Basin Scales

Sea Surface Temperature Anomalies (SSTA): Blob + ENSO

Sea Surface Height Anomalies (SSHA): Blob(?) + **ENSO**

Coastal Scales

NDBC records for strength, timing, spatial variations in T

Coastal Tide Gauges

Altimetry (Strub)

Wind forcing

Other Cases?

Effects of Stratification (Kurapov)

Many of the figures that follow were taken from the NANOOS Climatology app, reachable from http://nvs.nanoos.org. Thanks to the NANOOS DMAC group, including Craig Risien, Jonathan Allan, Troy Tanner, with contributions from Emilio Mayorga, Jan Newton, Charles Seaton, Amy Sprenger, and Rachel Wold.

Basin-Scale View of SST Anomalies, 2013-2015

SST Anomaly, Basin, 2013

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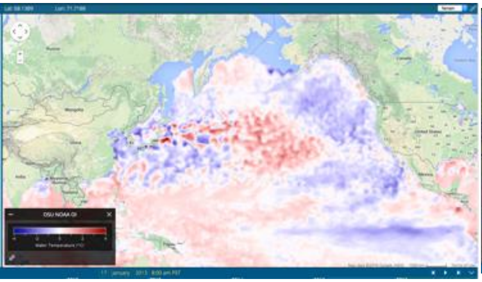

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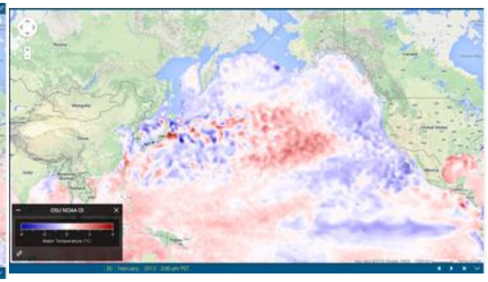

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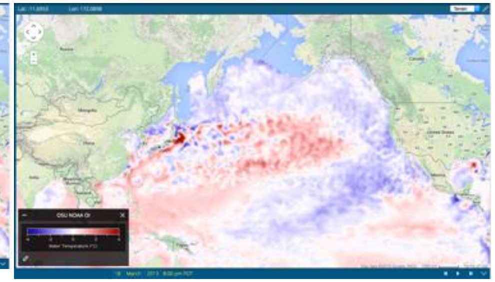

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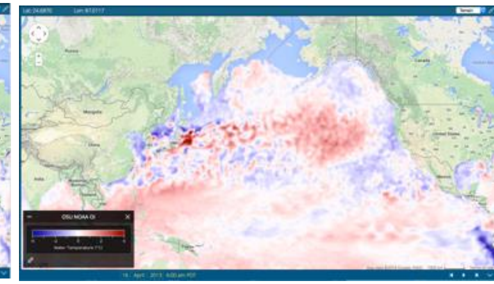

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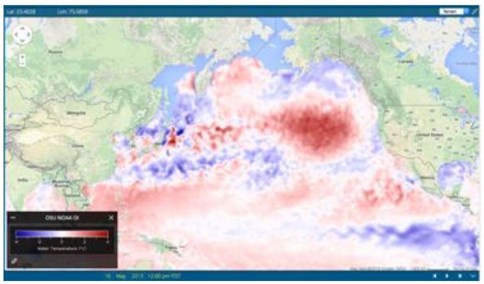

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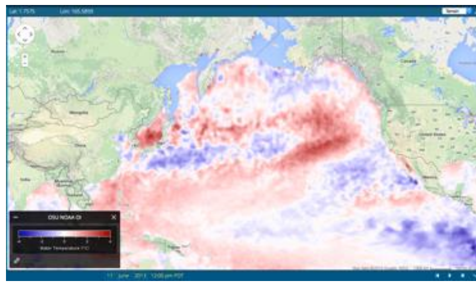

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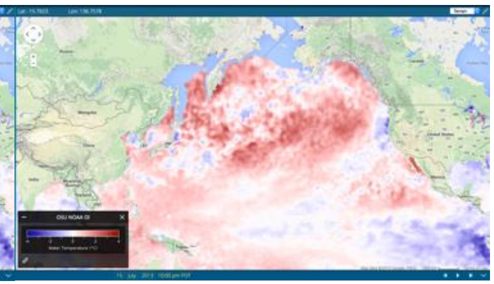

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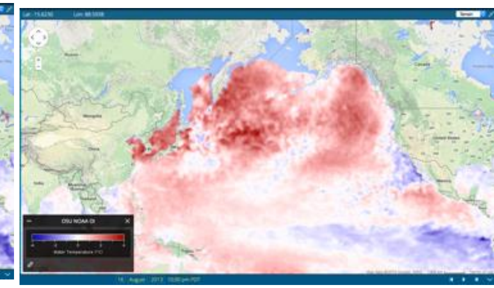

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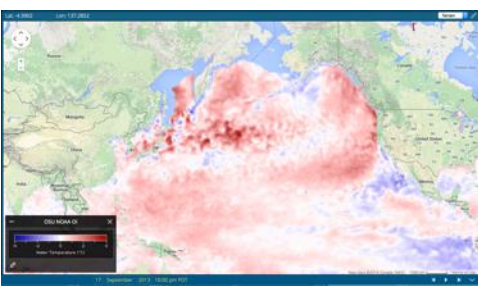

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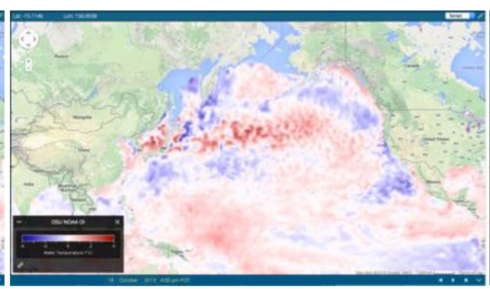

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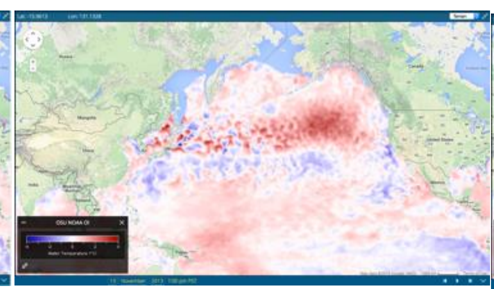

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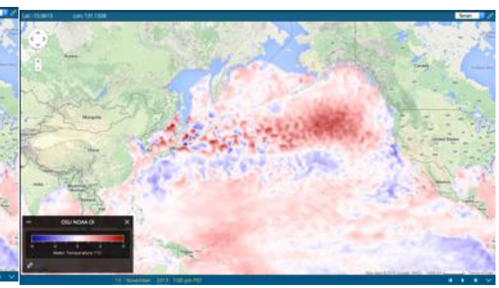

SST Anomaly, Basin, 2014

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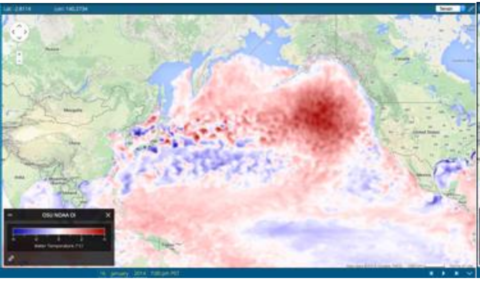

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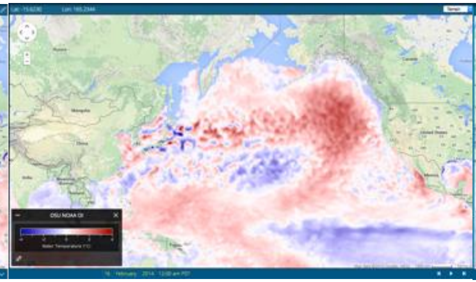

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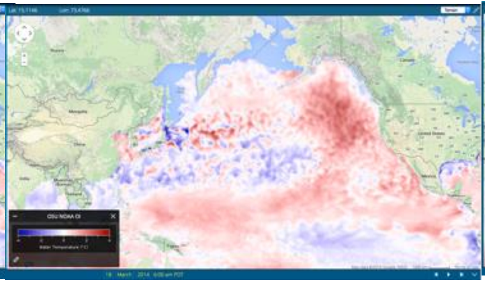

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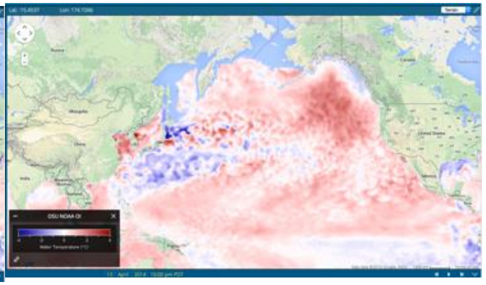

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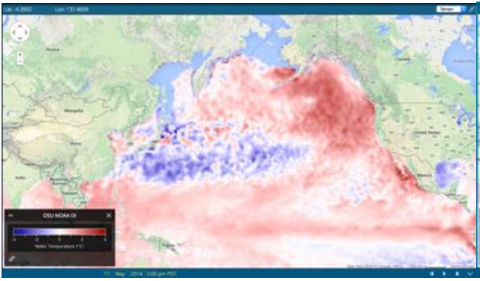

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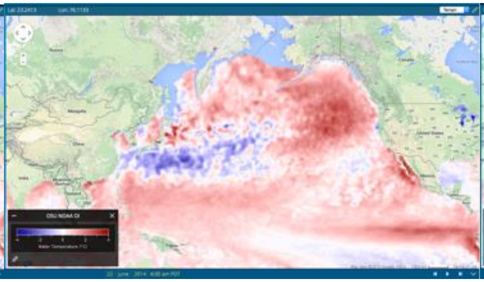

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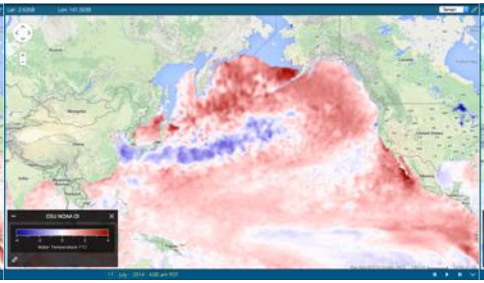

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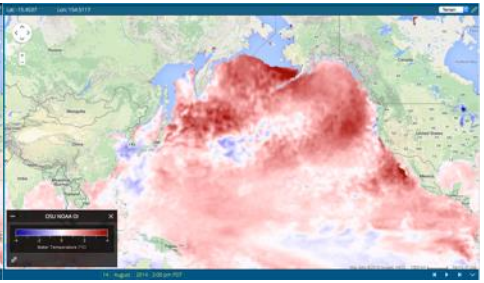

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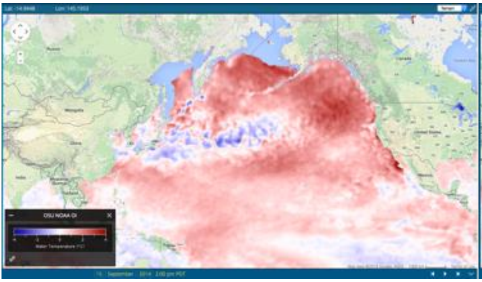

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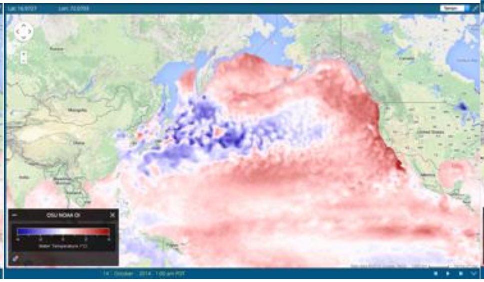

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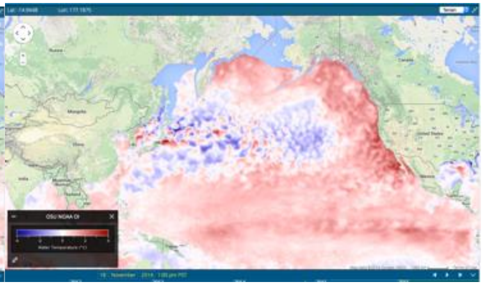

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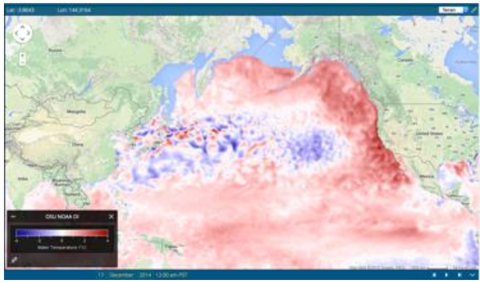

SST Anomaly, Basin, 2015

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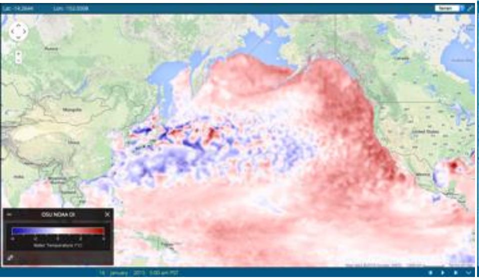

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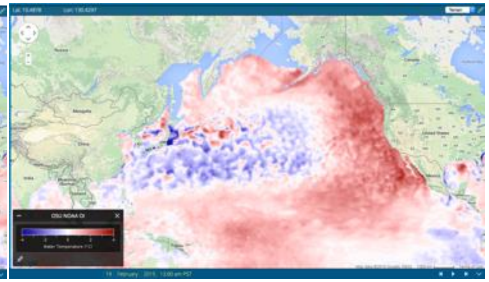

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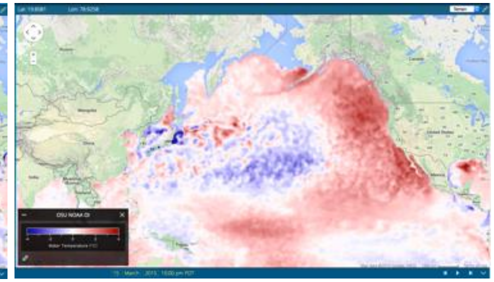

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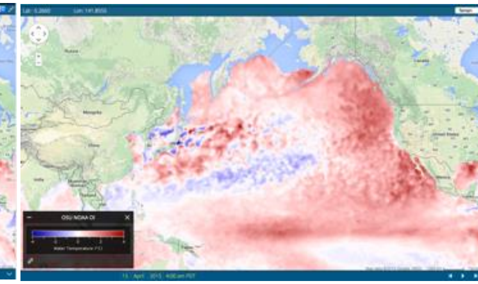

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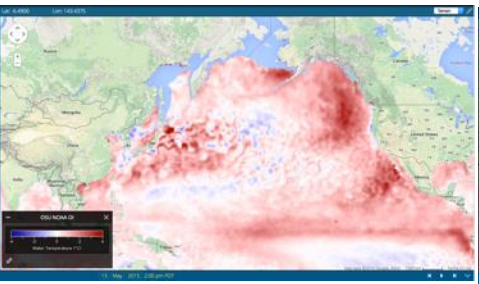

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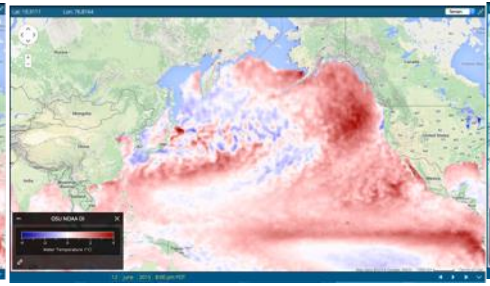

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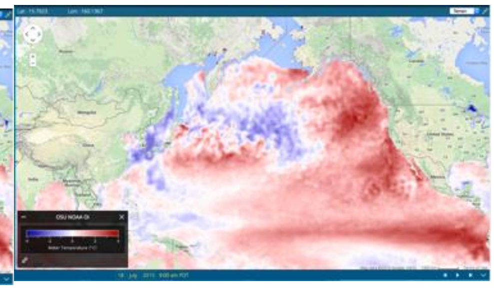

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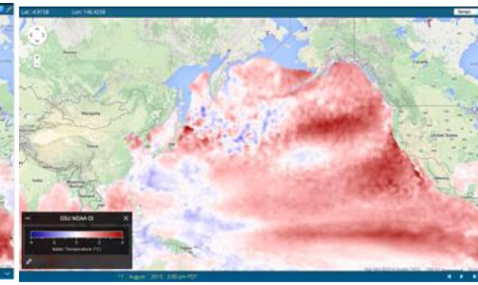

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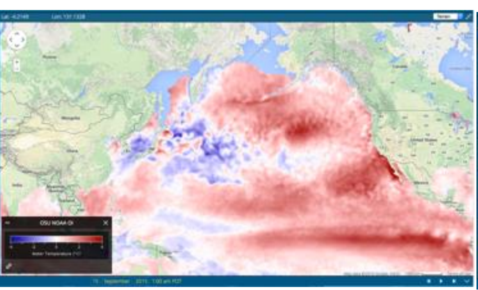

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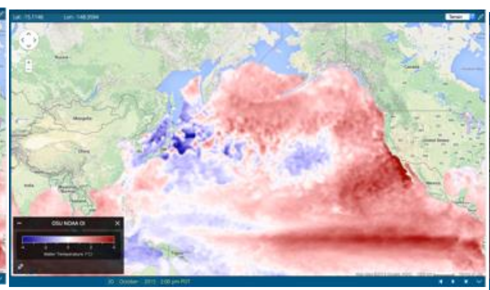

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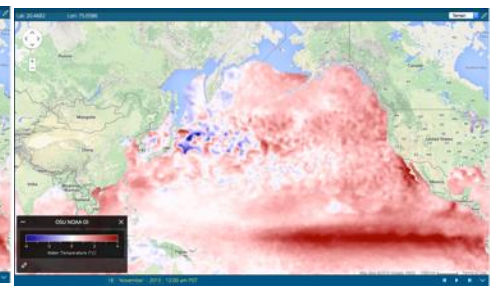


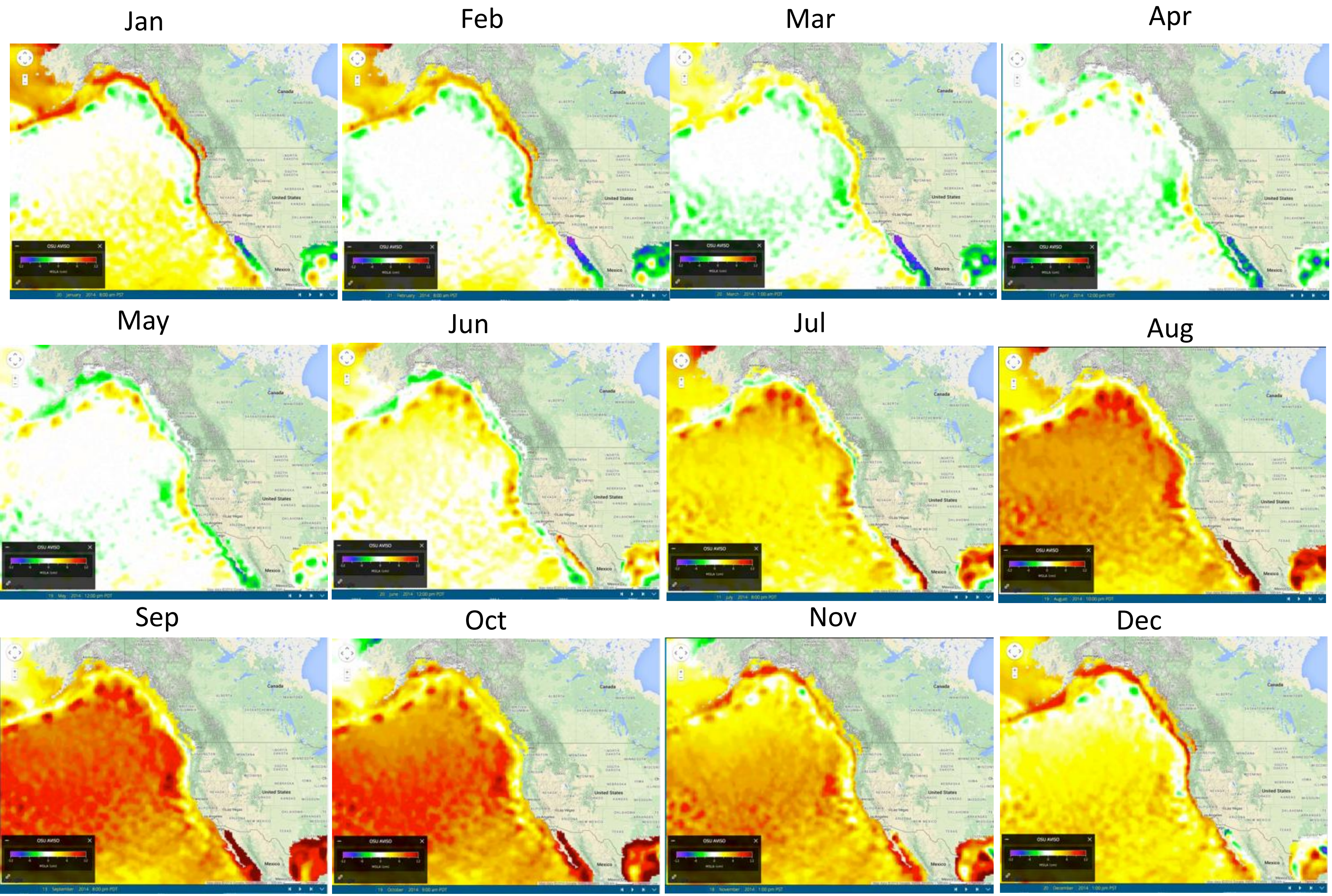
2015-12

Large-scale development of the temperature anomalies (blob & ENSO)

anomaly from early 2013 intensifies in May-Aug, covers larger region
fades in fall 2013 but returns in Nov/Dec 2013
waxes in early 2014, moves closer to shore in spring
May-June 2014, ENSO warming in equatorial eastern Pac and up Baja
intensifies in PNW and subarctic NW Pac. Stronger along US West coast, but weak in central Cal
ENSO fades in summer, weak echo in fall 2014
Warm US West Coast in early 2015, spring warm waters intensify of PNW and soCal/Baja, through fall 2015
ENSO reappears in spring 2015, intensifies greatly over summer and fall

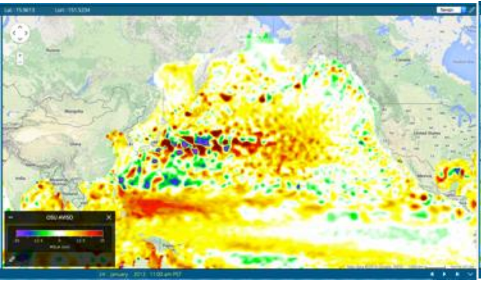
Basin-Scale View of SSH Anomalies, 2013-2015

SSH Seasonal Cycle, Aviso



SSH Anomaly, Basin, 2013

2013-01



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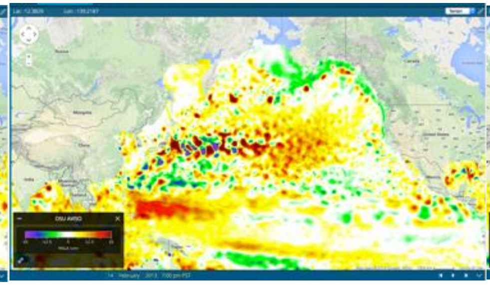

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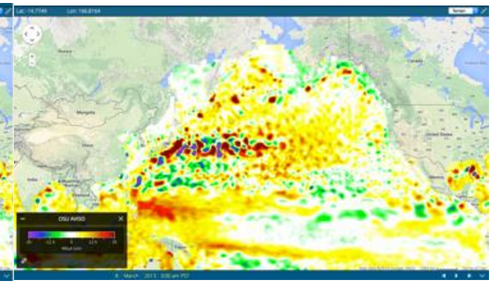

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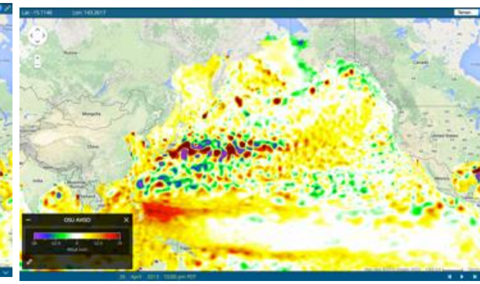

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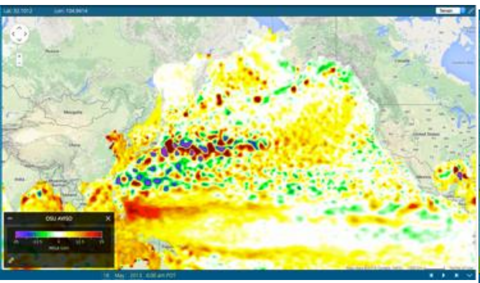

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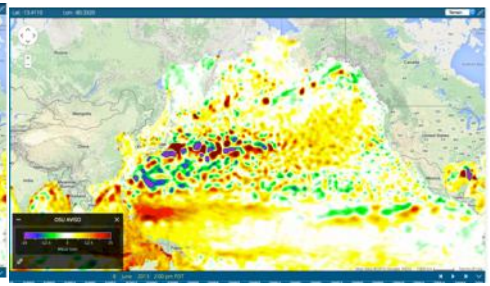

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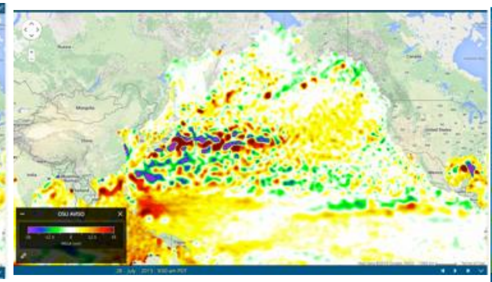

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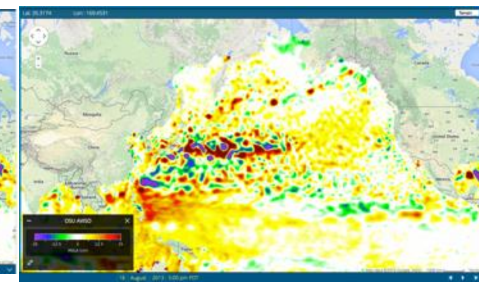

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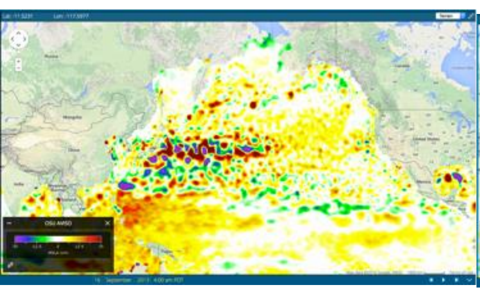

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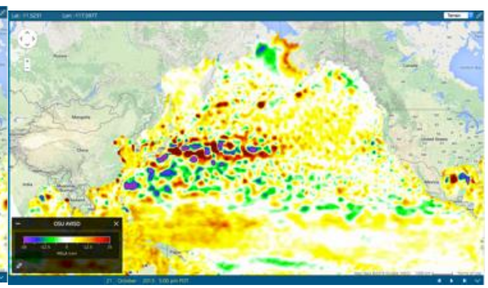

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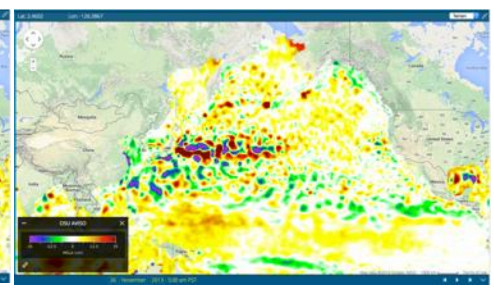

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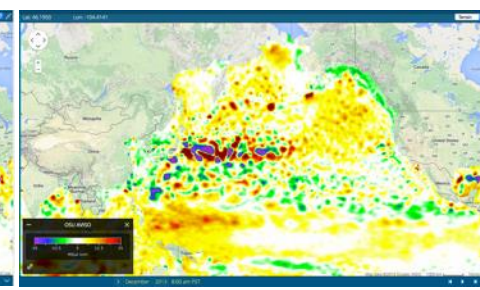

SSH Anomaly, Basin, 2014

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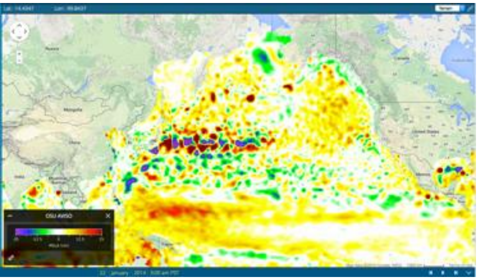

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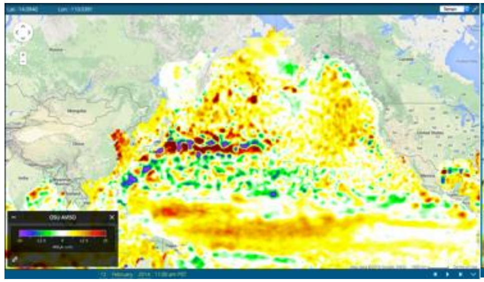

