Influence of eddies and mesoscale variability in the Gulf of Alaska

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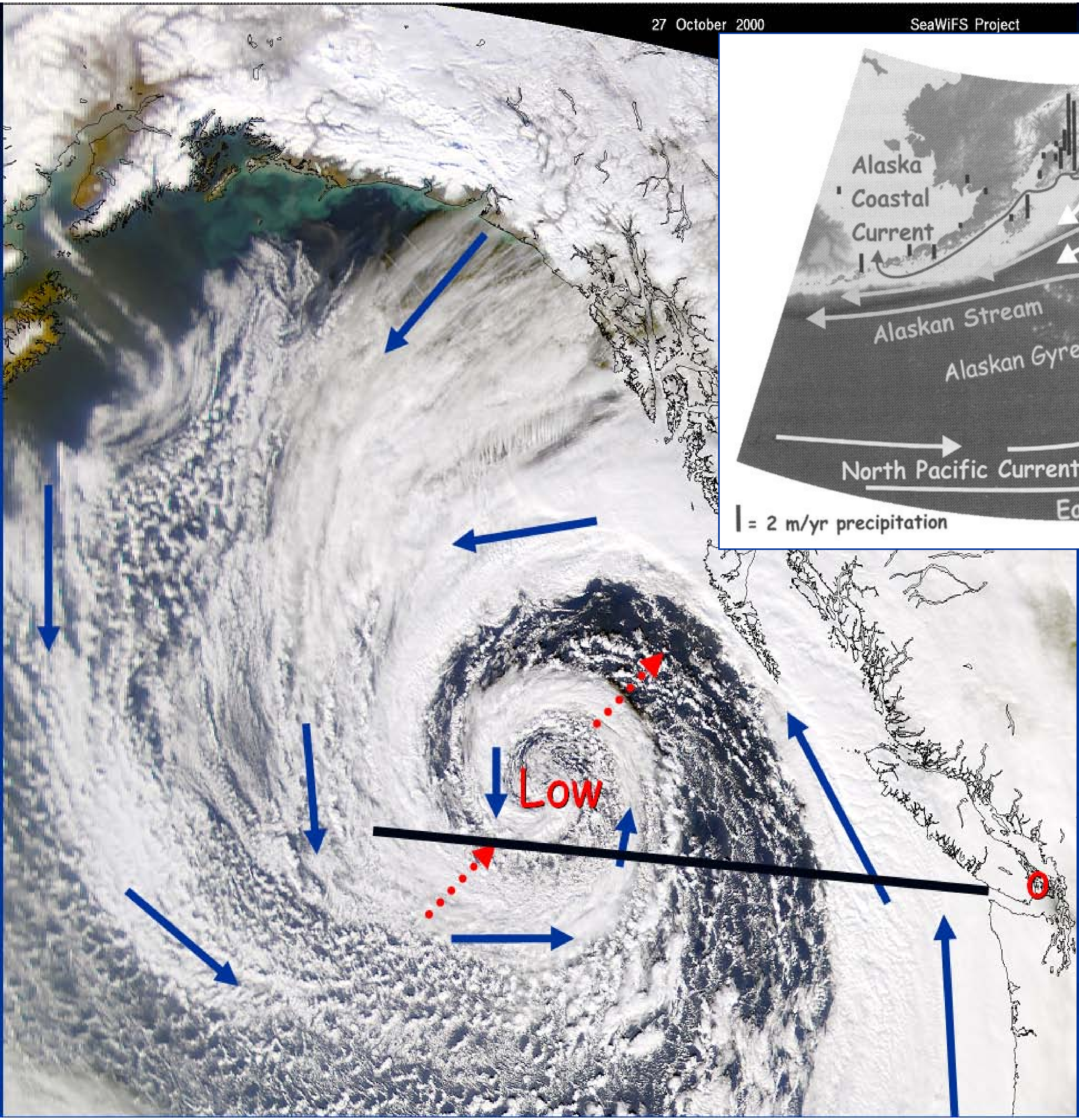


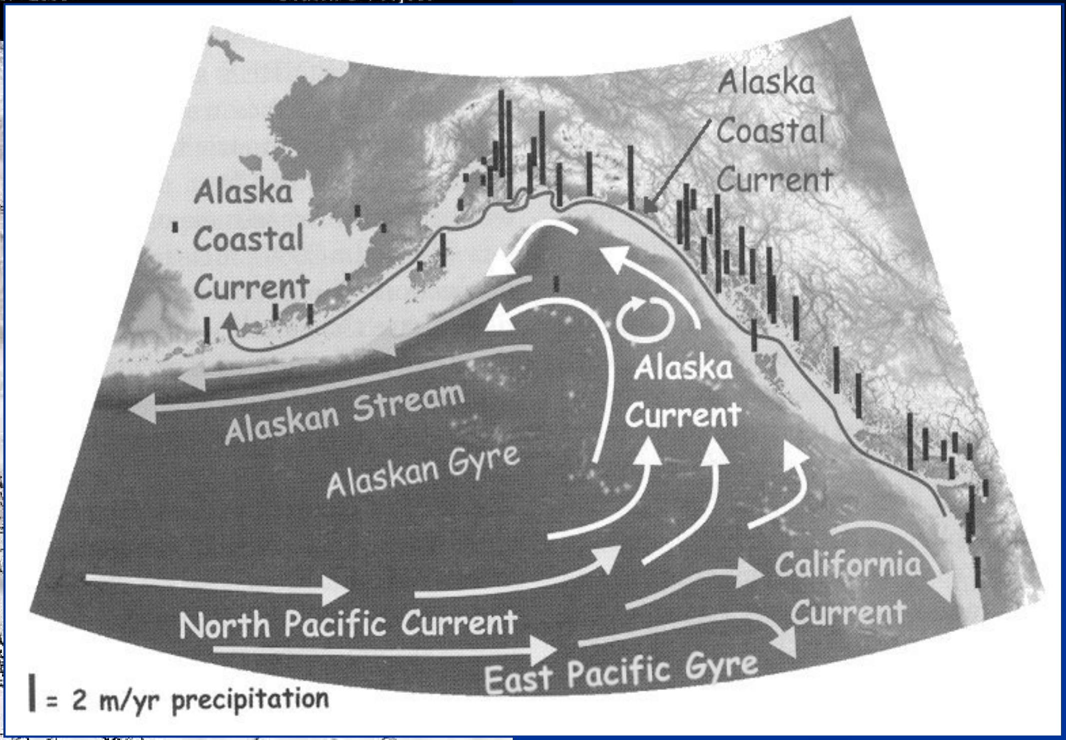
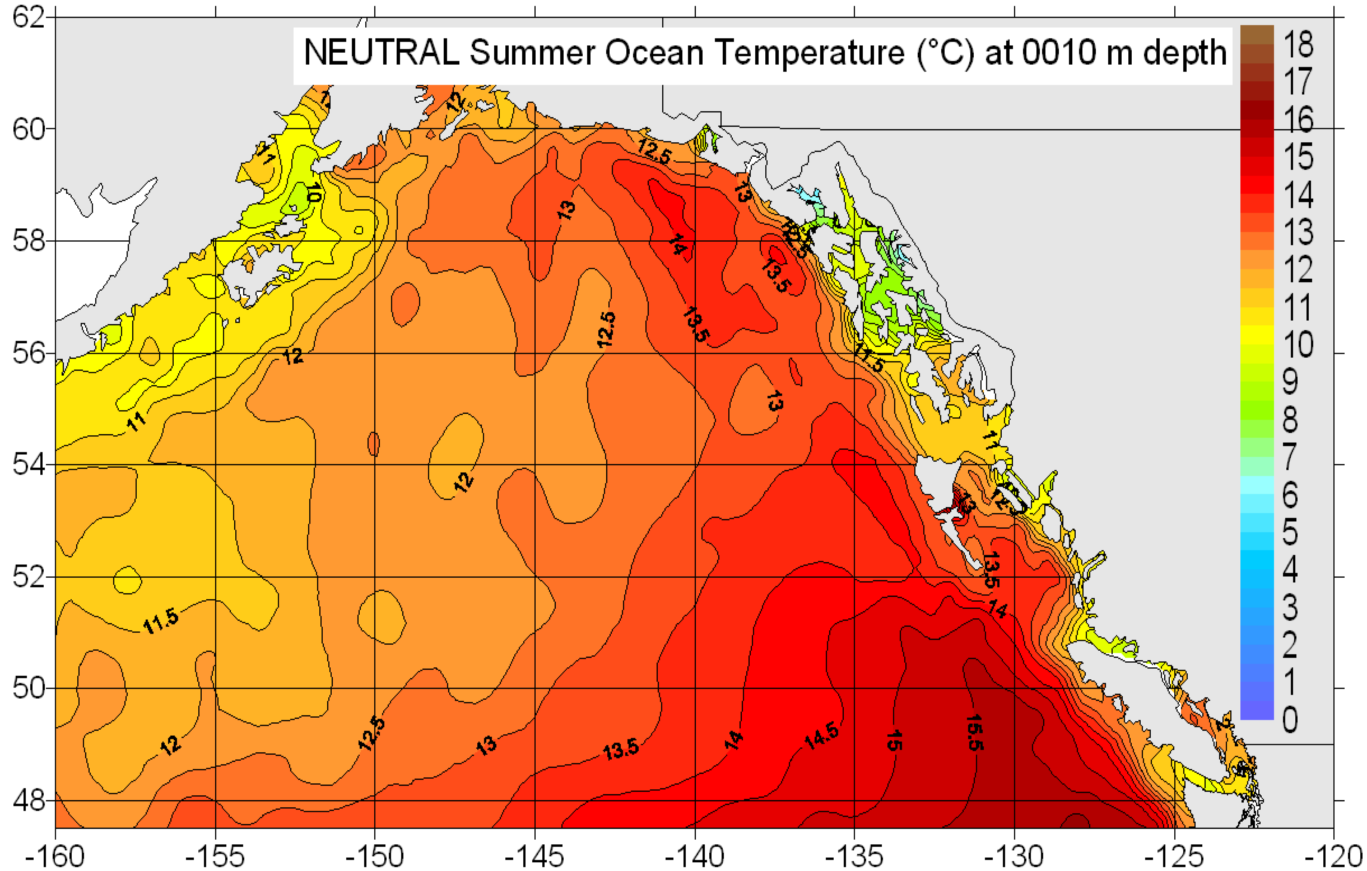


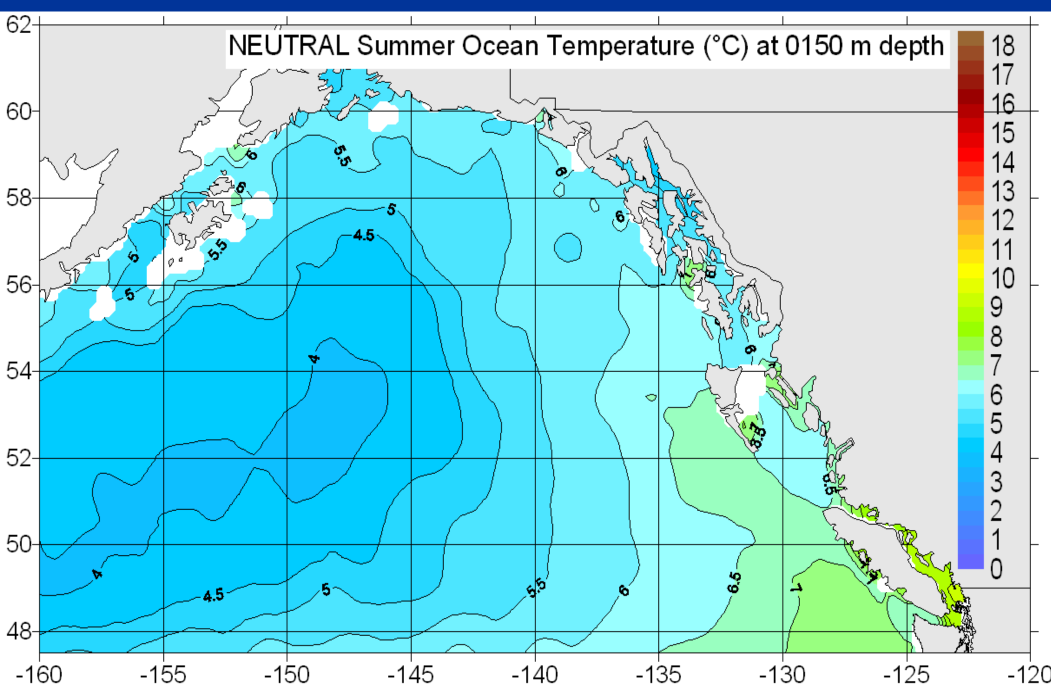
Figure above adapted from Mundy and Danielson

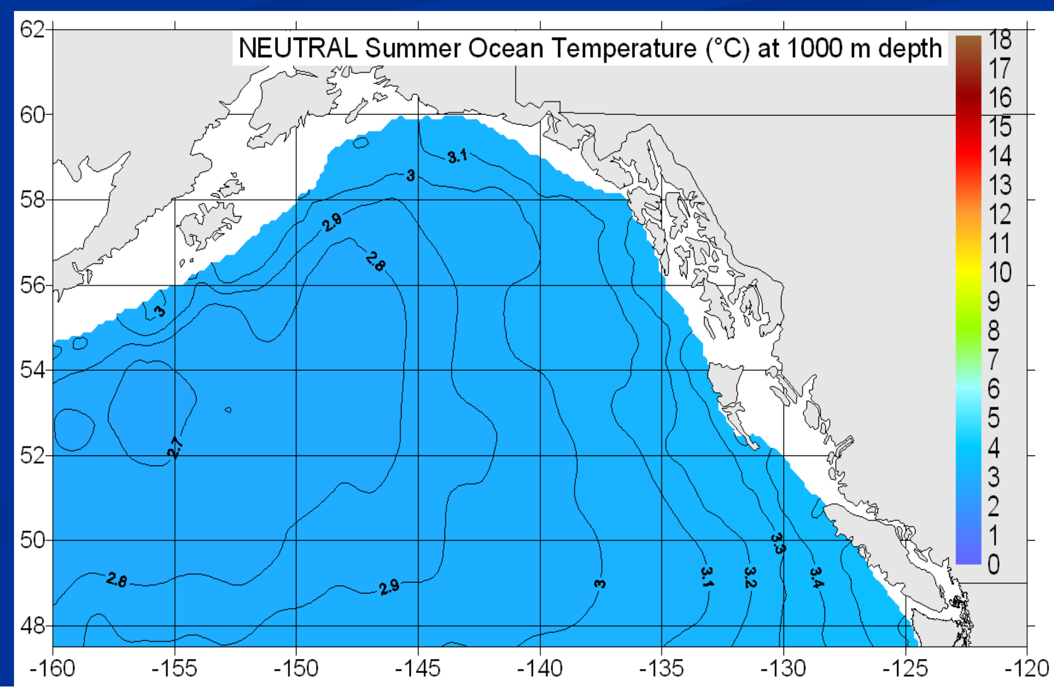
Winter winds set the general flow of currents and the temperatures, even in summer.

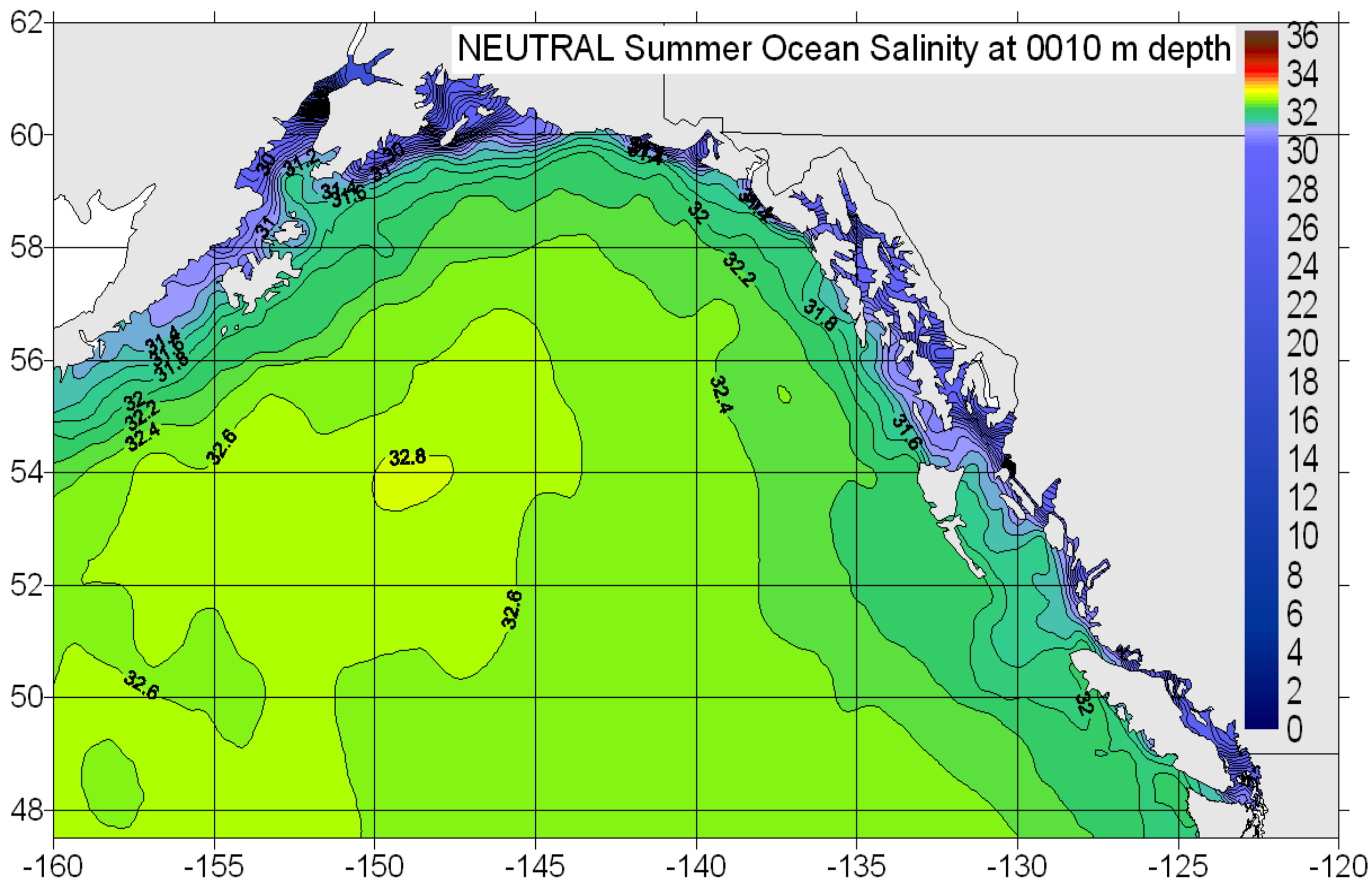


Jake Galbraith processed all profile of T and S observations from NODC, MEDS and IOS archives, with coverage all through coastal areas.

Median values were computed for August and September of years not impacted by major El Niño or La Niña events.







