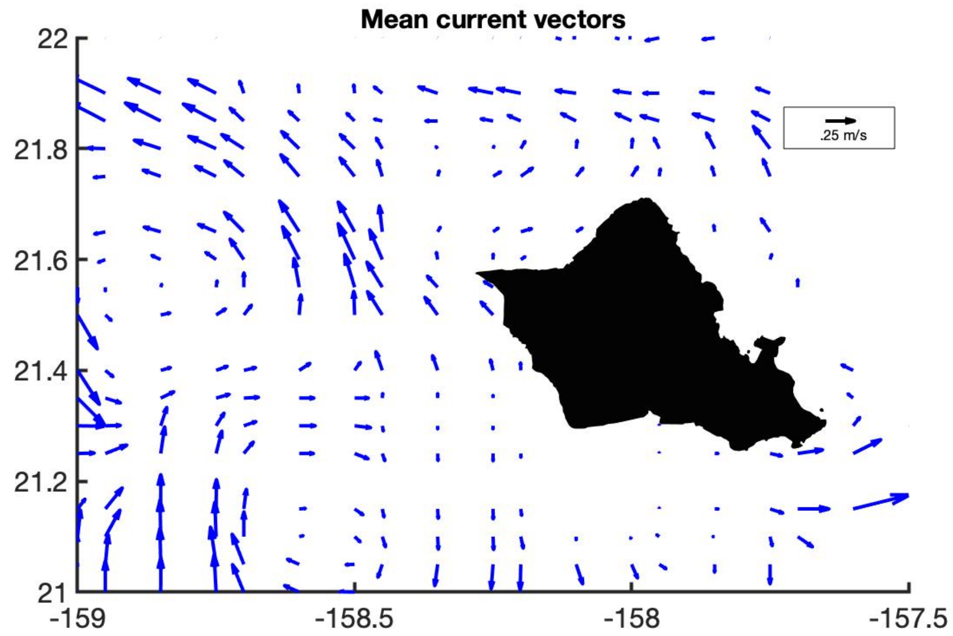
Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
Drifter statistics