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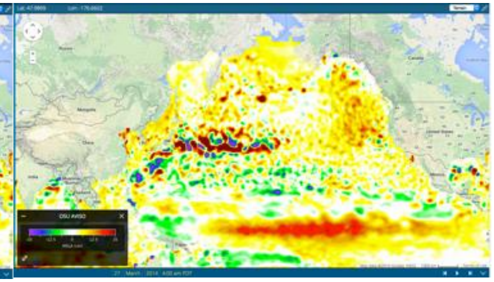

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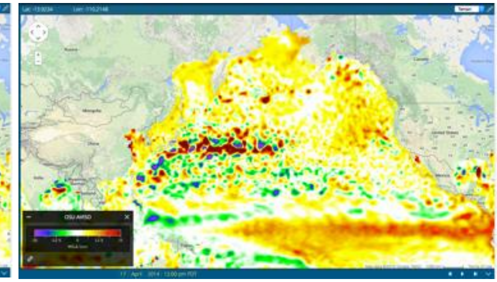

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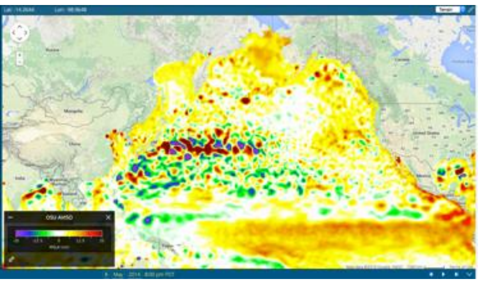

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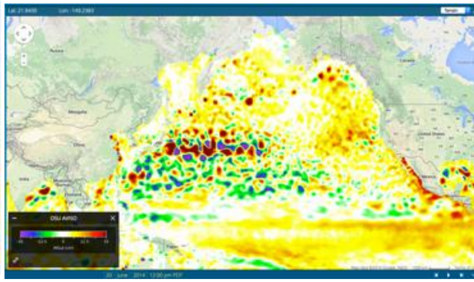

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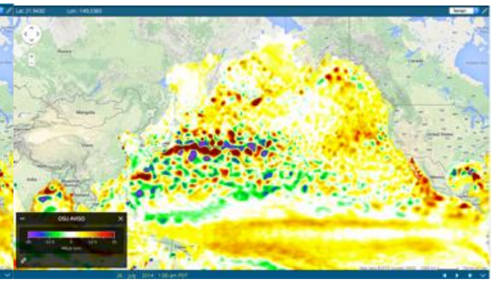

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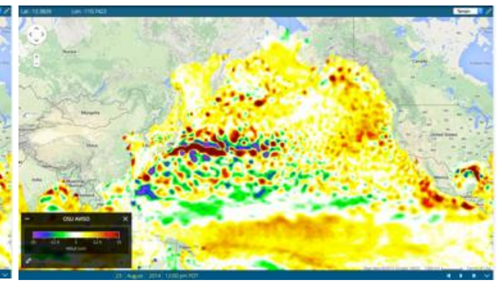

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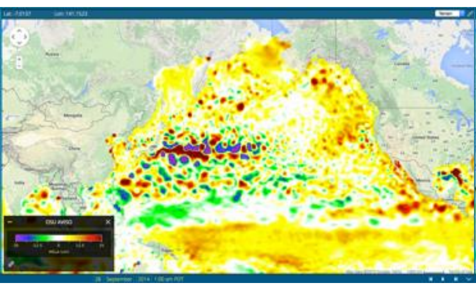

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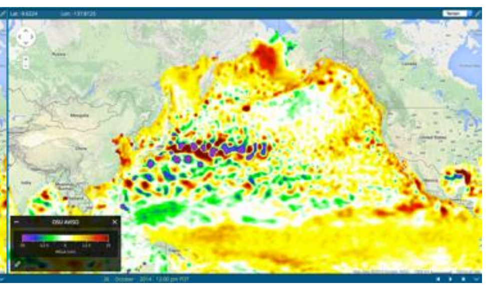

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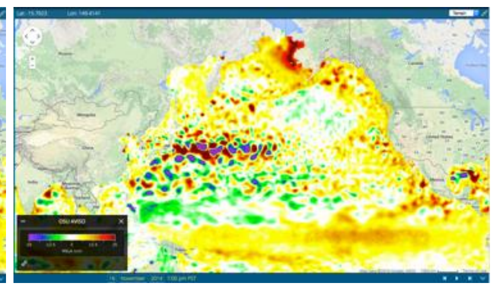

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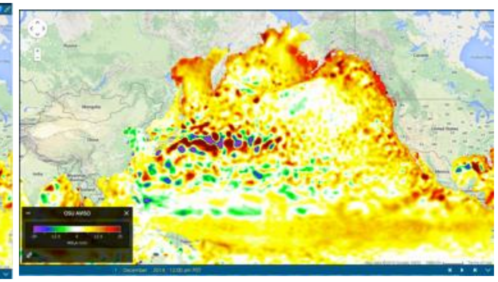

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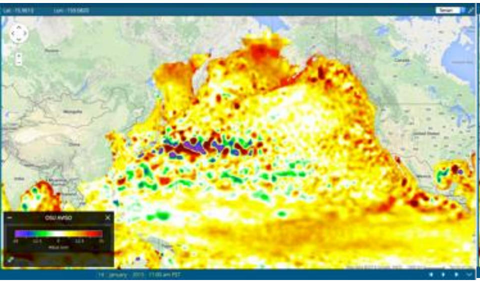

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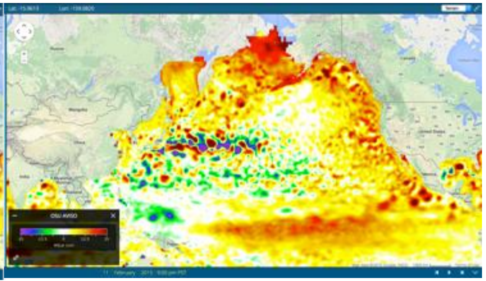

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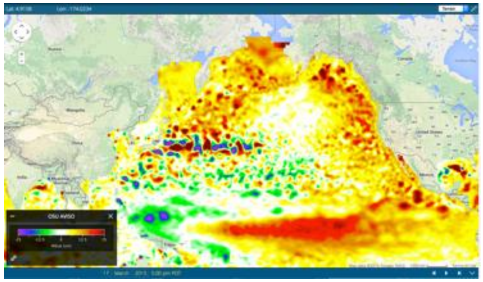

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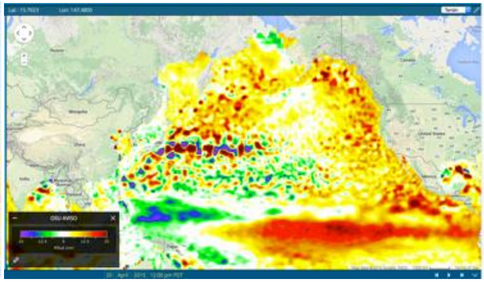

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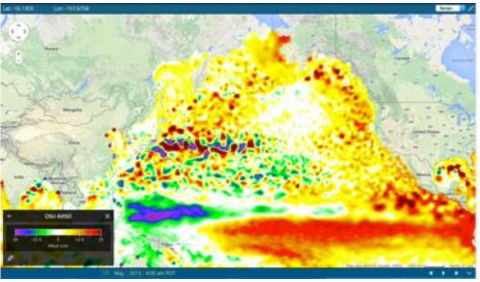

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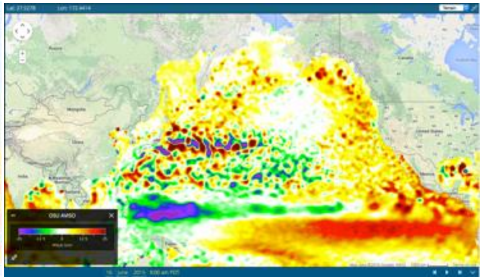

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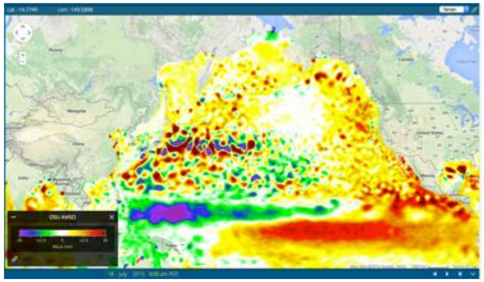

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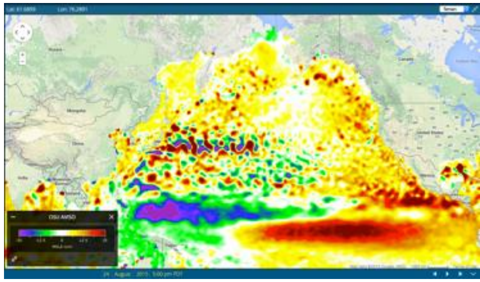

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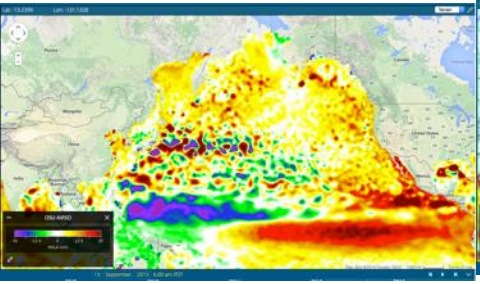

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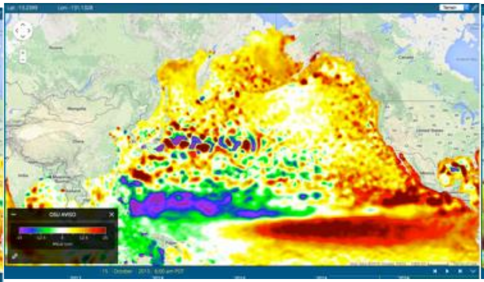
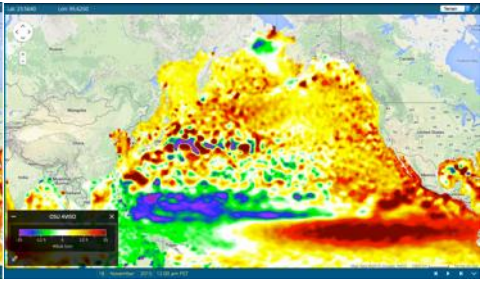


2015-11



2015-12

Large-Scale SSH:

Where's the Blob?

not strong in SSH?

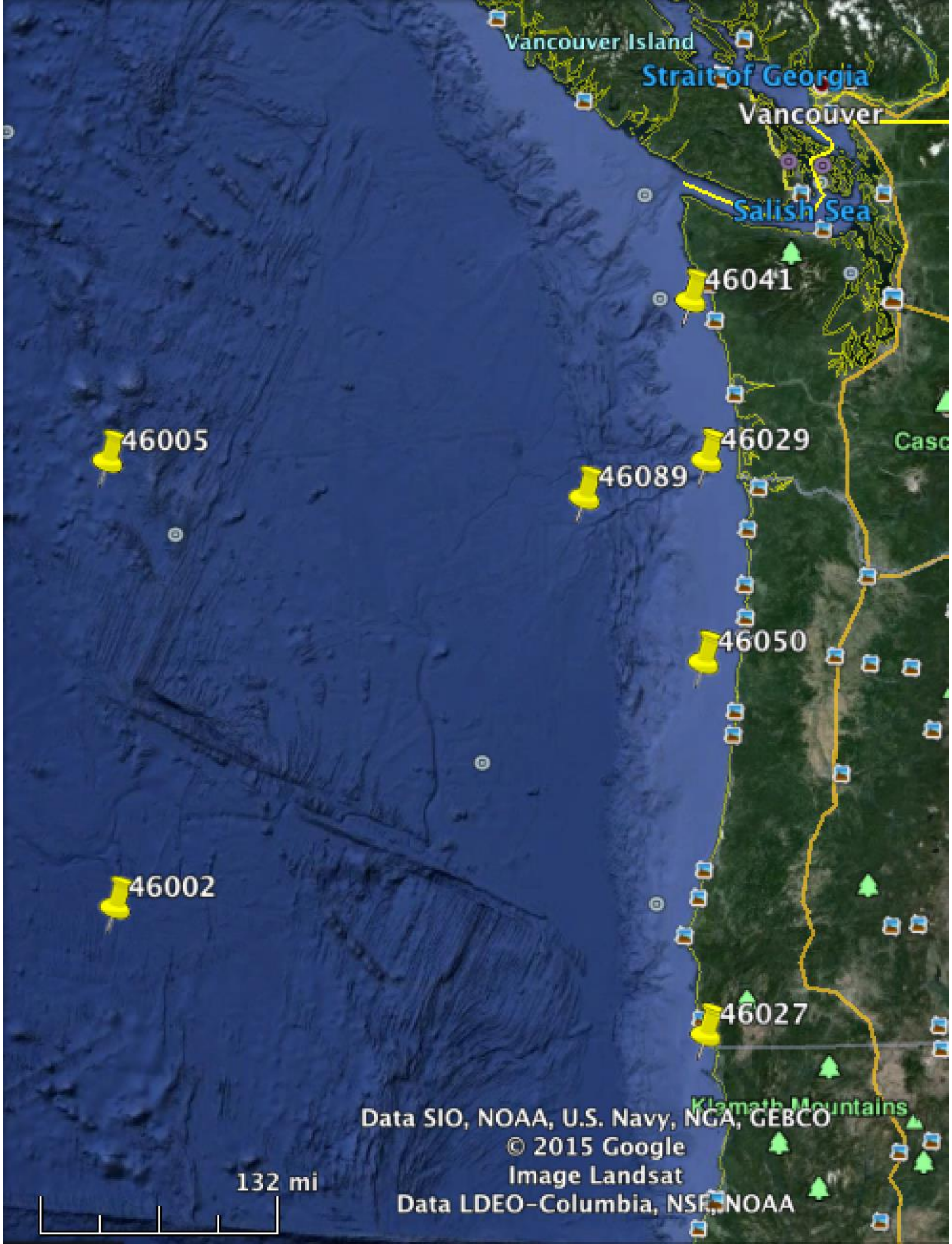
anomaly shallow?

ENSO appears more clearly earlier in 2014 in SSH than in SST

Coastal Scales

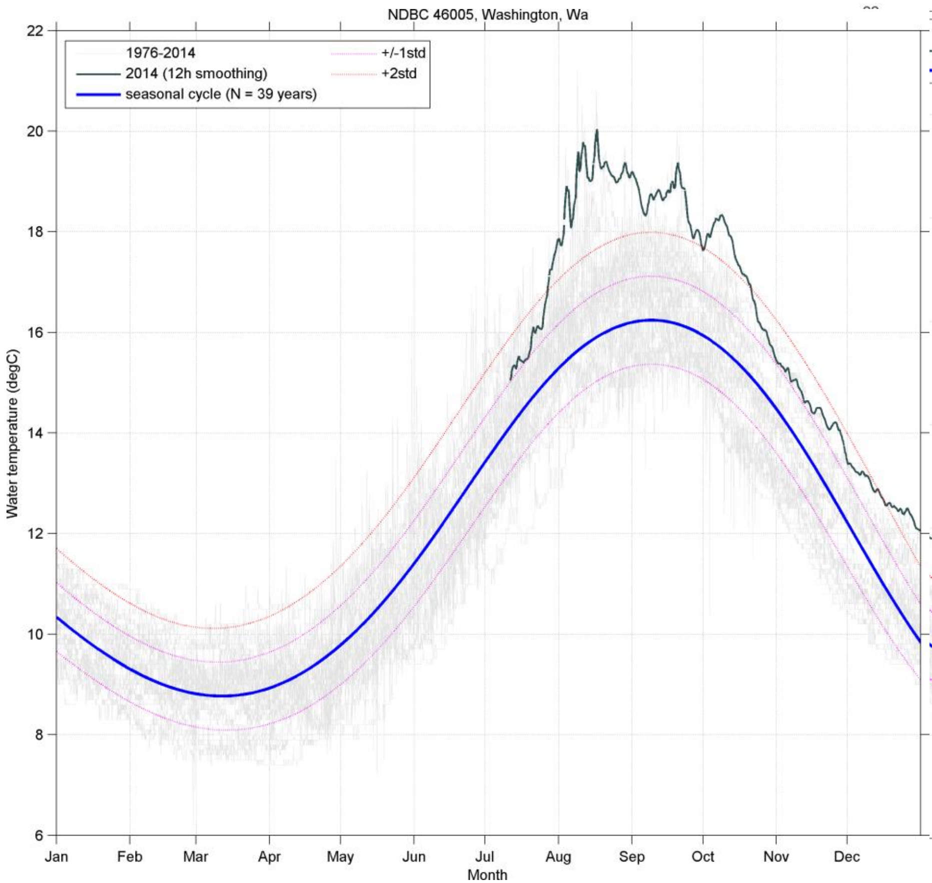
Coastal Scales: Buoy SSTs

NDBC buoys in OR/WA with Sea Surface Temperature (SST)

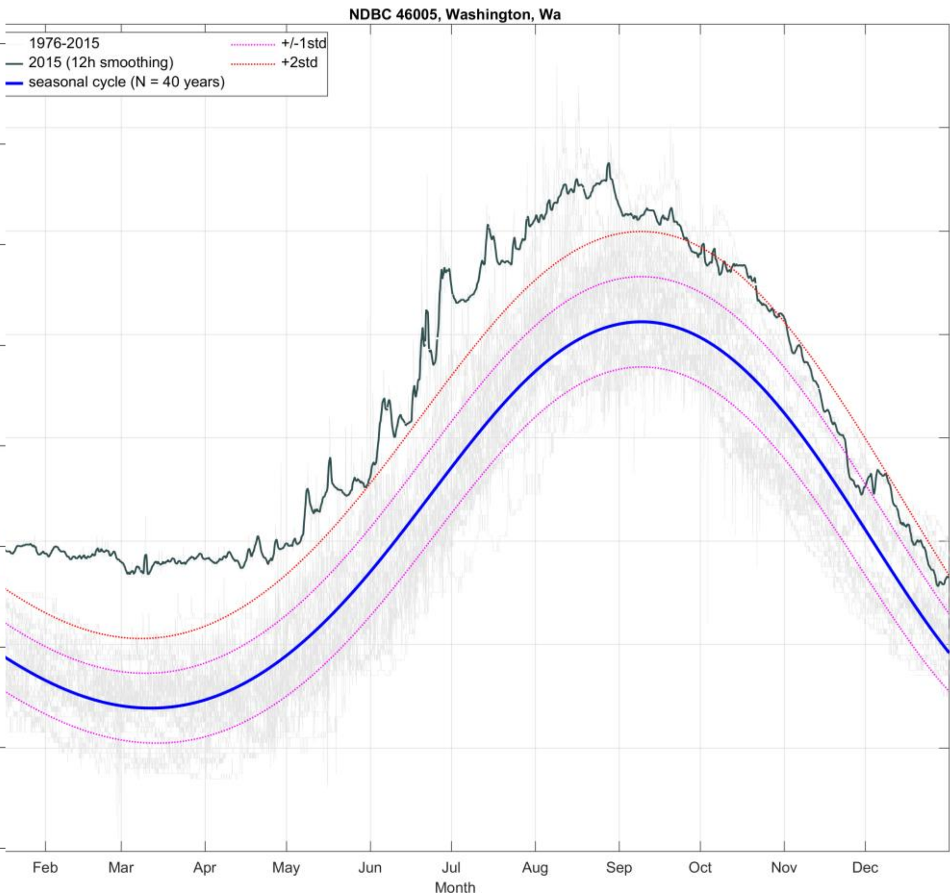


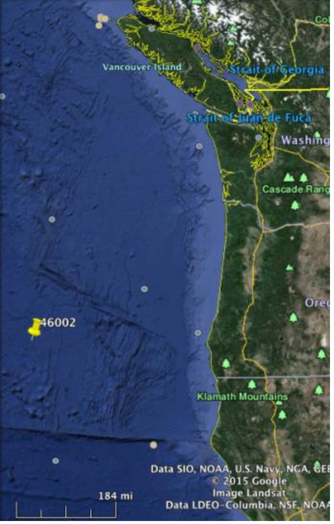
SST, 2014-2015, Buoy 46005 (far offshore WA)
300 nm west of Aberdeen, WA (45.96N, 131.00 W)

2014



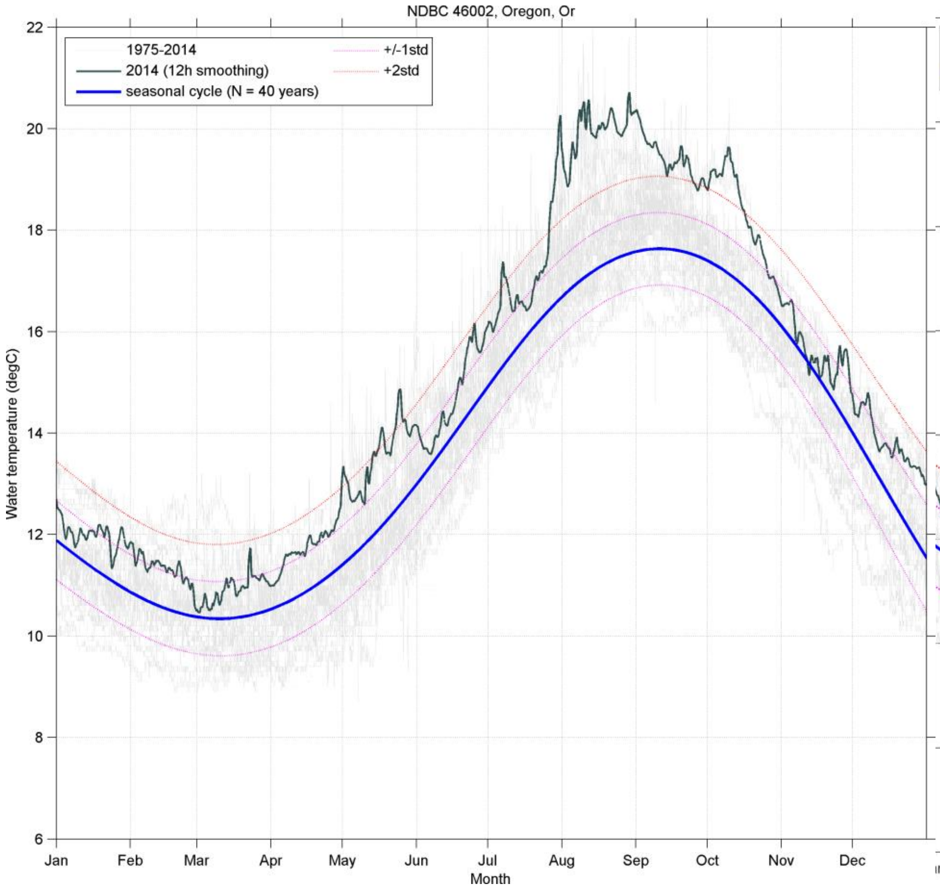
2015



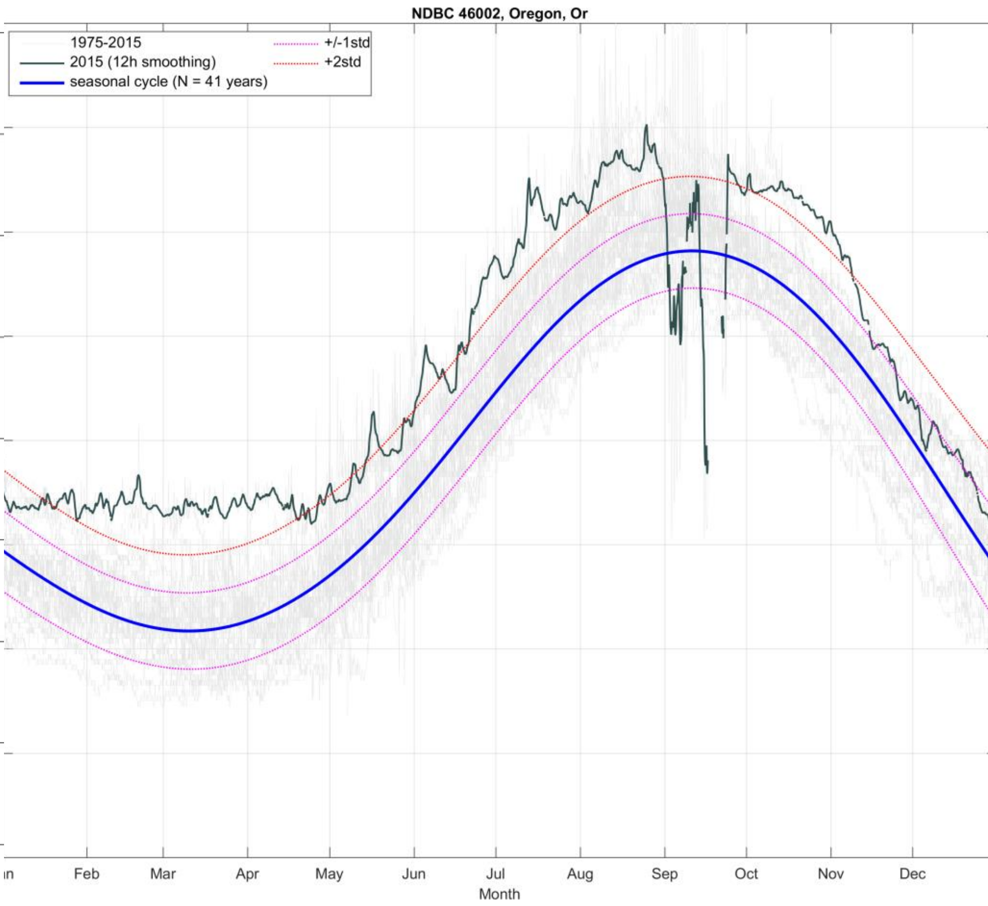


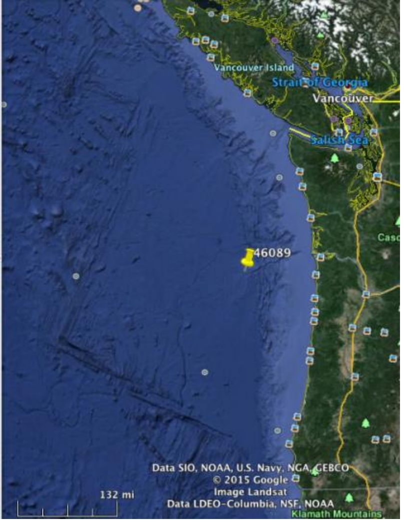
SST, 2014-2015, Buoy 46002, (far offshore OR)
275 nm west of Coos Bay, OR (42.6N, 130.5 W)