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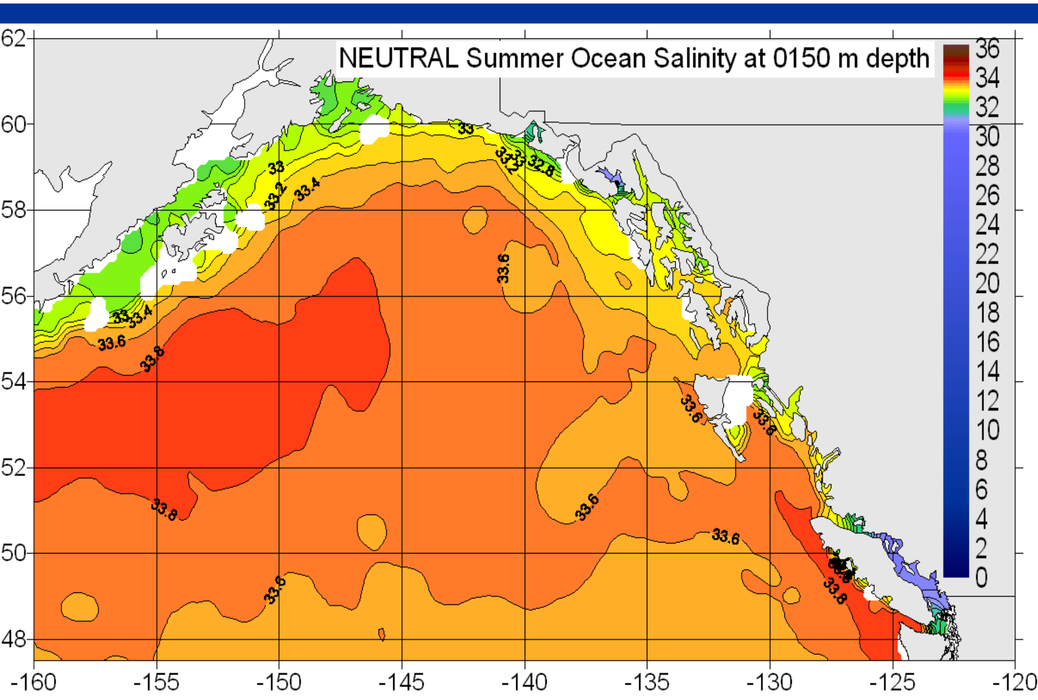
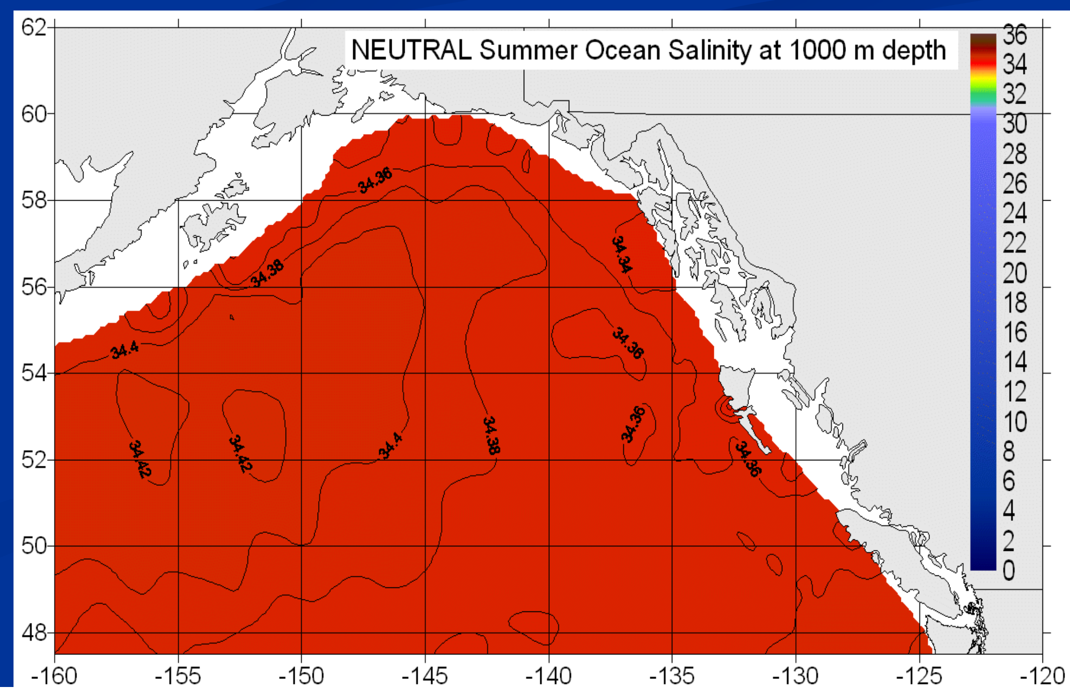
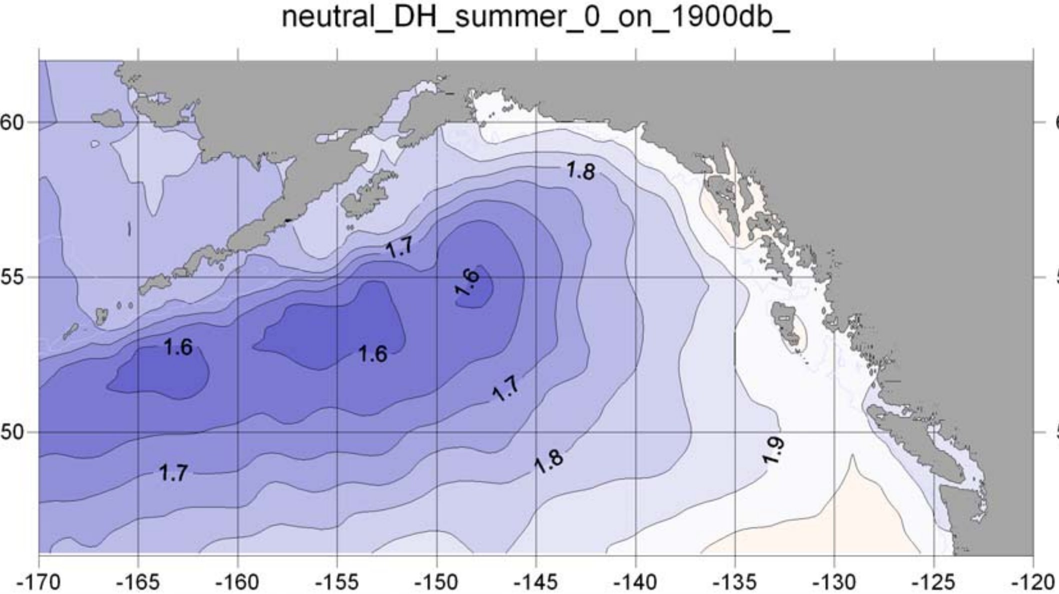
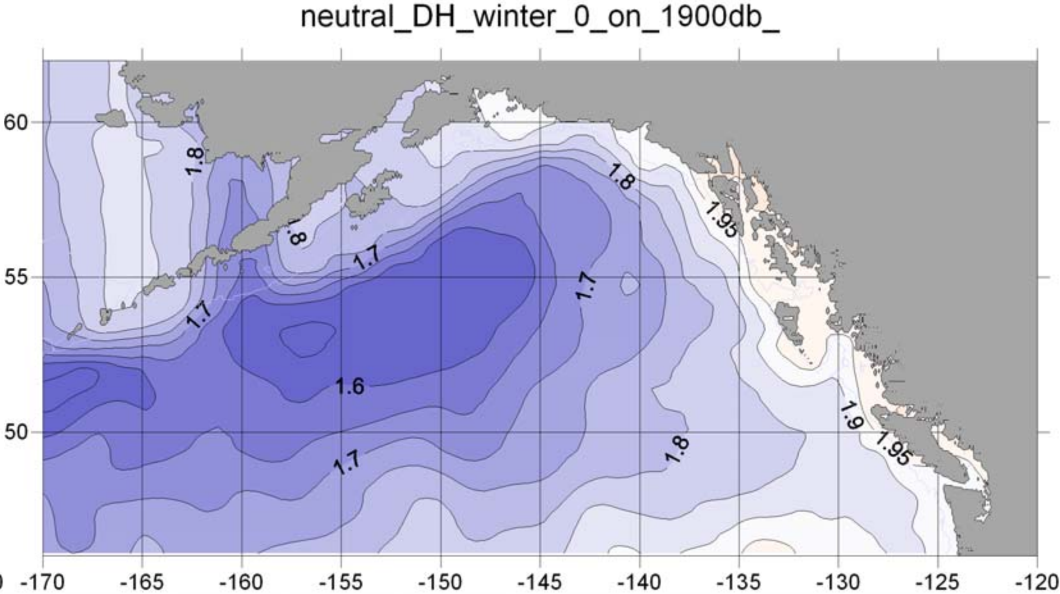




Nick Bolingbroke computed dynamic height anomalies from the climatology of temperature and salinity, referenced to 1900 m, which lies just above the deep limit of most Argo profilers.

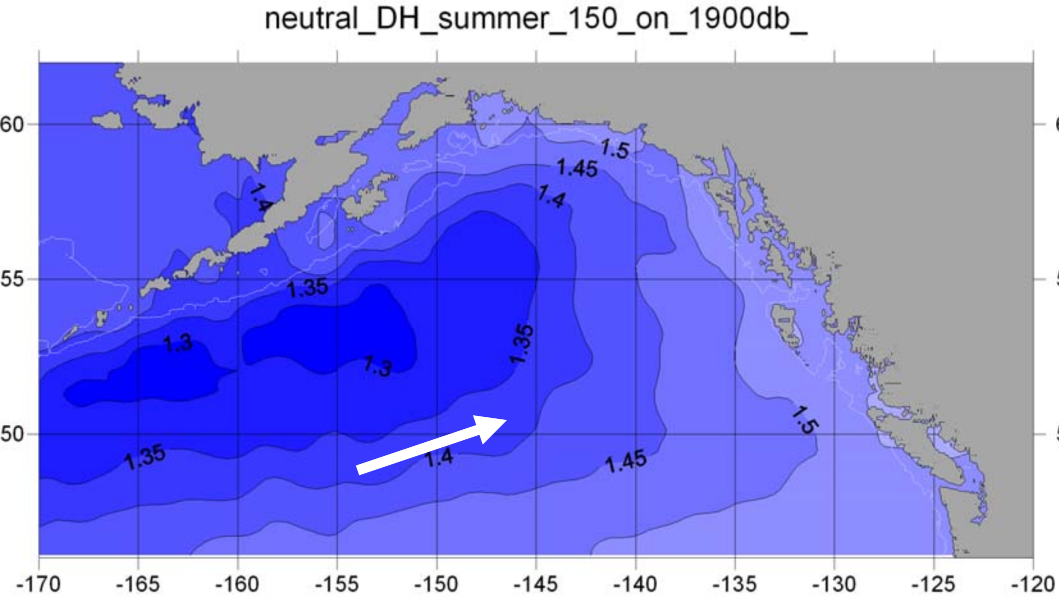
Note the streamlines change little from summer to winter, and from surface to 150 m depth.

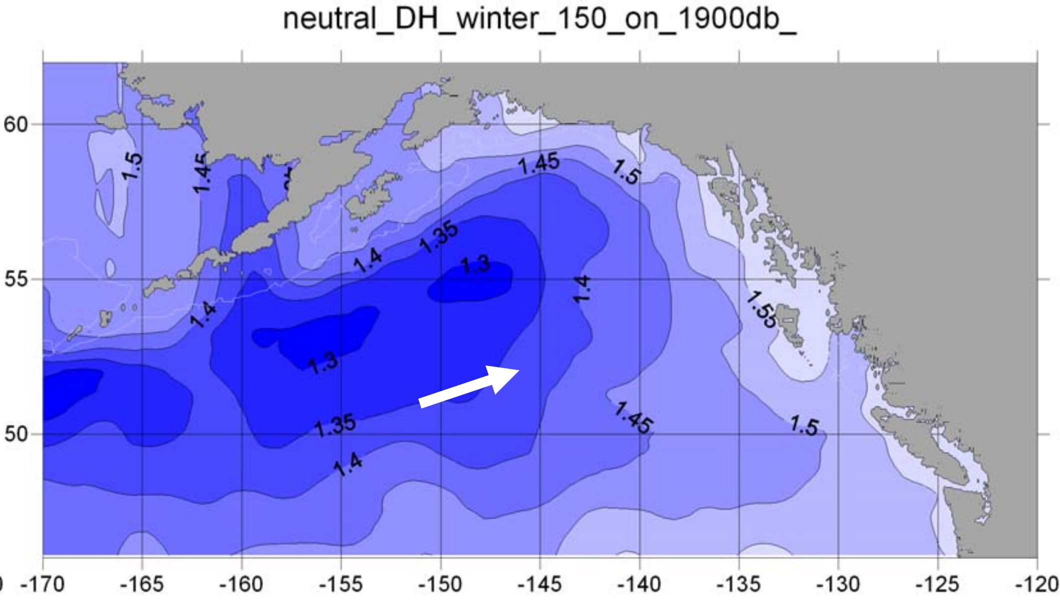


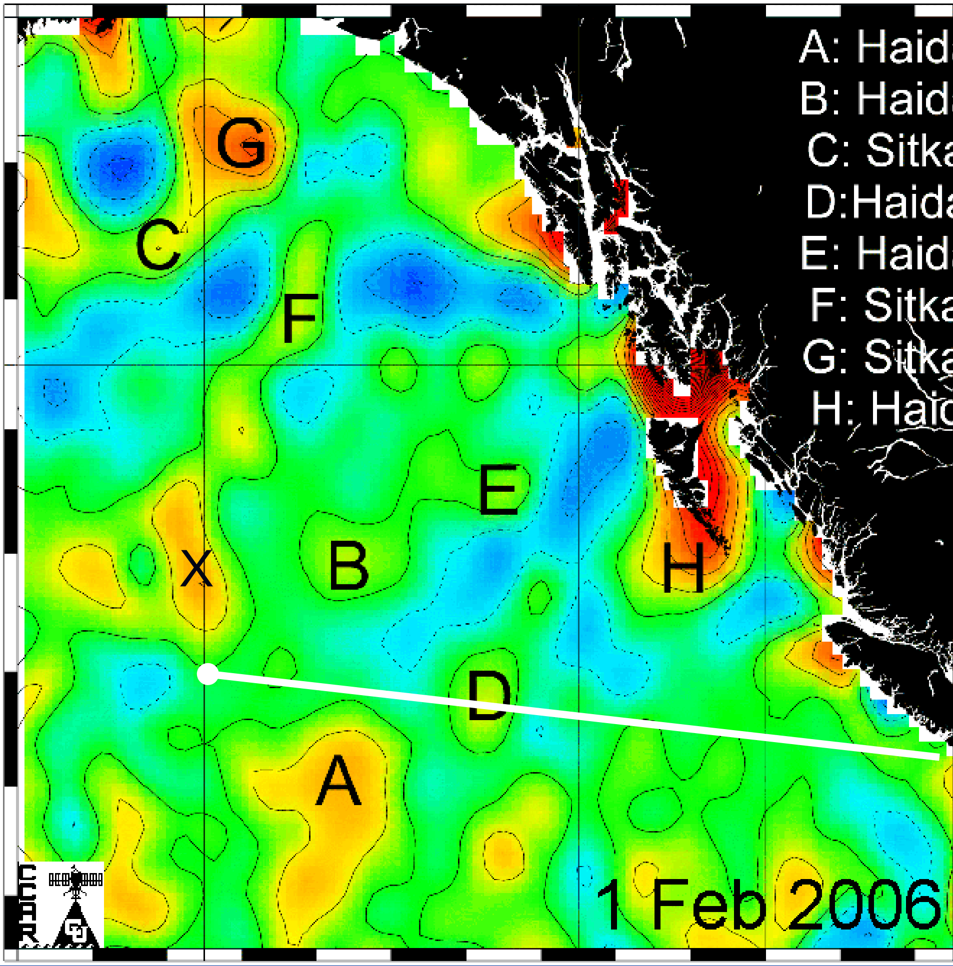


Nominal speed is 4 cm/sec ≈ 1500 km/year

Nominal speed is 3 cm/sec ≈ 1200 km/year.

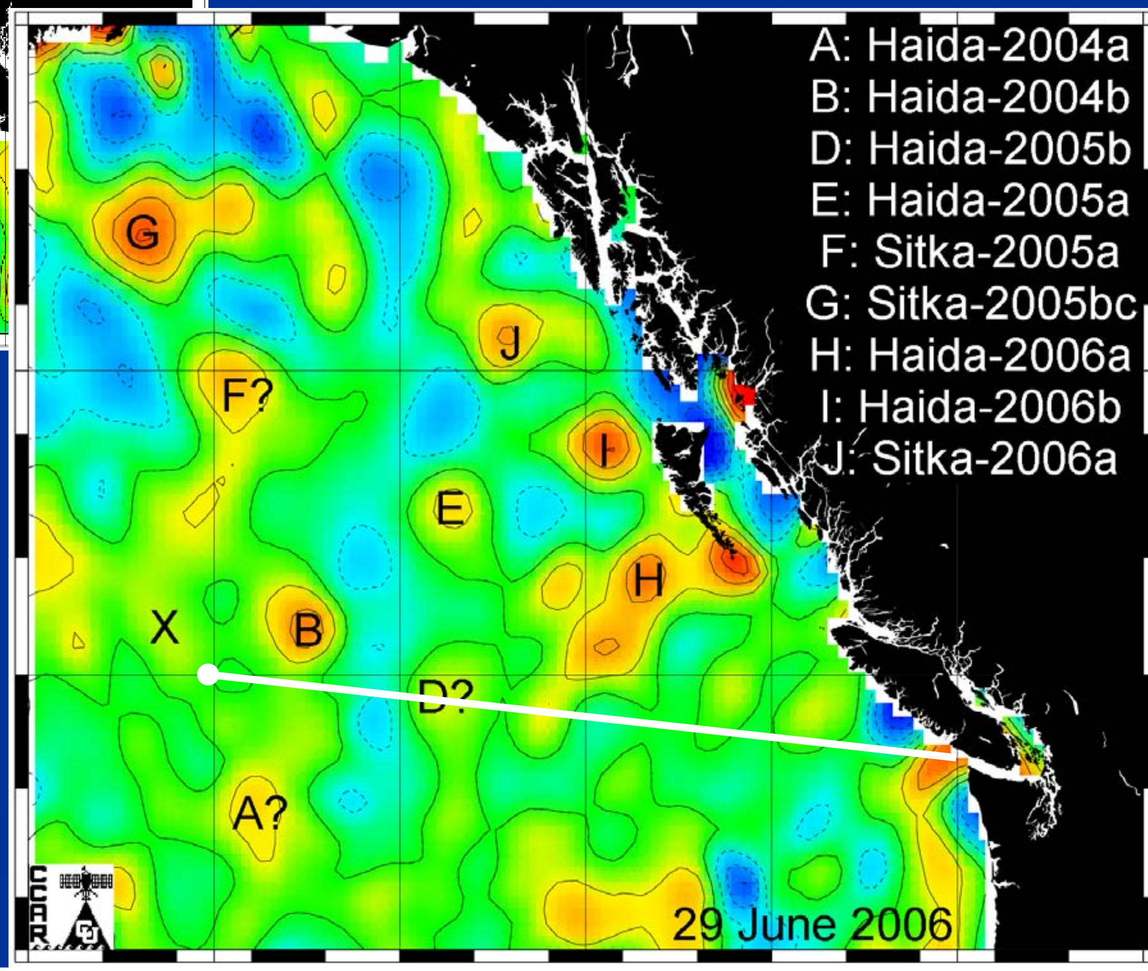




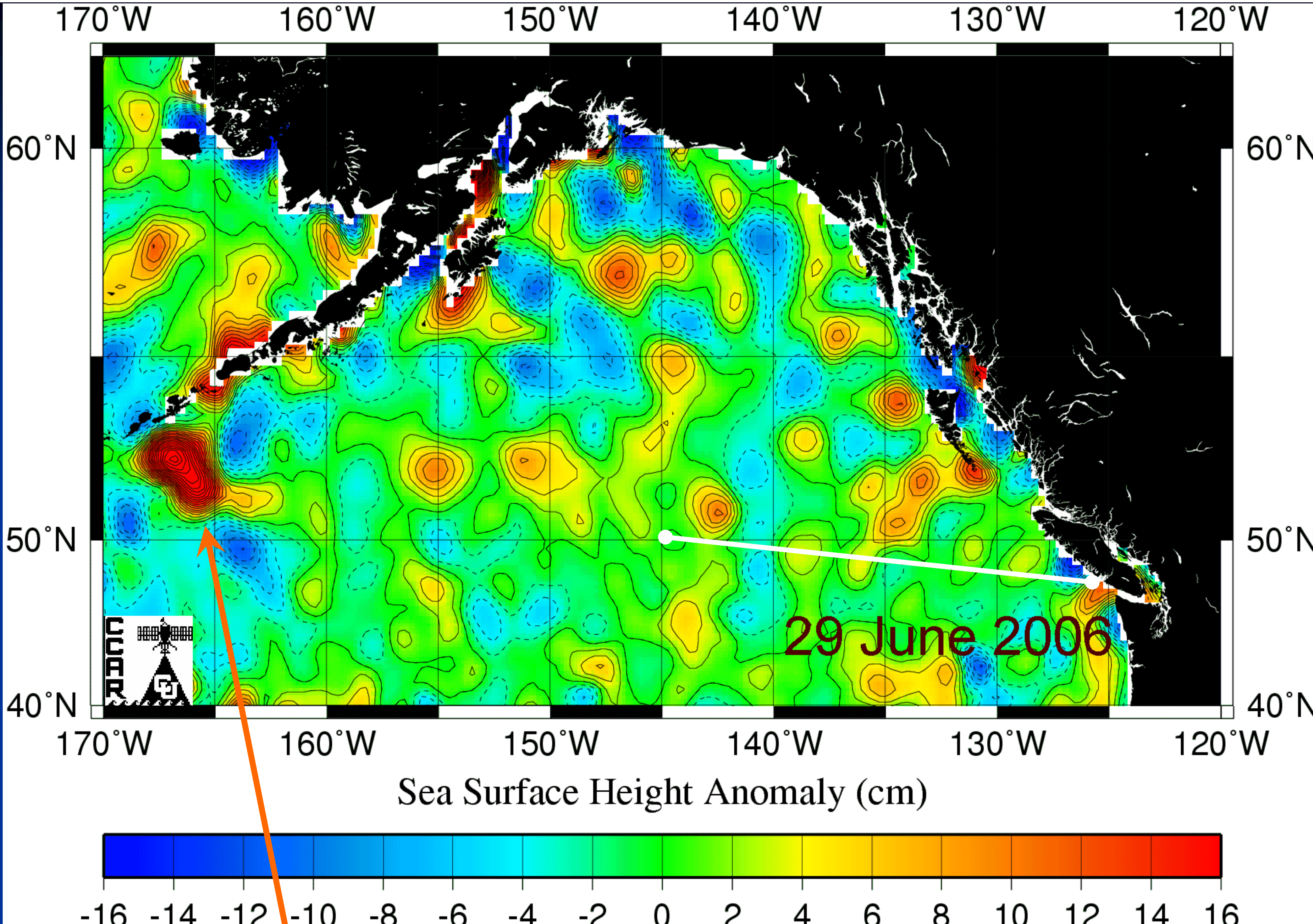


Contours of Sea Surface Height Anomaly (SSHA) based on Jason-1 and Envisat, reveal positions of mesoscale eddies in the NE Gulf of Alaska.

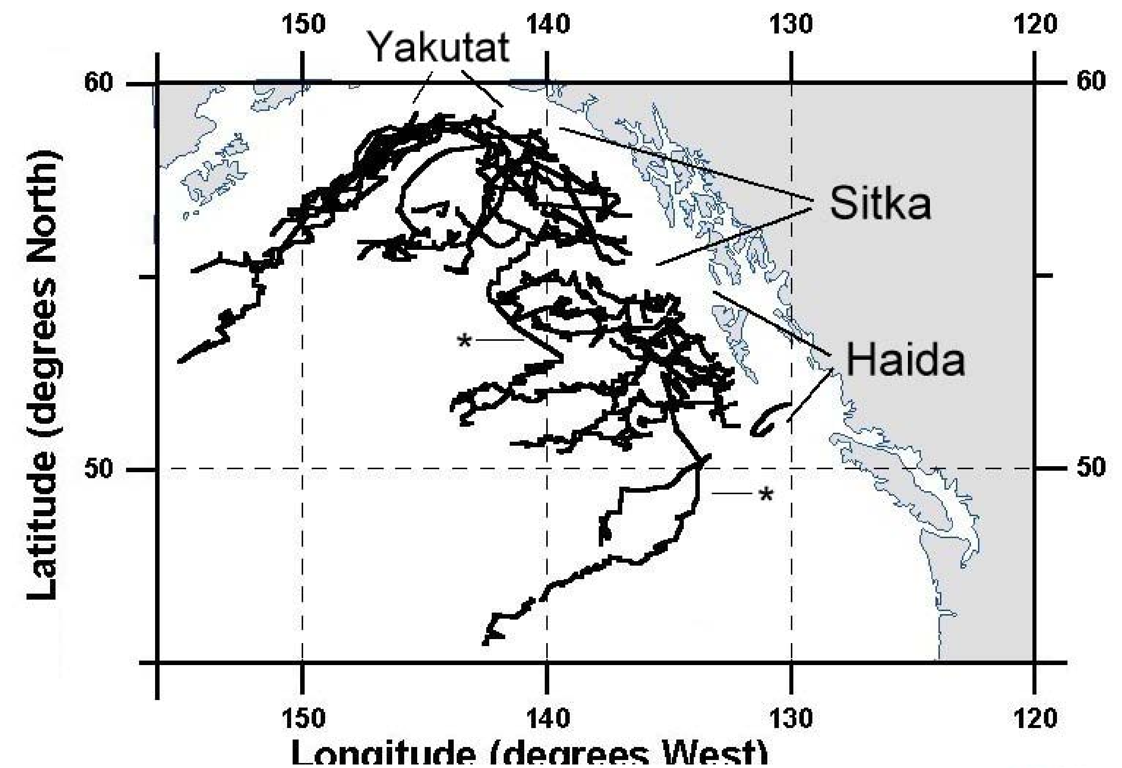
Each eddy is nominally 200 km diameter, forms in winter along the NE slope of the gulf, and drifts at about 1 km/day to the West or Southwest.