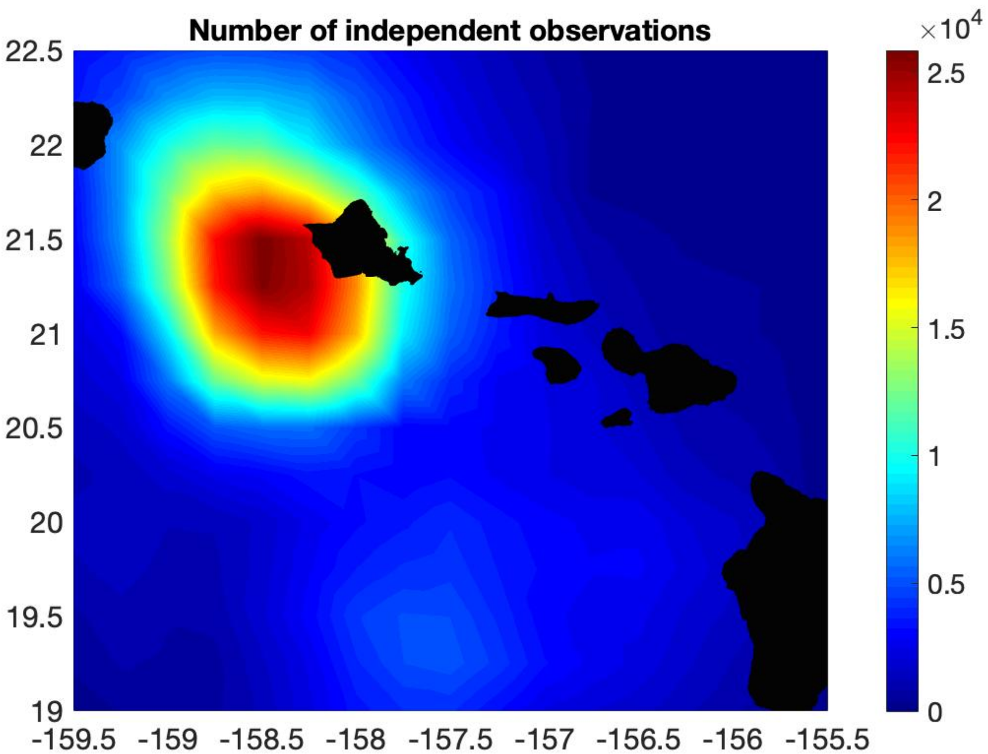


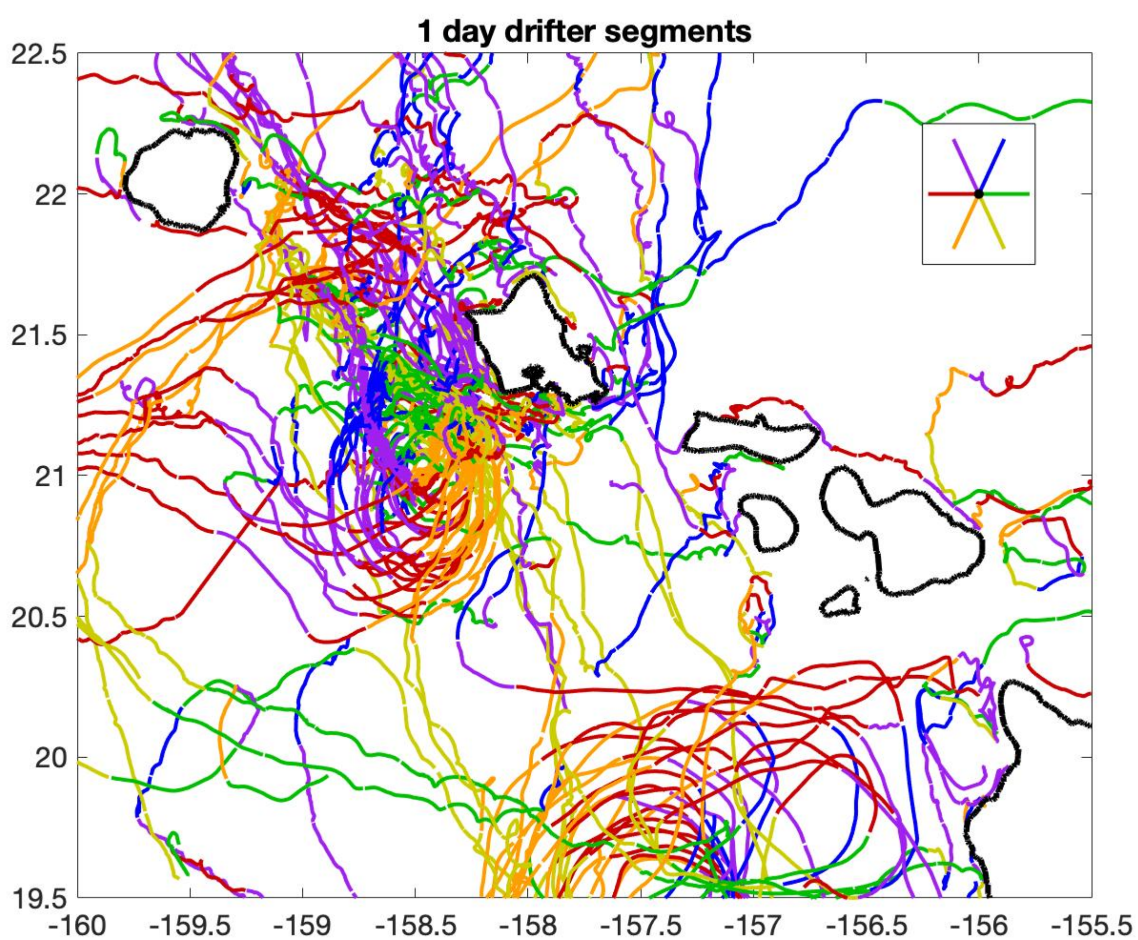


- Strong flow to the NW in between Oahu and Kauai.
- Counter-rotating flow pattern observable in mean currents from drifters
- Only eastward drifter movement through the Kaiwi channel.
- Variable and weaker flow off south shores of Oahu.
- For comparison, AC rotation visible in HFR monthly means in January and November. Cy rotation visible in March and September

Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
Drifter statistics







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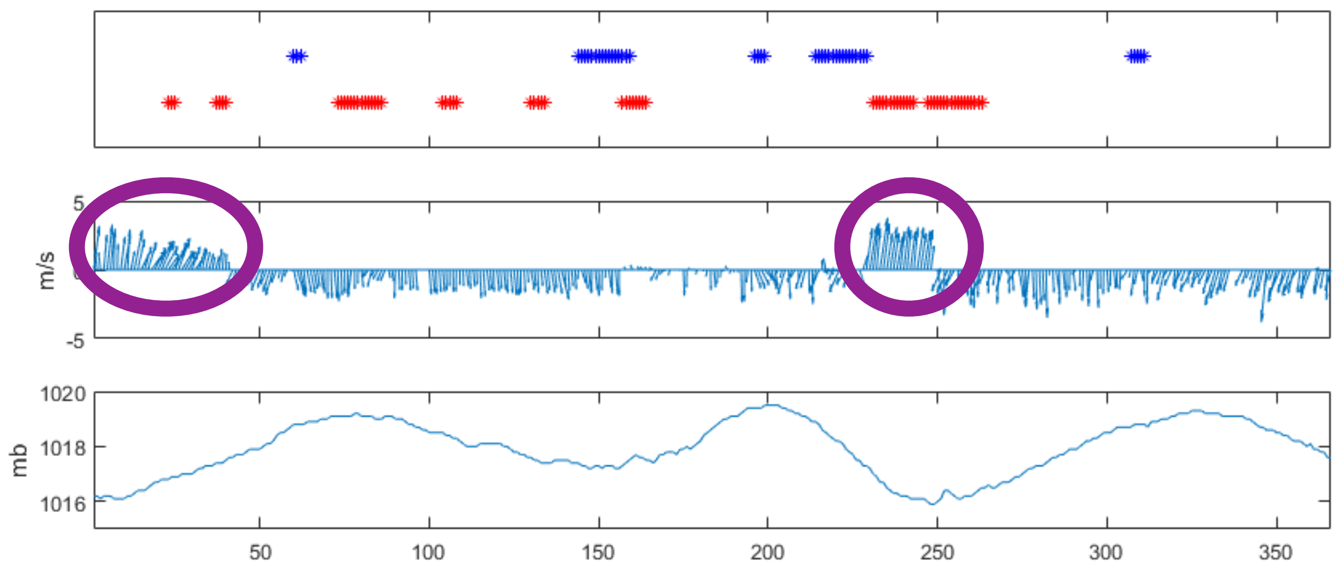
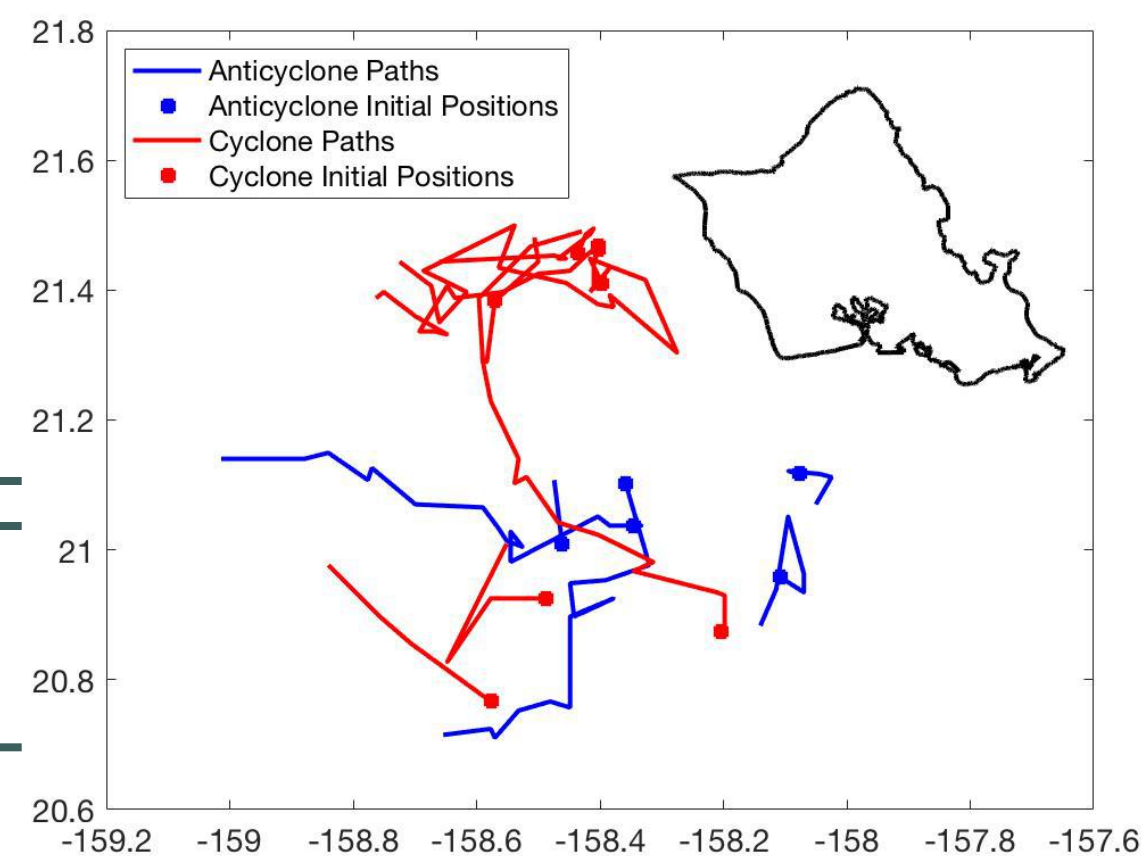
Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics HFR statistics