2014



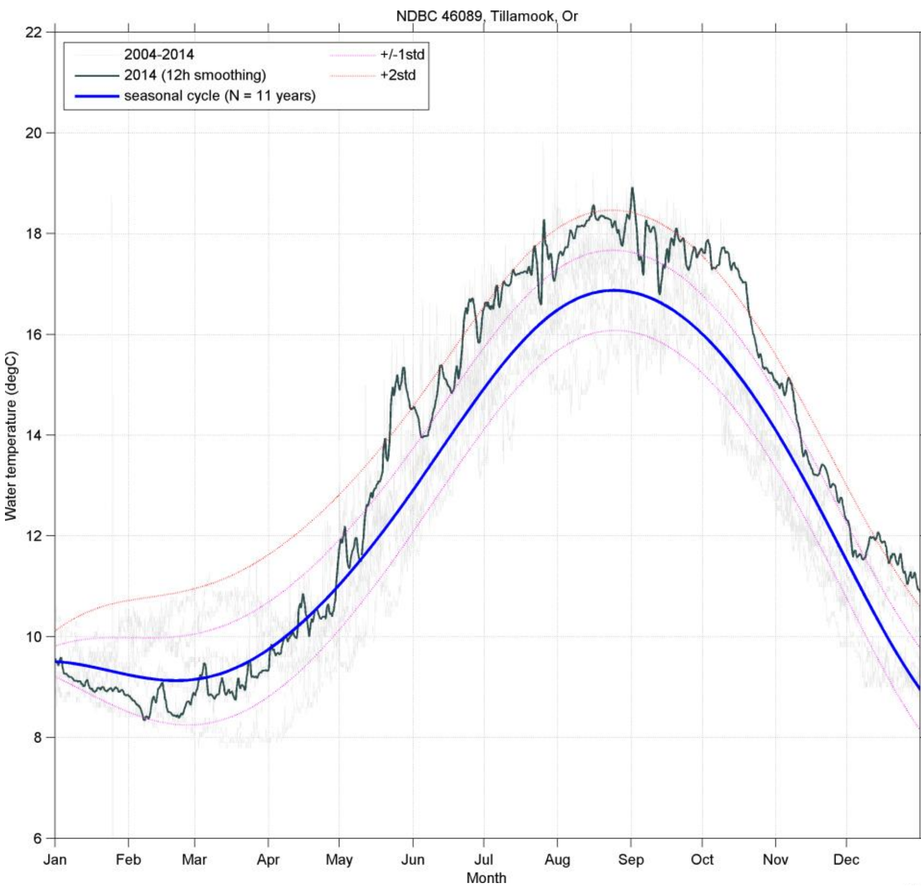
2015



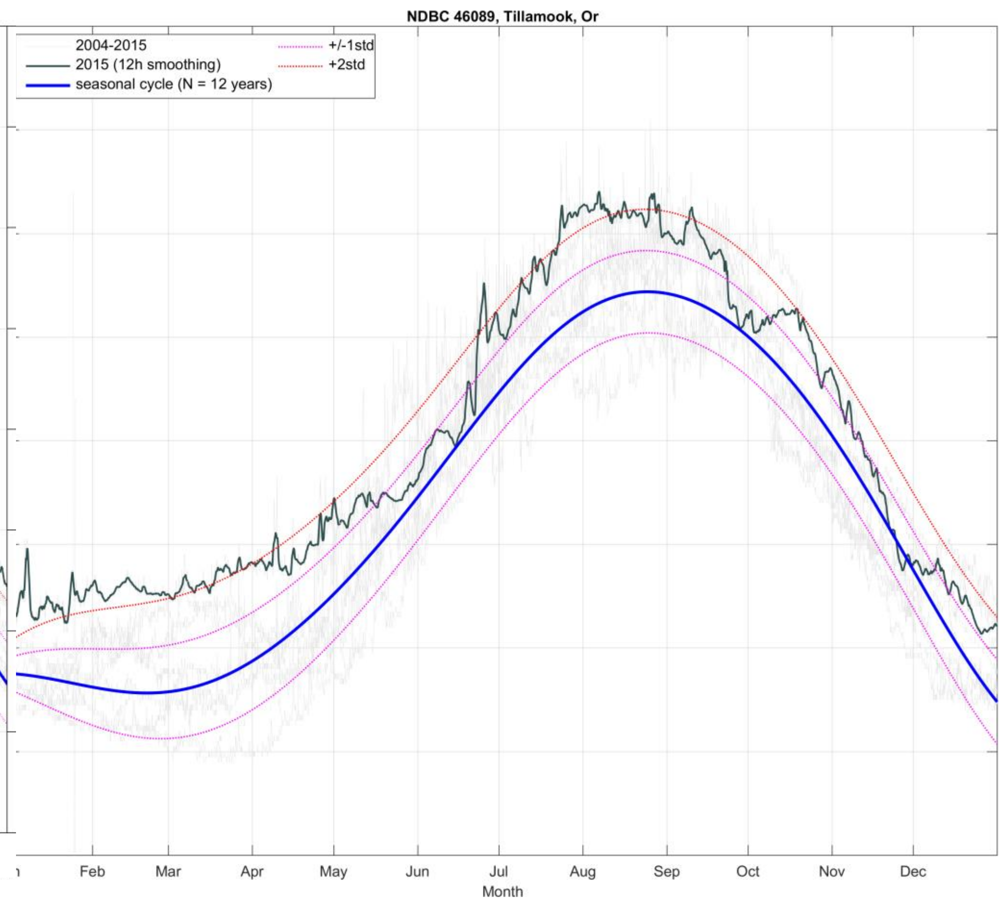


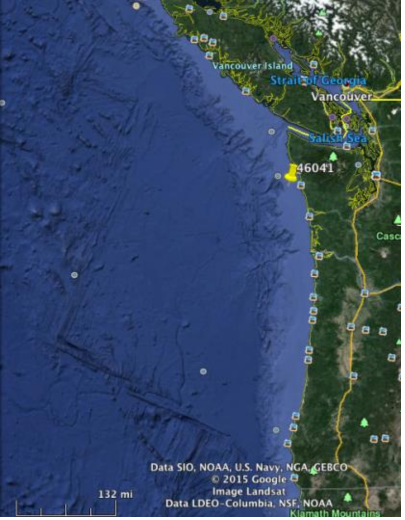
SST, 2014-2015, Buoy 46089 (off slope)
85 nm west of Tillamook, OR (45.9N, 125.8 W)

2014



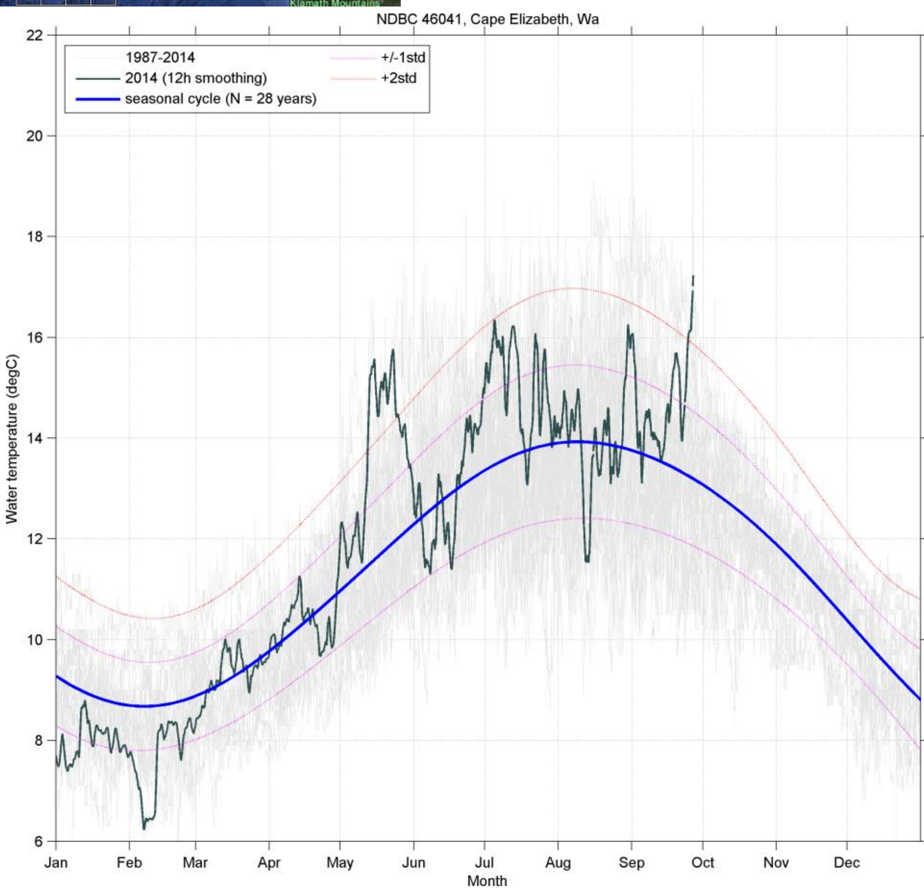
2015



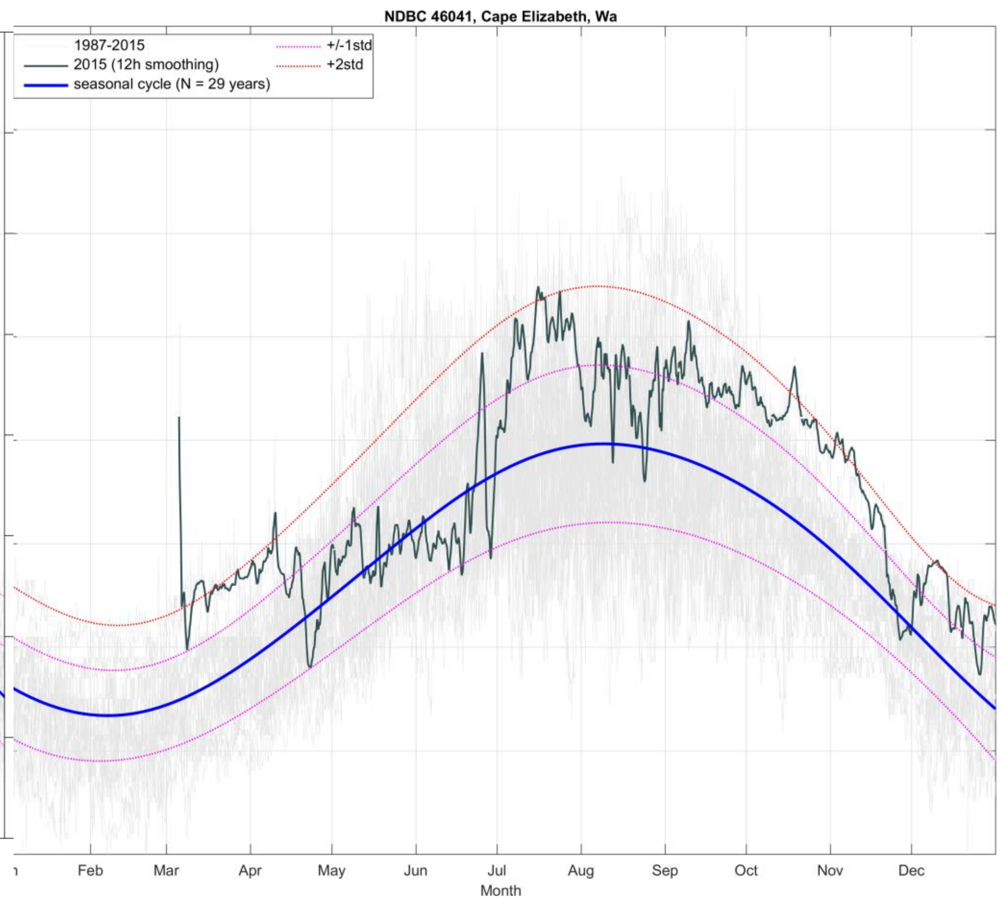


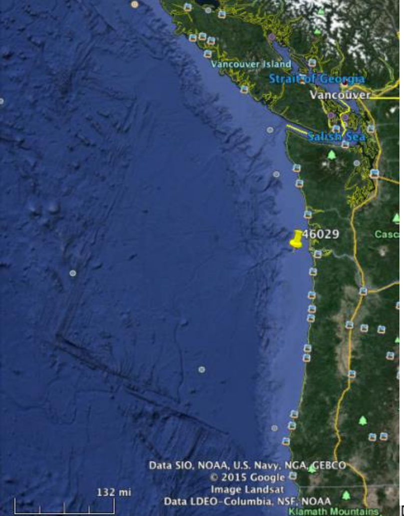
SST, 2014-2015, Buoy 46041 (coastal WA)
45 nm west of Aberdeen, WA (47.4N, 124.7 W)

2014



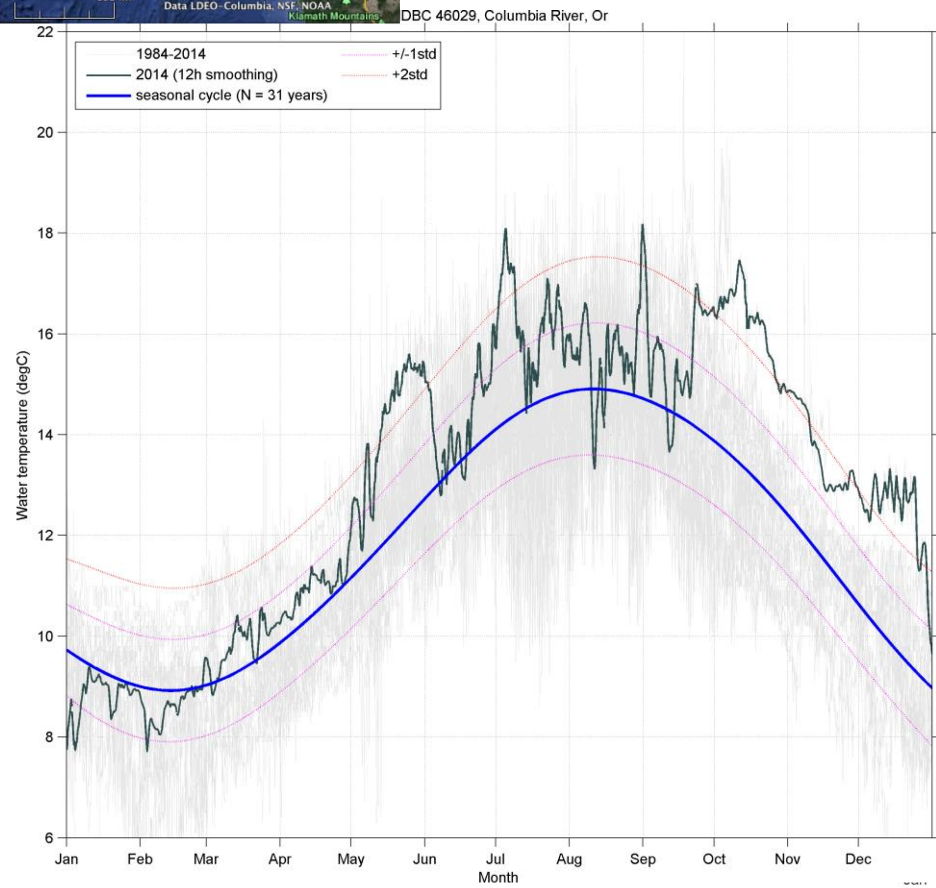
2015



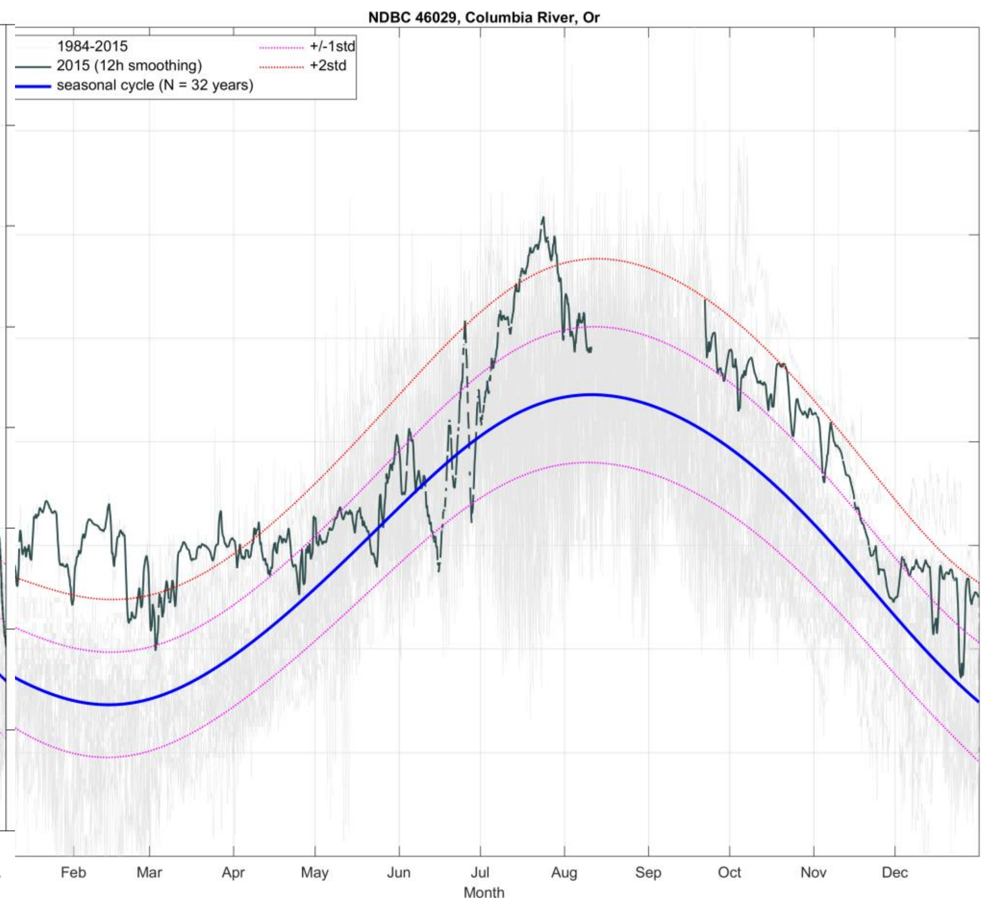


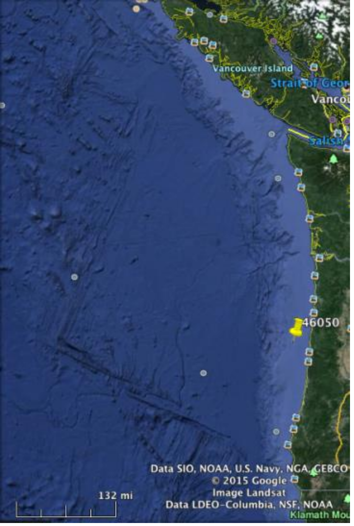
SST, 2014-2015, Buoy 46029 (coastal)
20 nm west of Columbia River (46.2N, 124.5 W)

2014



2015

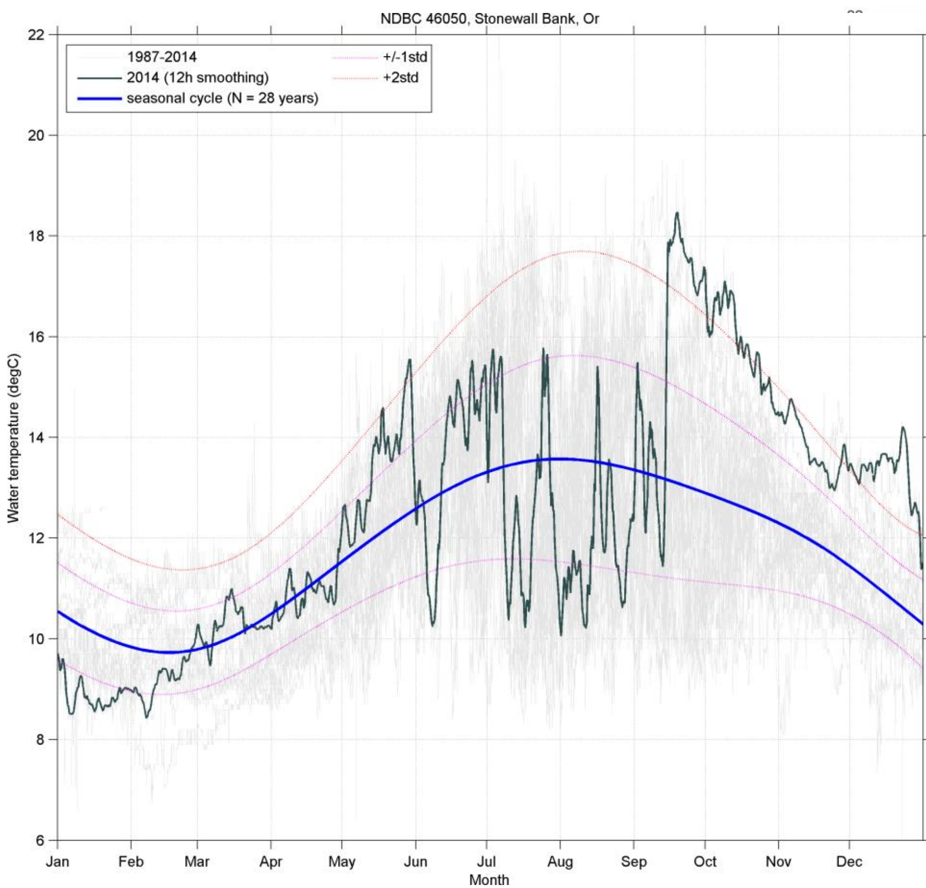


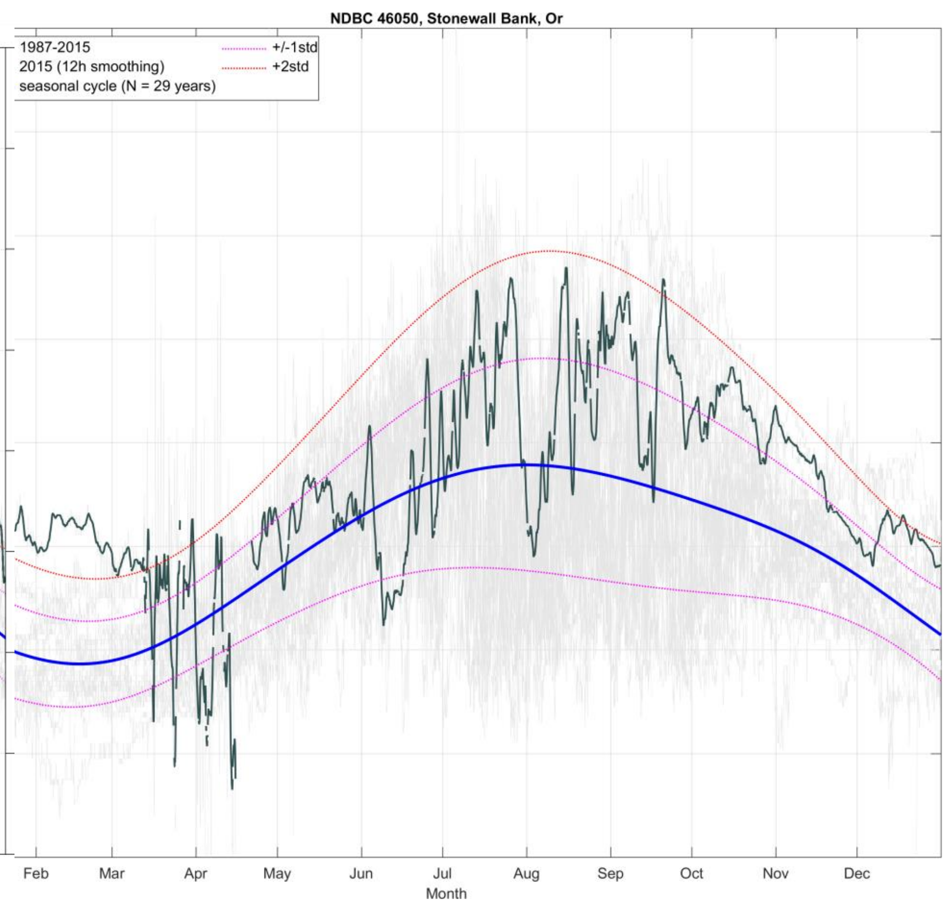


SST, 2014-2015, Buoy 46050 (coastal)
20 nm west of Newport, OR (44.7N, 124.5 W)

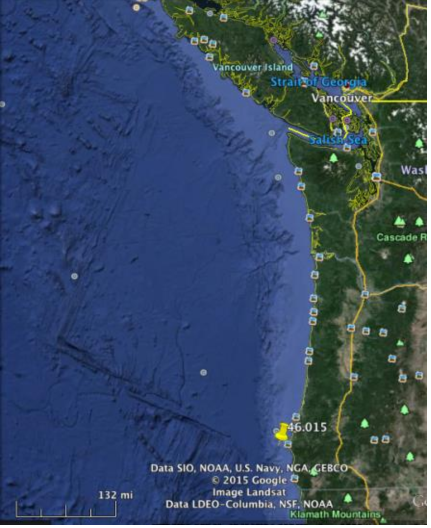
2014

2015



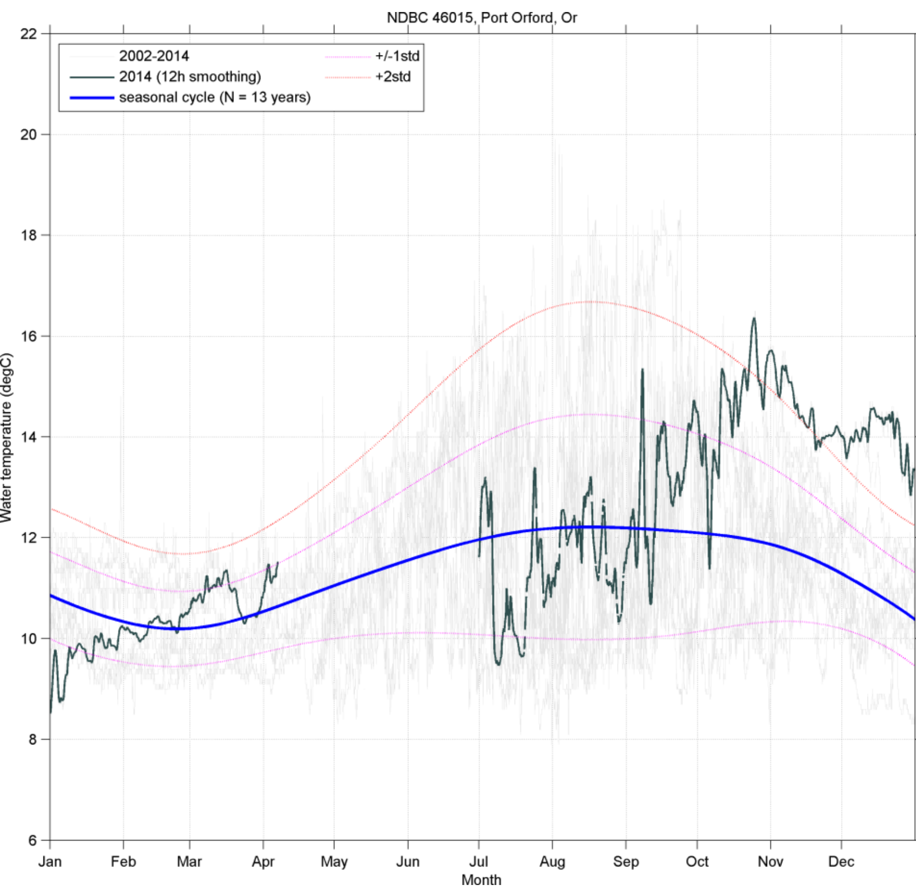


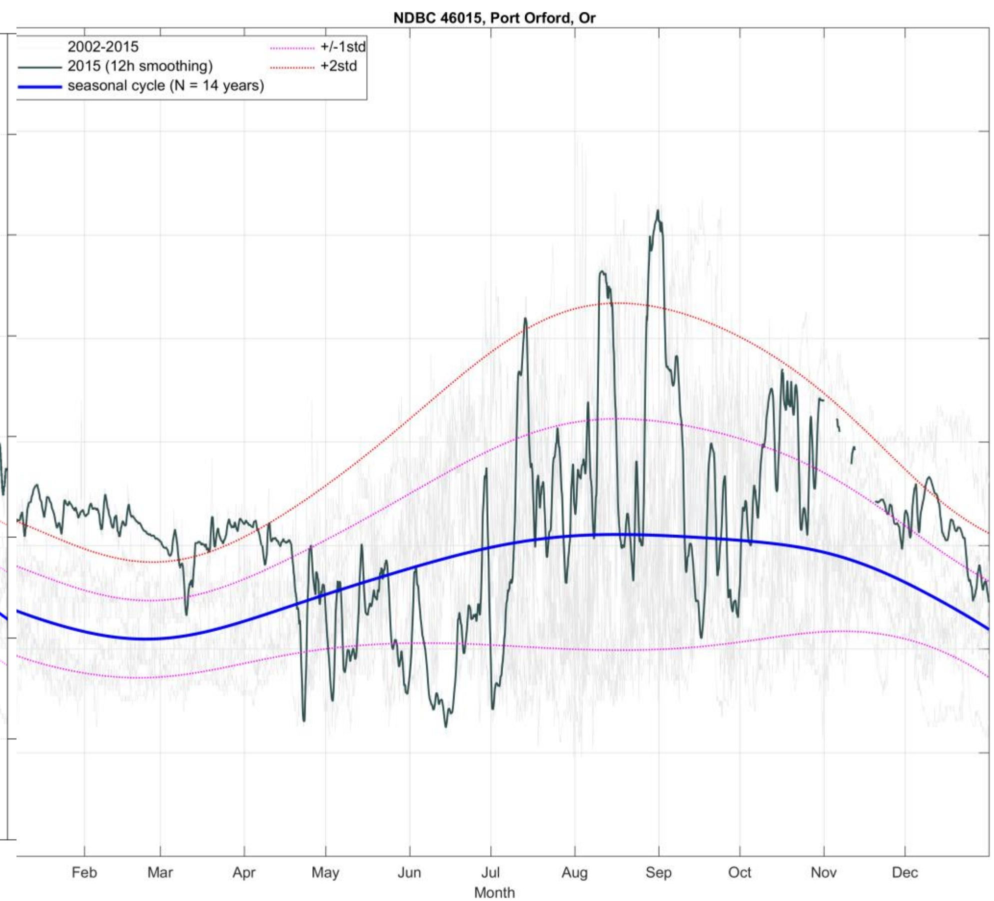
SST, 2014-2015, Buoy 46015 (coastal)
15 nm offshore near Cape Blanco, OR (42.8N, 124.8 W)