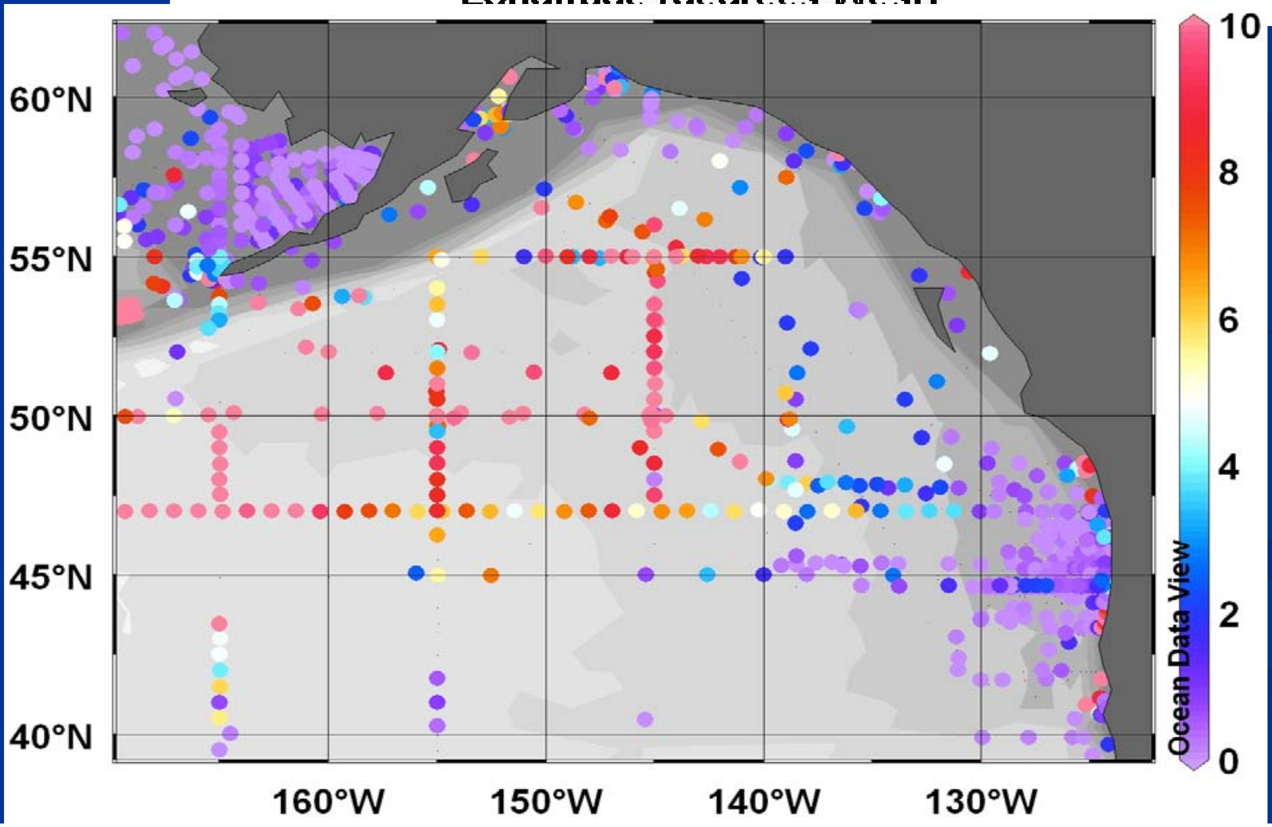


Contours were provided by an Internet site developed and maintained by R. Leben of the Colorado Centre for Astrodynamics Research (CCAR).



Largest, persistent eddies are generally in the Alaskan Stream, and originate in Northern Gulf of Alaska as Sitka-type eddies.



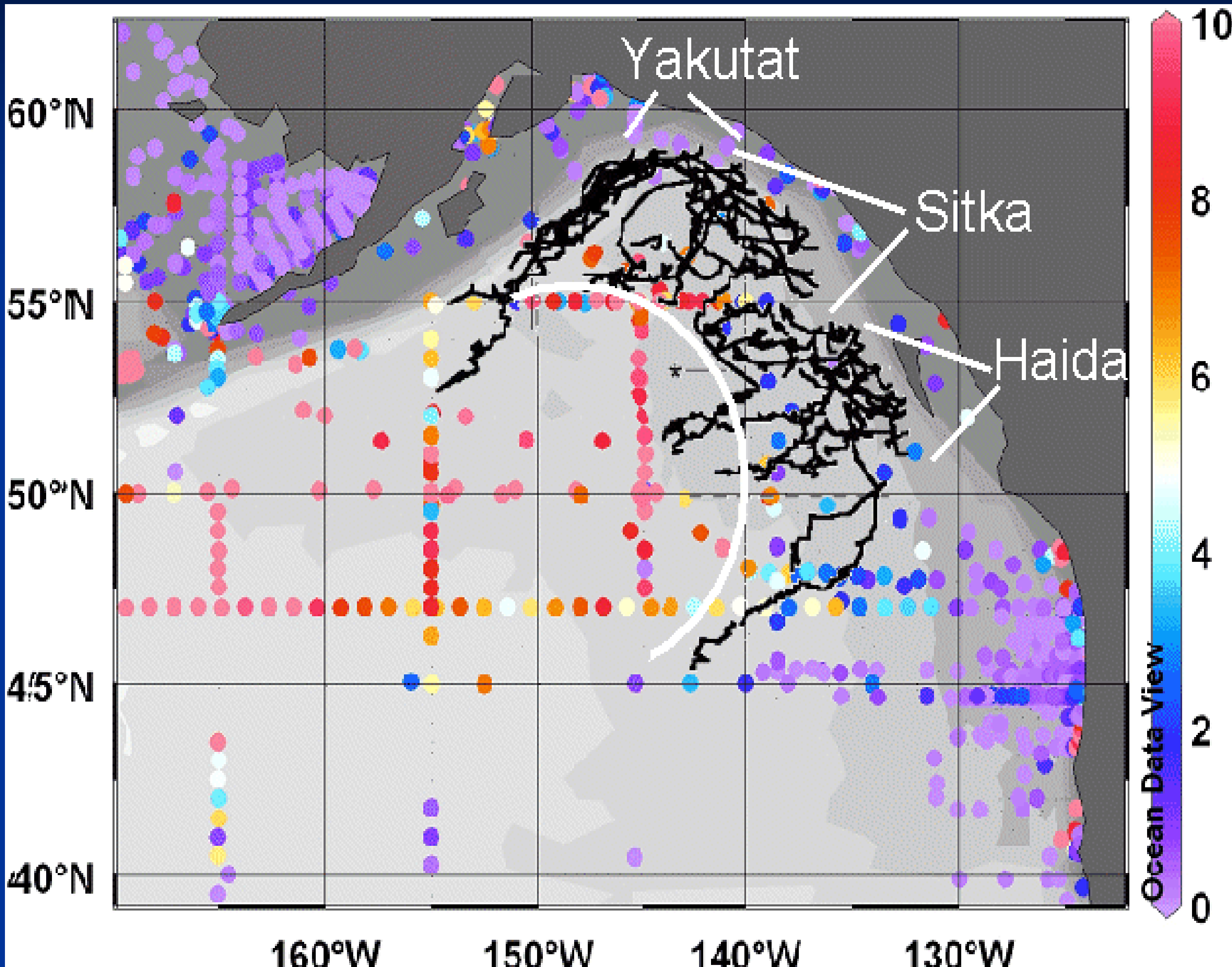


At left:
Tracks of "significant" Sitka-type Eddies from 1992 to 2002. All tracks begin near the NE sector of the Gulf. (I stopped plotting when the continuity became uncertain.)

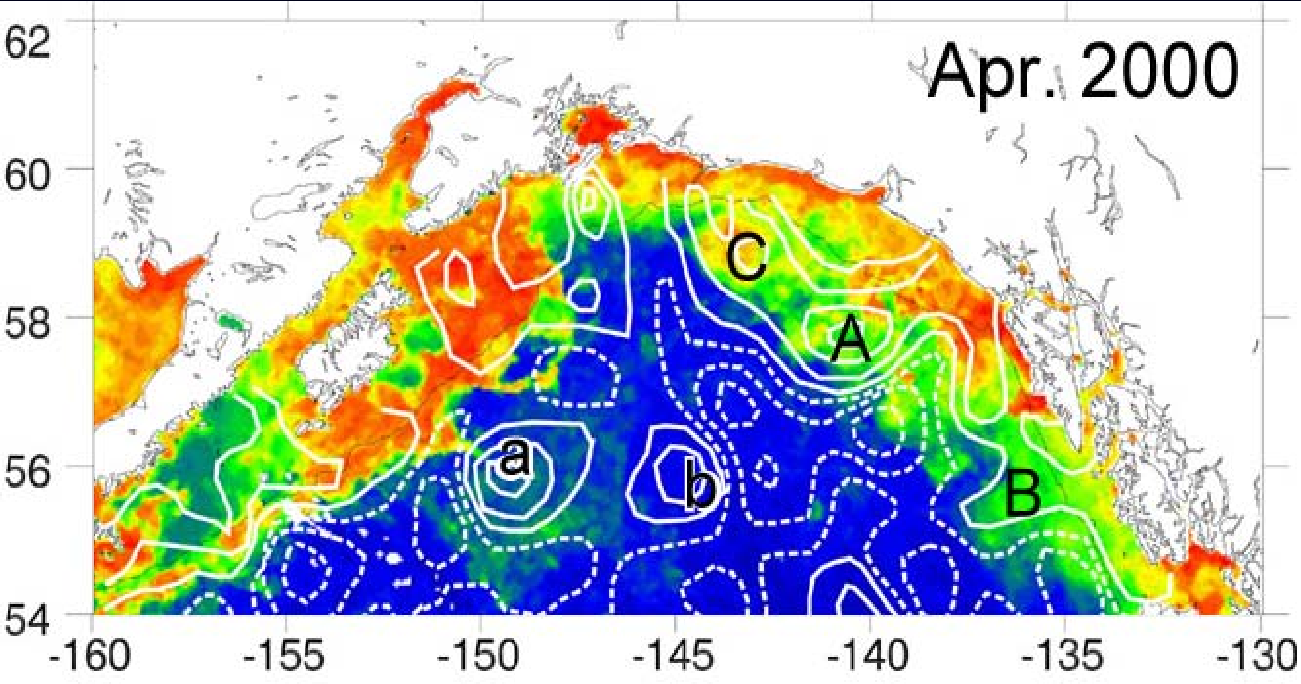
*Denotes eddies of 1998, which tracked farther to the south.

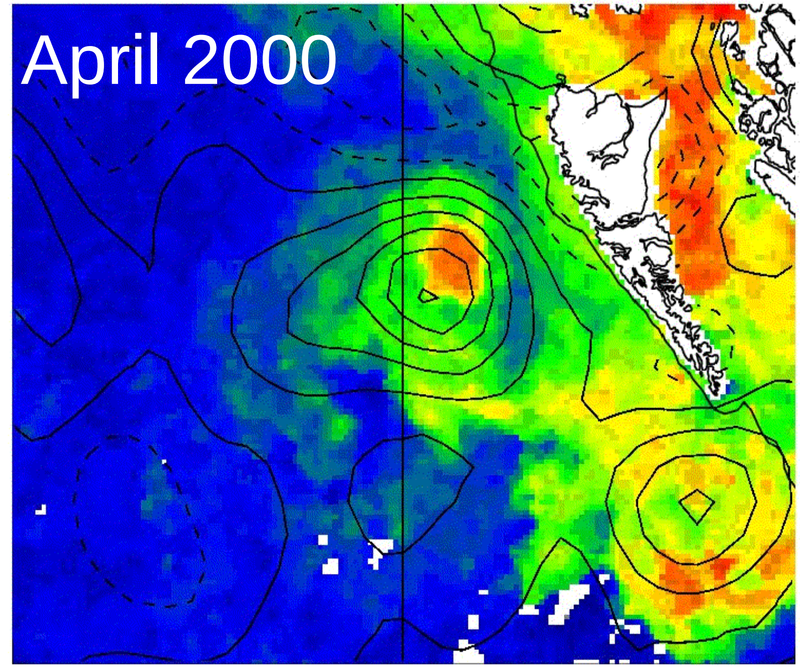
At left:
Surface nitrate concentrations in summer (ml/L) as archived by NODC.

Nitrate at ocean surface tends to be higher in regions less frequently traversed by eddies. Eddies define the NE sector of the HNLC waters.



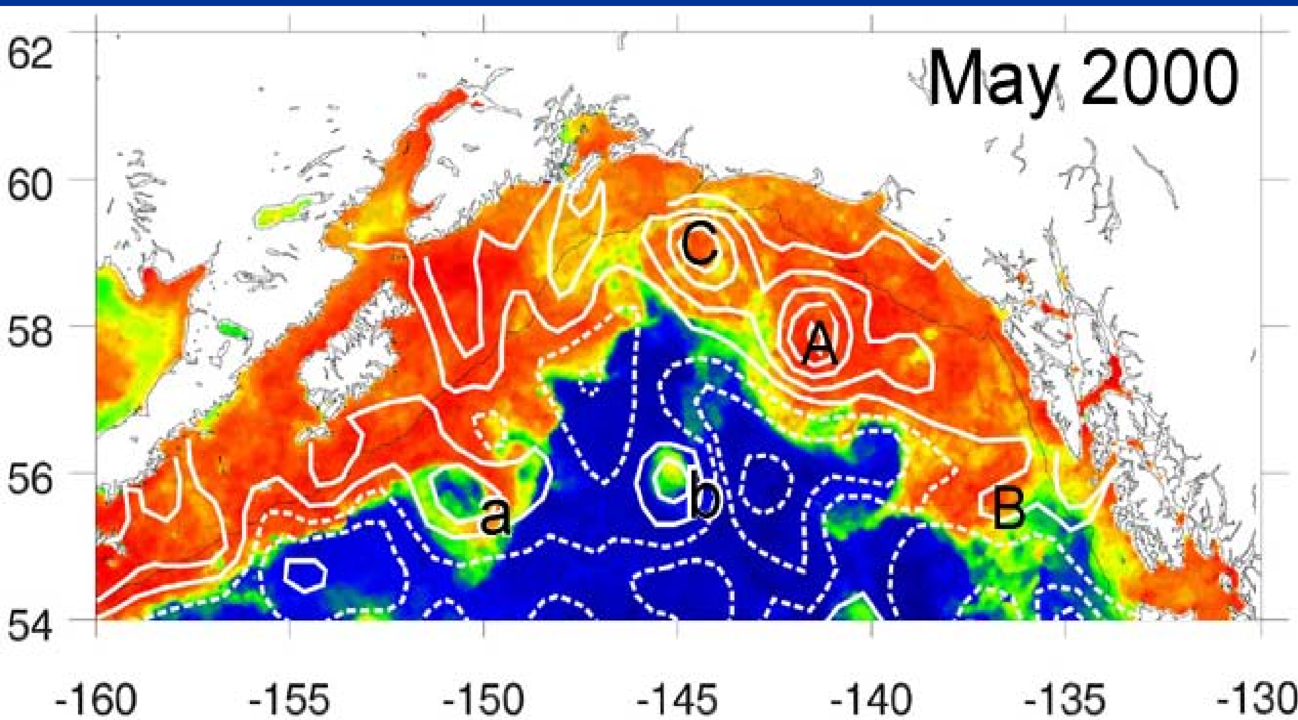
From Crawford, Brickley and Thomas, under review.

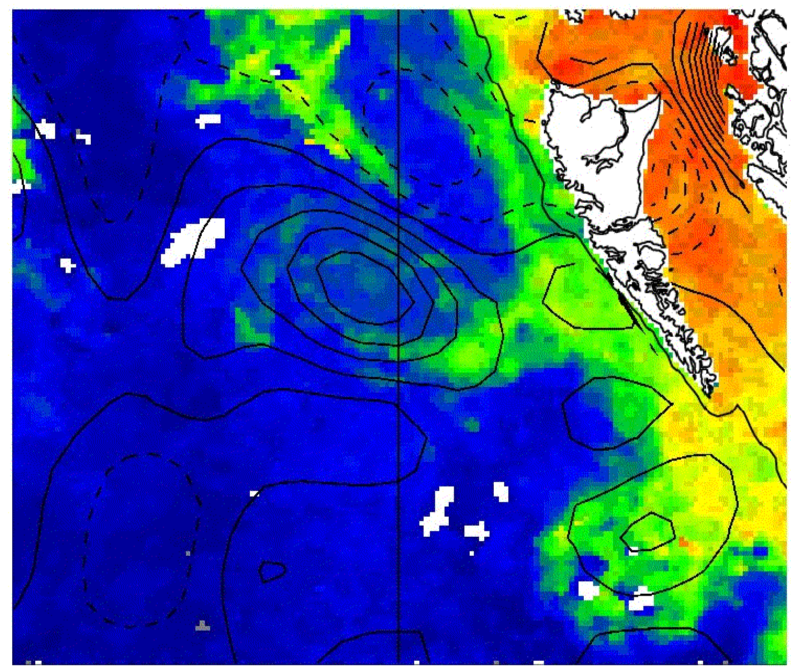


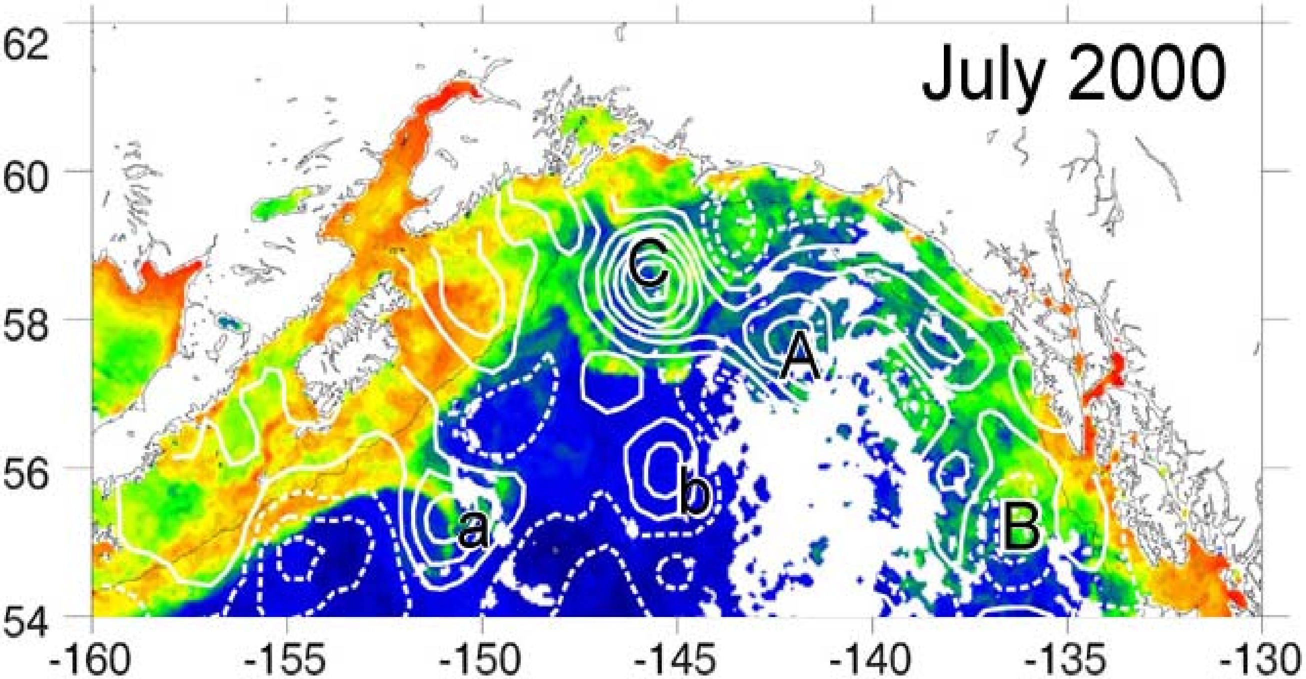


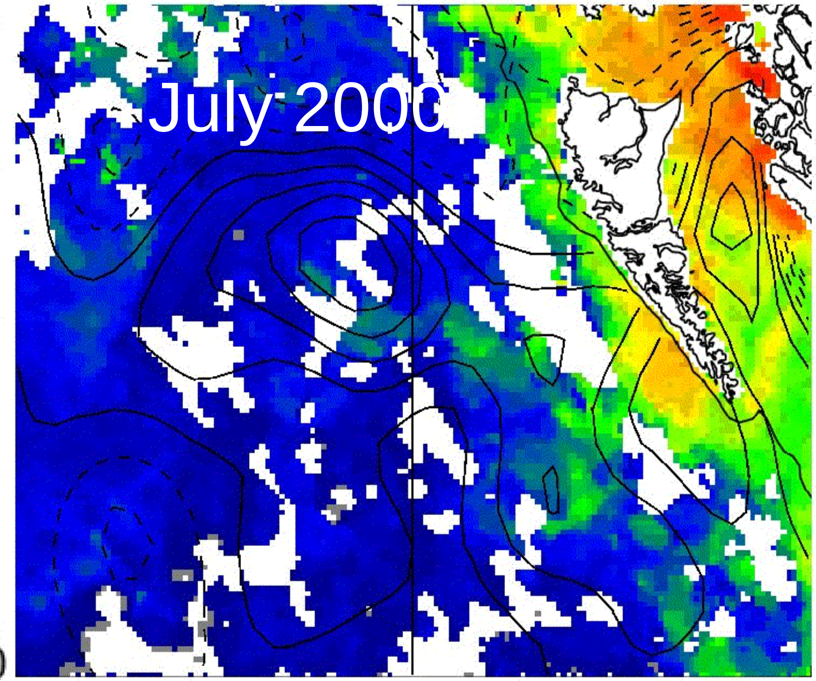
From Crawford, Brickley & Thomas, under review.

From Crawford Brickley, Peterson & Thomas, 2005.









From Crawford, Brickley & Thomas, under review.