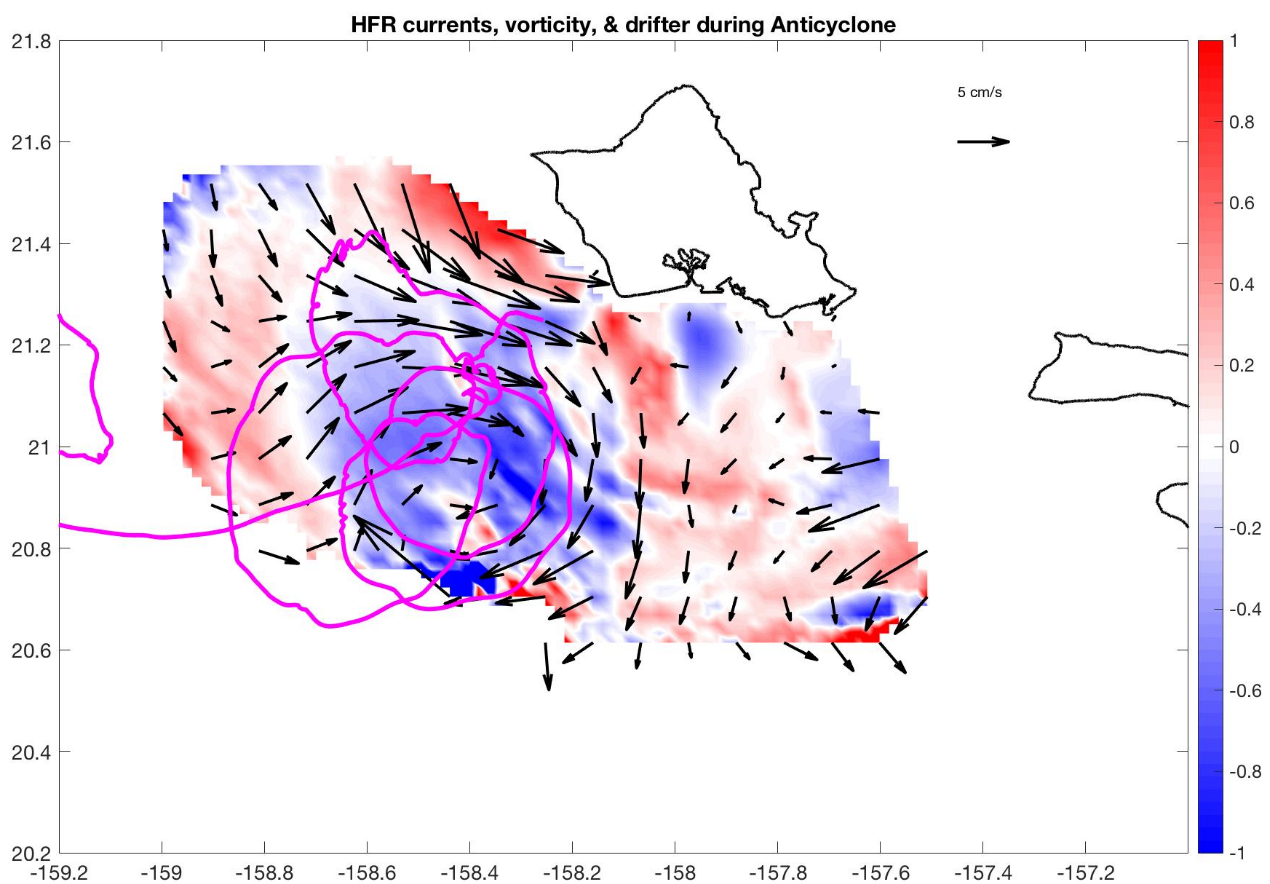
Top: Anticyclones (blue) and cyclones (red) in 2016. Middle: Daily mean wind direction at HNL. Bottom: Daily mean SLP.