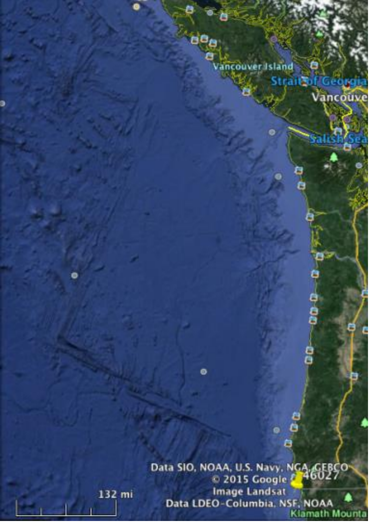


2014

2015



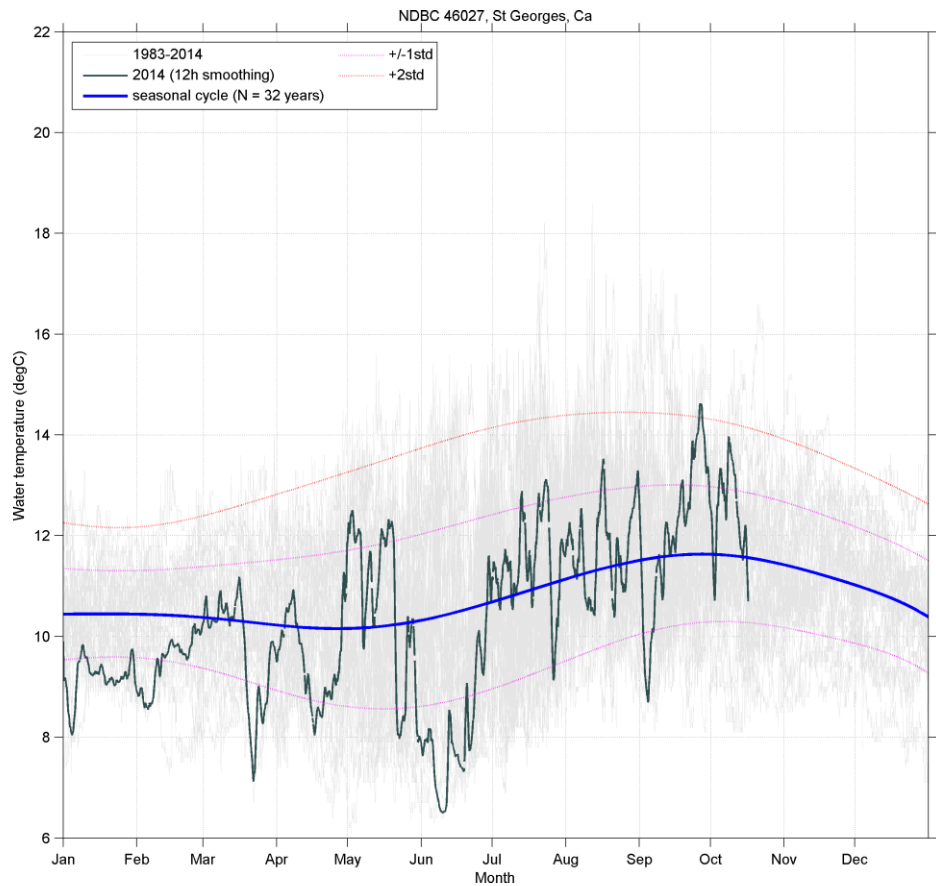


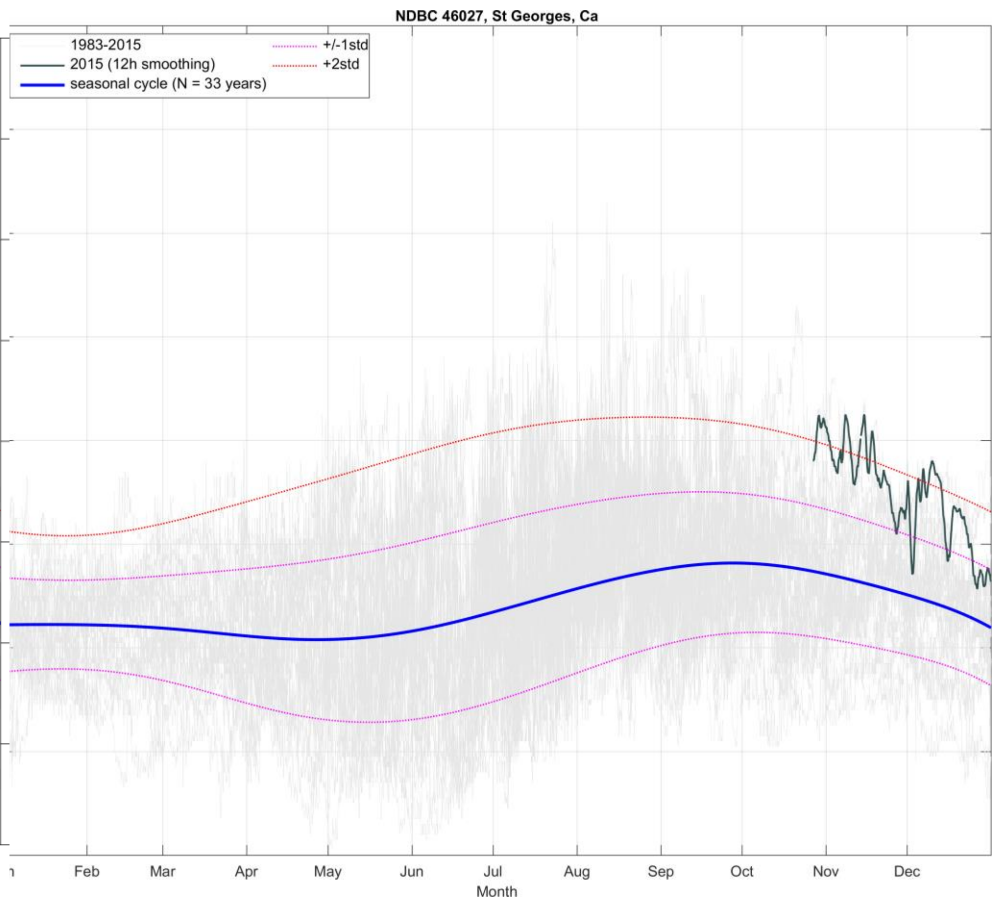


SST, 2014-2015, Buoy 46027 (coastal)
8 nm west of Crescent City, CA (41.9 N, 124.4 W)

2014

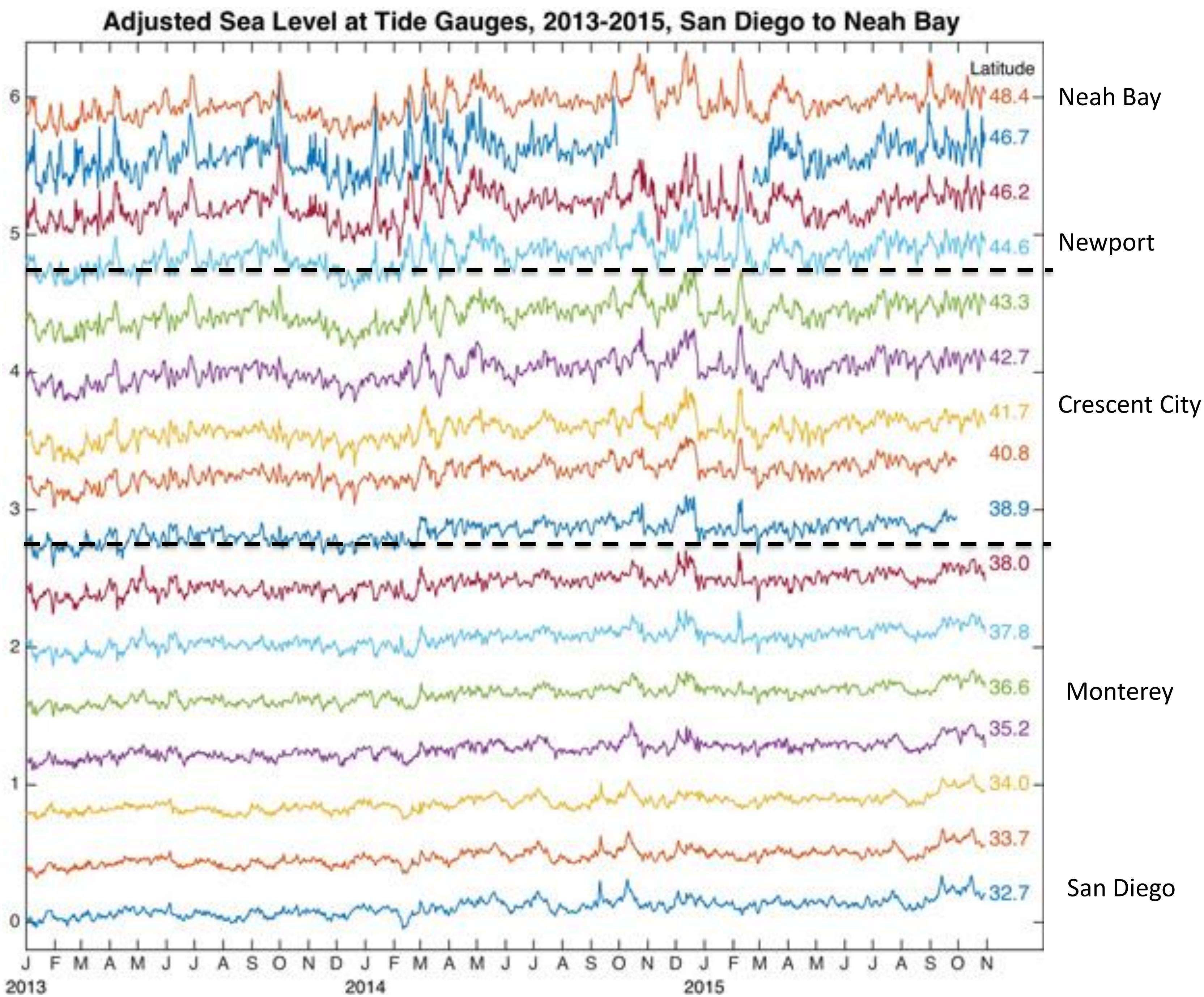
2015



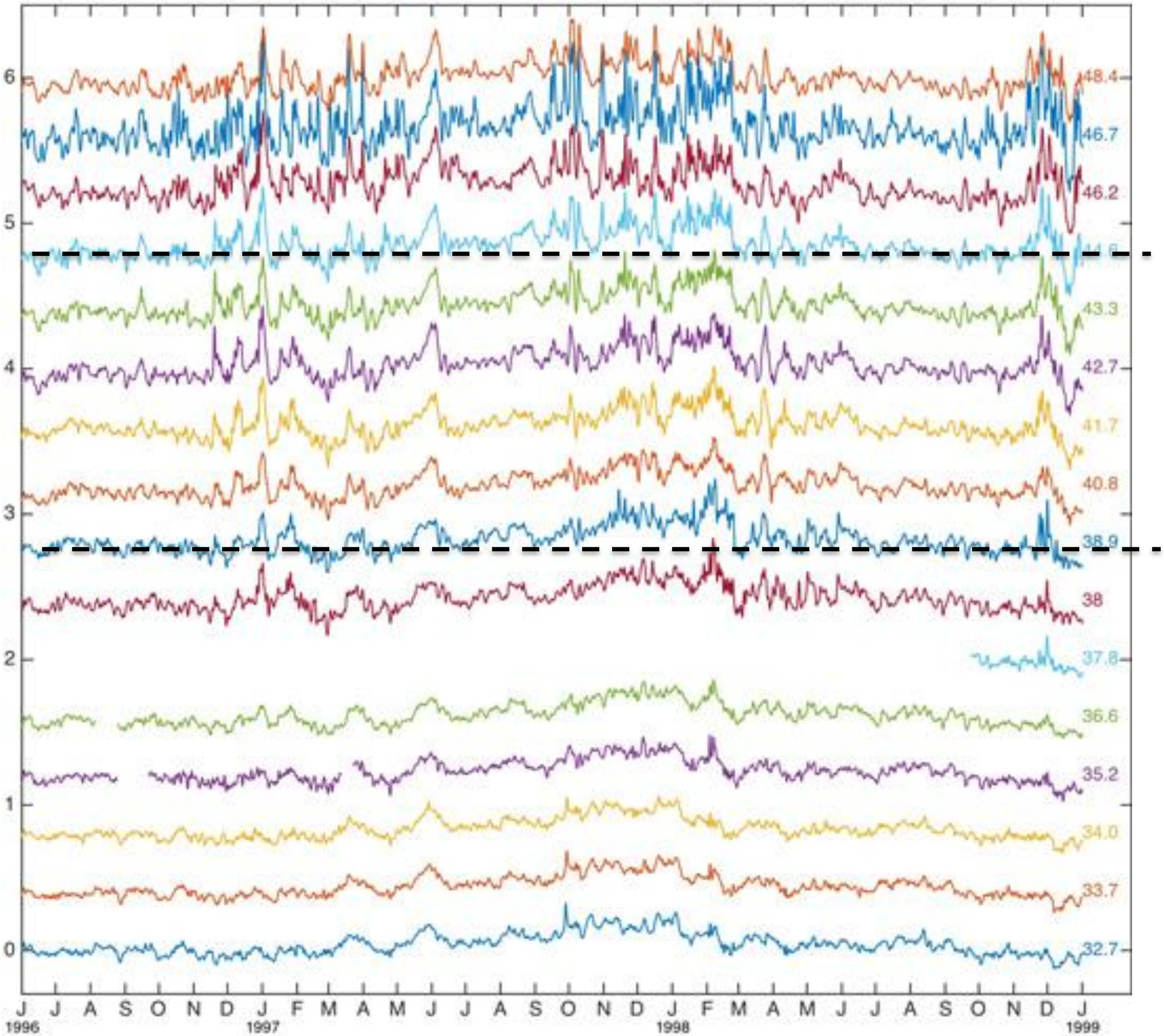


Coastal Scales: SSHA from Tide Gauges

Measured coastal sea level at tide gauge
Correct for atmospheric pressure “inverted barometer”
Remove tides and seasonal cycle


Adjusted Sea Level at Tide Gauges, 2013-2015, San Diego to Neah Bay
Latitude
48.4
46.7
46.2
44.6
43.3
42.7
41.7
40.8
38.9
38.0
37.8
36.6
35.2
34.0
33.7
32.7
6
5
4
3
2
1
0
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N
2013
2014
2015
Neah Bay
Newport
Crescent City
Monterey
San Diego

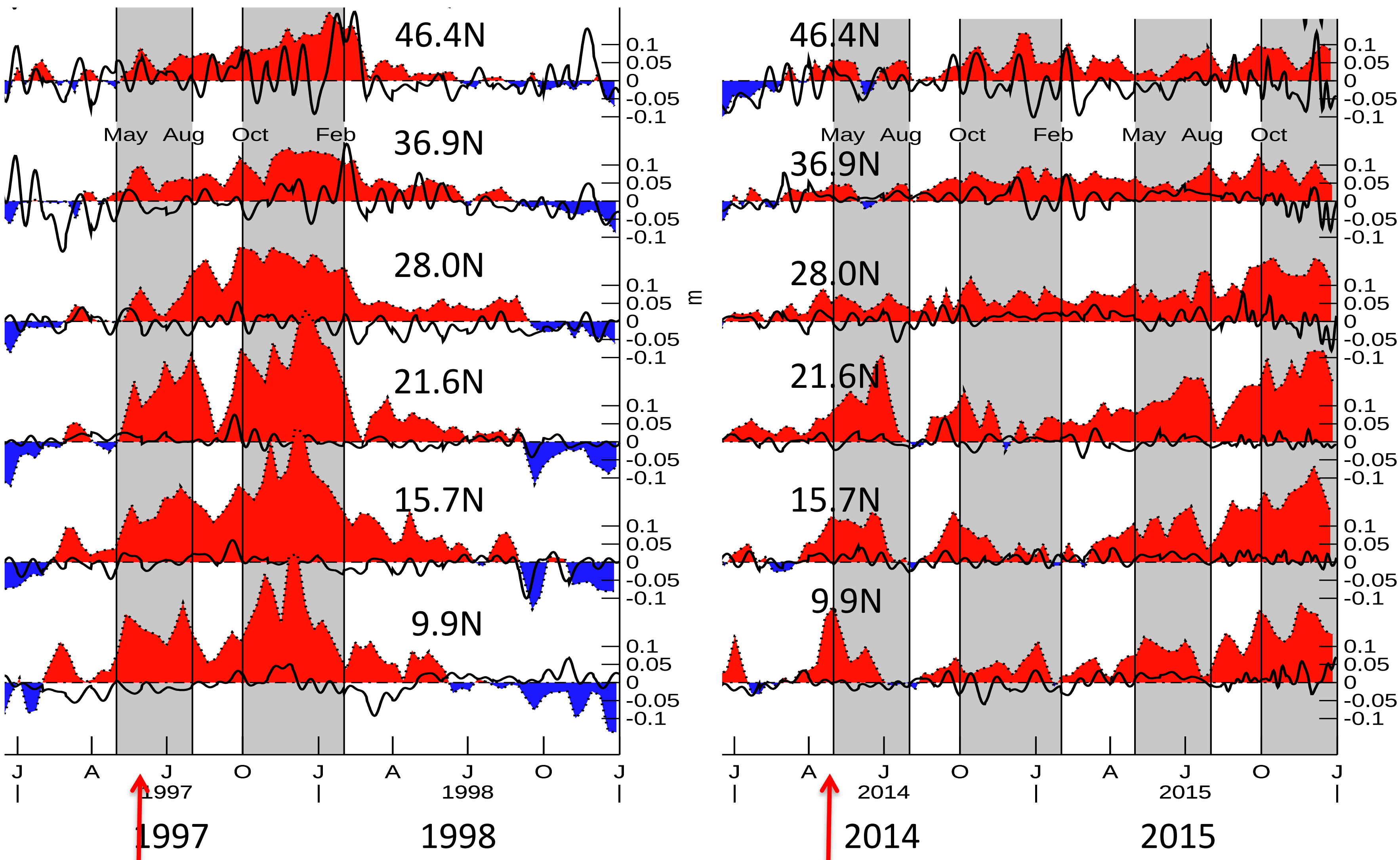
Adjusted Sea Level at Tide Gauges, 1996-1998, San Diego to Neah Bay



Rise in coastal sea level winter 2014, similar to rise in ENSO spring of 1997, but recent event is more persistent.

Coherent disturbances along coast, some travel at coastal wave speeds, others considerably faster.

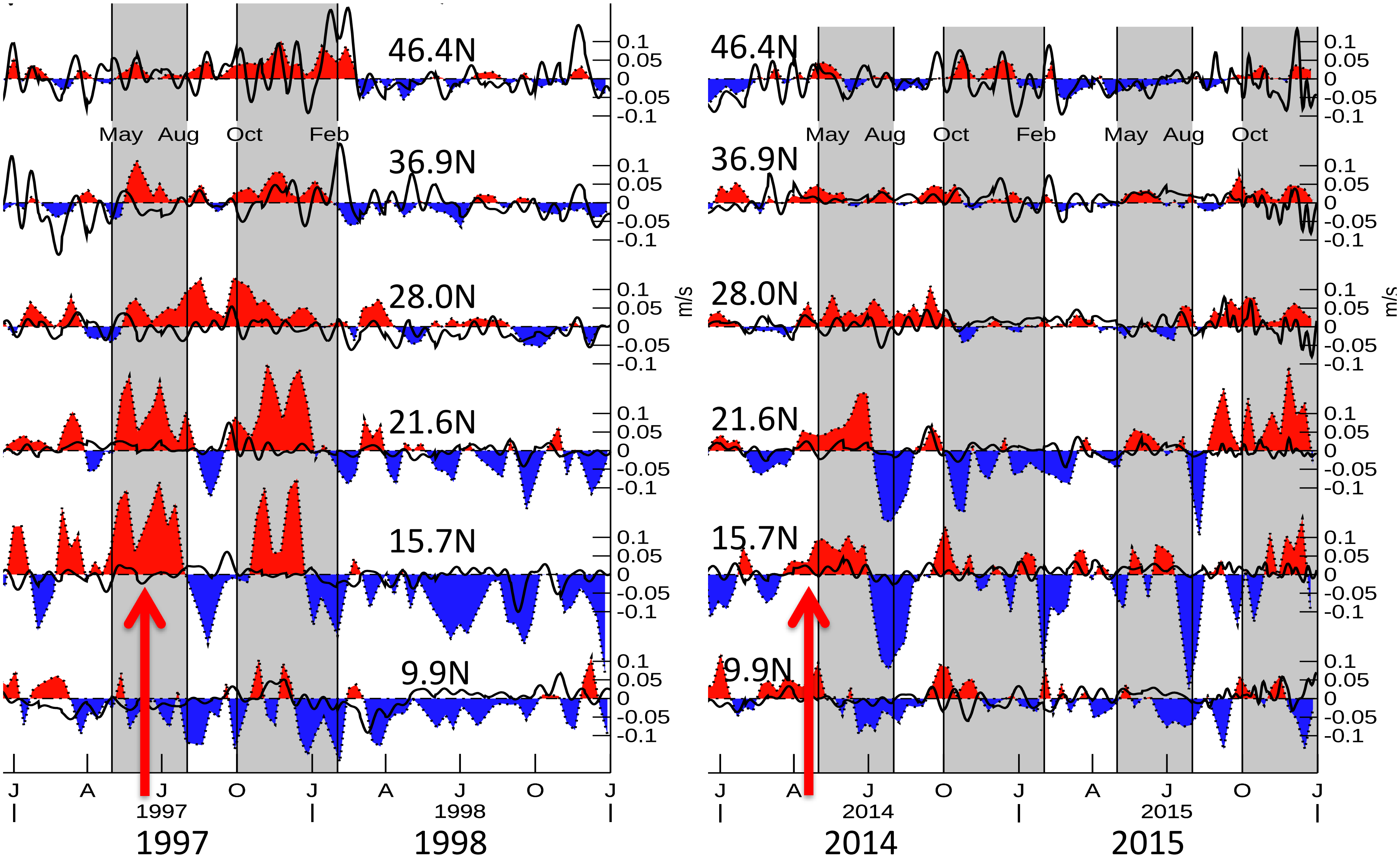
Non-Seasonal Alongtrack Altimeter Anomalies of SSH in the 100 km Next to the Coast (color) vs Poleward (Downwelling-Favorable) Wind Stress (lines)



During April-June 2014, high SSH spread from the Equator to the tip of Baja California, as it did during May-August 1997.

Strub

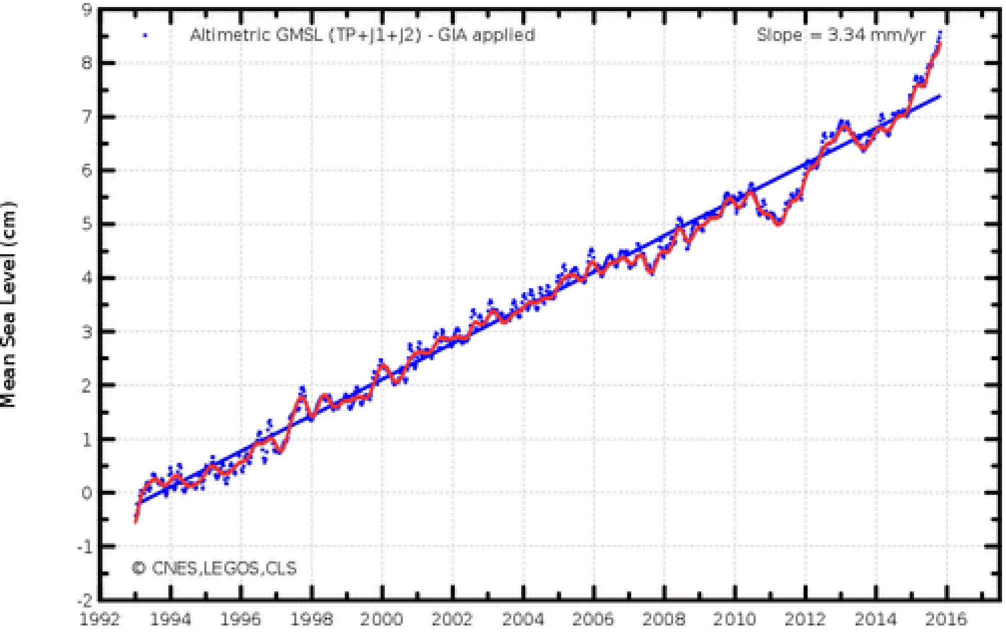
Non-Seasonal Cross-track Altimeter Velocities ~100 km from the Coast (color) vs Poleward (Downwelling-Favorable) Wind Stress (lines)

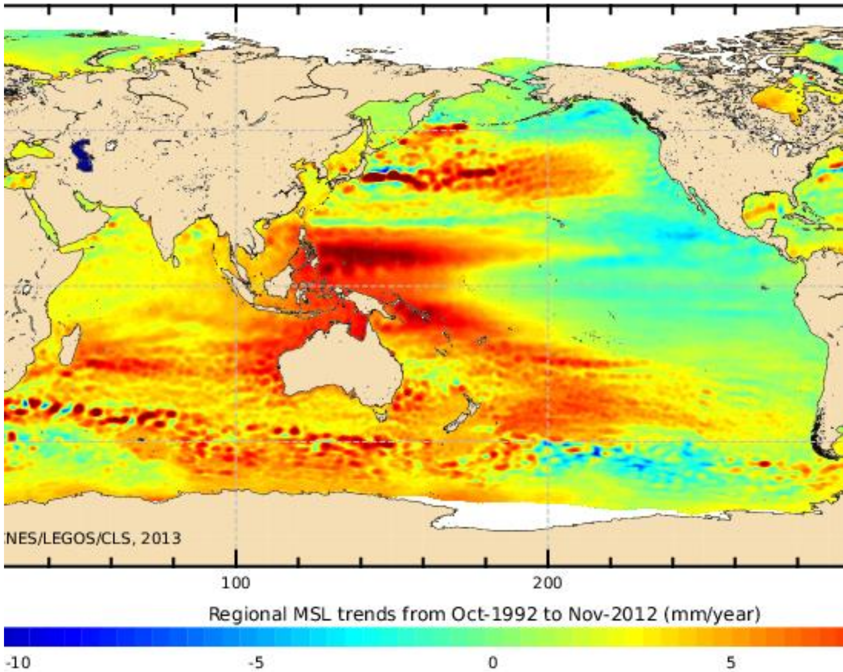


Poleward flow developed during April 2014 from Central America to Baja California. During 2014-15, however, poleward flow is never as meridionally coherent and strong as in 1997-98.

Strub

Global Sea Level Rise – Changing Patterns in the Pacific?