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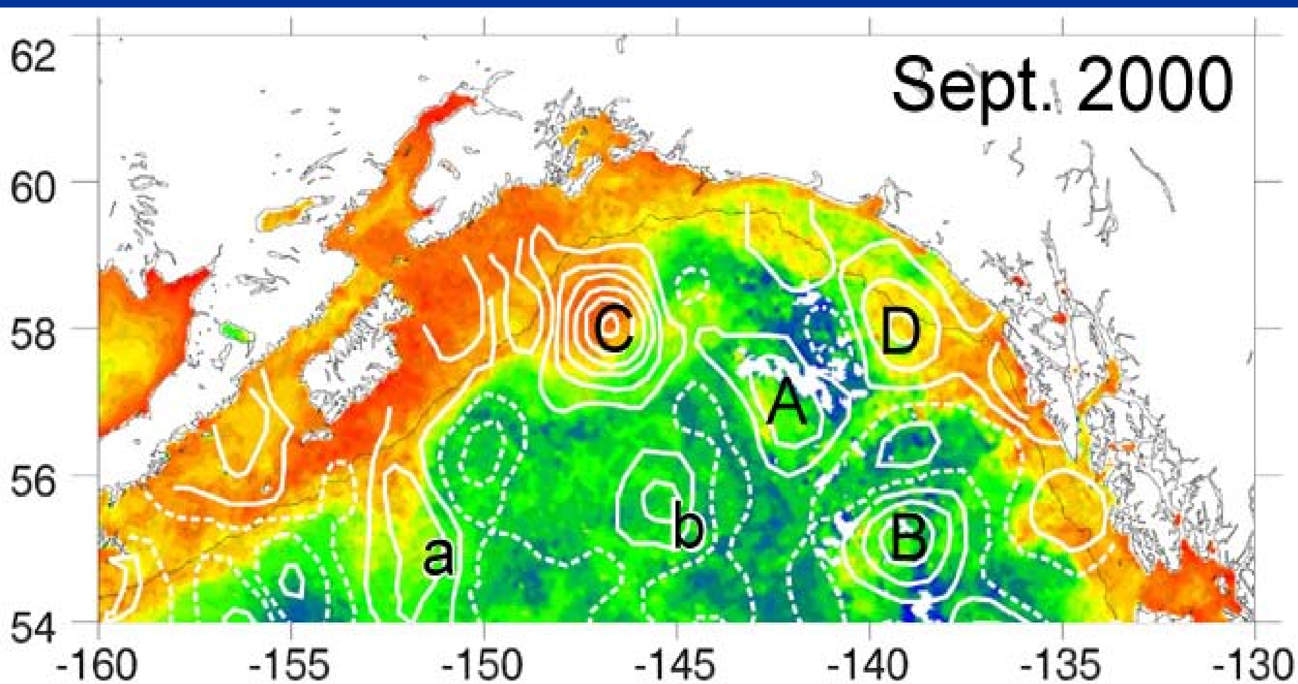
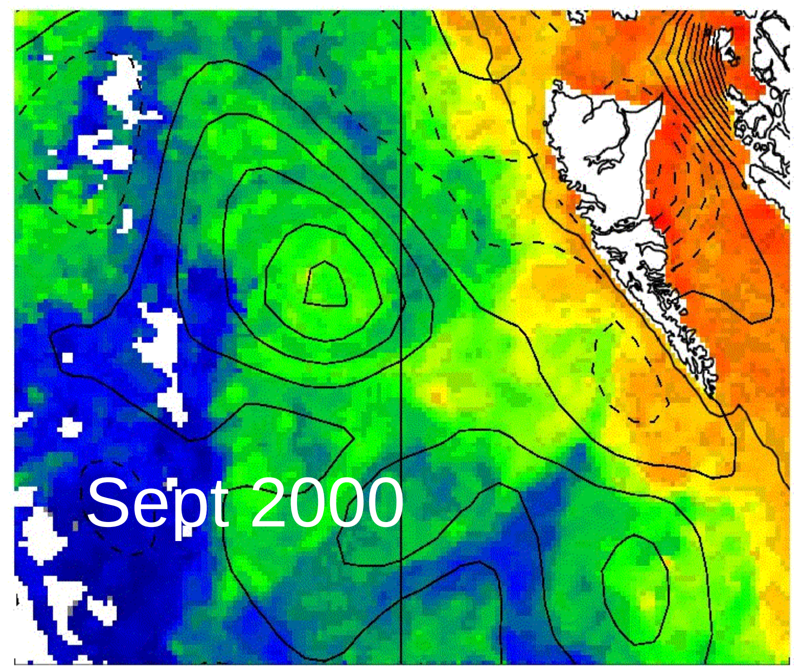
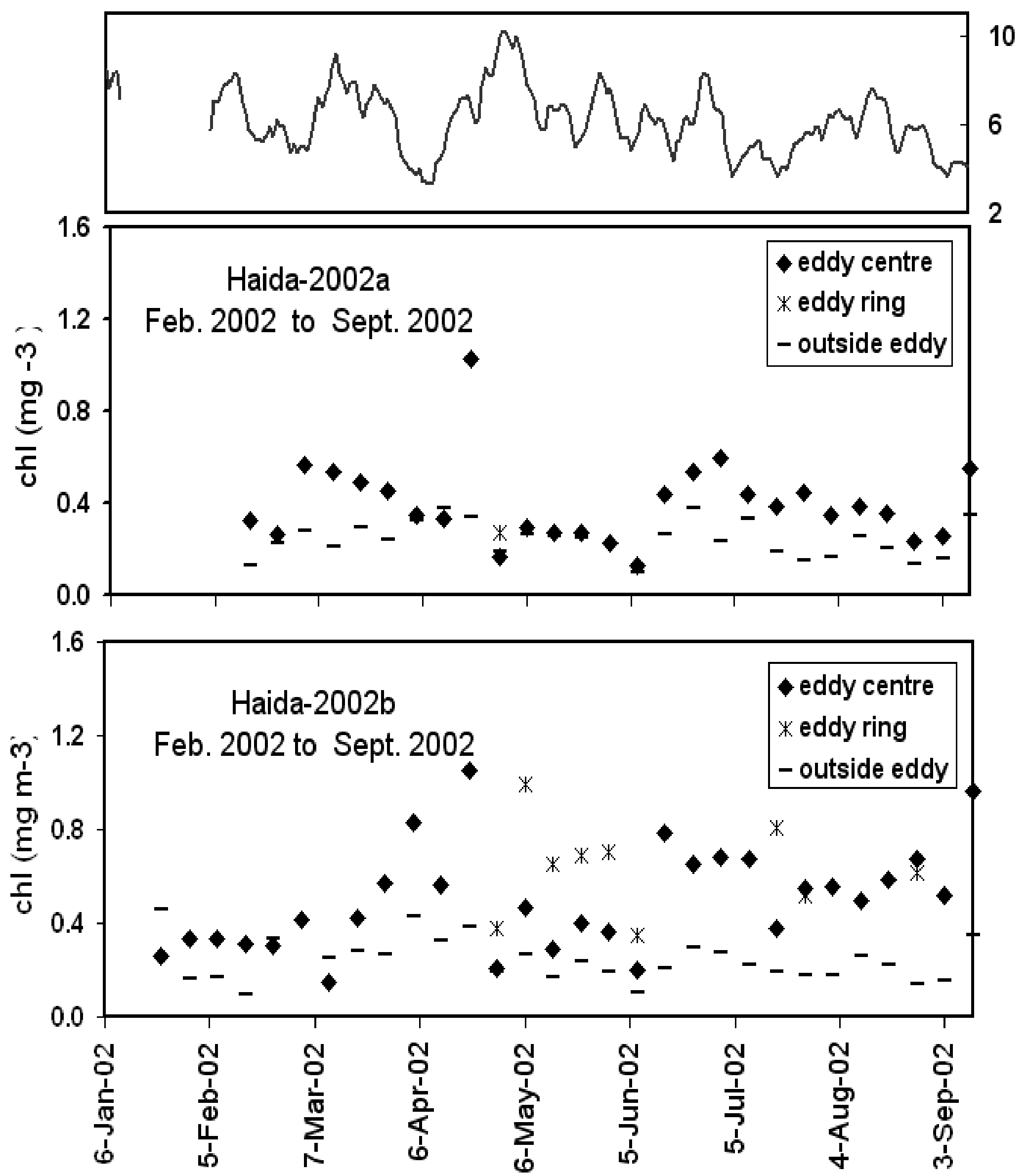
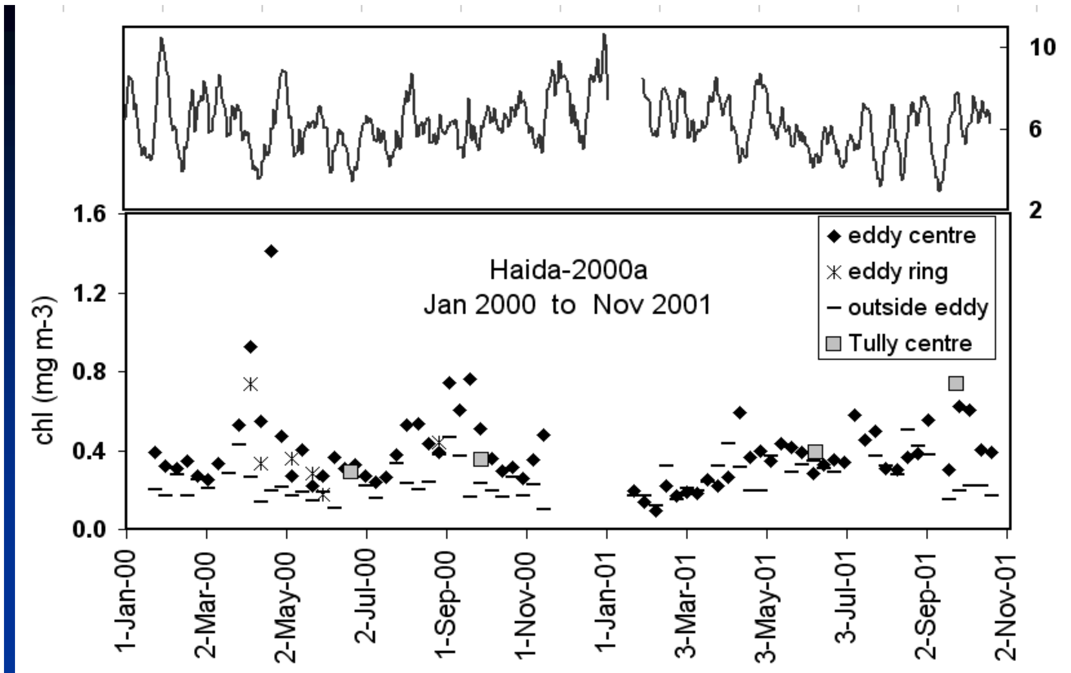






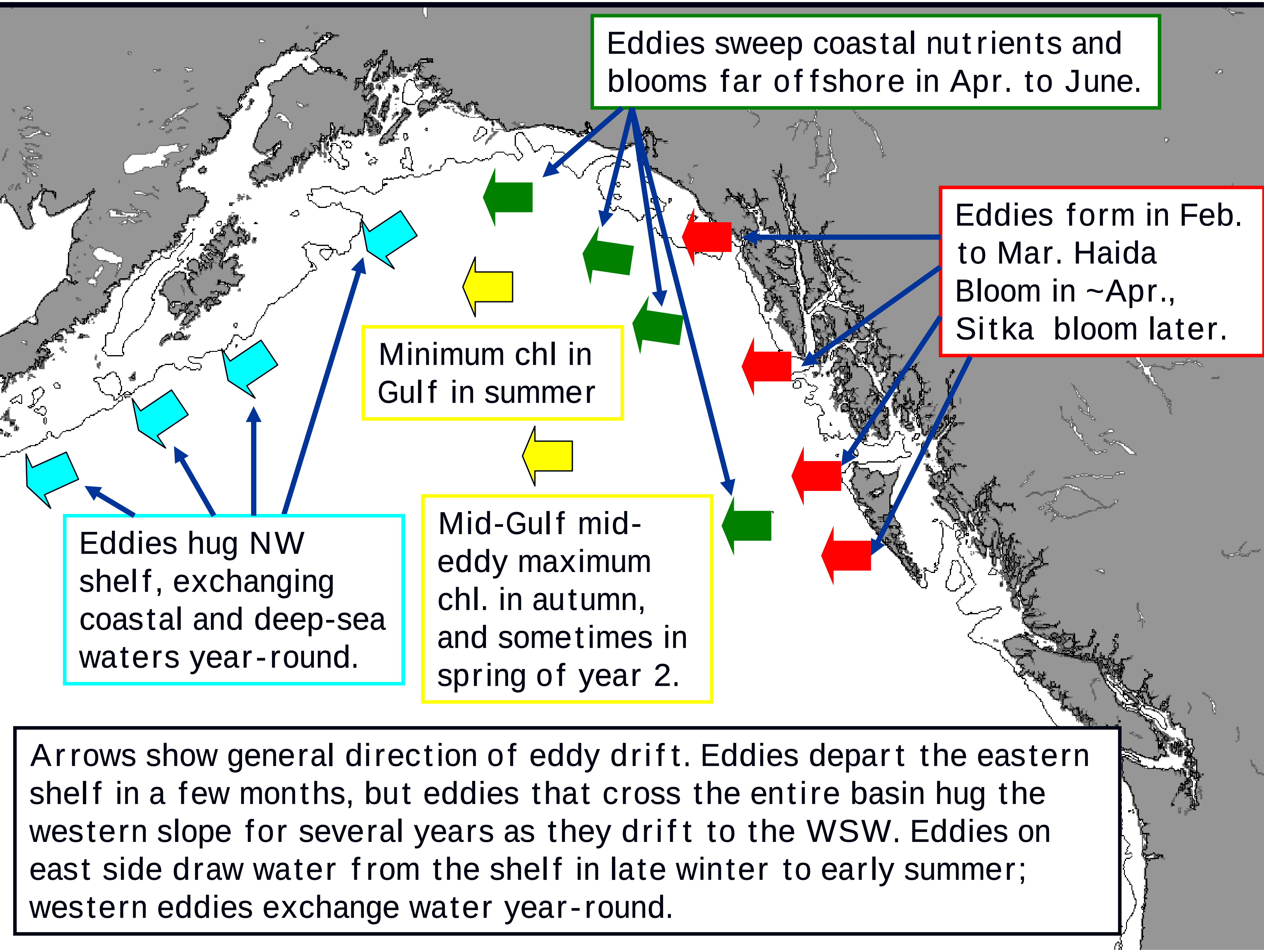


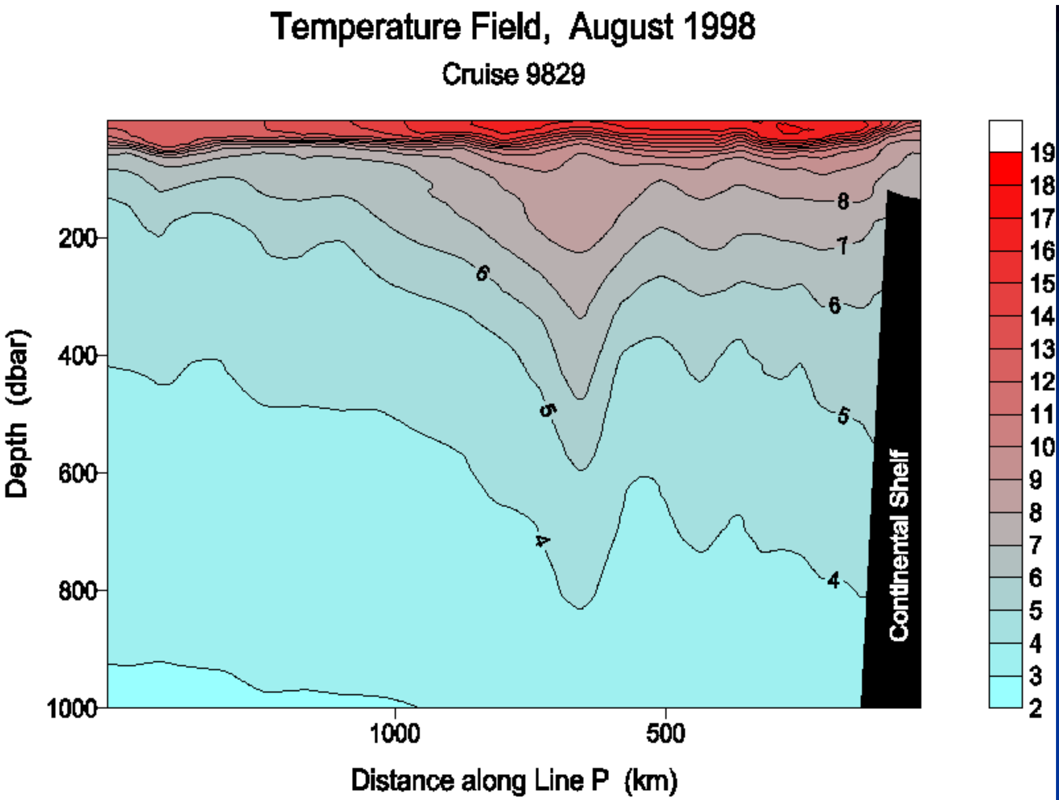
Several studies note that iron, silicate and even nitrate can be drawn down to near-zero concentrations in surface waters in the middle of Haida Eddies, but following this drawdown, chlorophyll levels still tended to be higher in eddies and in outside rings of eddies at surface.

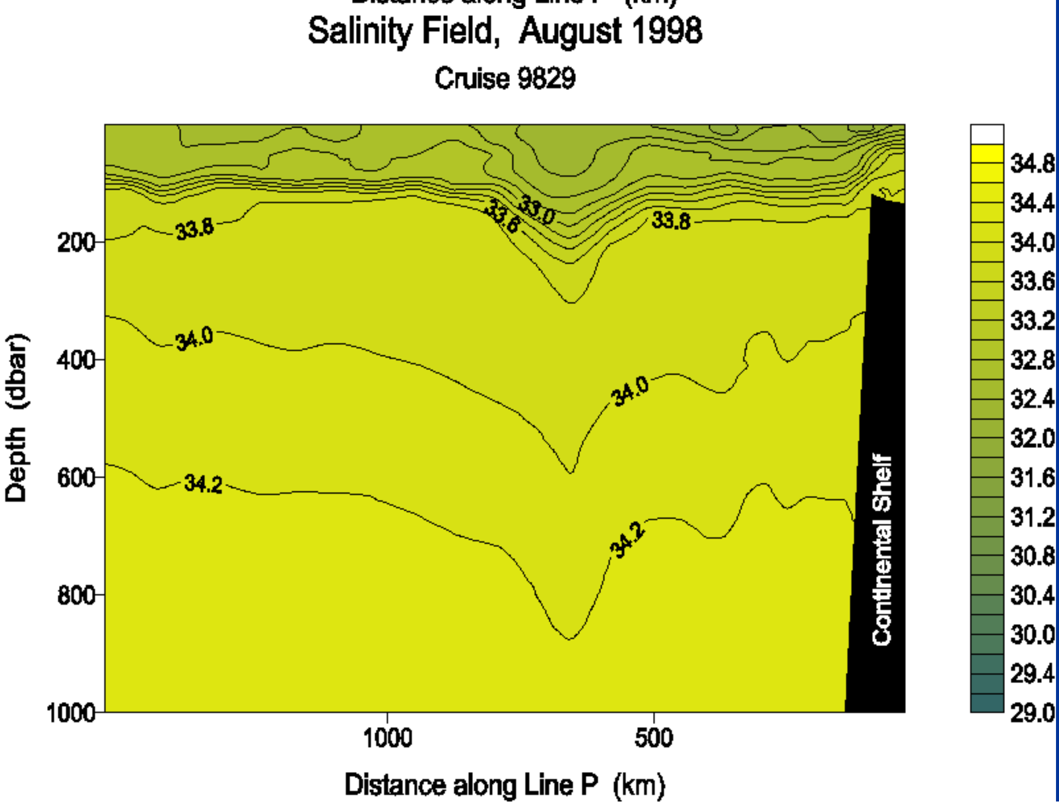
The graphs above display the chlorophyll-enrichment of Haida Eddy waters compared to surrounding deep-sea waters, as determined from SeaWiFS data. Eddy waters are enriched in almost every month.

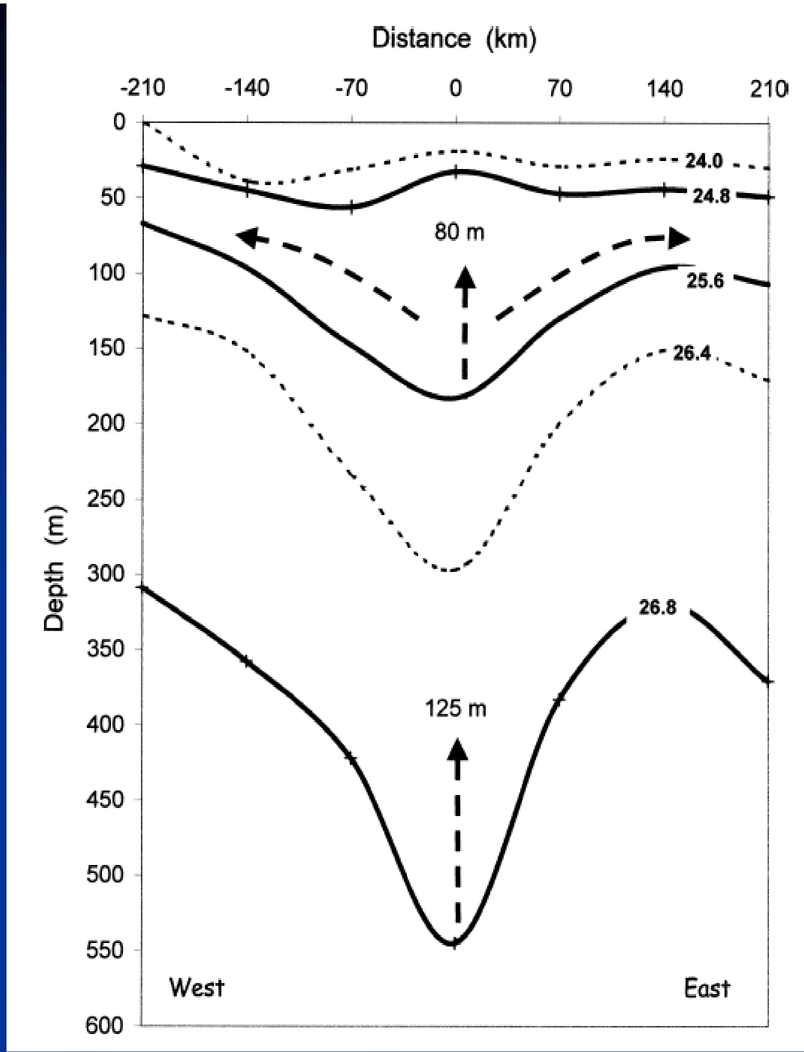
Crawford, Brickley, Peterson & Thomas, 2005.