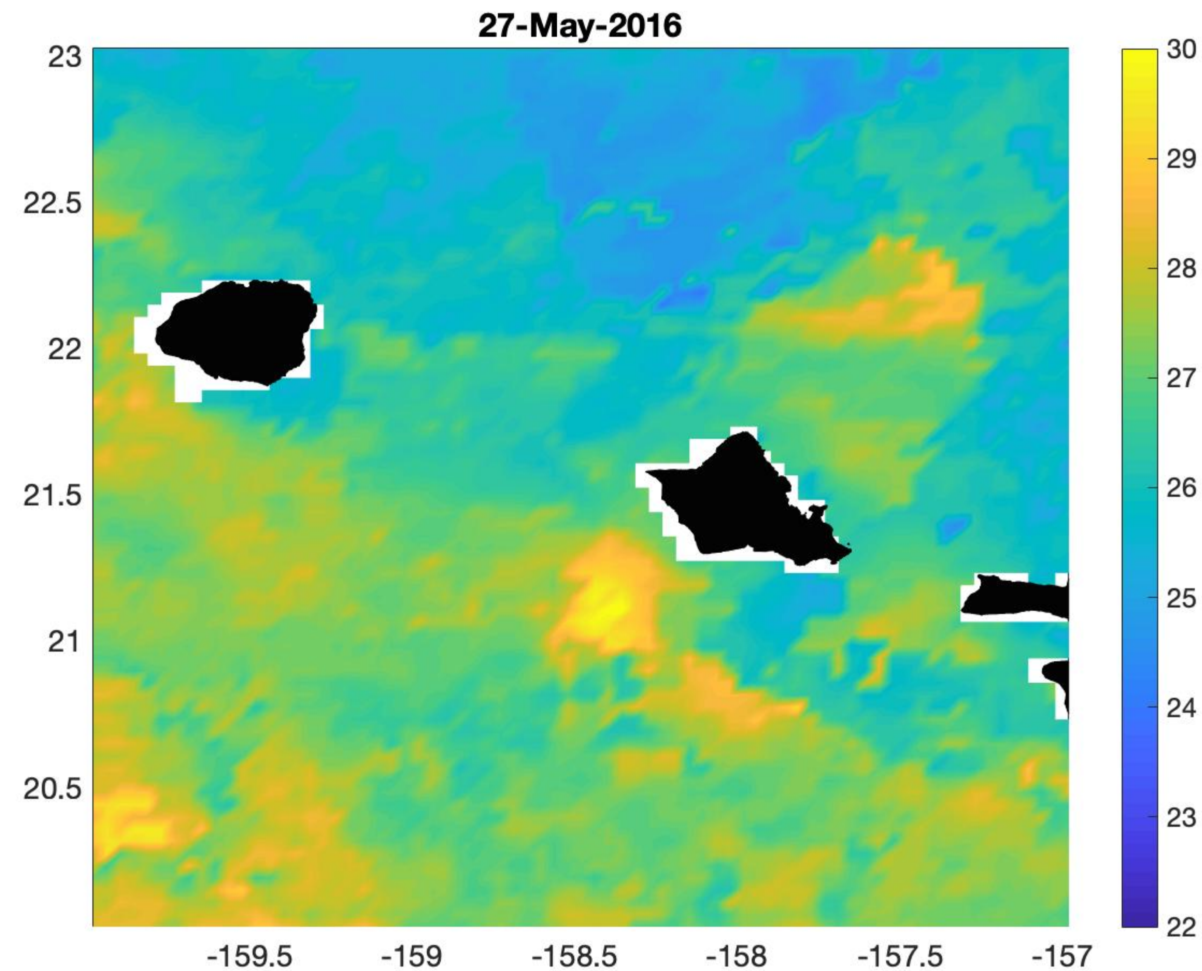
- 5 Anticyclones, 8 cyclones visible in HFR data in 2016.
- With exception of two day overlap in end of August, counter-rotating vortices not observed at same time.
- Two strong Kona wind events.
- No Anticyclones during Kona winds
- 3 cyclones during Kona winds.