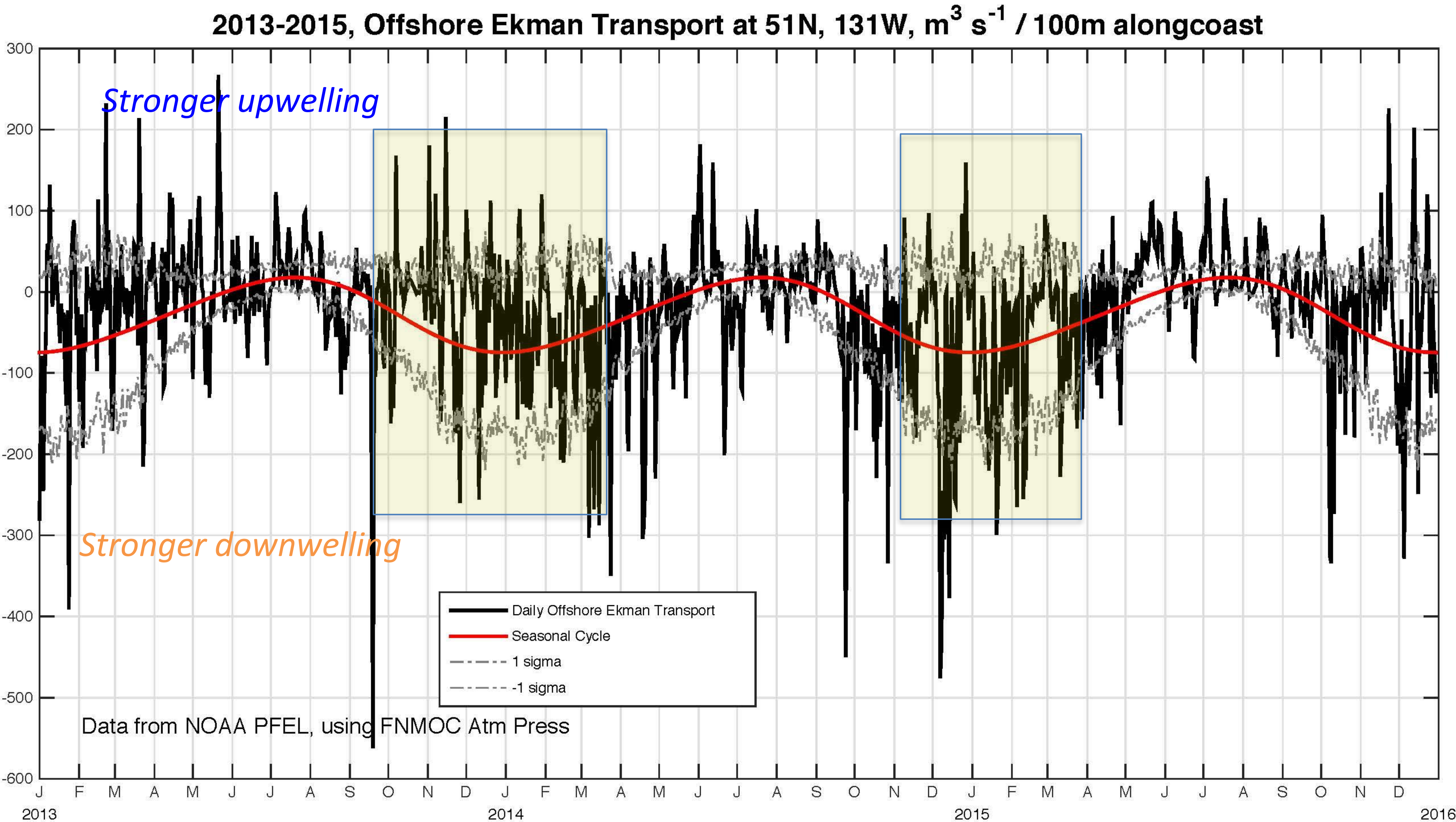


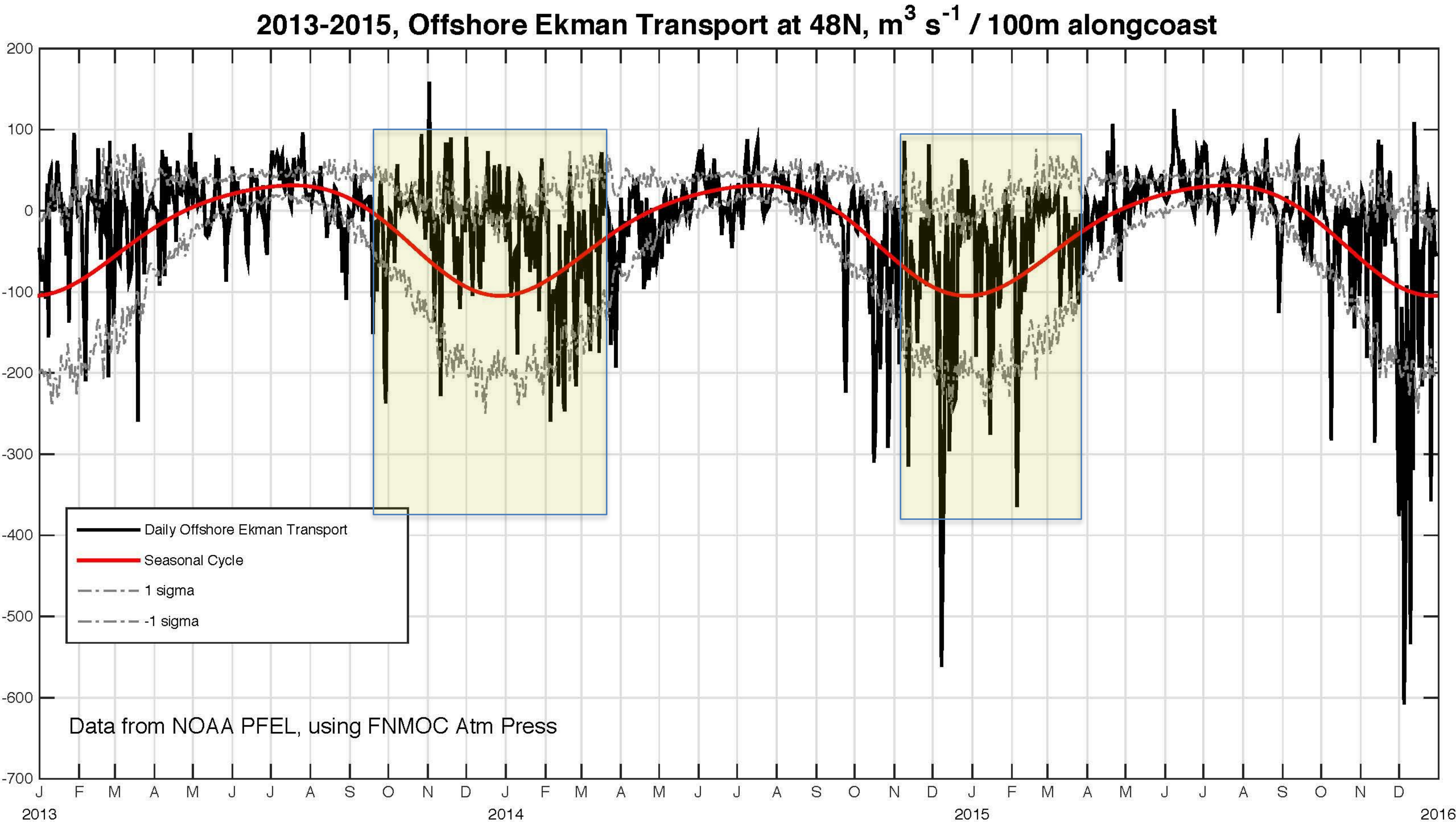
The pattern on the right shows the 20-year (10/1992 – 11/2012) trend values for sea level rise (-10 through +10 mm/year). On the left is the global average rise of ~3.3 mm/year. Off the U.S. West Coast (USWC), the values have been near zero, compared to 5-10 in the western Tropical Pacific. If the rise in sea level has been minimized along the USWC by the large scale circulation with decadal time scales (the PDO?), then when that circulation relaxes or reverses, the USWC will experience a rapid increase of 10-20 cm. If the warm anomaly or other recent data present evidence of this type of large-scale change in North Pacific Circulation, it represents a potential increase in sea level, inundation and erosion along the USWC.

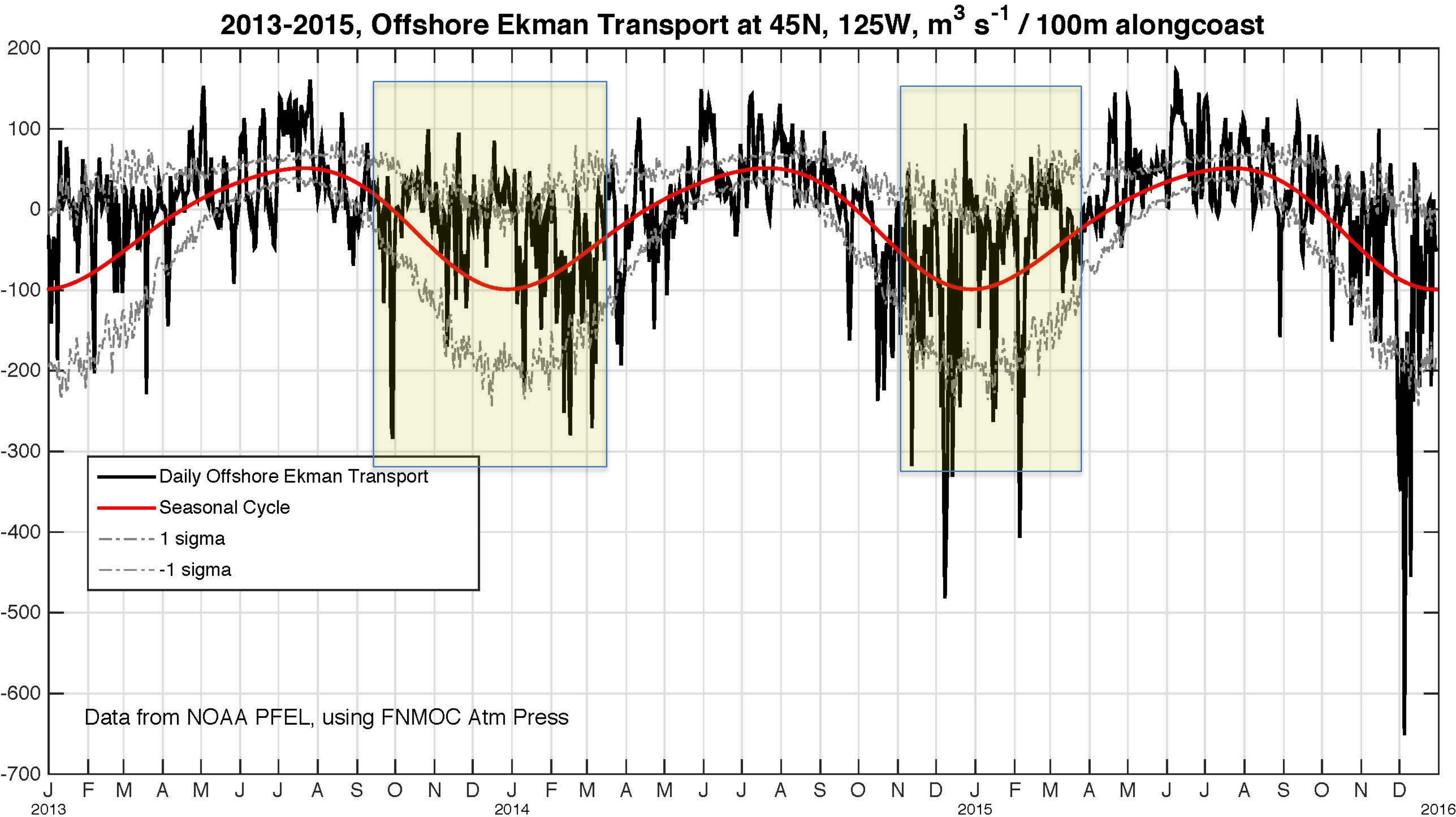
Strub

Coastal Scales: Wind Forcing as Coastal Upwelling Index (offshore transport per 100m alongcoast, estimated by PFEG from FNMOC).

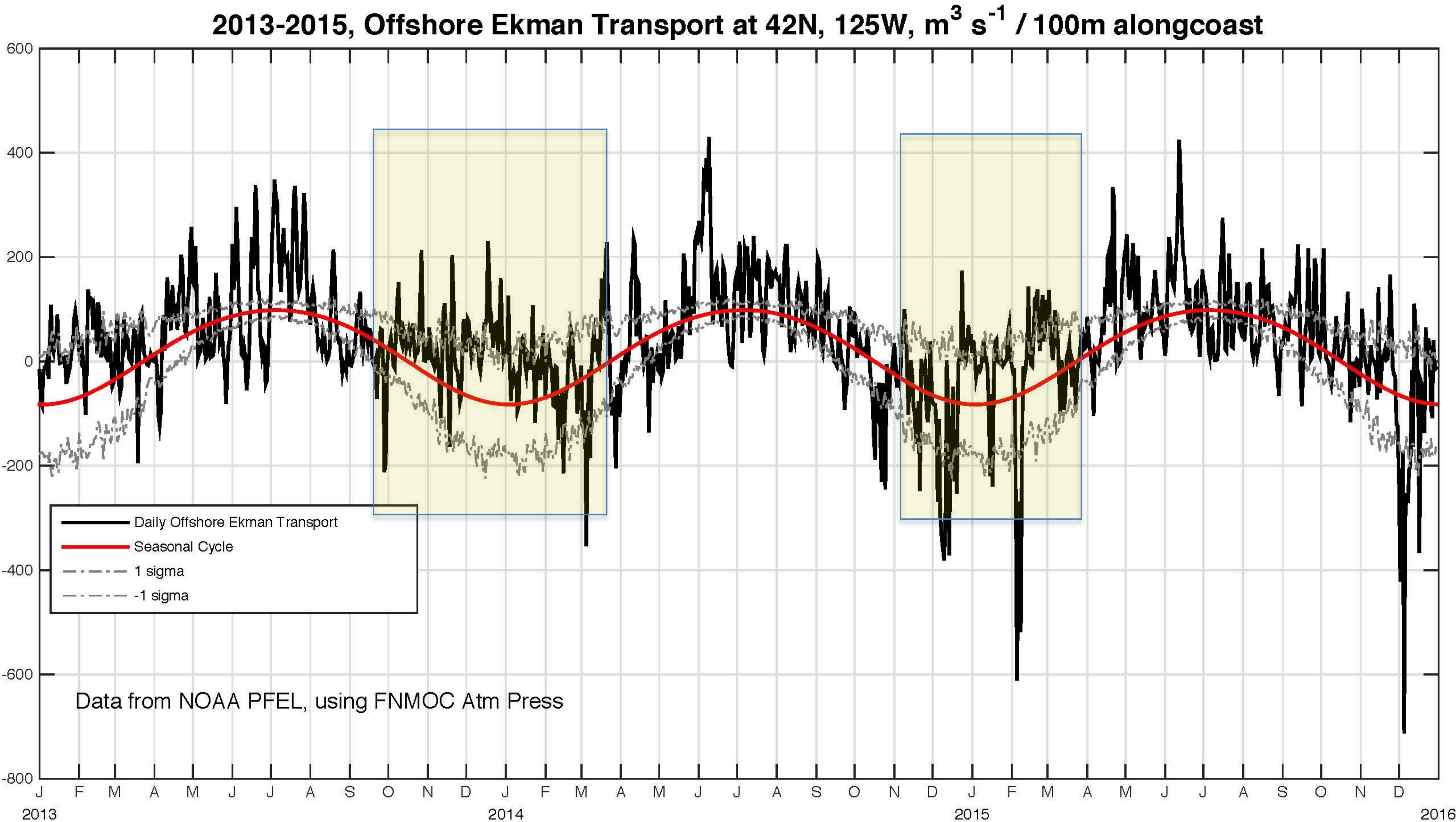
Upwelling or downwelling?
Timing?
Variation alongshore?


2013-2015, Offshore Ekman Transport at 51N, 131W, m3 s-1 / 100m alongcoast
Stronger upwelling
Stronger downwelling
Daily Offshore Ekman Transport
Seasonal Cycle
1 sigma
-1 sigma
Data from NOAA PFEL, using FNMOC Atm Press
300
200
100
0
-100
-200
-300
-400
-500
-600
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2013
2014
2015
2016

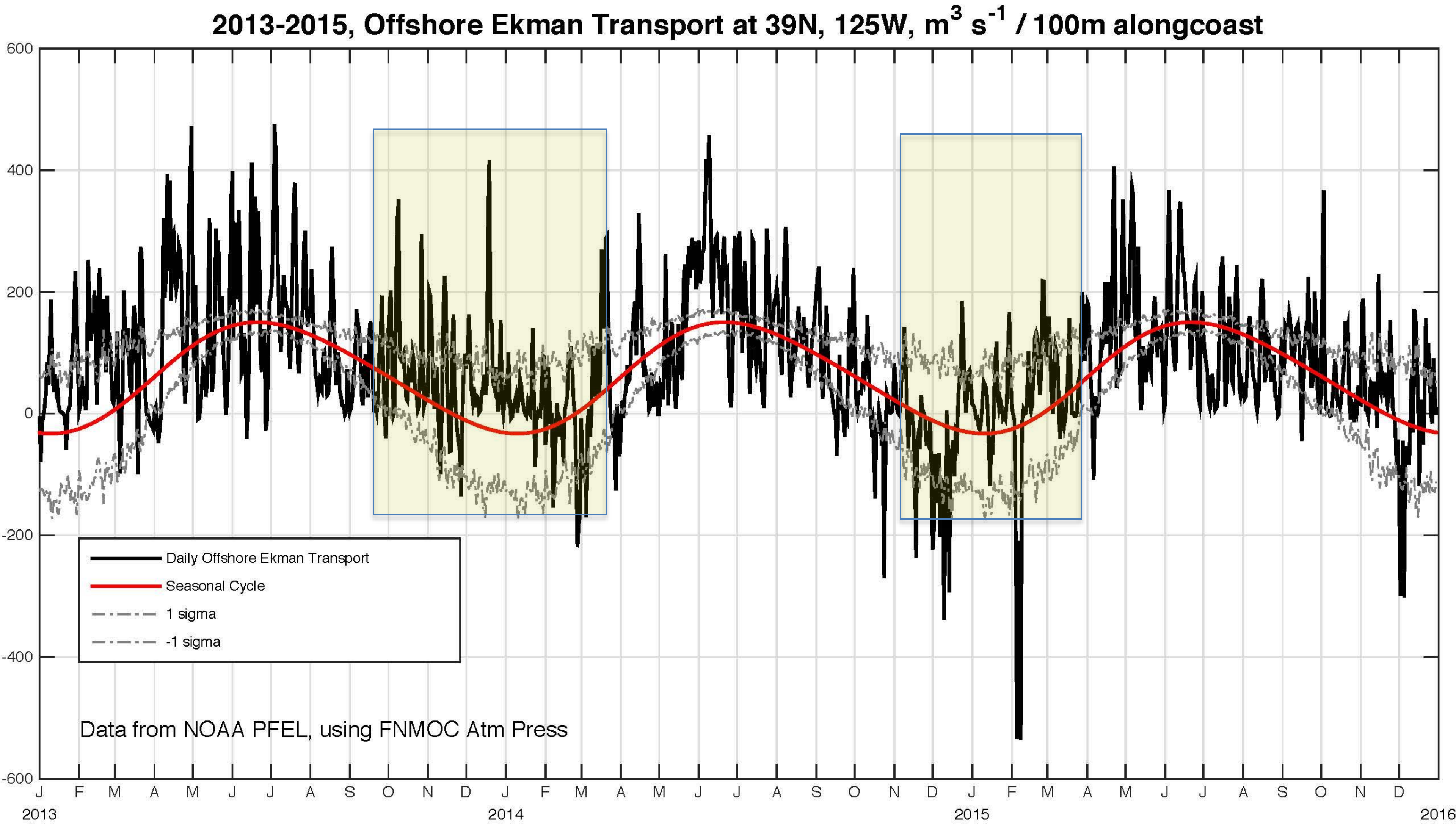

2013-2015, Offshore Ekman Transport at 48N, m3 s-1 / 100m alongcoast
200
100
0
-100
-200
-300
-400
-500
-600
-700
Daily Offshore Ekman Transport
Seasonal Cycle
1 sigma
-1 sigma
Data from NOAA PFEL, using FNMOC Atm Press
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2013
2014
2015
2016



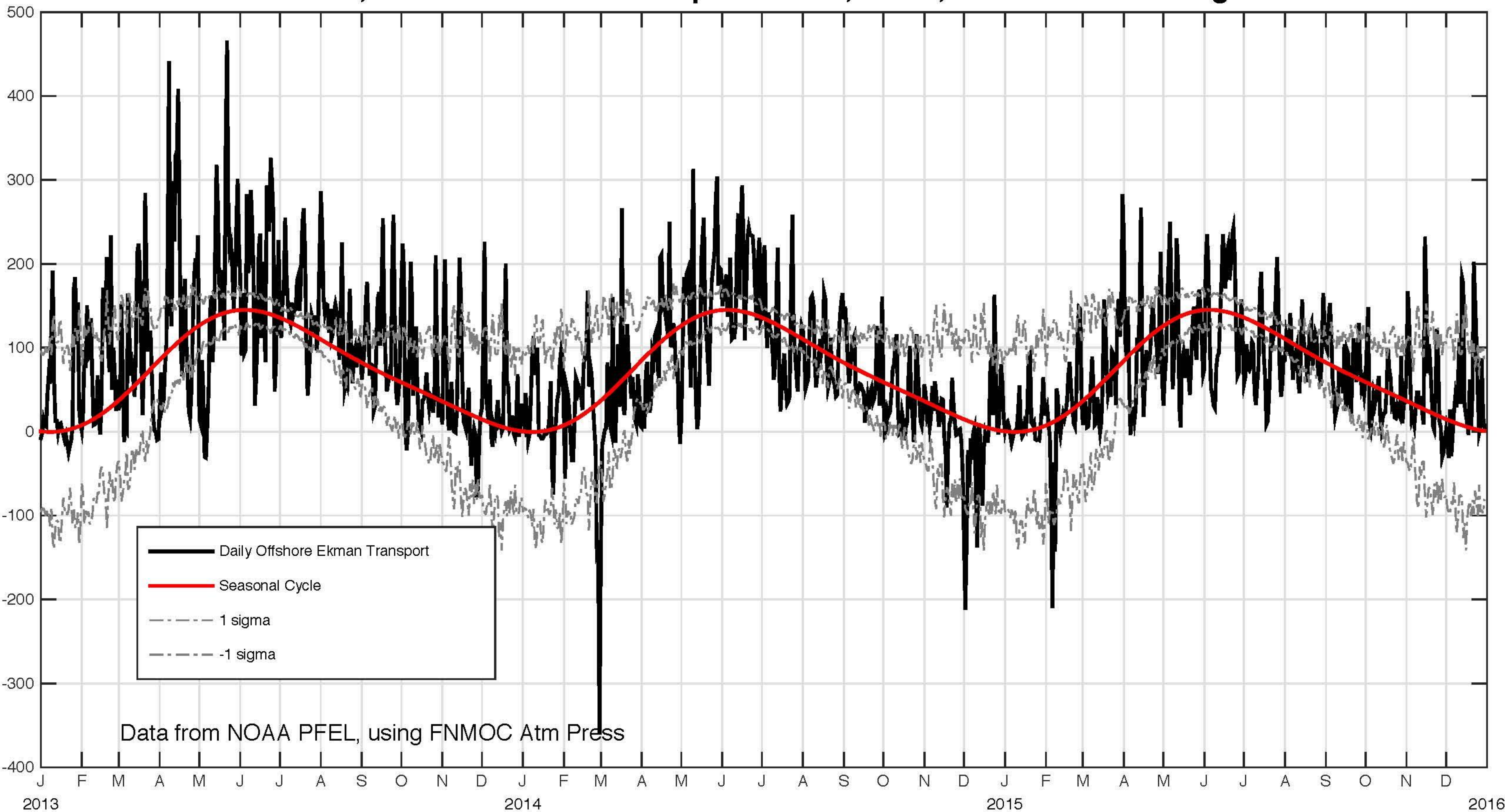
2013-2015, Offshore Ekman Transport at 45N, 125W, m3 s-1 / 100m alongcoast
200
100
0
-100
-200
-300
-400
-500
-600
-700
Daily Offshore Ekman Transport
Seasonal Cycle
1 sigma
-1 sigma
Data from NOAA PFEL, using FNMOC Atm Press
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2013
2014
2015
2016

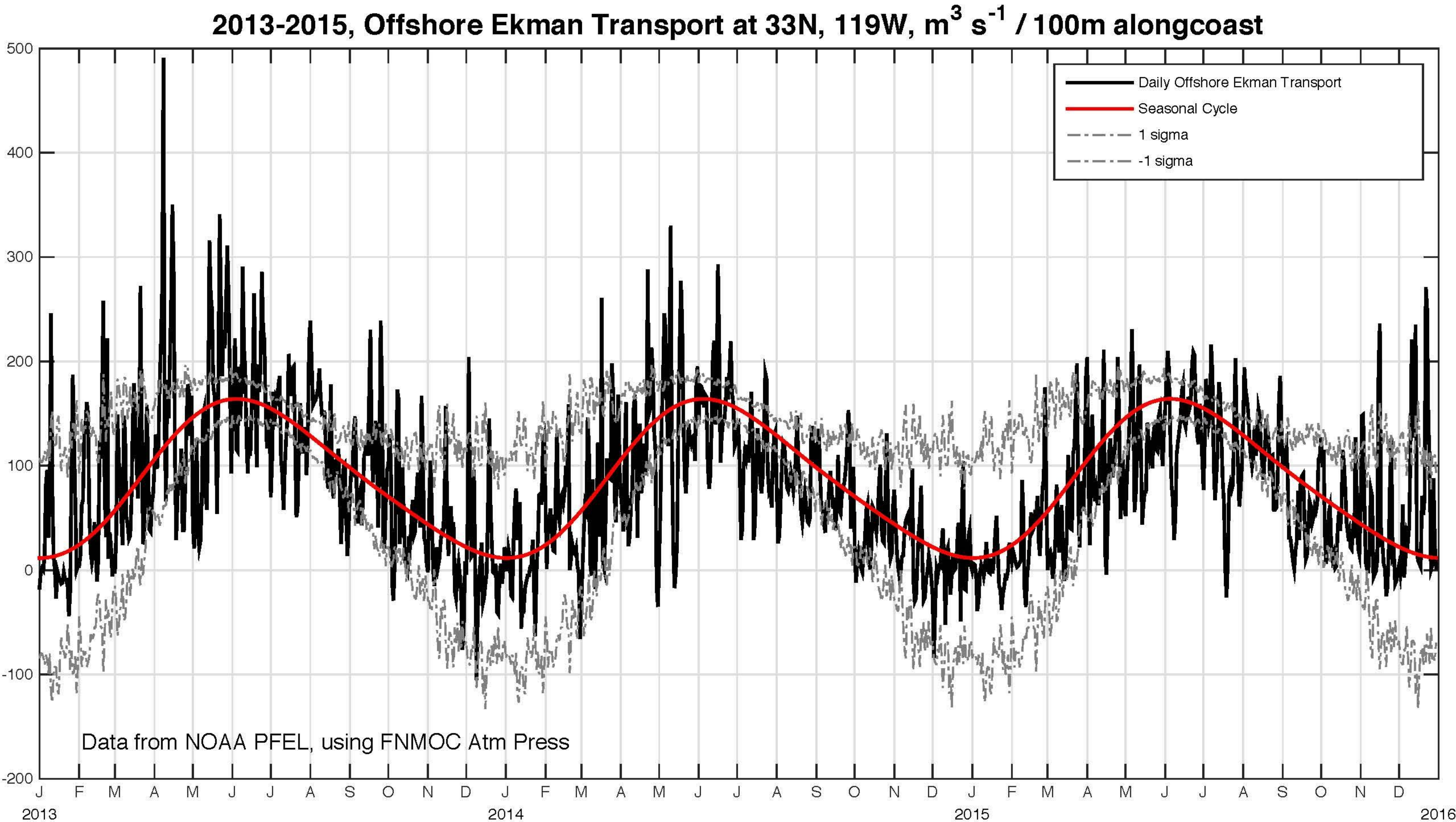


2013-2015, Offshore Ekman Transport at 42N, 125W, m3 s-1 / 100m alongcoast
600
400
200
0
-200
-400
-600
-800
Daily Offshore Ekman Transport
Seasonal Cycle
1 sigma
-1 sigma
Data from NOAA PFEL, using FNMOC Atm Press
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2013
2014
2015
2016

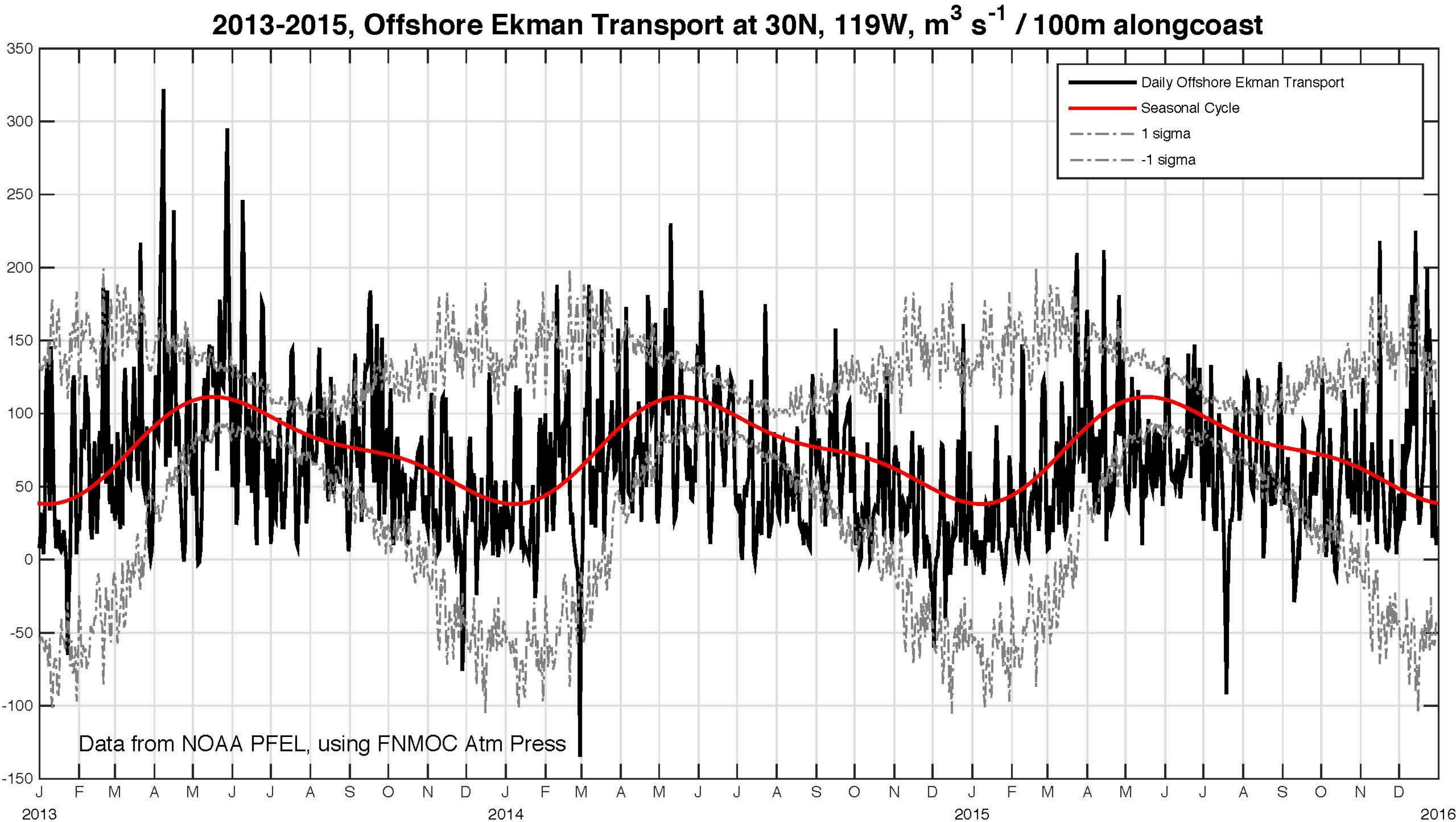

2013-2015, Offshore Ekman Transport at 39N, 125W, m3 s-1 / 100m alongcoast
600
400
200
0
-200
-400
-600
Daily Offshore Ekman Transport
Seasonal Cycle
1 sigma
-1 sigma
Data from NOAA PFEL, using FNMOC Atm Press
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2013
2014
2015
2016