A similar study north of 54N found that 50% of **surface** chlorophyll in deep-sea waters observed by SeaWiFS in spring and summer was within the 4 cm contour of Sitka eddies. Yet these eddies occupied only 10% of the area. (Crawford, Brickley, and Thomas, under review). Eddies are the hot spots in deep-sea waters (>500 m depth) . Recent cruises have noticed more marine mammals in outer rings of eddies.


Eddies sweep coastal nutrients and blooms far offshore in Apr. to June.
Eddies form in Feb. to Mar. Haida Bloom in ~Apr., Sitka bloom later.
Minimum chl in Gulf in summer
Eddies hug NW shelf, exchanging coastal and deep-sea waters year-round.
Mid-Gulf mid-eddy maximum chl. in autumn, and sometimes in spring of year 2.
Arrows show general direction of eddy drift. Eddies depart the eastern shelf in a few months, but eddies that cross the entire basin hug the western slope for several years as they drift to the WSW. Eddies on east side draw water from the shelf in late winter to early summer; western eddies exchange water year-round.







Above: Fig. 8 from Whitney and Robert (2002).

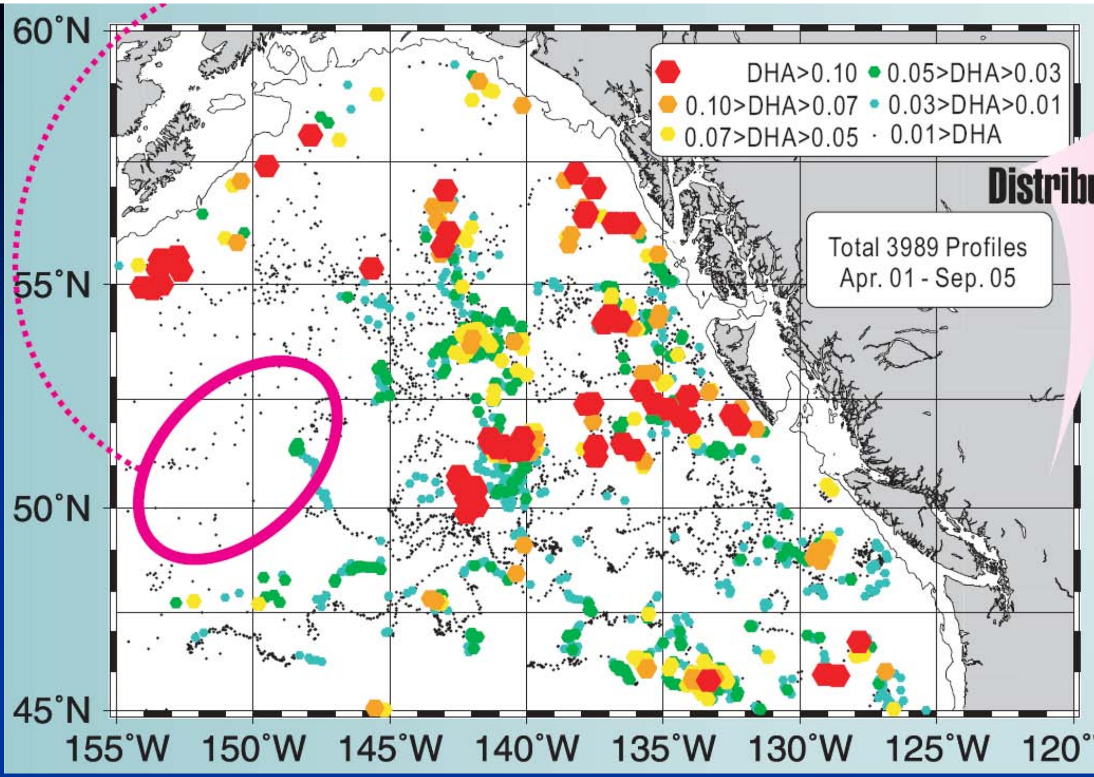
Sigma-t of Haida-1998 in Sept 1998, with estimates of the degree of isopycnal rebound between 09/98 and 06/99 for the 25.4 surface, which sits near the base of the winter mixed layer, and the 26.8 surface, which is the maximum density at which anomalous water properties are seen.

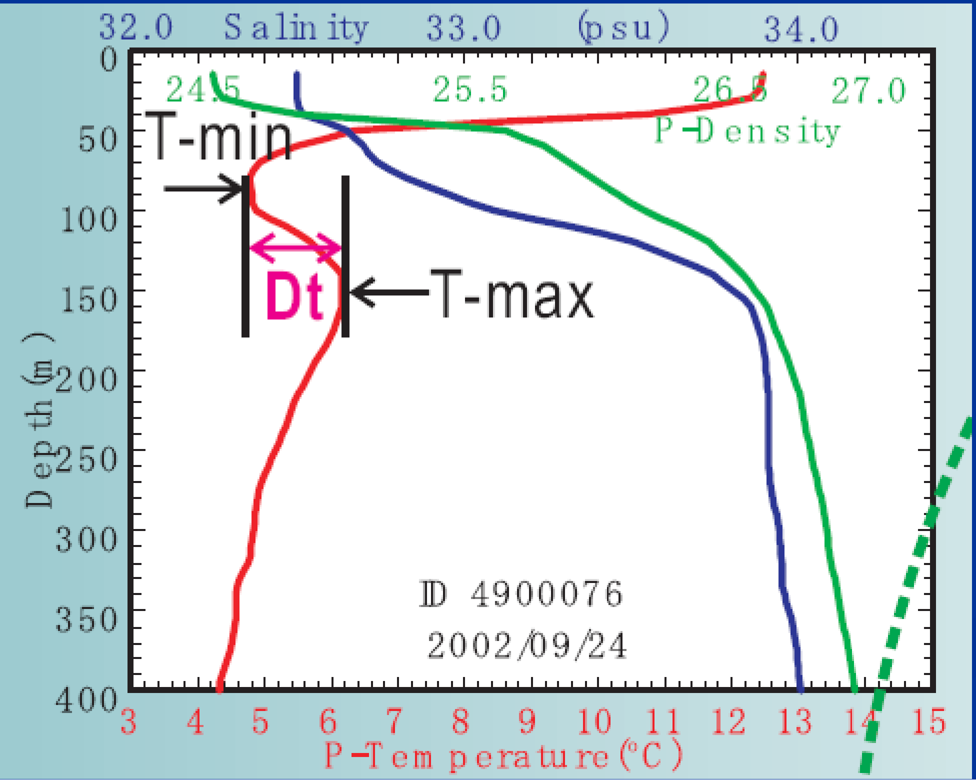
Extracted from poster of
Onishi, Ueno & Crawford:
Effects of warm eddies on temperature inversions in the Gulf of Alaska

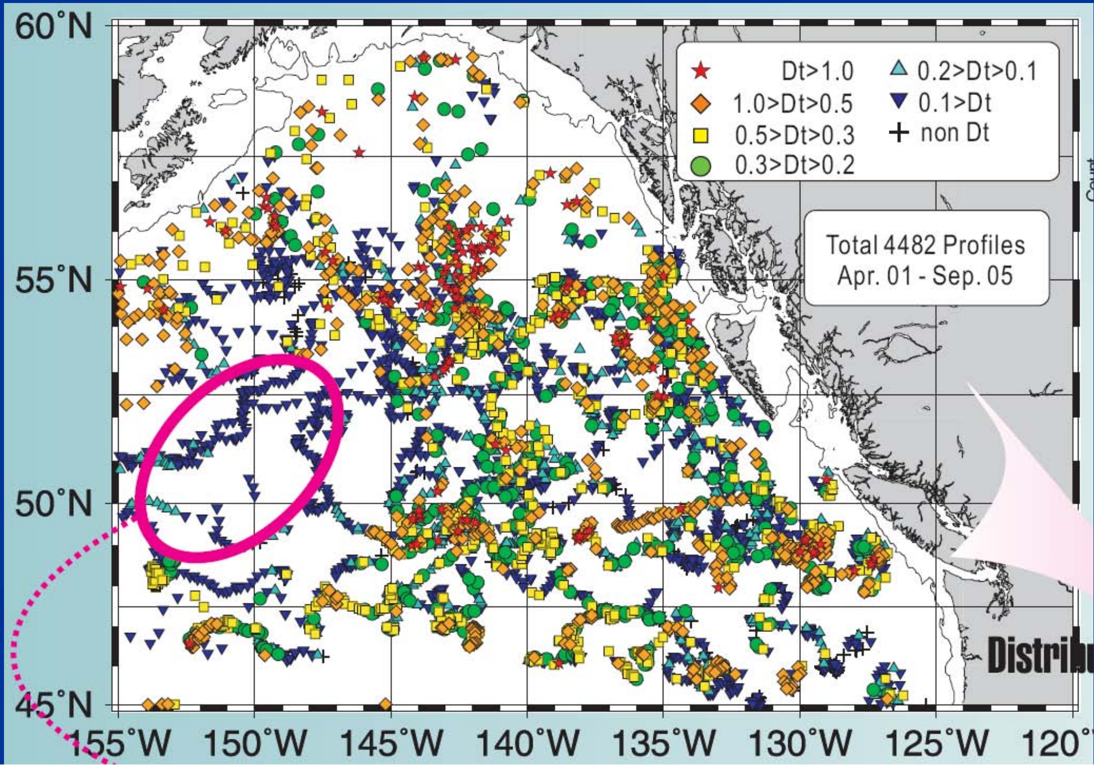
Top right: +ve dynamic height anomalies.

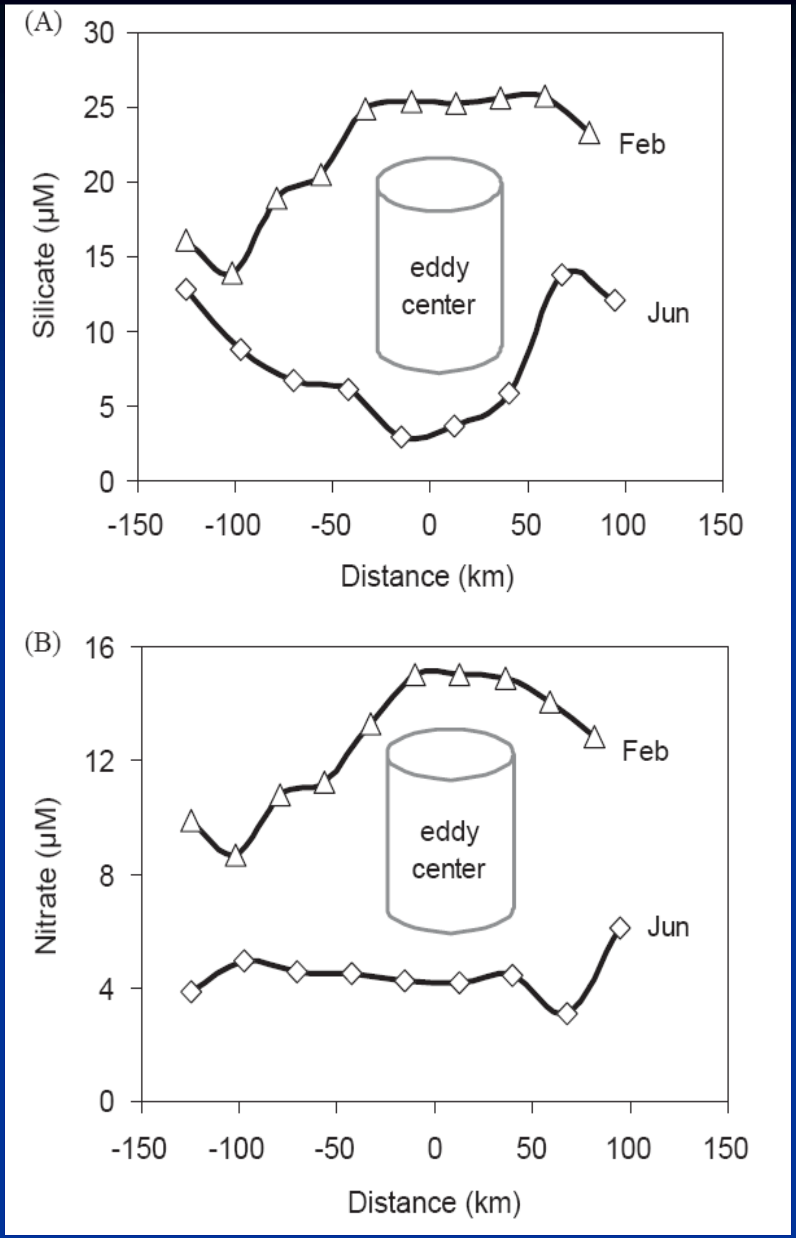
Bottom right: temperature inversions.

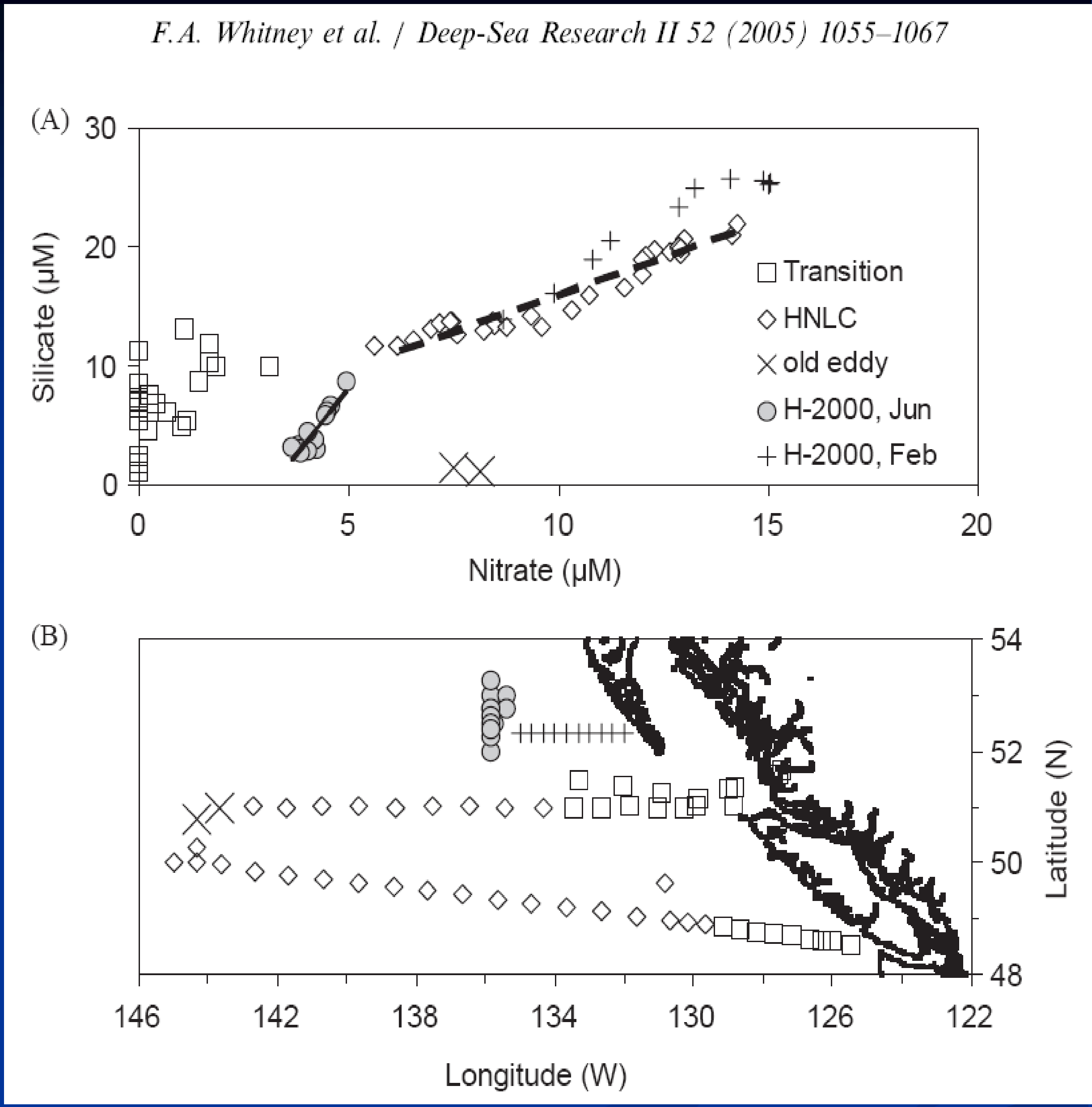
Both are indicators of mesoscale anticyclonic eddies.











Above: nutrient levels at surface as measured in Feb and June 2000 (Whitney et al, 2005).

Surface waters in eddies initially carry more nutrients than surrounding NHLC waters in late winter, but their higher iron levels permit more drawdown of silicate and nitrate in spring, and silicate tends to disappear first, perhaps due to diatom blooms.

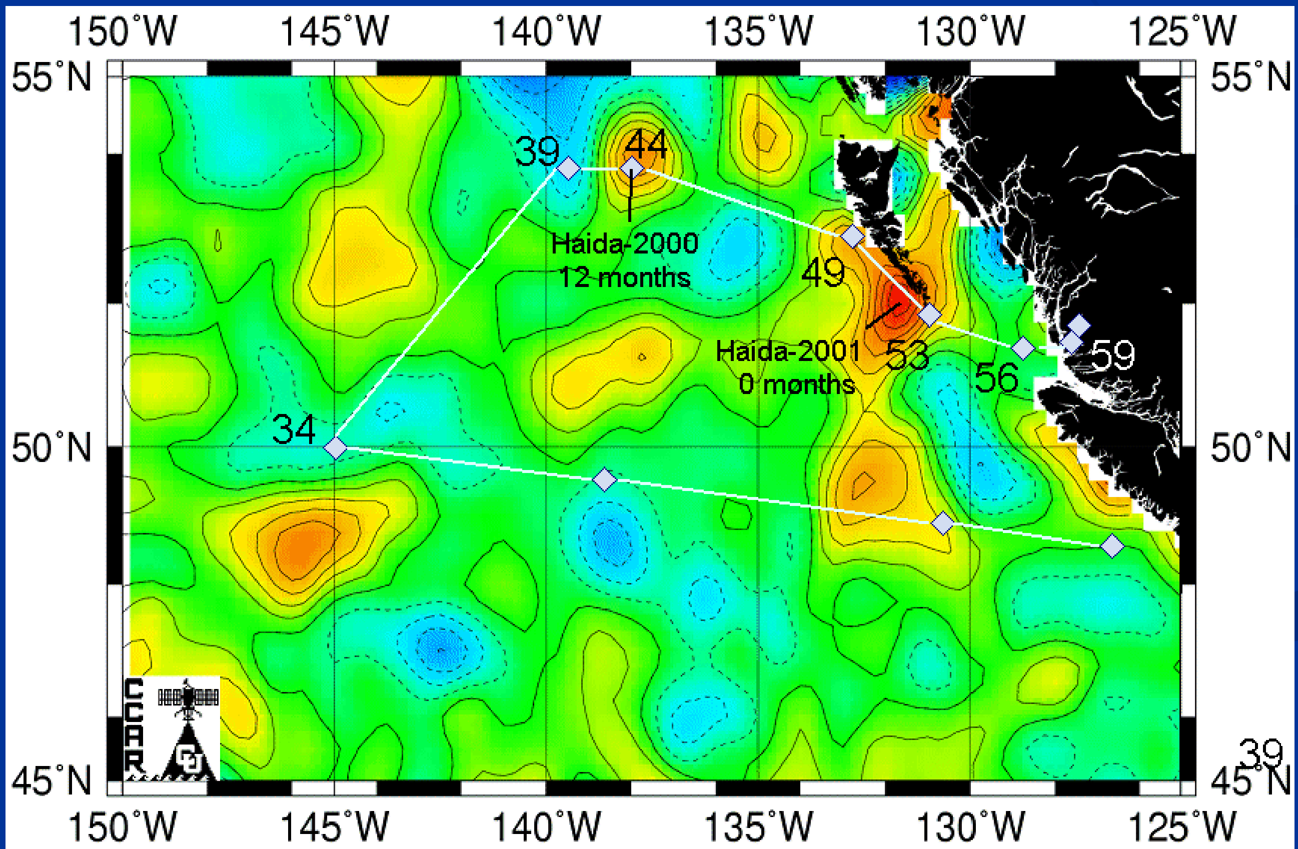
Subsurface waters?

Young Haida and Sitka Eddies tend to be warmer, saltier, higher in nutrients (and iron) and lower in oxygen than surrounding subsurface, deep-sea waters at the same density. Eddies carry these properties into mid-gulf, and we can follow eddies by tracking these properties.

Coastal sub-surface waters along the eastern continental shelf bottom and slope are especially low in oxygen and high in iron, due to enhanced biological decomposition in these highly productive regions. North Pacific Current waters are higher in oxygen, so we follow the studies of Ayden, Fine and Olson (1998) and use % Oxygen Saturation as a tracer of coastal water, and as a tracker of eddies.