Anticyclone	*DOB*	*Duration(days)*	*Radius(km)*	*Vorticity*	*Period*
1	29FEB	3	47	$-0.50f$	5.6
2	23MAY	16	20	$-0.80f$	3.5
3	14JUL	4	32	$-0.59f$	4.7
4	01AUG	16	21	$-0.96f$	2.8
5	02NOV	5	21	$-0.44f$	6.2
Cyclone	*DOB*	*Duration(days)*	*Radius(km)*	*Vorticity*	*Period*
1	23JAN	3	27	$0.52f$	5.1
2	06FEB	4	31	$0.80f$	3.4
3	13MAR	14	22	$1.1f$	2.5
4	13APR	4	47	$0.47f$	6
5	09MAY	5	36	$1.3f$	2.1
6	05JUN	8	36	$0.5f$	5
7	18AUG	13	42	$1.4f$	2
8	03SEP	17	37	$1.3f$	2.1



Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
Anticyclone case study





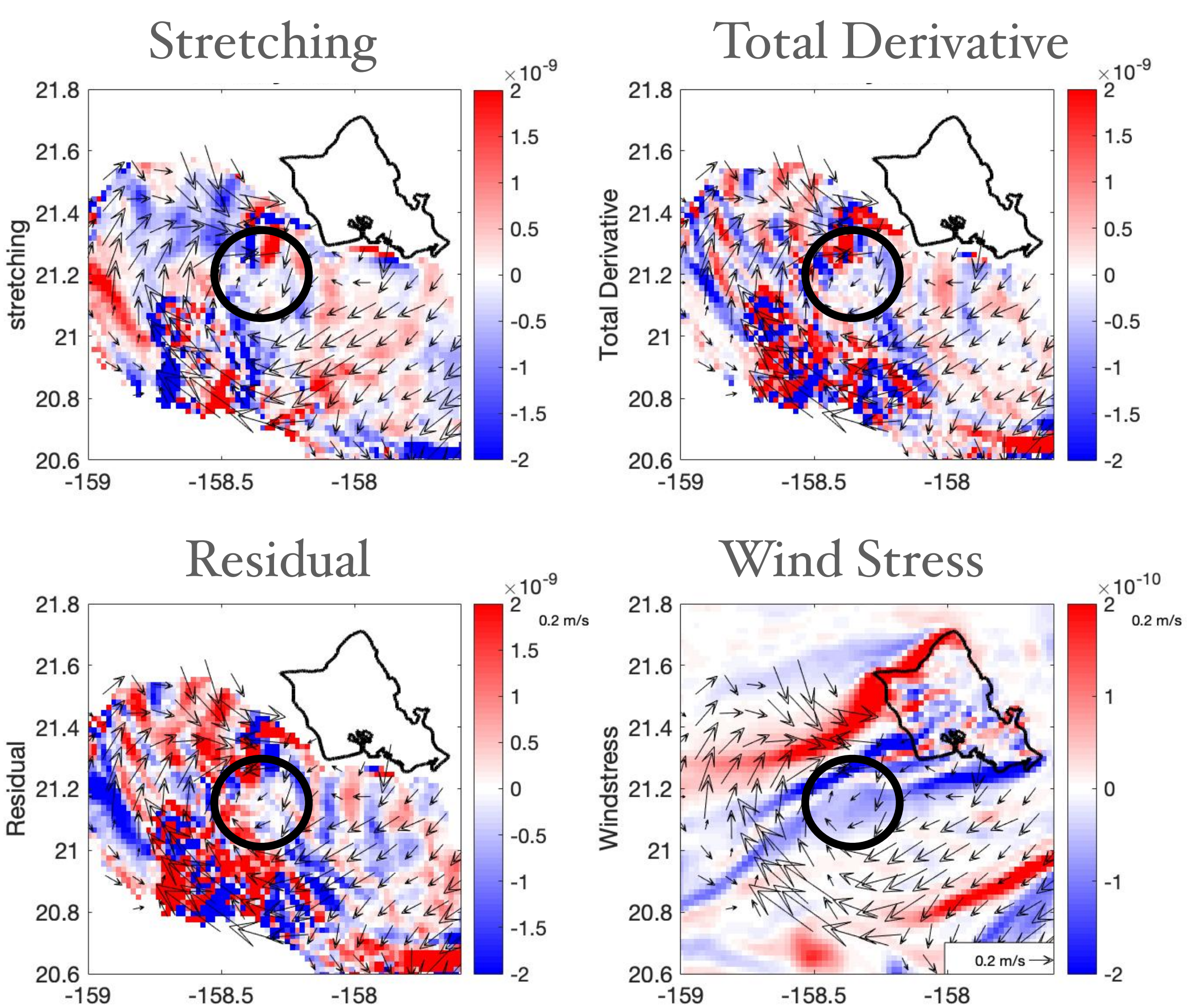
- Formed on May 23rd, 2016. Visible in HFR data for 16 days.
- Mean radius 20km
- Minimum vorticity -0.8f
- Period, 3.5 days
- SST signature 3 degree Celsius above background SST.

Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
Vorticity Balance

$$\overbrace{\frac{D\zeta}{Dt}}^{a} = \overbrace{\frac{\partial\zeta}{\partial t}}^{b} + \overbrace{(\mathbf{u}\frac{\partial\zeta}{\partial x} + \mathbf{v}\frac{\partial\zeta}{\partial y})}^{c} = -\overbrace{\mathbf{v}\beta}^{d} + \overbrace{(\zeta + f)(\frac{\partial\mathbf{u}}{\partial x} + \frac{\partial\mathbf{v}}{\partial y})}^{e} + \overbrace{(\frac{\partial F^y}{\partial x} - \frac{\partial F^x}{\partial y})}^{f}$$

- a = The total derivative of vorticity
- b = local rate of change in vorticity
- c= advective rate of change of vorticity.
- d= Beta, changes in vorticity due to changes in latitude
- e= vortex stretching
- f= Residual, wind or ocean stresses.

Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
Vorticity Balance

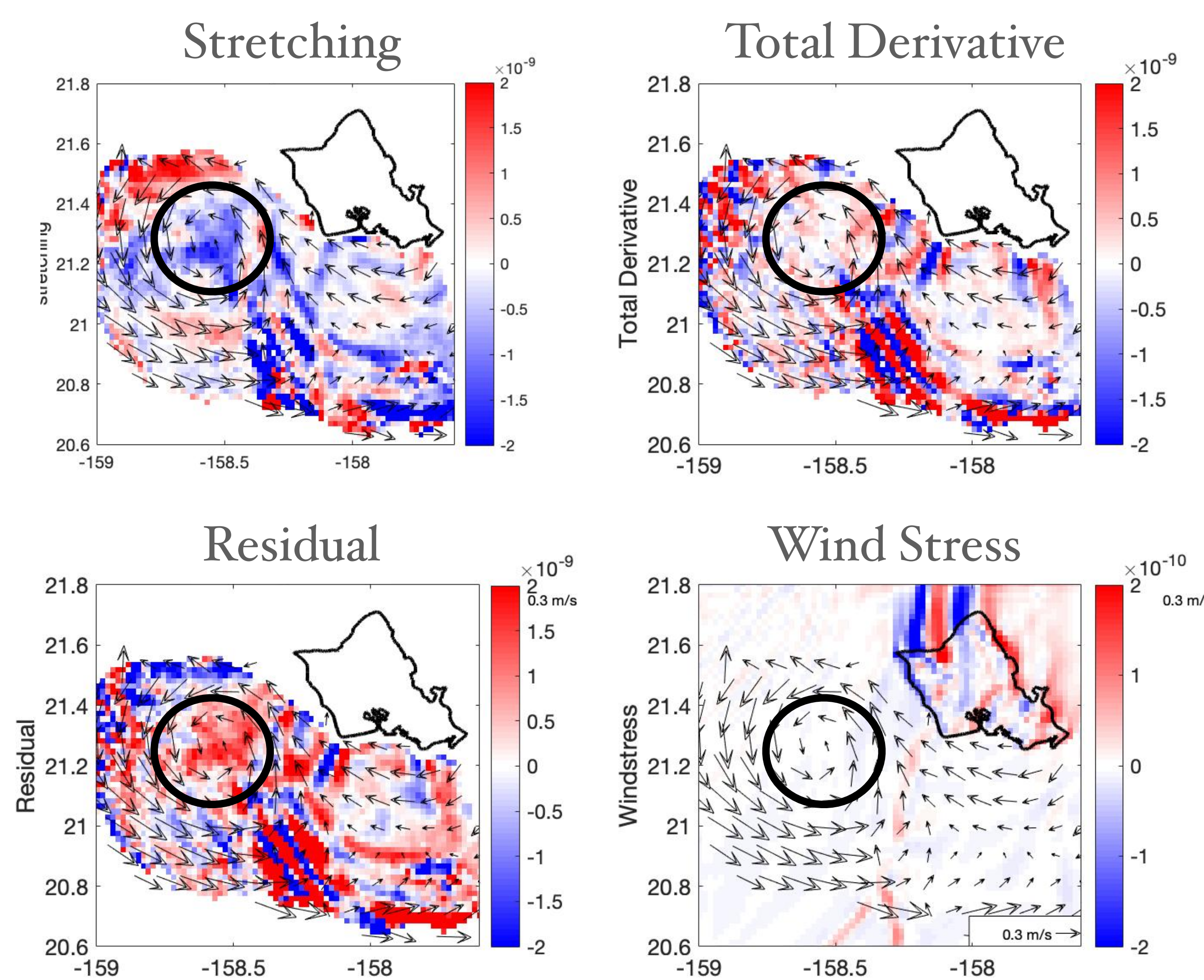


Anticyclone in Trade winds

- There is negative vorticity from wind stress curl in center of anticyclone
- Weak positive stretching, weak negative TD, weak positive residual.
- Could be wind induced but requires additional vorticity from ocean stress

- There is negligible vorticity input from wind stress
- Stretching and residual terms nearly balance out.
- Not wind induced

Cyclone in Kona winds



Drifter Statistics in West Oahu Coastal Waters: Island Lee Dynamics
Conclusions

* Oahu’s lee broken down into cyclonic sector, quiet zone, and anticyclonic sector.
* Sector’s small and confined to near island lee. Vortices nearly stationary with low (3-4 cm/s) propagation speeds and residence time in HFR are up to 16 days.
* Only cyclones formed in Kona wind events, when lee side shifted to Northern edge of island. These cyclones were not wind induced.
* There was wind stress forcing for anticyclones, but not enough to close vorticity budget.
* Anticyclones identifiable in SST, with core temperatures in excess of 3°C warmer than the surrounding waters.

Unanswered Questions…

* In addition to the flow past south point, there are few observations of the flow volume and direction through the channels separating islands.
* The extended Kona winds created a reversal in the wind stress forcing off Oahu and during this time cyclones were formed in the normally anticyclonic sector. What is creating these cyclones?

Acknowledgements

Questions?

Questions?