2013-2015, Offshore Ekman Transport at 36N, 122W, $m^3\ s^{-1}$ / 100m alongcoast





2013-2015, Offshore Ekman Transport at 33N, 119W, m3 s-1 / 100m alongcoast
500
400
300
200
100
0
-100
-200
Daily Offshore Ekman Transport
Seasonal Cycle
1 sigma
-1 sigma
Data from NOAA PFEL, using FNMOC Atm Press
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2013
2014
2015
2016

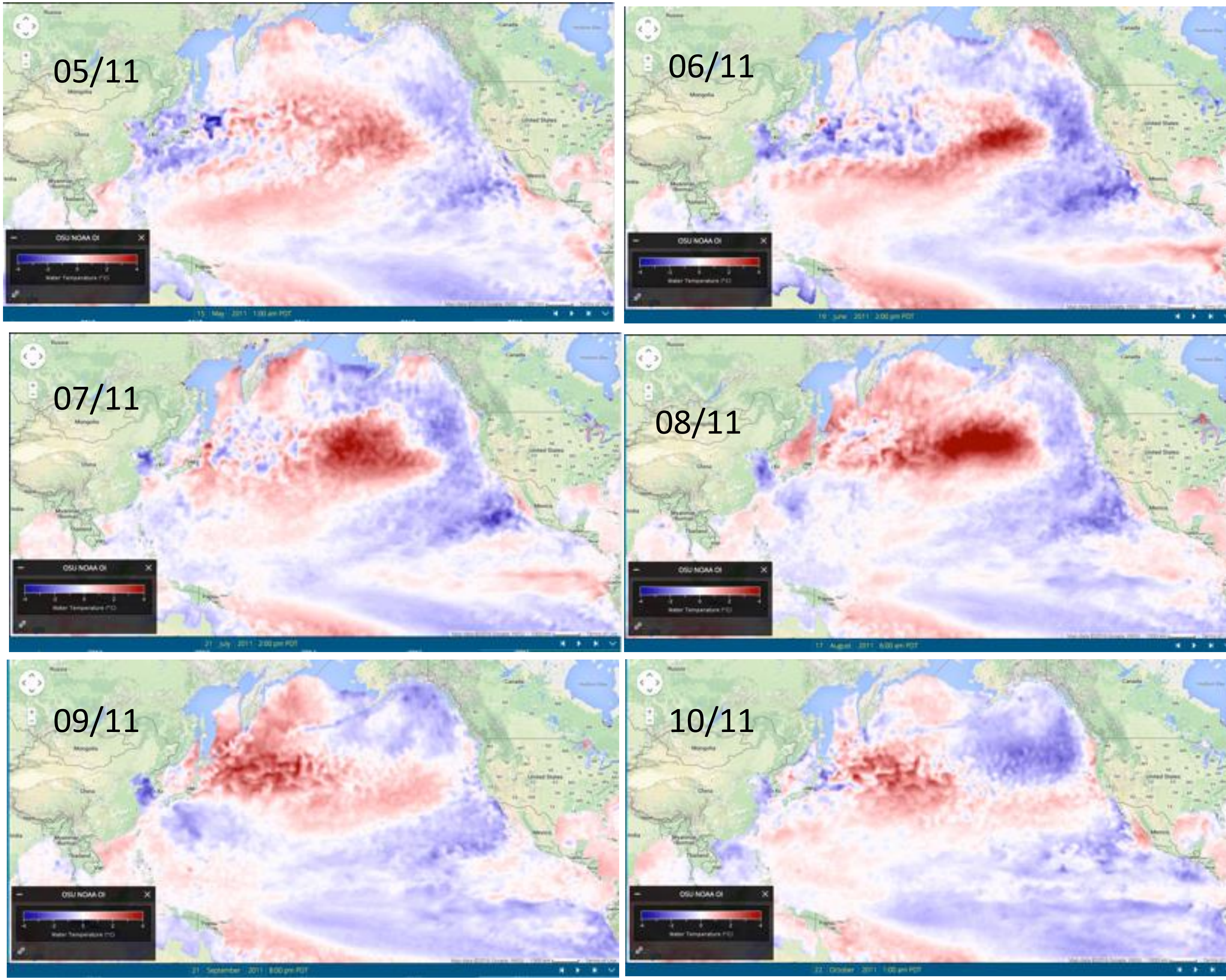

2013-2015, Offshore Ekman Transport at 30N, 119W, m3 s-1 / 100m alongcoast
Daily Offshore Ekman Transport
Seasonal Cycle
1 sigma
-1 sigma
Data from NOAA PFEL, using FNMOC Atm Press
350
300
250
200
150
100
50
0
-50
-100
-150
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J
2013
2014
2015
2016

Coastal winds: north of SF, fall/winter poleward-forcing/onshore-transport was anomalously weak or reversed in 2013-14 and 2014-15.

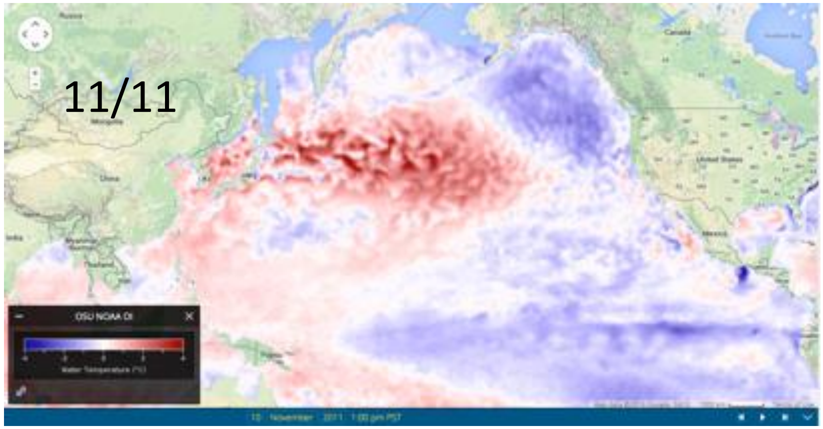
Is the recent “blob” unprecedented, or could we have other case histories to study?

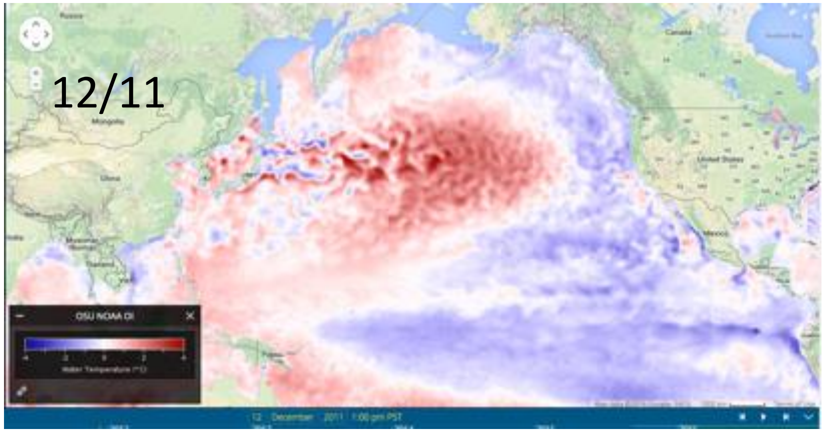
Reynolds SST Anomaly, May 2011– Feb 2012 (slide 1 of 2)

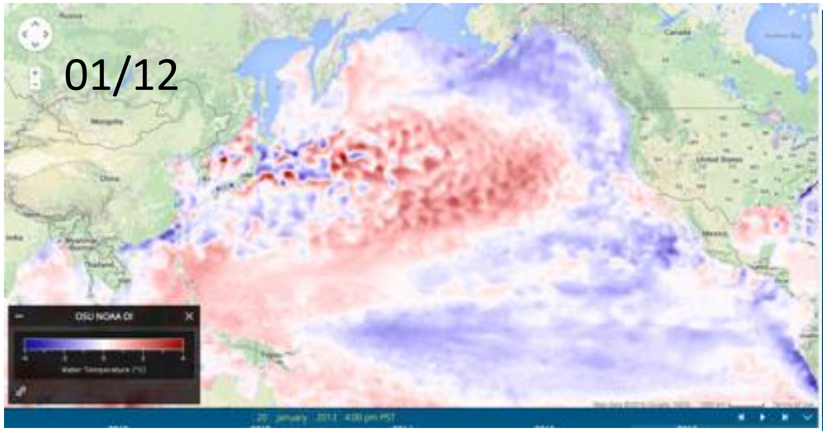
T scale: -4C to 4C

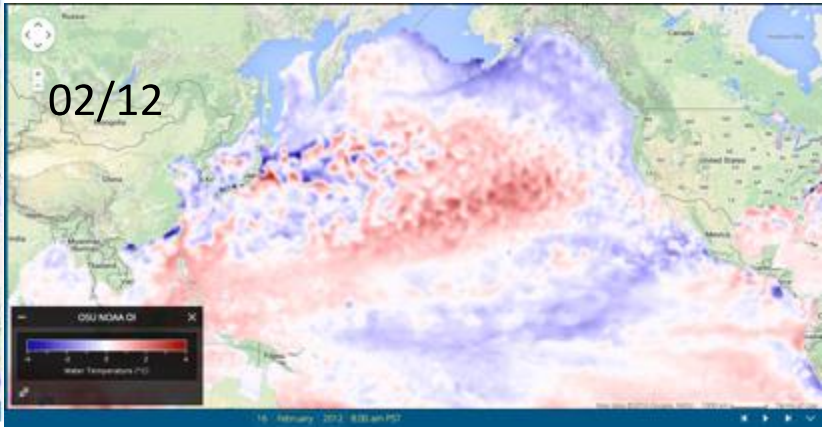


Reynolds SST Anomaly, May 2011– Feb 2012 (slide 2 of 2)



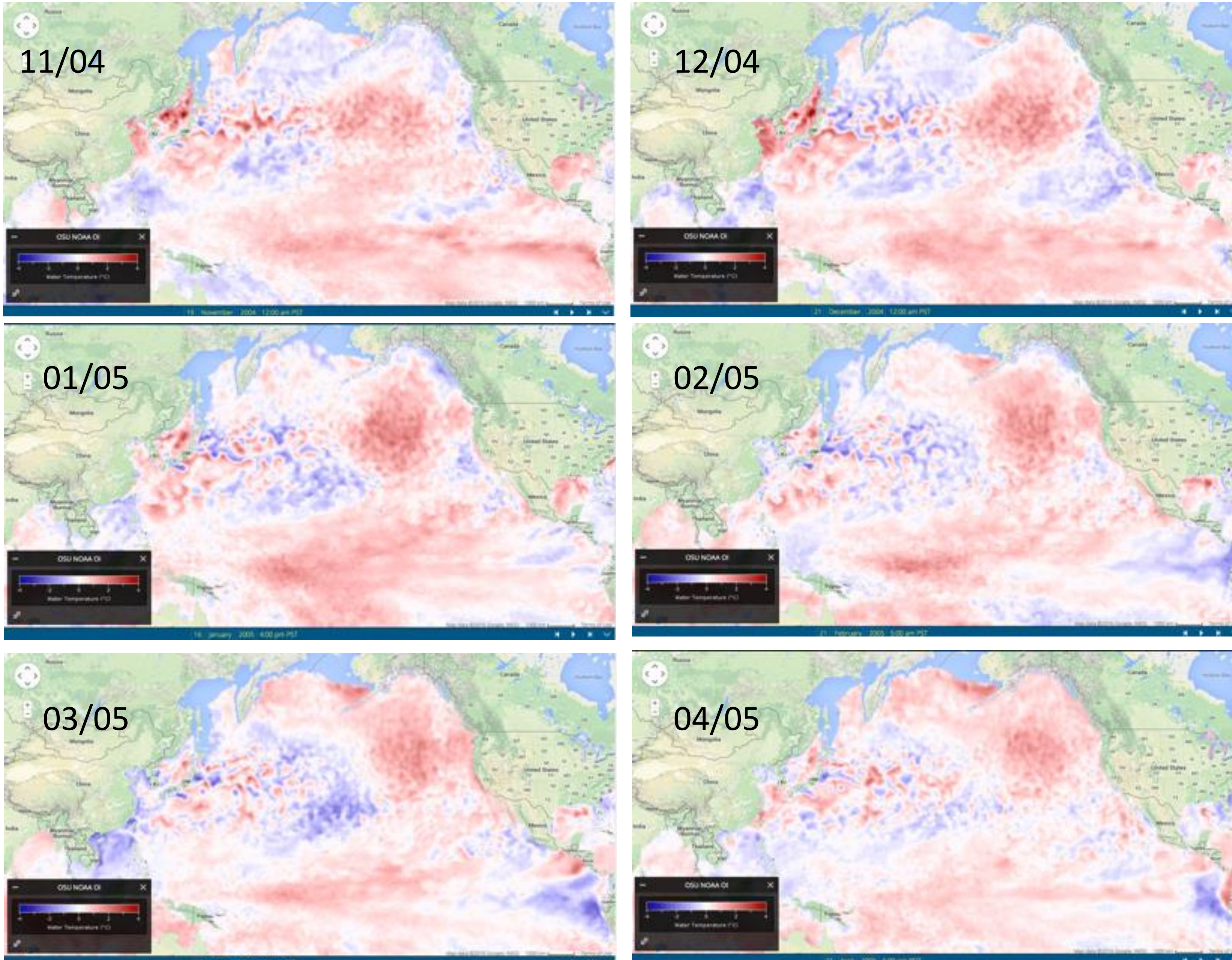




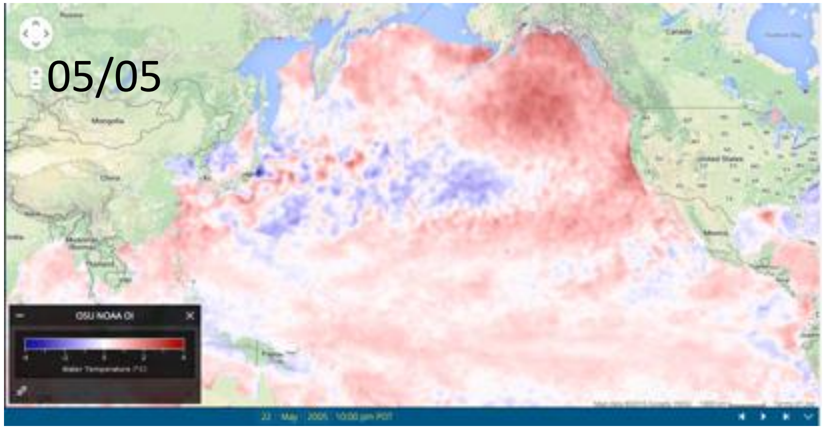


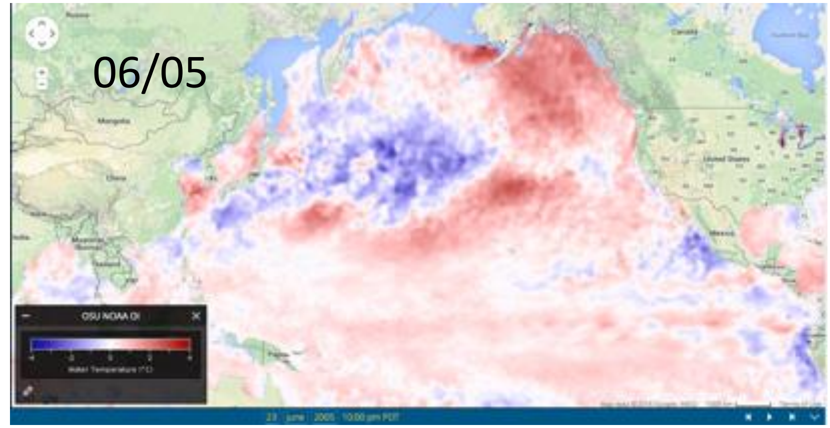
Reynolds SST Anomaly, Nov 2004 – Oct 2005 (slide 1 of 2)

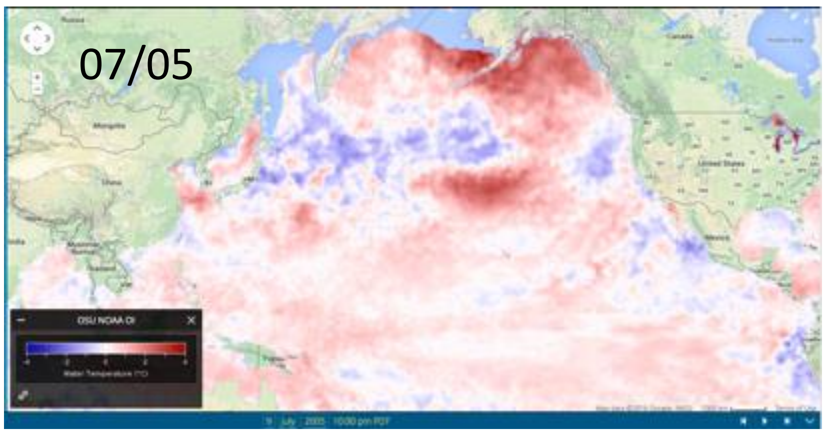
T scale: -4C to 4C

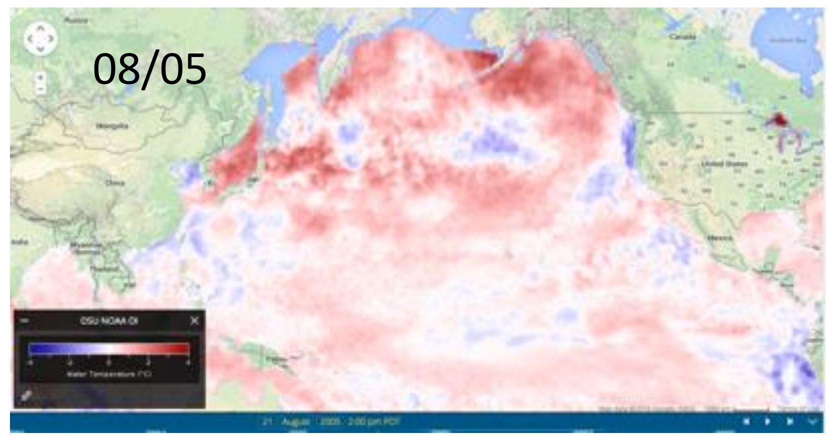


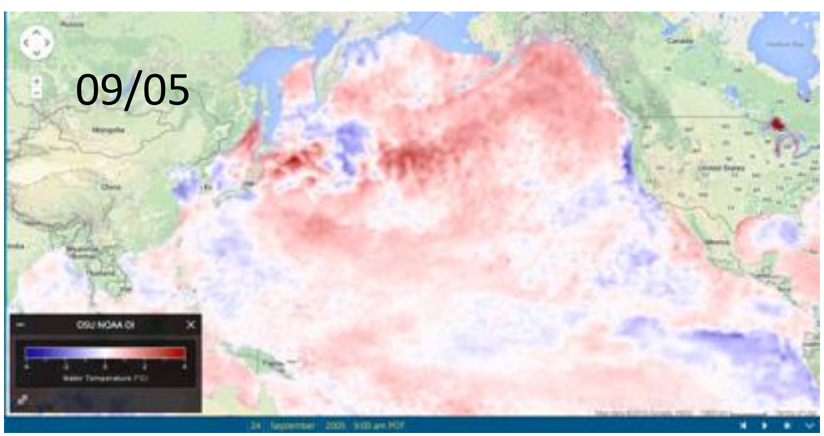
Reynolds SST Anomaly, Nov 2004 – Oct 2005 (slide 2 of 2)

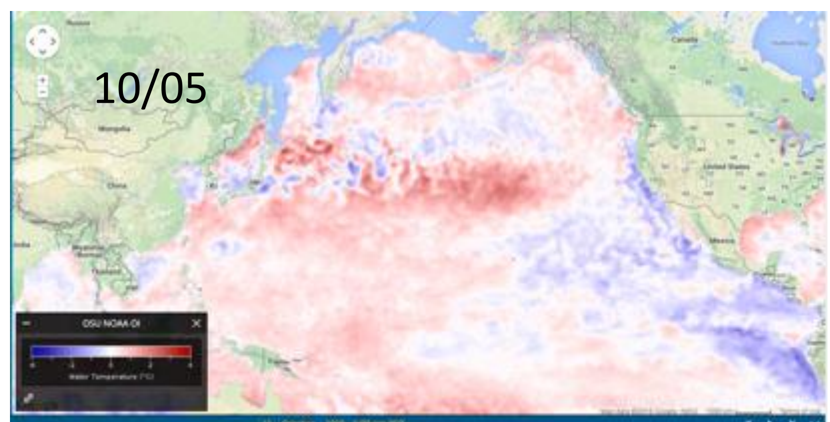












Needs?

External Heat Forcing?
Solar forcing/cloudiness (Atm models? See Bond et al.)

Diffusion/Mixing/Depth of surface layer
Kurapov WCOFS model – changes in stratification
Argo system

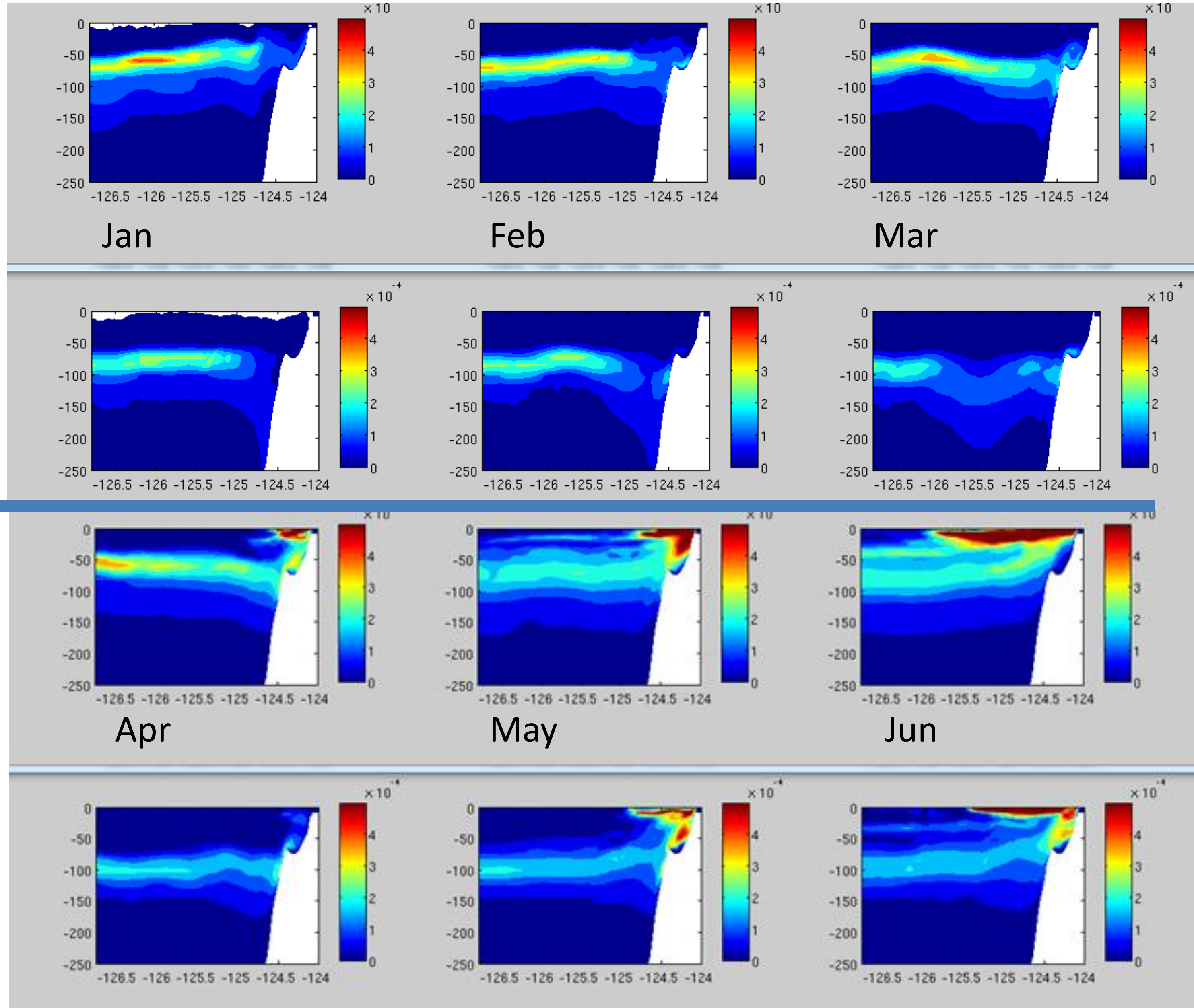
Compare strength of stratification (buoyancy frequency sq. N^2, $1/s^2$), monthly fields Jan – Jun. 2010 (strong mixing in winter) VS. 2014 (weak mixing in winter) **/ WCOFS Exp18-19**

2014 (weak winter winds)

2010 (strong winter winds)

2014 (spring following weak winter)

2010 (spring following strong winter)



Kurapov

Comments:

2014: weaker winter winds (effect of the anomalous atm. conditions over NEP),
2010: strong winter winds ("moderate El Nino winter")

In 2014, the seasonal winter pycnocline is stronger and shallower than in 2010. By May-Jun, surface warming creates a second thermocline, in each layer. Stronger in 2014.

Q: Does this have dramatic effect on vertical heat transport?
Q: Is it possible that in 2014 the increased heat flux was also captured in a shallower layer, which additionally contributed to anomalous SST?

Next steps:
(1) Compare to ARGO profiles, possibly glider
(2) Compute monthly-average vertical turbulent heat flux: K_T dT/dz, its vertical divergence: d/dz (K_T dT/dz).