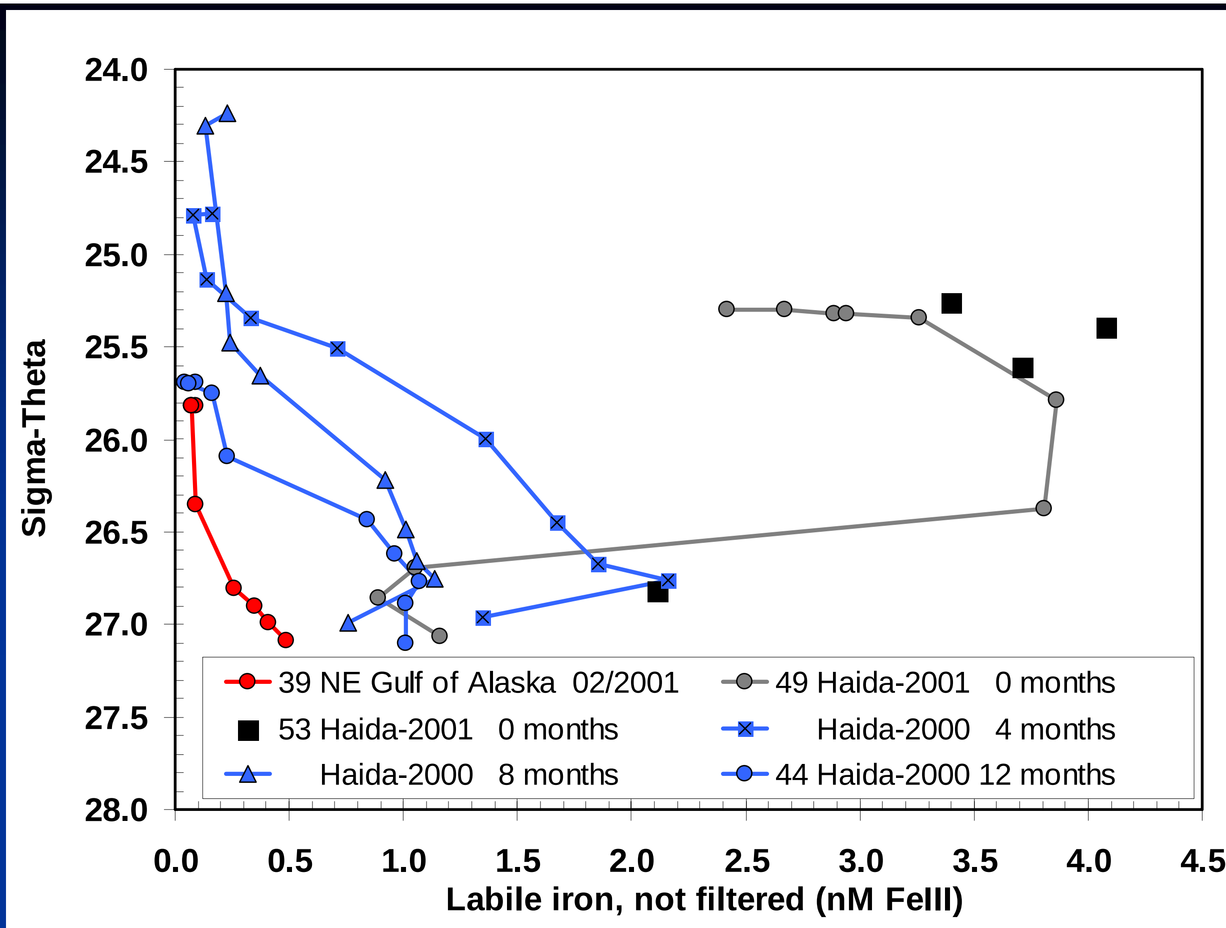
We will show iron and oxygen levels at hydro-stations sampled at right in February 2001 with additional profiles in 2000 from Haida Eddies.

The stations near the Queen Charlotte Islands are in source waters for Haida Eddies.



February 2001 Winter cruise along Line-P, into Haida-2000, and source of Haida 2001

Cruise 2001-06

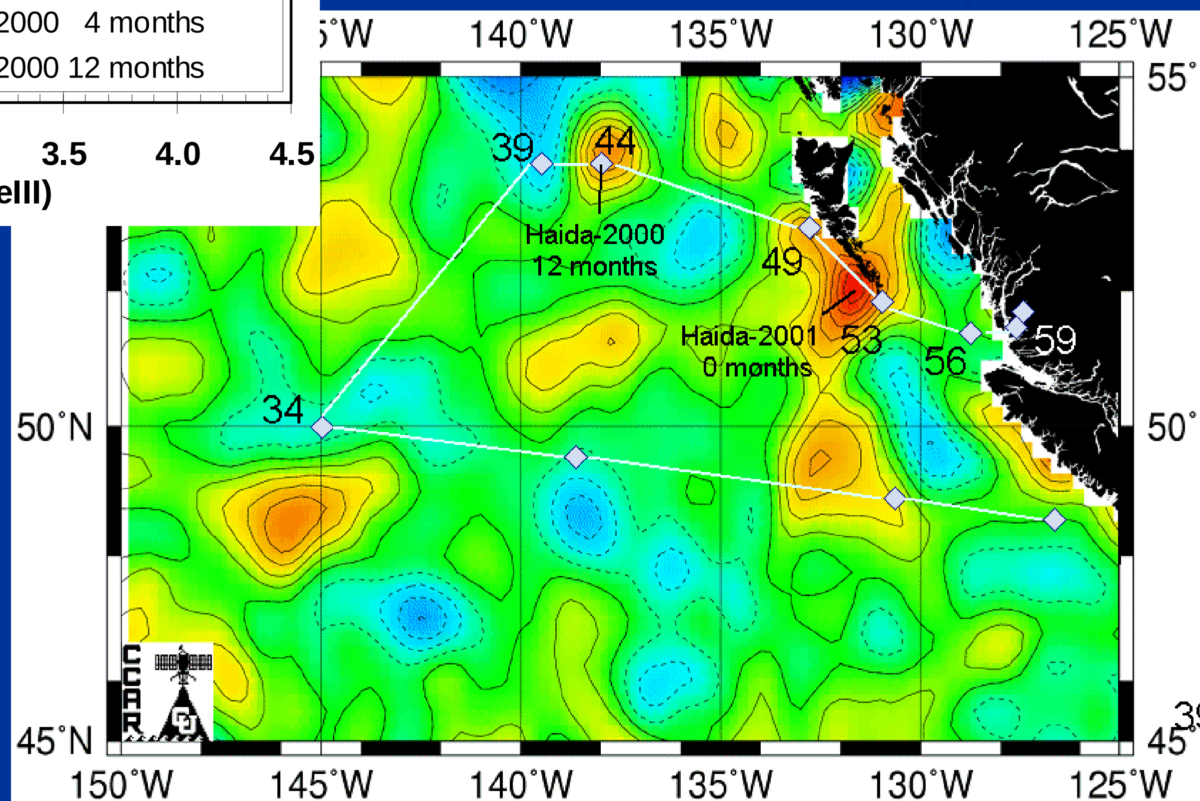


A Line-P cruise returned to the coast along a northern route in Feb 2001, as part of the DFO "Haida Eddy" project.

Plotted at left are labile iron levels determined by Keith Johnson of IOS/DFO, as posted on the DFO Haida Eddy Web site.

Labile = unfiltered, pH 3.2 for 1-2 h.

Labile iron in eddies decreases steadily in concentration from high values in coastal and slope regions. Even after 12 months, it is not down to background levels below the mixed layer.



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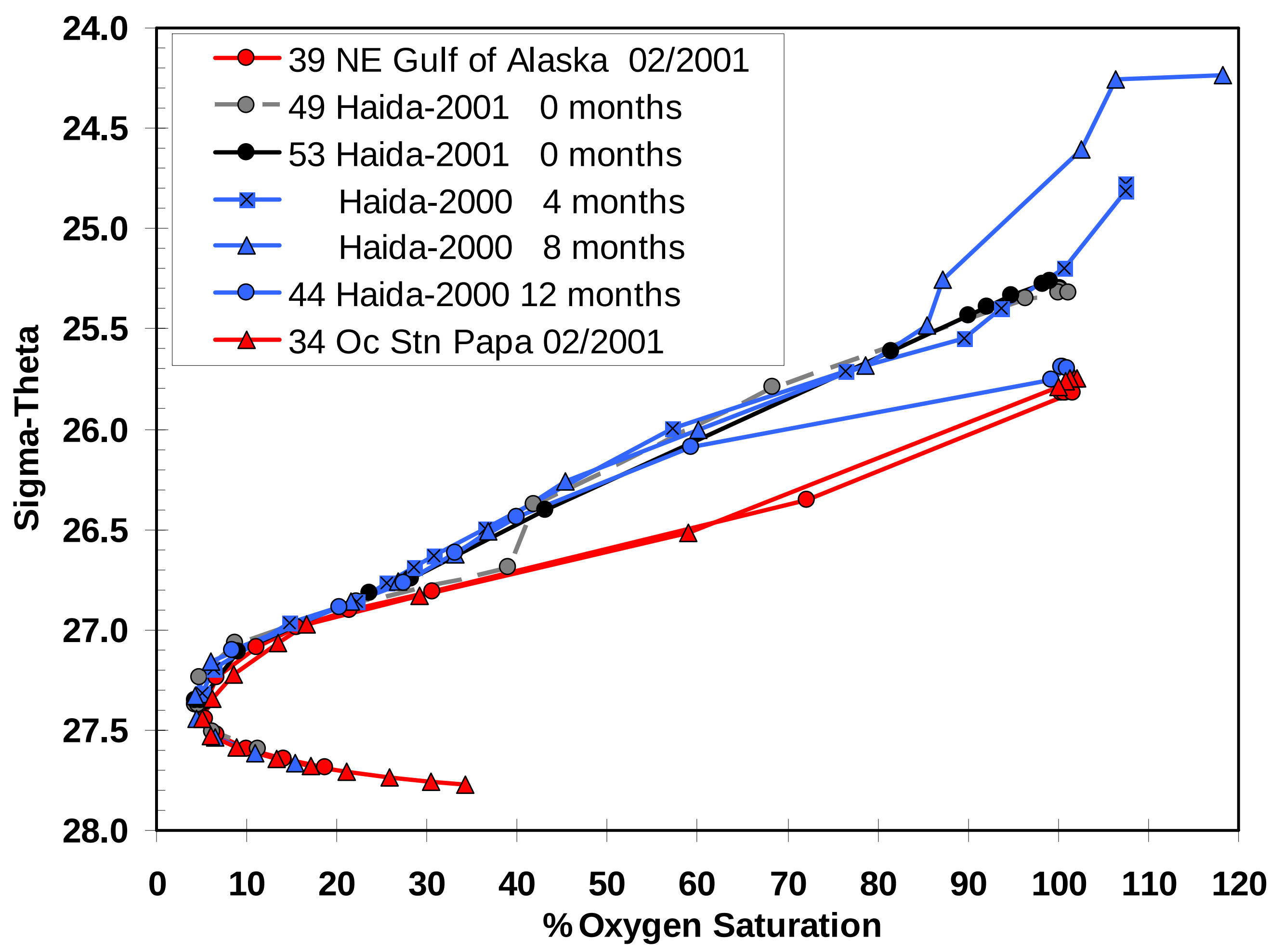
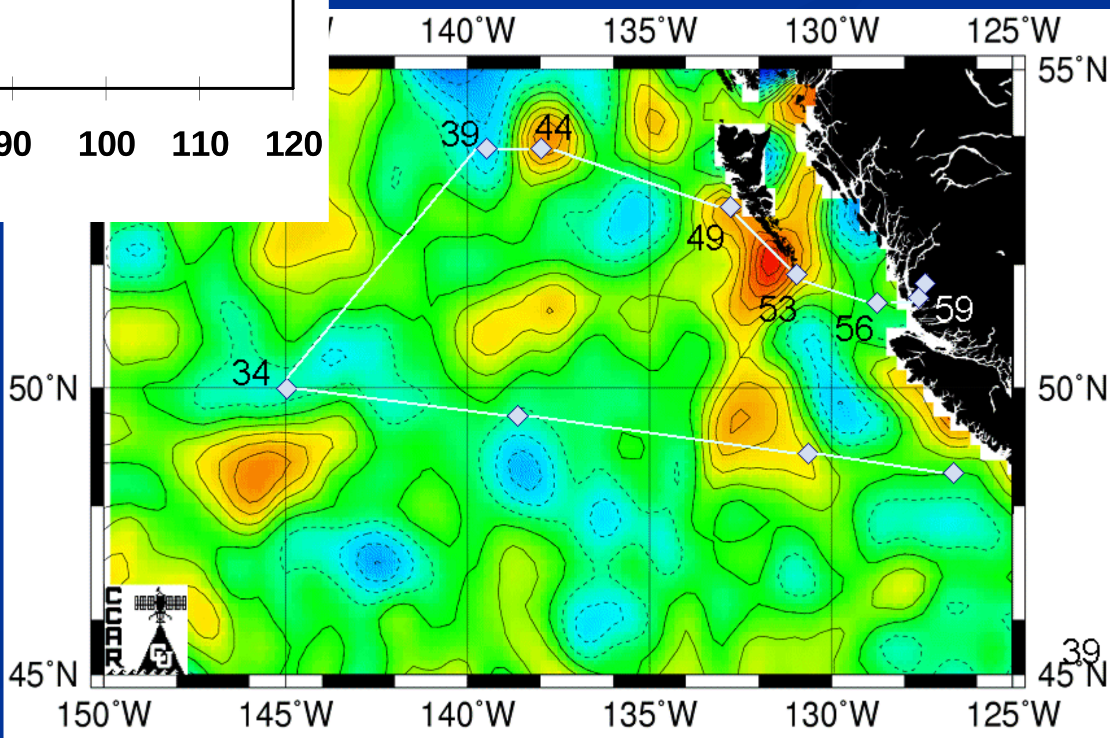


A Line-P cruise returned to the coast along a northern route in Feb 2001, as part of the DFO "Haida Eddy" project.

O2 % Saturation levels are lower in Haida-2000 and in Haida-2001 source waters.

Oxygen levels at stations 34 and 39 are similar, despite their large separation.

Oxygen levels are similar for sigma-theta more than 26.9, which lies near 250-300 m in shelf waters, and 200 m in deep-sea waters



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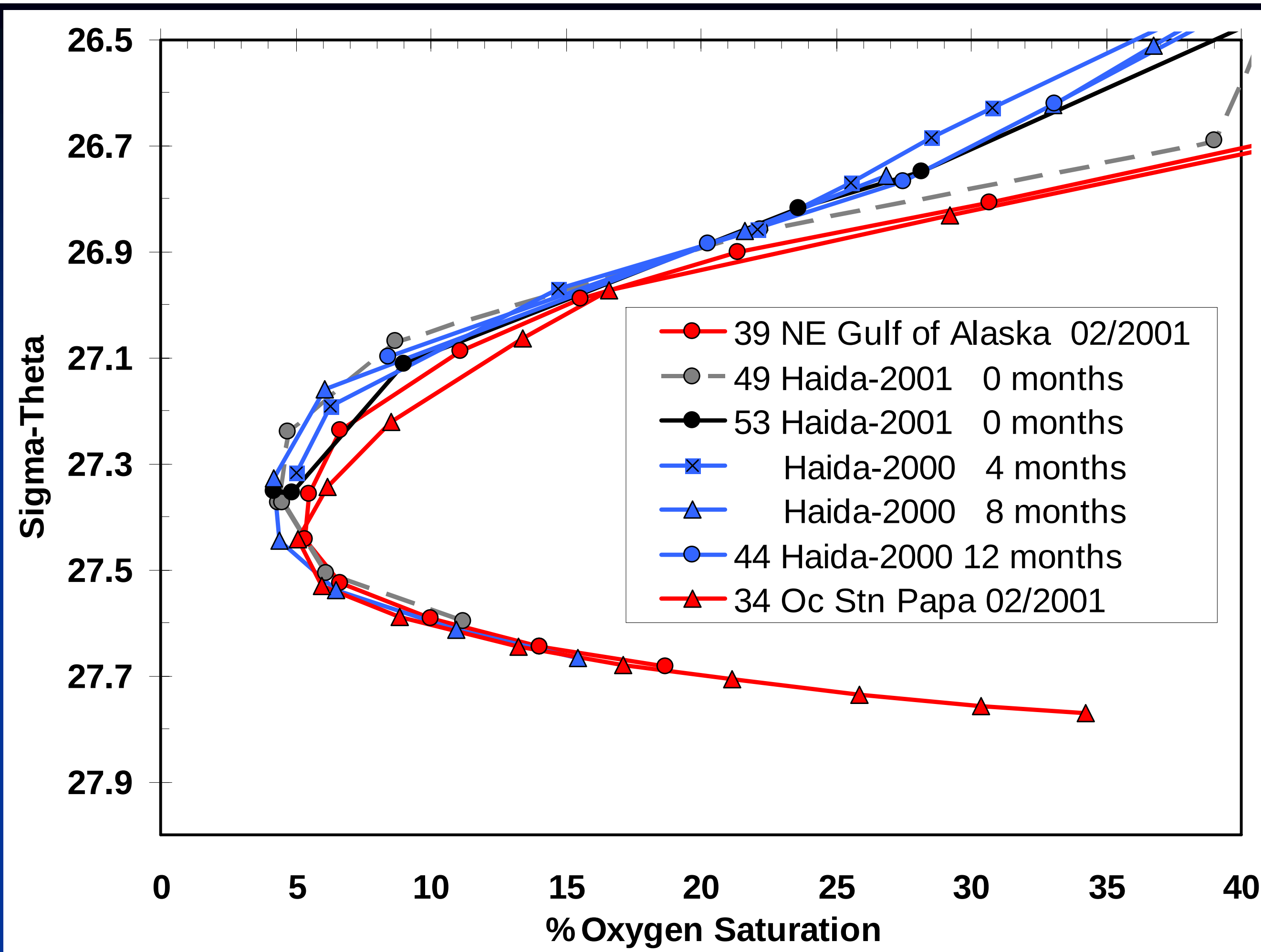

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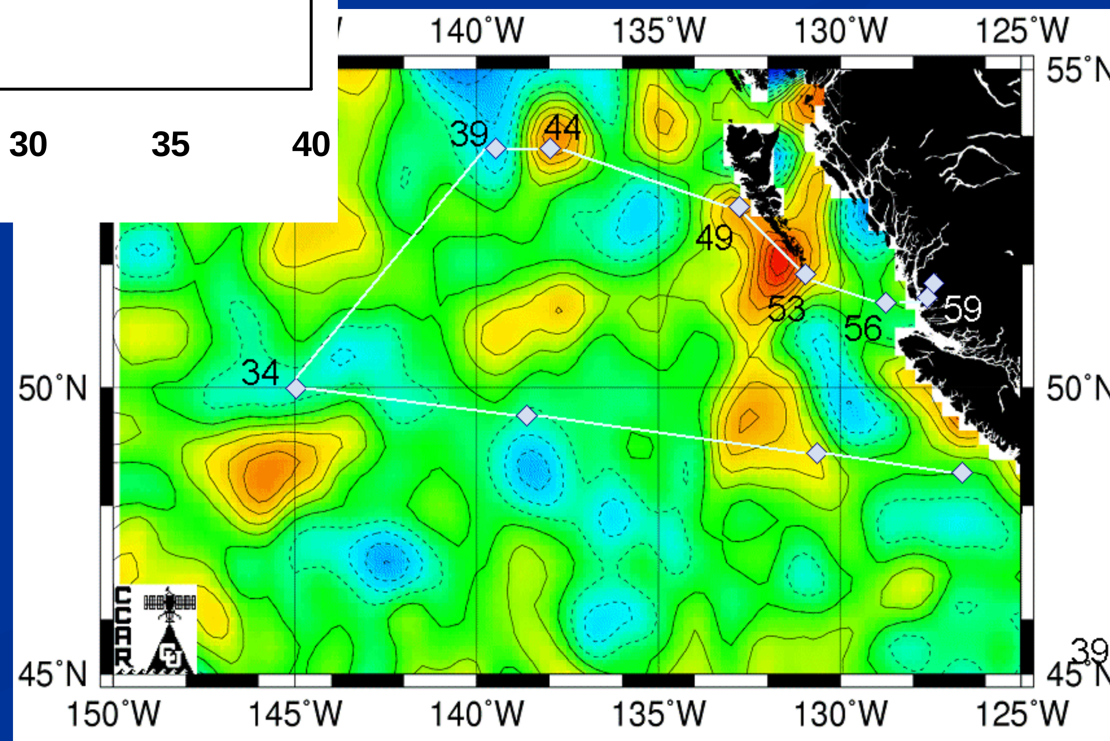

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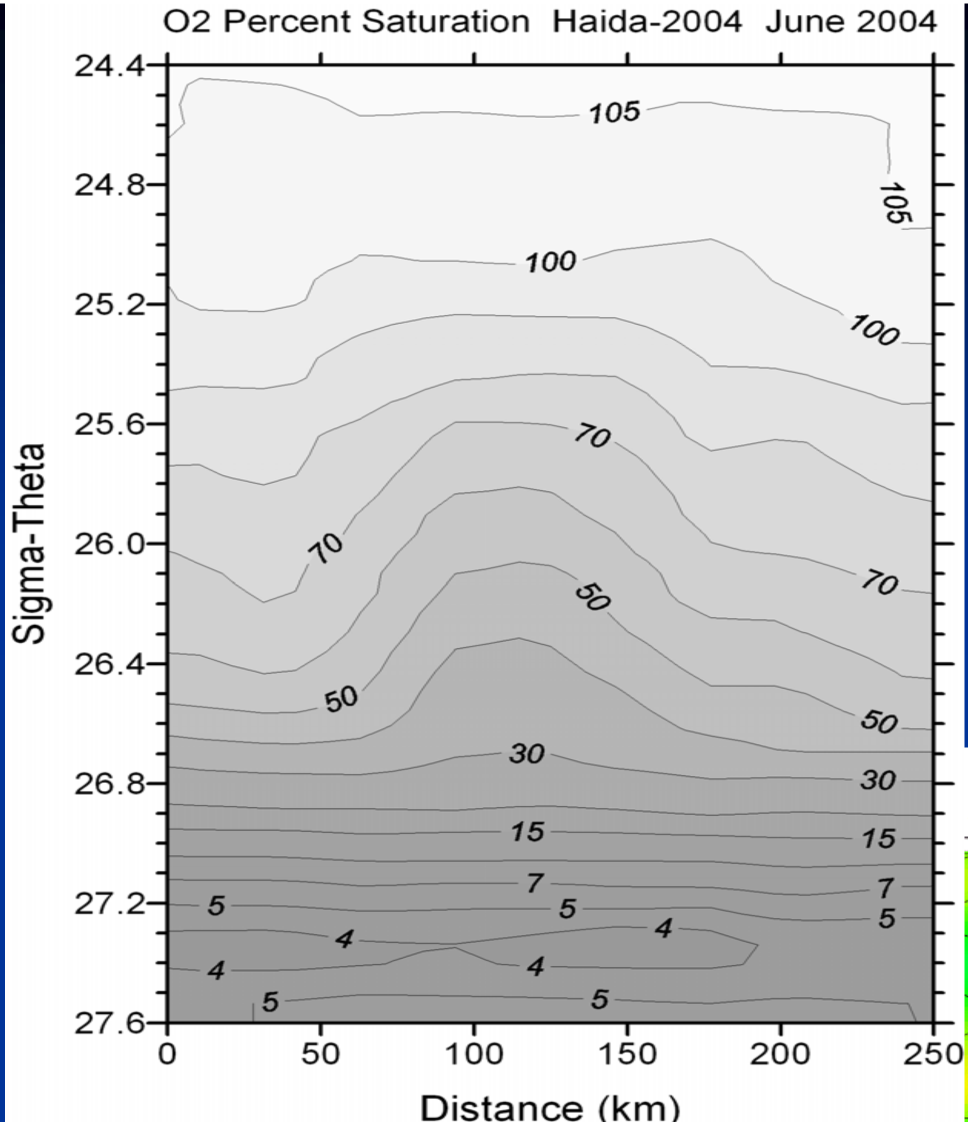
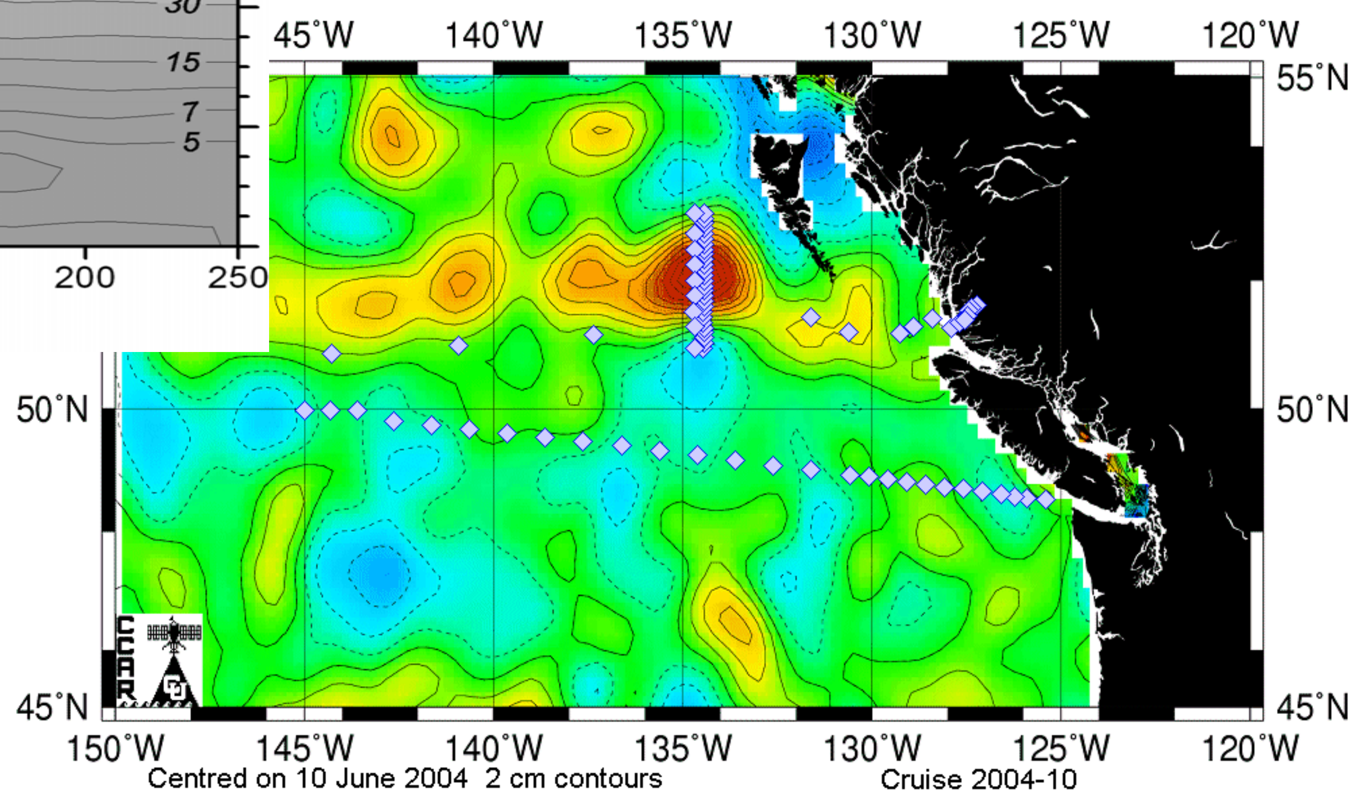


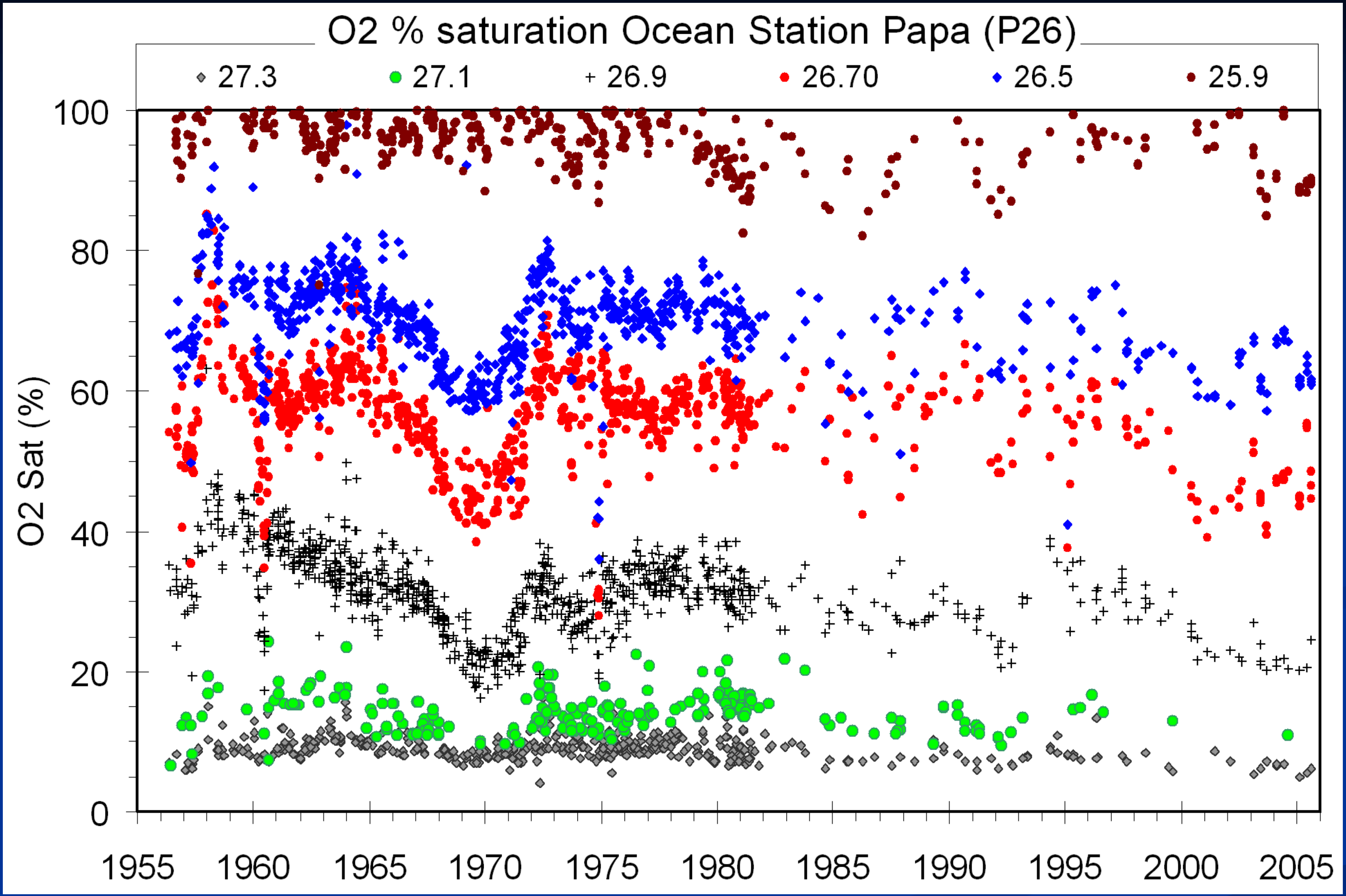
Next:
Summer Line-P cruise with a return track through a new Haida Eddy and shelf waters.

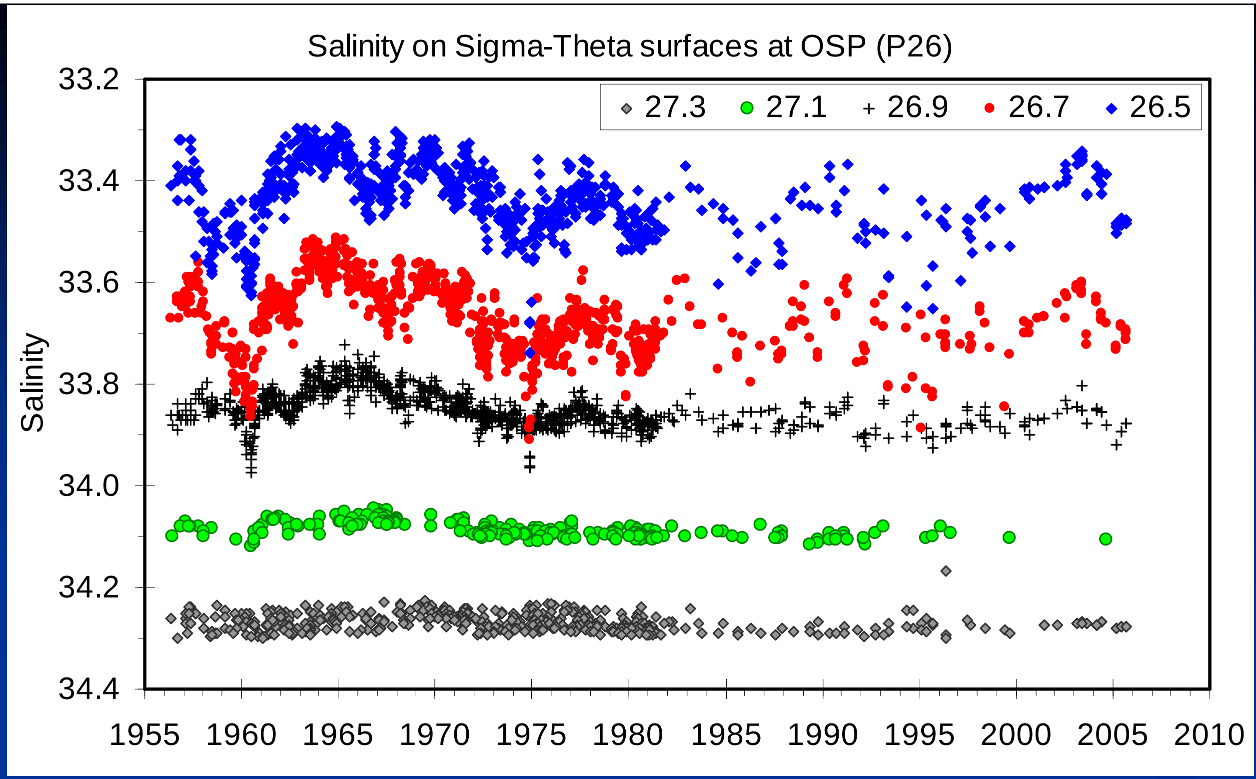
The O2 % saturation contours clearly define the eddy core waters, which extend to 26.8 sigma-theta.

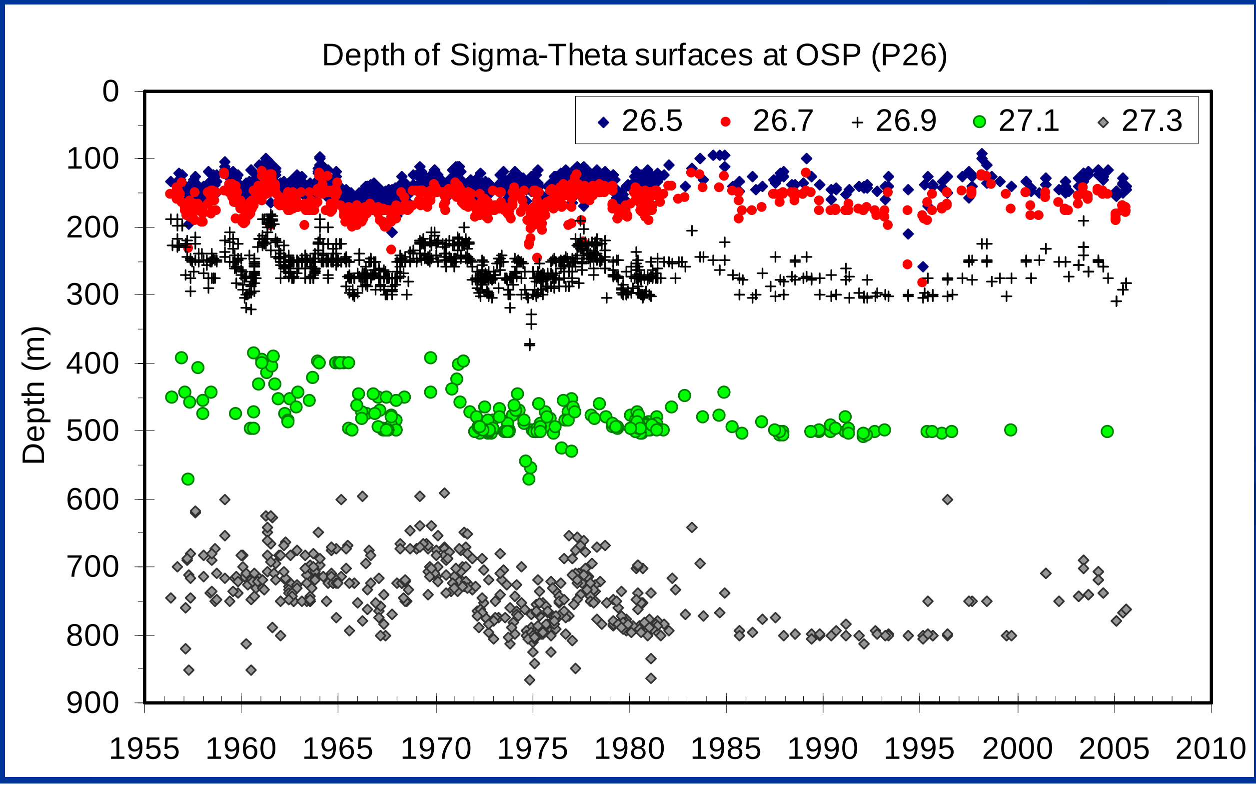
Below this depth the isopycnals are depressed, but oxygen levels are similar inside and outside the eddy.



DFO Cruise 2004-10
on CCGS *John P. Tully*
with Marie Robert as
senior scientist


O2 % saturation Ocean Station Papa (P26)
27.3
27.1
26.9
26.70
26.5
25.9
O2 Sat (%)
0
20
40
60
80
100
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005


Salinity on Sigma-Theta surfaces at OSP (P26)
27.3
27.1
26.9
26.7
26.5
Salinity
33.2
33.4
33.6
33.8
34.0
34.2
34.4
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

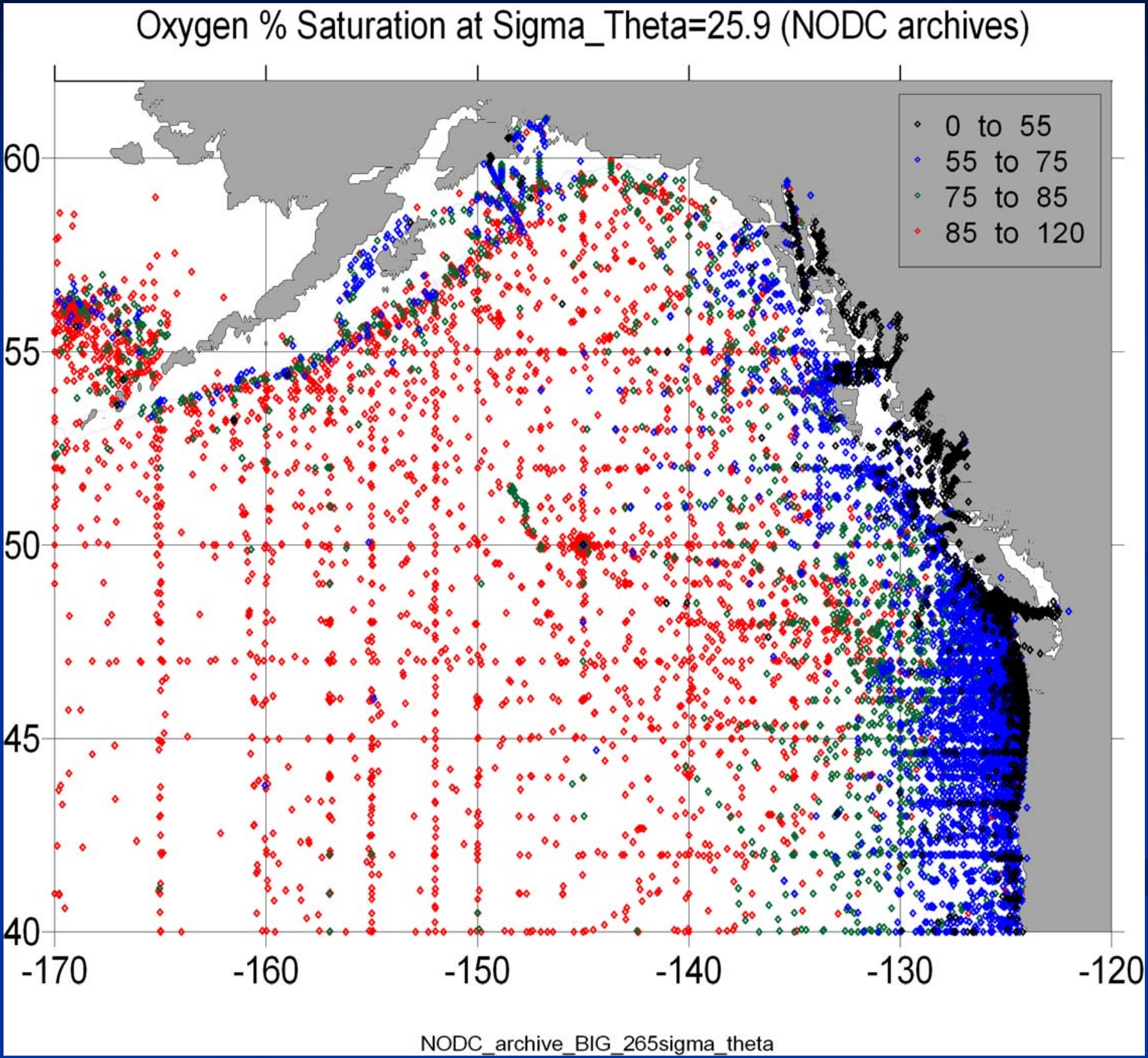

Depth of Sigma-Theta surfaces at OSP (P26)
26.5
26.7
26.9
27.1
27.3
Depth (m)
0
100
200
300
400
500
600
700
800
900
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

Murat Aydin, Zafer Top, Rana A. Fine, and Donald B. Olson
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. C13, PAGES 30,923–30,940, DECEMBER 15, 1998

Plot of O2 % saturation levels of all profile data in NODC archives.

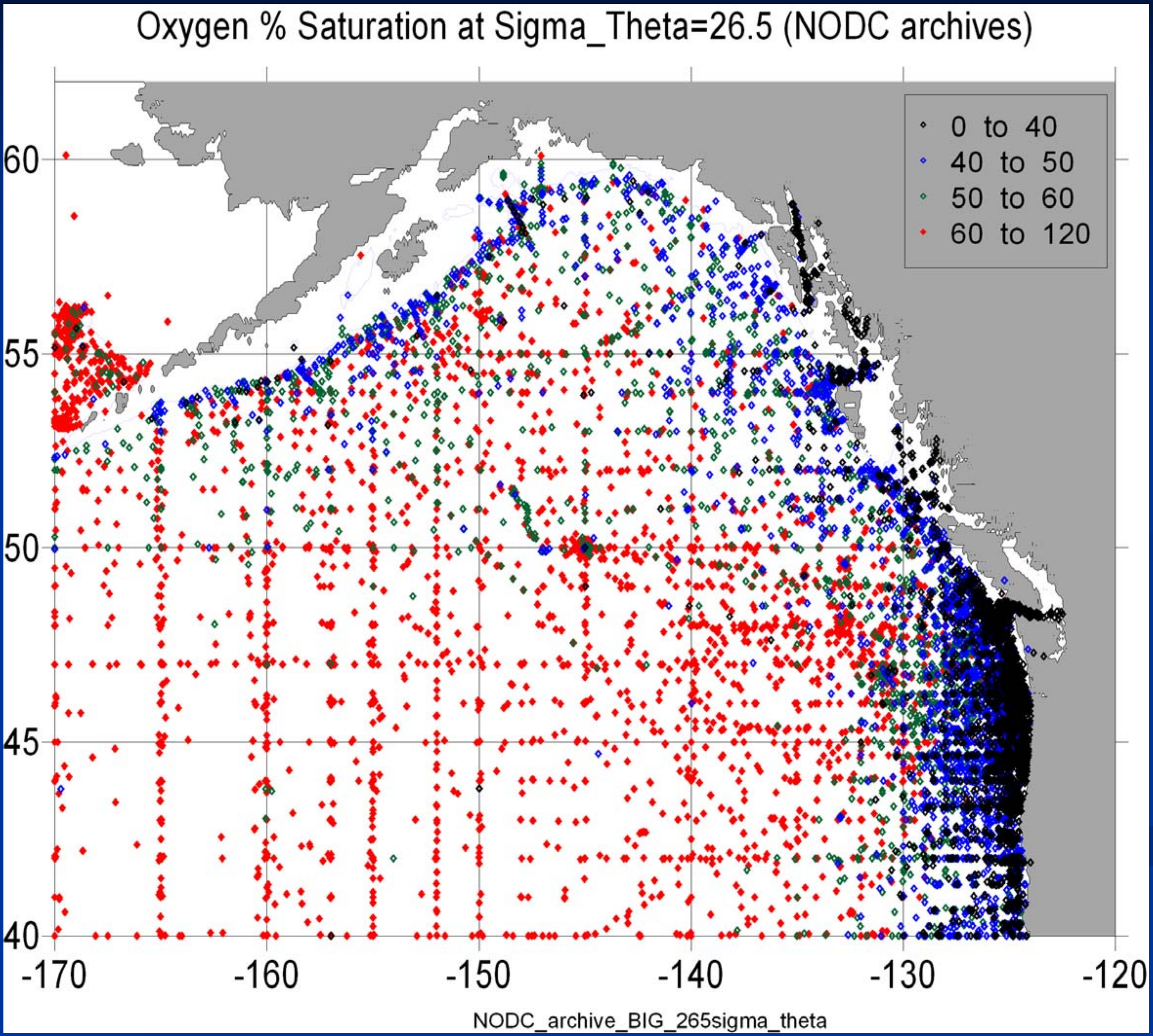
Sigma-θ =25.9

This density surface outcrops in mid-Alaska Gyre.