Kurapov

From Alex Kurapov

A. Kurapov, Pacific Anomaly Workshop

Hypothesis: not only higher atmospheric flux, but also stronger than average near-surface stratification contributed to higher near-surface ocean temperatures in the PNW in spring 2014

Positive pressure anomaly over GoA in winter 2013 => weaker winter winds => shallower than usual (and stronger) seasonal thermocline in March 2014 => inhibited vertical turbulent flux of heat

Analysis tool: West Coast Ocean Forecast System (WCOFS) simulation (ROMS: 24-55N, 2-km resolution, **no** data assimilation, analyzing runs for Oct 2008-Dec 2011 and Oct 2013-2014; each run starts from Navy HYCOM initial conditions)

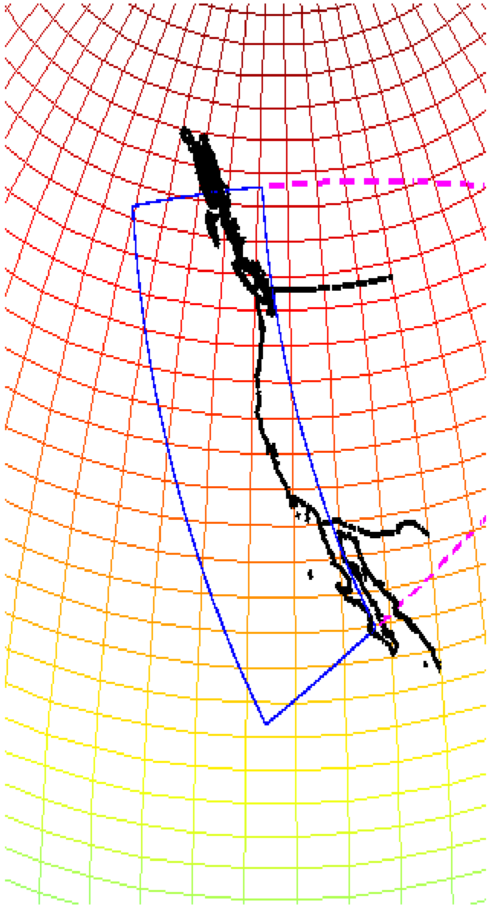
WCOFS: being developed and tested at NOAA (in partnership with OSU)

Model: Based on Regional Ocean Modeling System - ROMS (www.myroms.org)

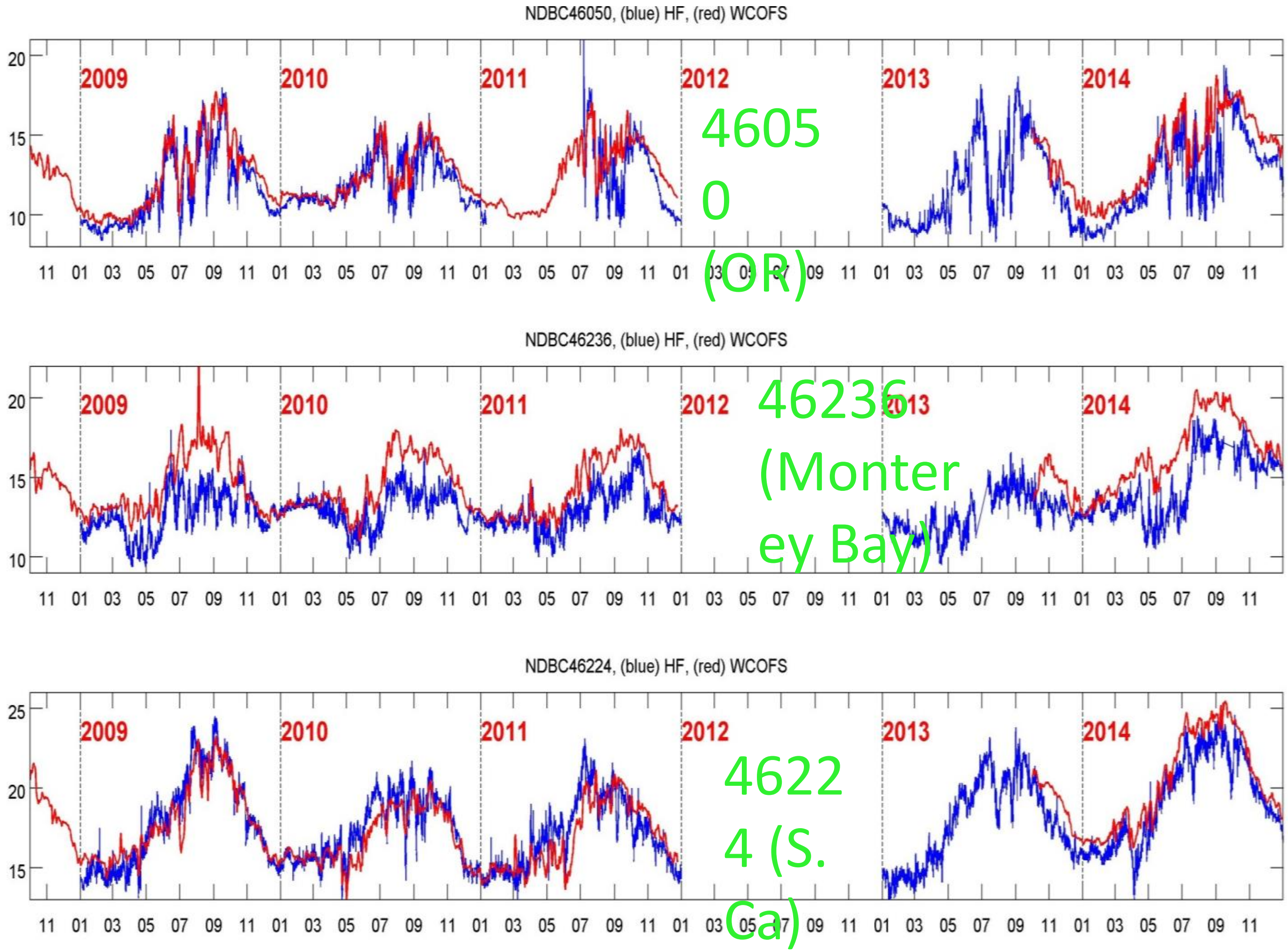
1000 x 4000 km domain
2-km resolution
Atm forcing: NOAA NAM
IC/BC: 1/12 degree global HYCOM (Navy, NOAA RTOFS)

Rivers: Columbia R., Fraser R., Puget Sound inputs

Verified against observations: HF radar surface velocity, coastal sea level, moored and satellite near-surface temperature, glider T and S sections



T at NDBC buoys (near-surface surface): WCOFS (daily-ave) vs. buoys (incl. high freq.)



Month of the year

“Warm blob”:

- Anomalously warm conditions in PNE in 2013-14.

Bond, Cronin, Freeland & Mantua, GRL, 2015

Figure 1. (a) Sea surface temperature anomalies (°C) in NE Pacific Ocean for February 2014. Anomalies are calculated relative to the mean from 1981 to 2010. (b) Upper ocean temperature anomalies (°C) along “Line P”

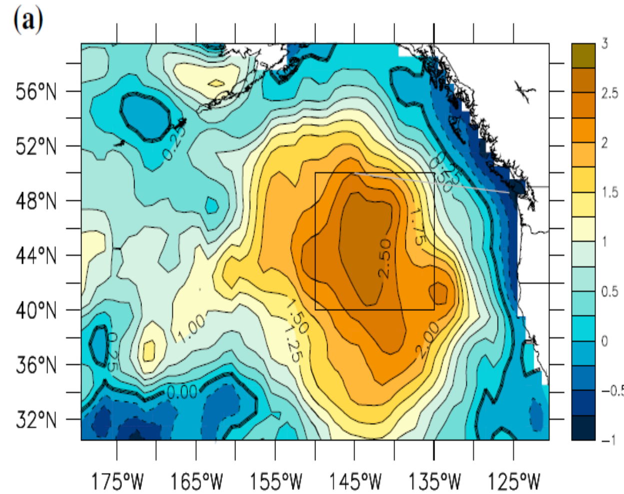


Figure 2. Mean sea level pressure anomalies (hPa) in the NE Pacific Ocean for the period of October 2013 through January 2014. Anomalies are calculated relative to the mean from 1981 to 2010.

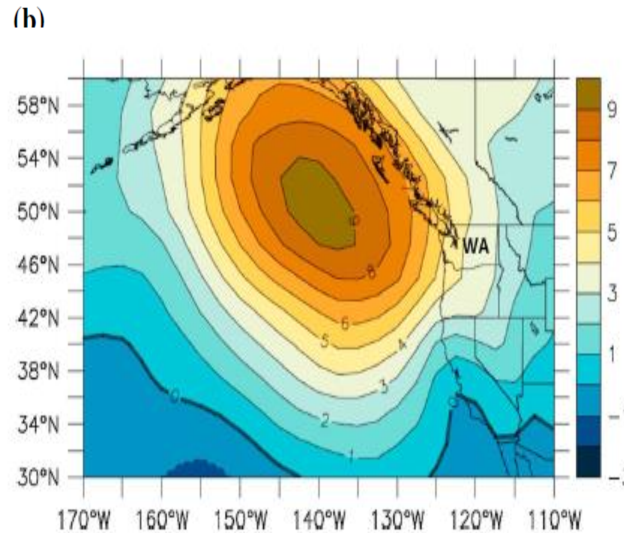
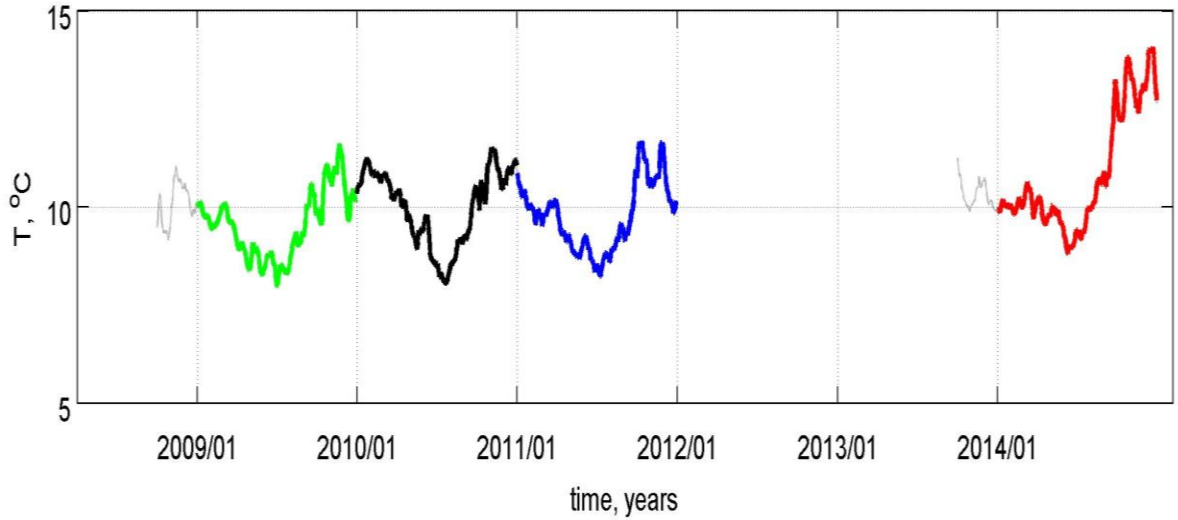


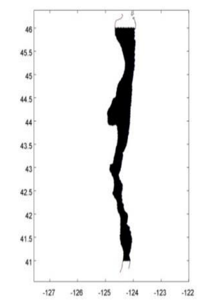
Figure 2. Mean sea level pressure anomalies (hPa) in the NE Pacific Ocean for the period of October 2013 through January 2014. Anomalies are calculated relative to the mean from 1981 to 2010.

Notes:

- Anomalously weak winter winds in 2014
- Warmer ocean conditions starting 2014

Timeline
(shown is volume-averaged model temperature off Oregon
(41-46N, H<=200 m)





Two runs (each started from HYCOM IC): Oct 2008-2011,
Oct 2013-2014

How do we address the "blob" issue?
WCOFS is run for Oct 2013-2014 and is compared to the Oct 2008-2011 run

Volume average temperature balance analysis
(sim. to Durski et al., Oc. Dyn., 2015**):**

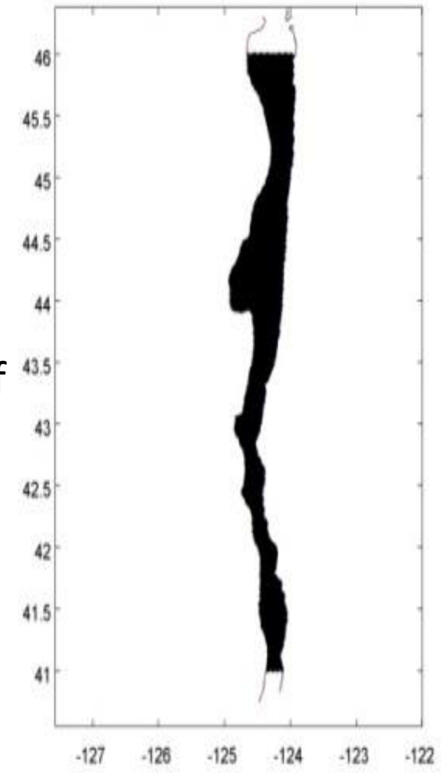
- to understand relative contributions of the atmospheric heat flux and ocean advection to rising the temperature on the Oregon shelf

Integrate heat equation in horizontal over a shelf area (41-47N, H<200 m), in vertical from bottom to surface

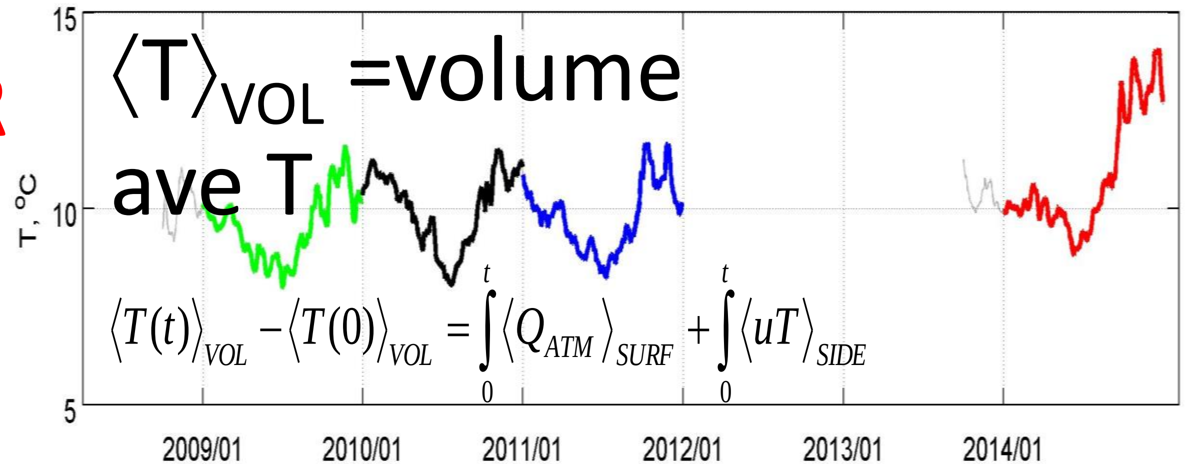
$\langle T \rangle_{VOL}$ =volume ave T

Integrate in time from Jan 1 to t (terms are appropriately normalized to obtain units of ^{o}C):

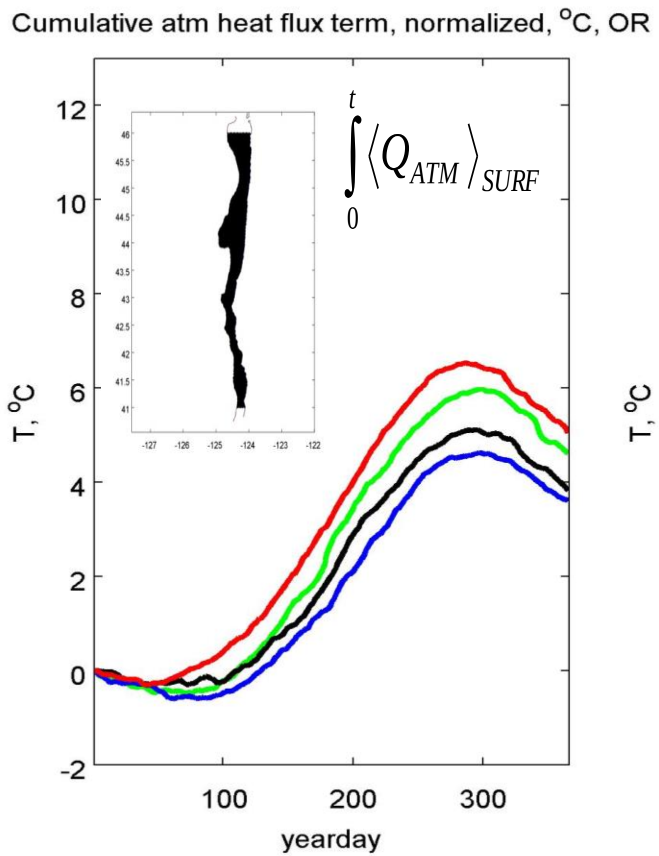
$$\langle T(t) \rangle_{VOL} - \langle T(0) \rangle_{VOL} = \int_0^t \langle Q_{ATM} \rangle_{SURF} + \int_0^t \langle uT \rangle_{SIDE}$$



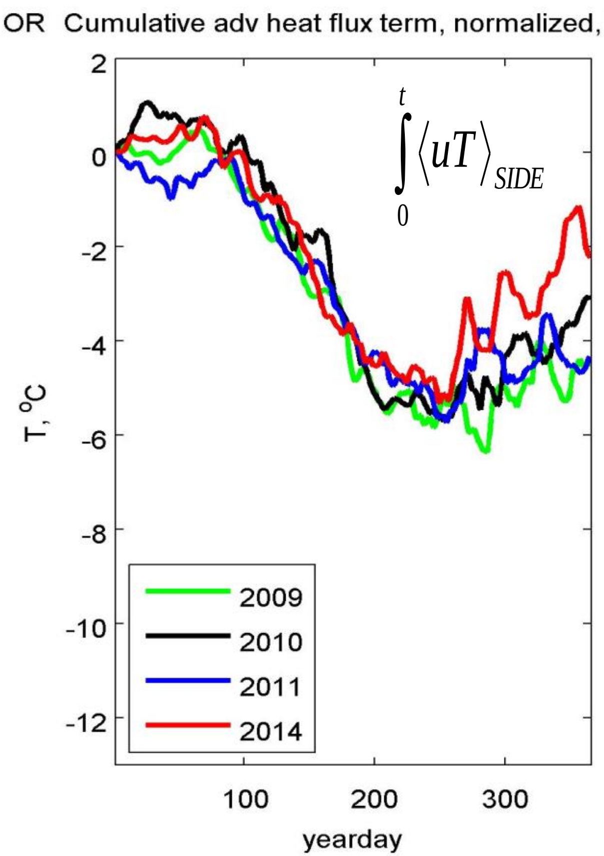
OR



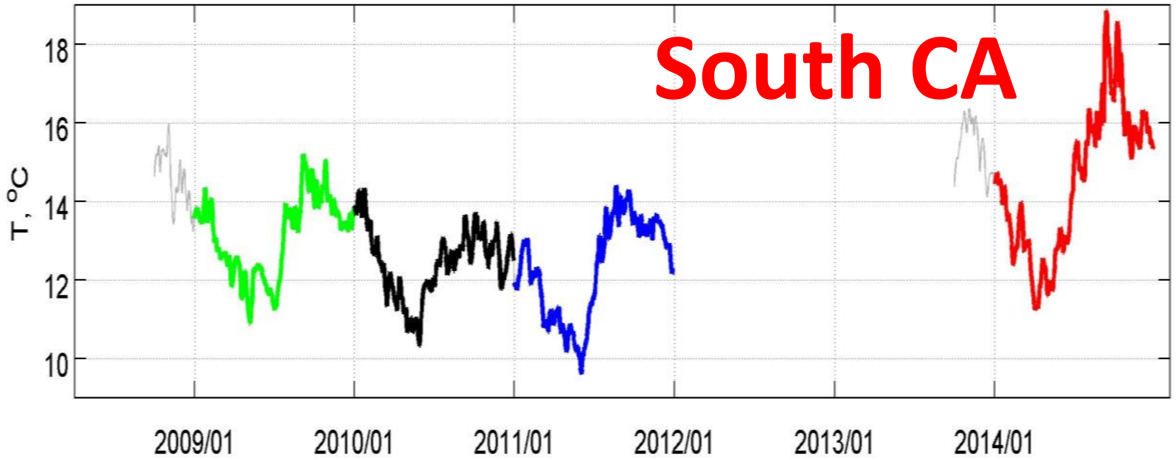
$$\langle T(t)\rangle_{VOL} - \langle T(0)\rangle_{VOL} = \int_0^t \langle Q_{ATM}\rangle_{SURF} + \int_0^t \langle uT\rangle_{SIDE}$$

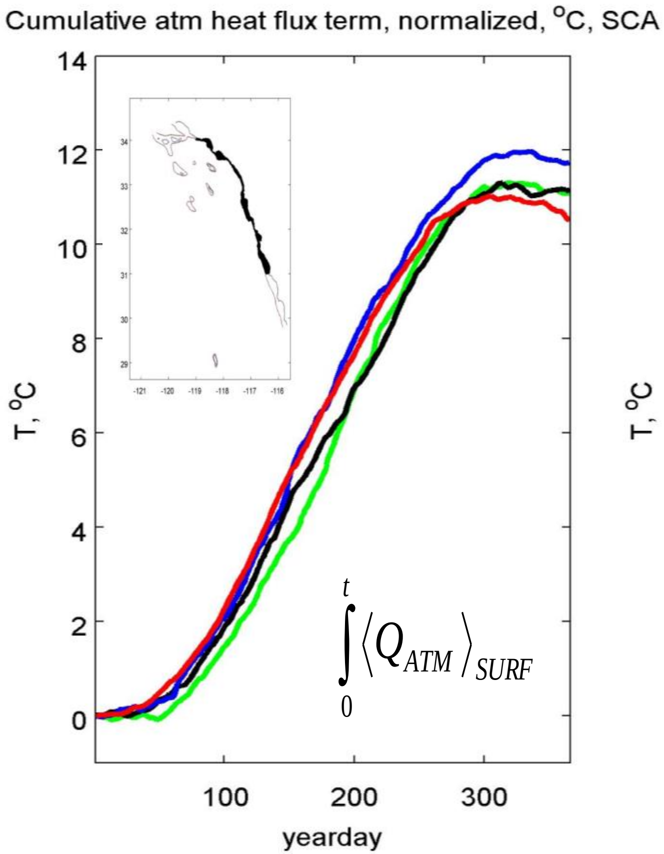


$$\int_0^t \langle Q_{ATM}\rangle_{SURF}$$



$$\int_0^t \langle uT\rangle_{SIDE}$$


South CA
T, °C
18
16
14
12
10
2009/01
2010/01
2011/01
2012/01
2013/01
2014/01


Cumulative atm heat flux term, normalized, °C, SCA
T, °C
yearday
$\int_0^t \langle Q_{ATM} \rangle_{SURF}$

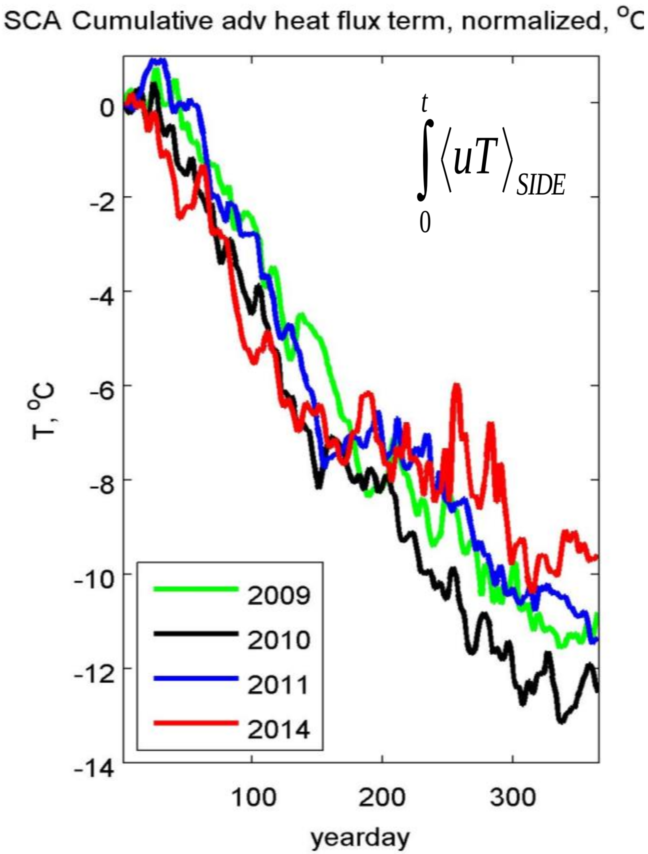
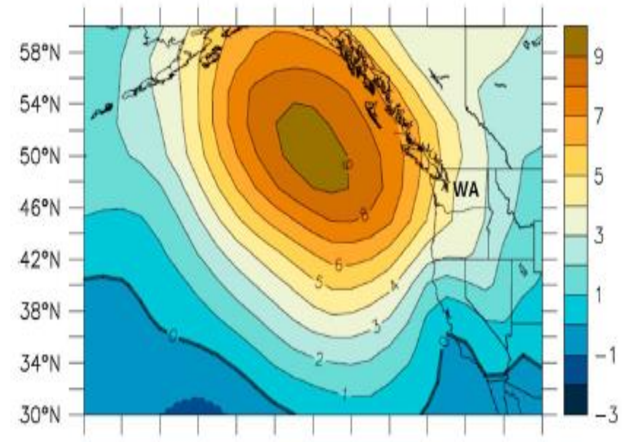
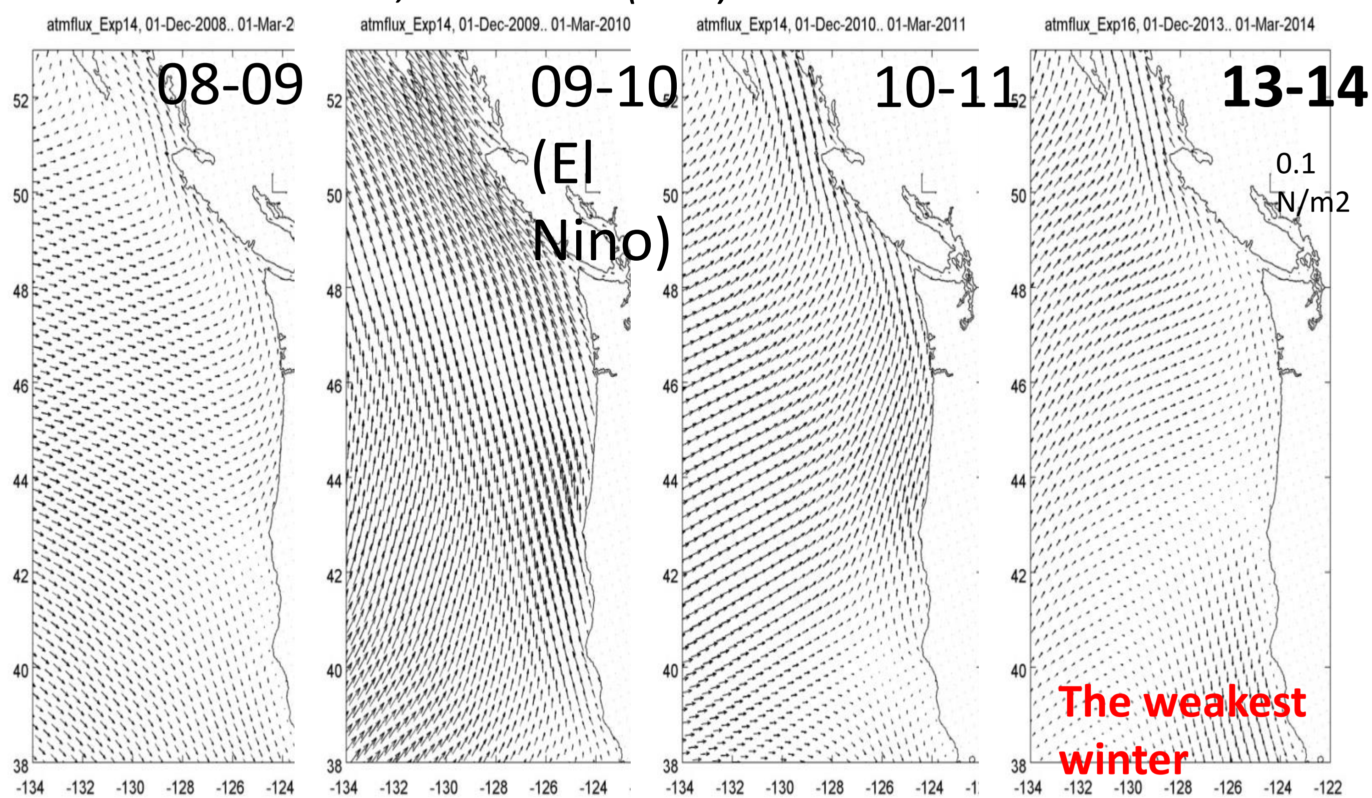
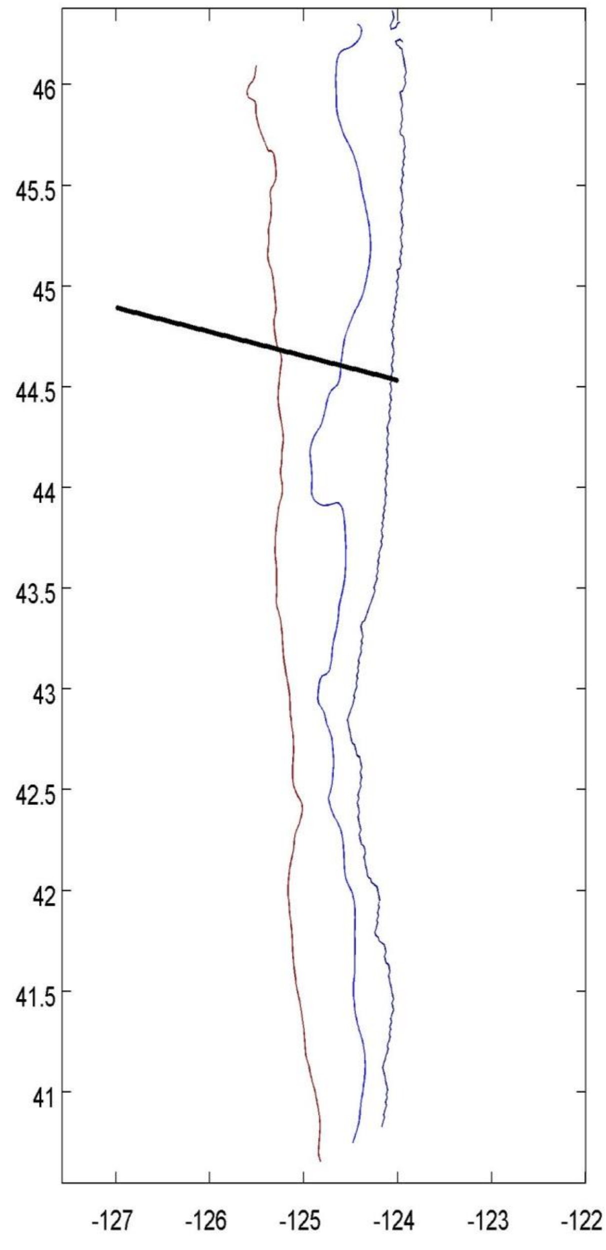

Cumulative adv heat flux term, normalized, °C
T, °C
yearday
$\int_0^t \langle uT \rangle_{SIDE}$
2009
2010
2011
2014

Figure 2 from ***Bond, Cronin, Freeland & Mantua, GRL, 2015:*** *Mean Sea Level P anomaly (hPa) Oct 2013-Jan 2014, relative to 1981-*



model wind stress, 3-mo ave. (DJF)




46
45.5
45
44.5
44
43.5
43
42.5
42
41.5
41
-127
-126
-125
-124
-123
-122

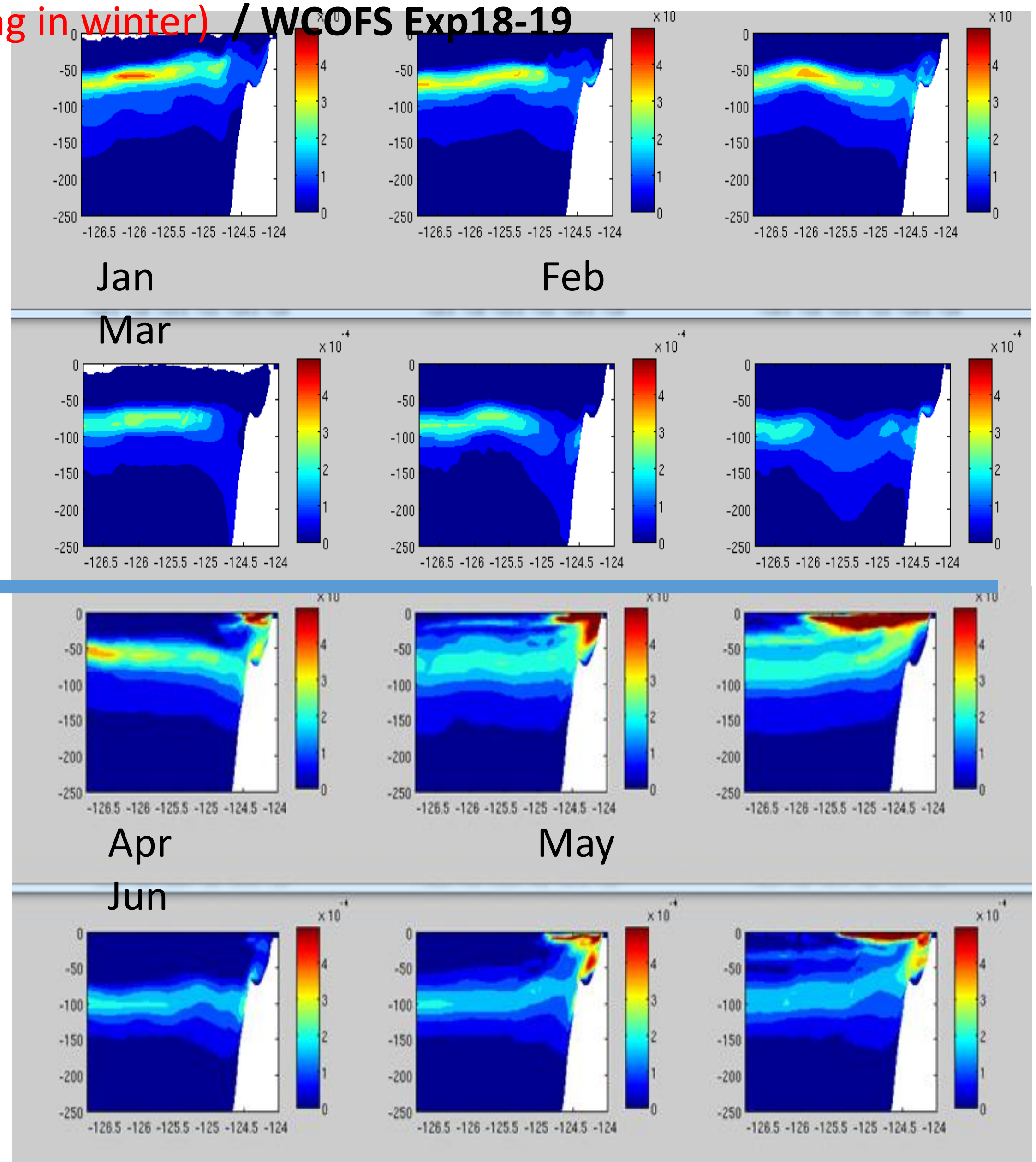
Compare strength of stratification (buoyancy frequency sq. N^2, $1/s^2$), monthly fields Jan – Jun. 2014 (weak mixing in winter) vs 2010 (strong mixing in winter) / **WCOFS Exp18-19**

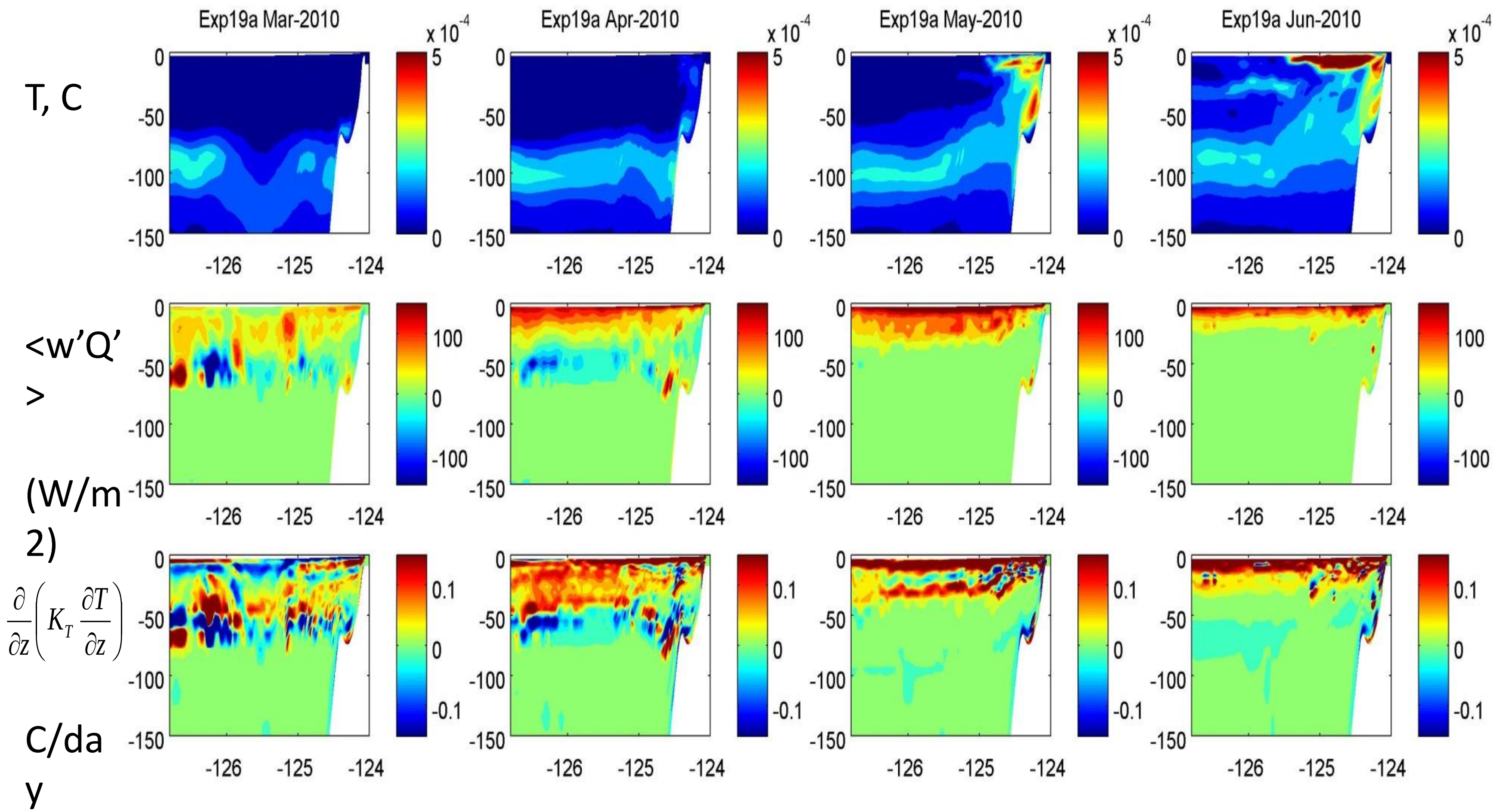
2014 (weak winter winds)

2010 (strong winter winds)

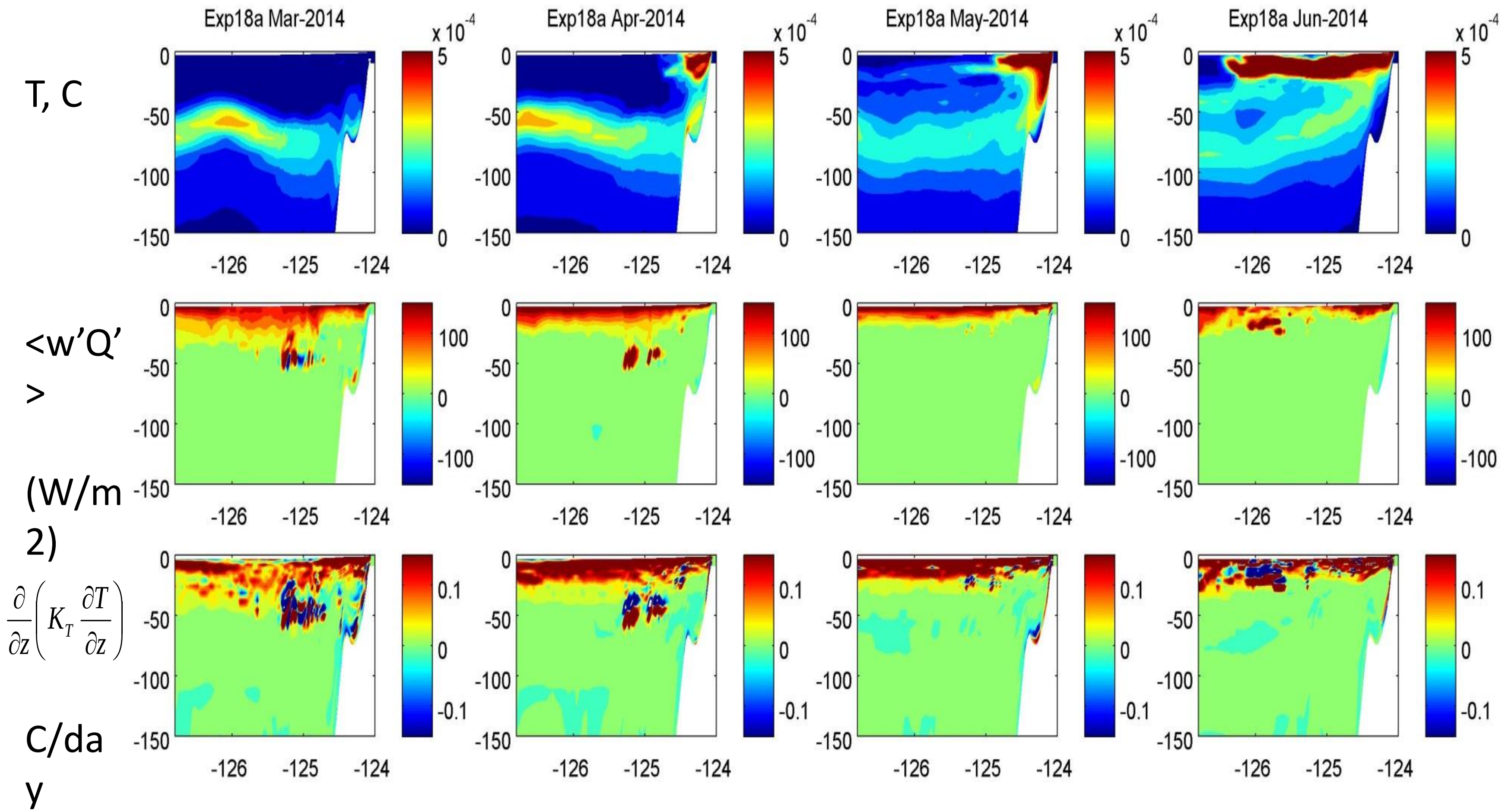
2014 (spring following weak winter)

2010 (spring following strong



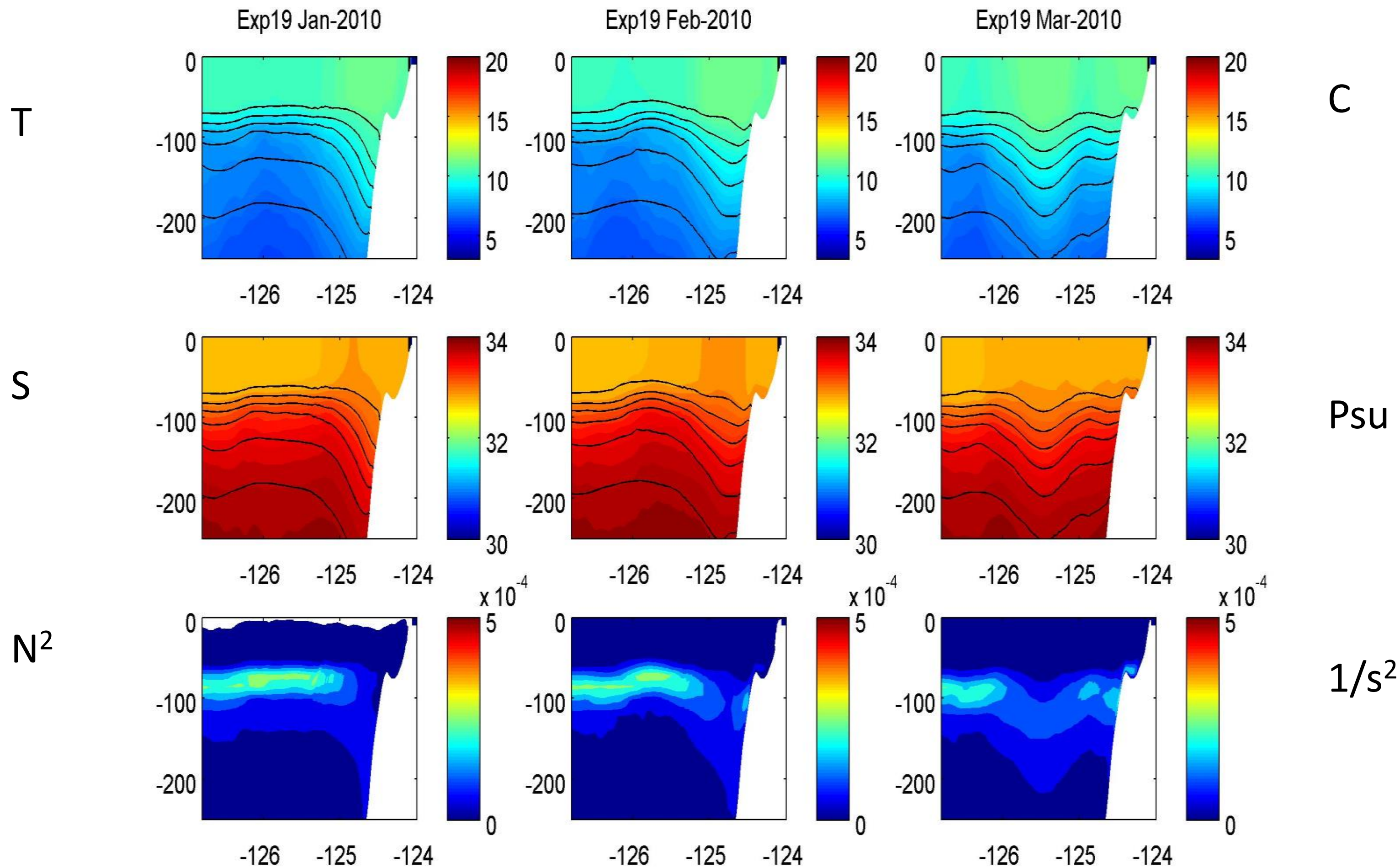


T, C
<w'Q'>
(W/m2)
$\frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z}\right)$
C/day
Exp19a Mar-2010
Exp19a Apr-2010
Exp19a May-2010
Exp19a Jun-2010
x 10^-4
0
5
-50
-100
-150
-126
-125
-124
100
-100
0.1
-0.1

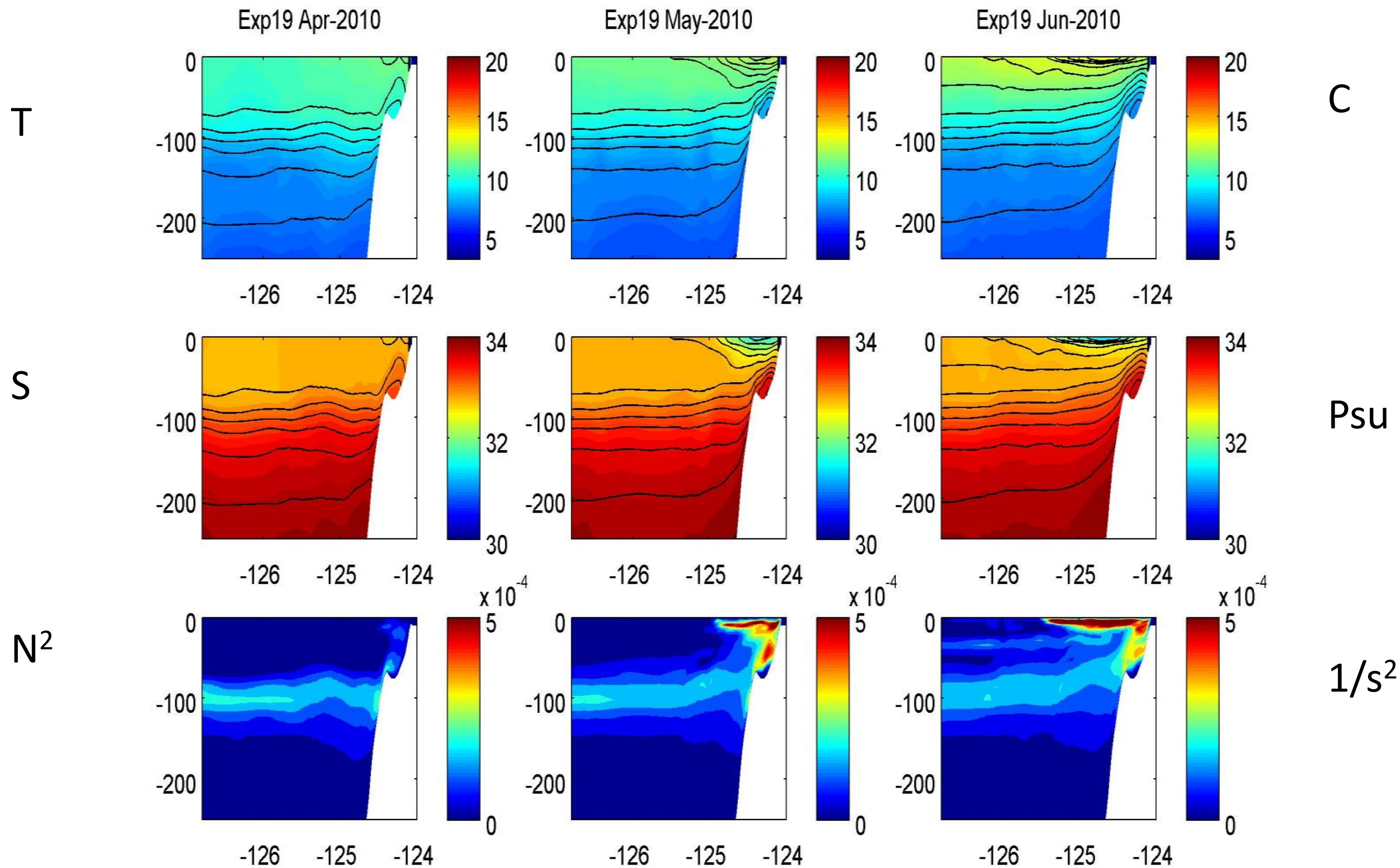


T, C
<w'Q'>
(W/m2)
$\frac{\partial}{\partial z}\left(K_T \frac{\partial T}{\partial z}\right)$
C/day
Exp18a Mar-2014
Exp18a Apr-2014
Exp18a May-2014
Exp18a Jun-2014
x 10^-4
5
0
100
-100
0.1
-0.1
-50
-150
-126
-125
-124

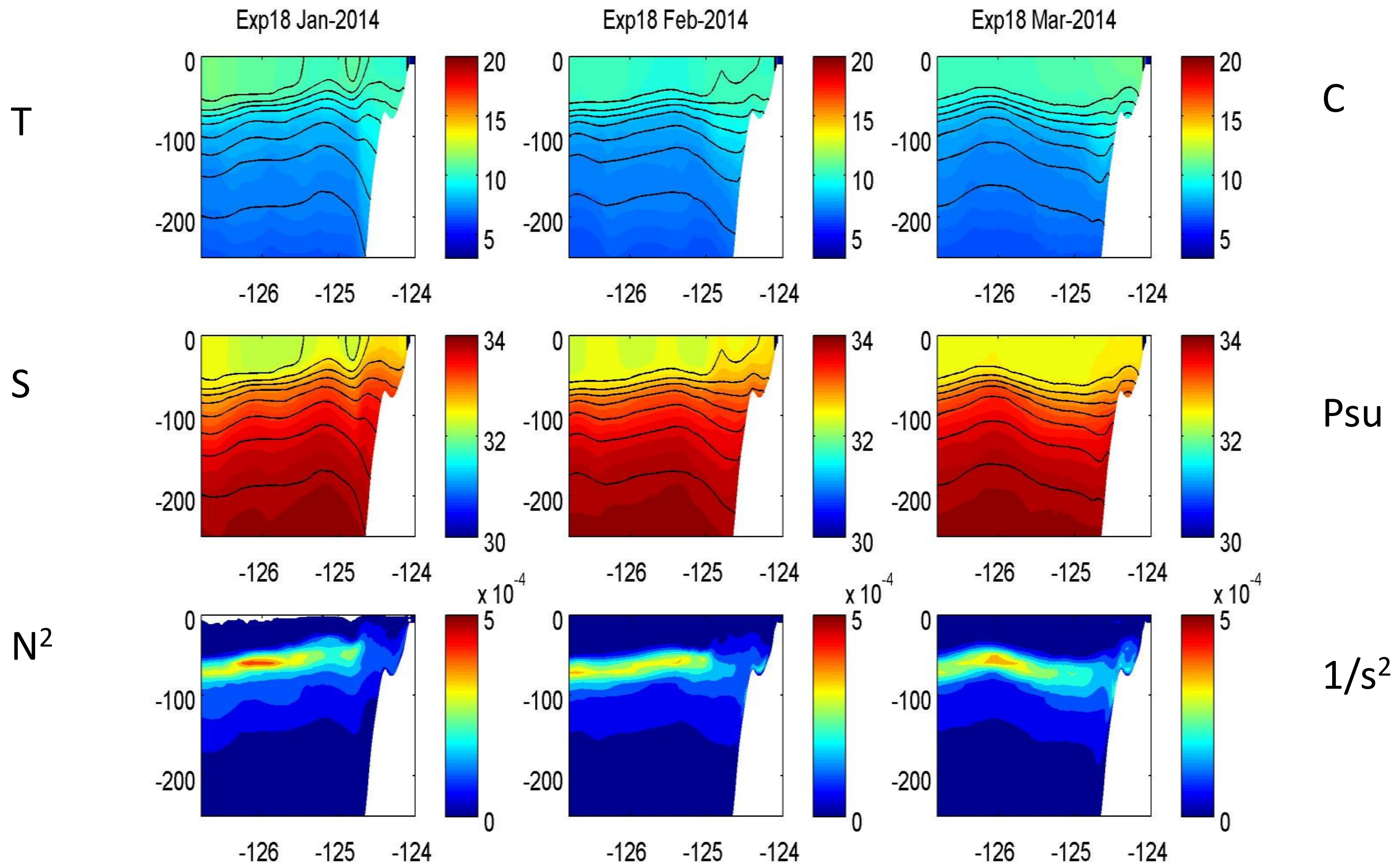
Extras: sections of monthly ave T, S, N2.



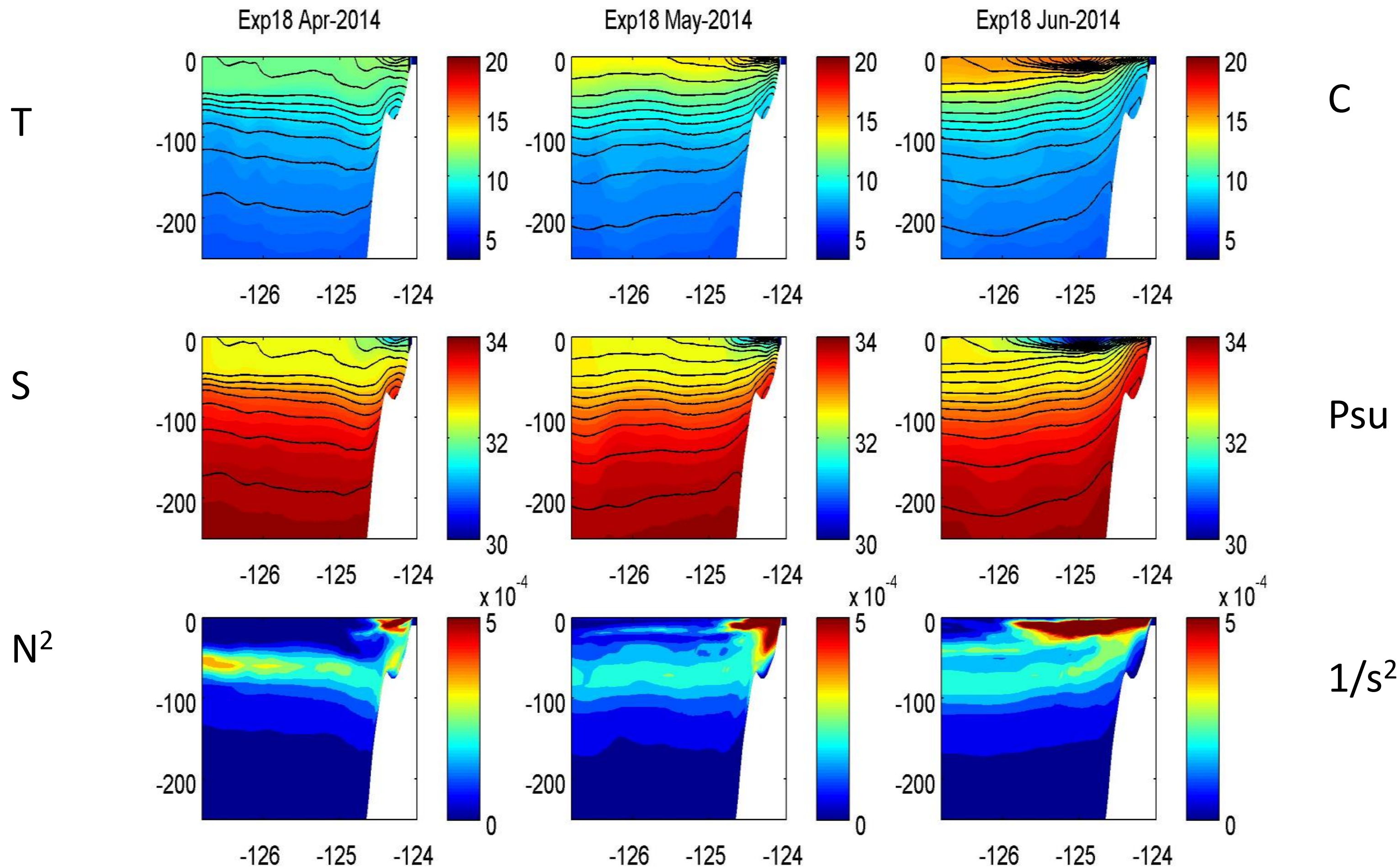
Exp19 Jan-2010
Exp19 Feb-2010
Exp19 Mar-2010
T
C
S
Psu
N2
1/s2
x 10-4
0
-100
-200
-126
-125
-124
20
15
10
5
34
32
30



Exp19 Apr-2010
Exp19 May-2010
Exp19 Jun-2010
T
S
N2
C
Psu
1/s2
x 10-4
0
-100
-200
-126
-125
-124
20
15
10
5
34
32
30



Exp18 Jan-2014
Exp18 Feb-2014
Exp18 Mar-2014
T
C
S
Psu
N²
1/s²
0
-100
-200
-126
-125
-124
20
15
10
5
34
32
30
x 10⁻⁴
5
0



Exp18 Apr-2014
Exp18 May-2014
Exp18 Jun-2014
T
S
N2
C
Psu
1/s2
x 10-4
0
-100
-200
-126
-125
-124
20
15
10
5
34
32
30