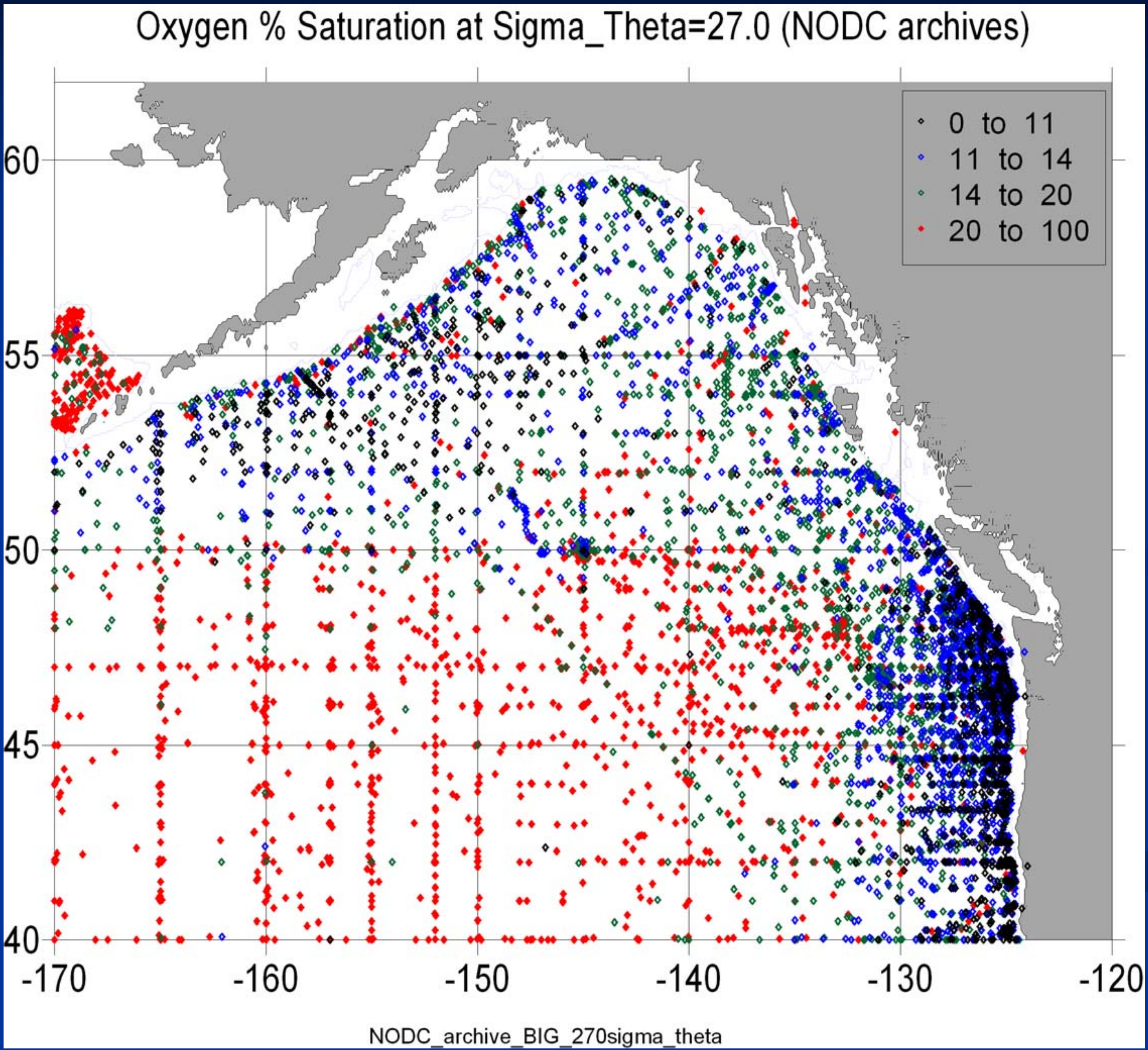


Sigma-θ =26.5

Just below based of winter mixed layer at OSP



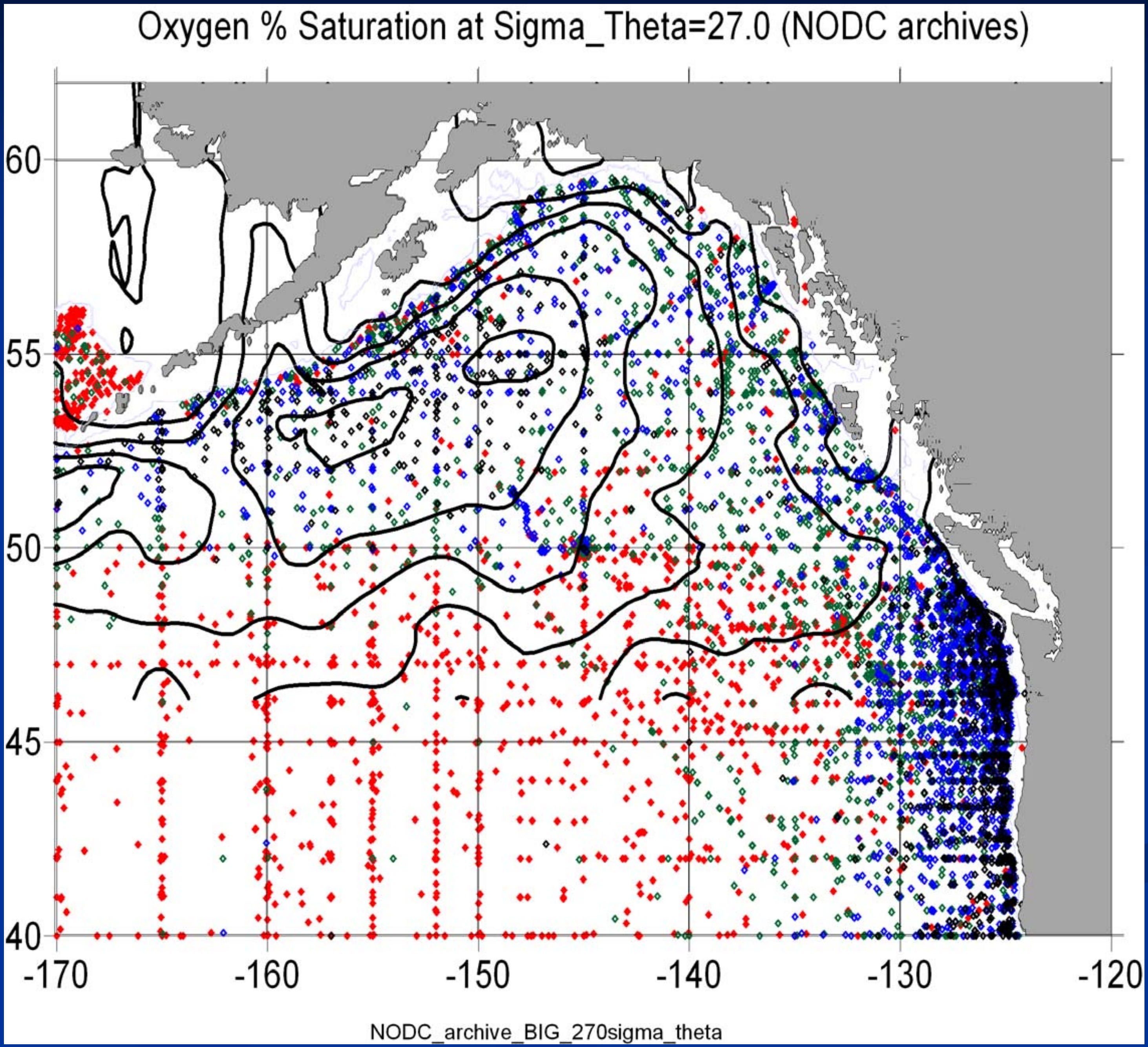
Sigma-θ =27.0



Oxygen % Saturation at Sigma_Theta=27.0 (NODC archives)
0 to 11
11 to 14
14 to 20
20 to 100
60
55
50
45
40
-170
-160
-150
-140
-130
-120
NODC_archive_BIG_270sigma_theta

Black contours denote dynamic height at 150-m depth relative to 1900 metres.

Sigma-θ =27.0



Murat Aydin, Zafer Top, Rana A. Fine, and Donald B. Olson

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. C13, PAGES 30,923–30,940, DECEMBER 15, 1998

They observed significant patches of coastal-origin, low-oxygen water in the higher-oxygen WSW waters in the Alaska Current, at the depth range of Western Subpolar Waters: 27.0 to 27.3 Sigma-theta.

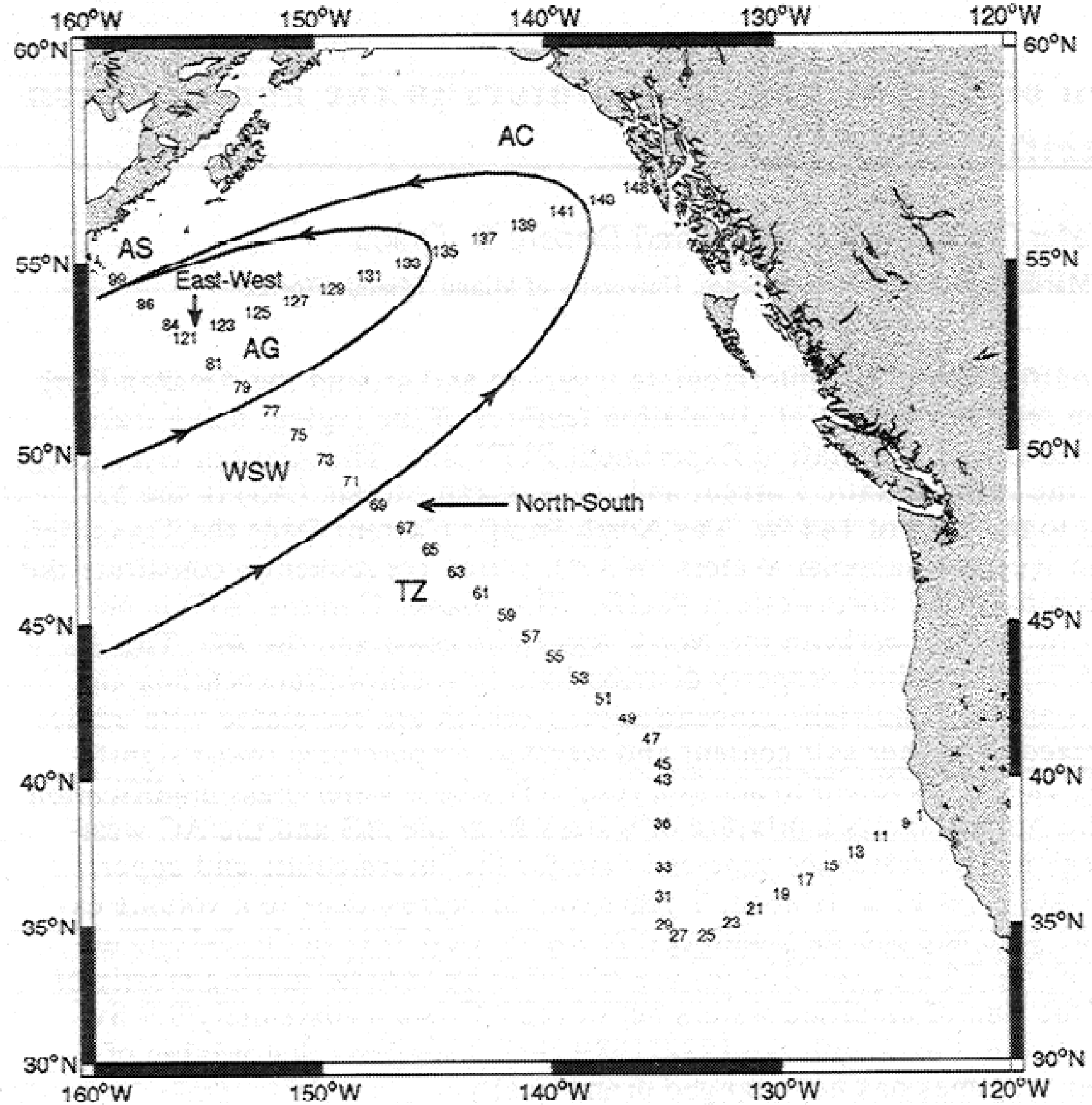
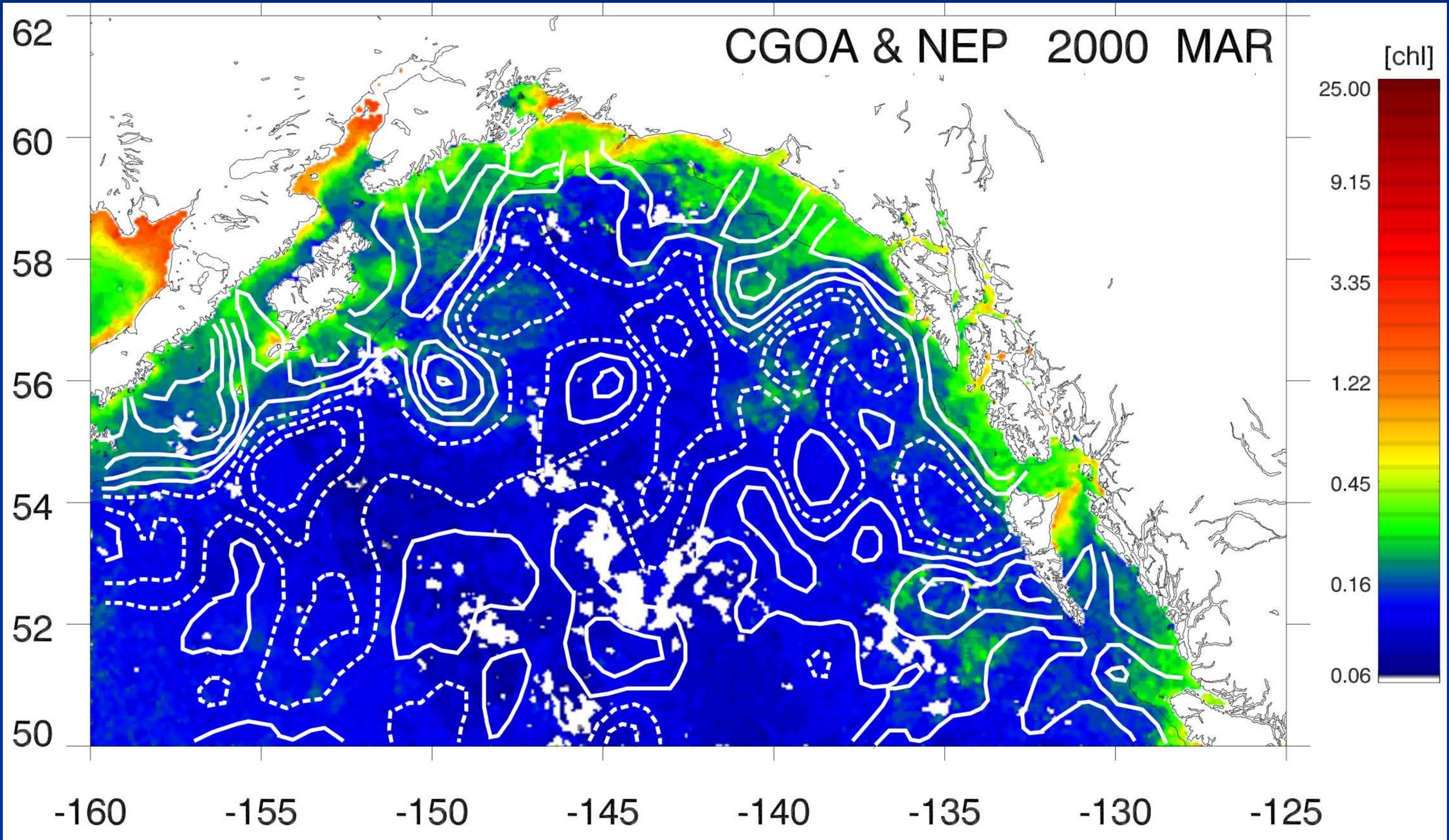


Figure 1. The cruise track of World Ocean Circulation Experiment (WOCE) P17N. It consists of two branches: the north-south (N-S) and the east-west (E-W) sections, which correspond to stations 46-99 and 99-148, respectively. For clarity, alternate stations are shown on the map. Five major water masses mentioned in the text are the transition zone (TZ), Western Subpolar Waters (WSW), Alaskan Gyre (AG), Alaskan Stream (AS), and the Alaska Current (AC).

Summary of transport and mixing into the Gulf waters by Sitka-class eddies.

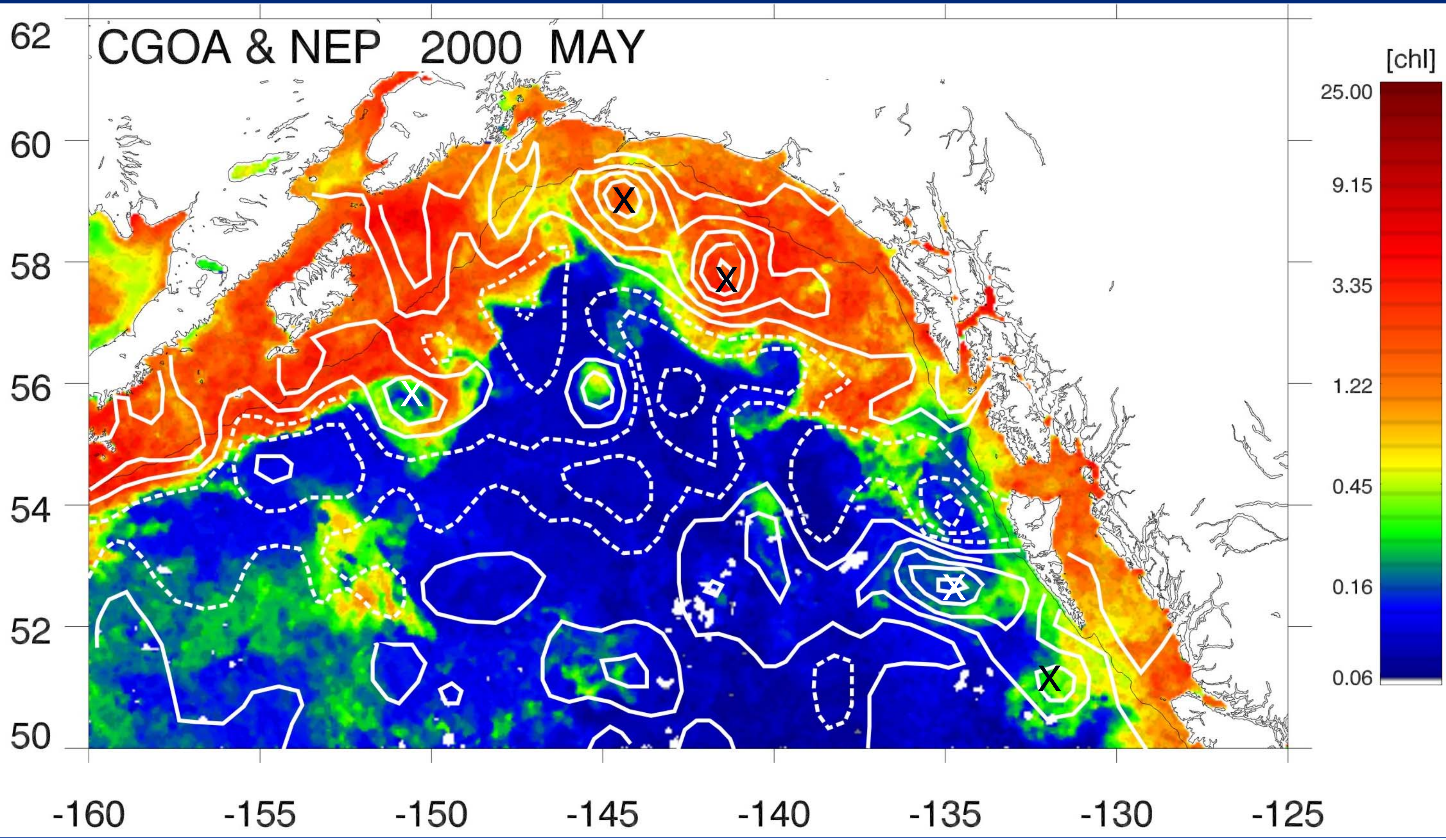
A: Advect surface waters in eddy centres.

In winter and spring, eddies carry coastal surface waters into the gulf and often start blooming earlier than surrounding waters, by as much as a month. Cause of earlier bloom is uncertain. Could be warmer waters in eddies, or more iron?



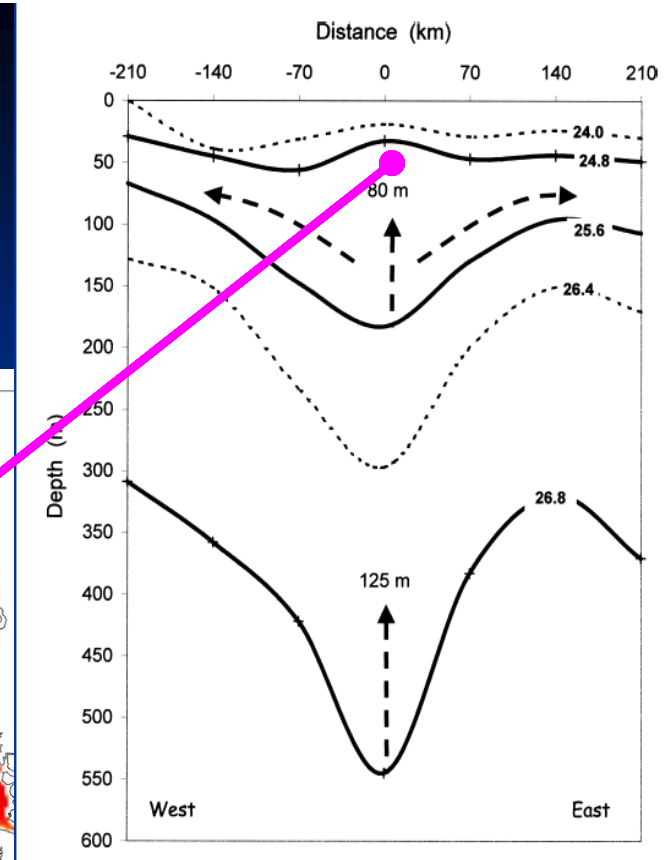
B: Advect surface waters into outer eddy rings.

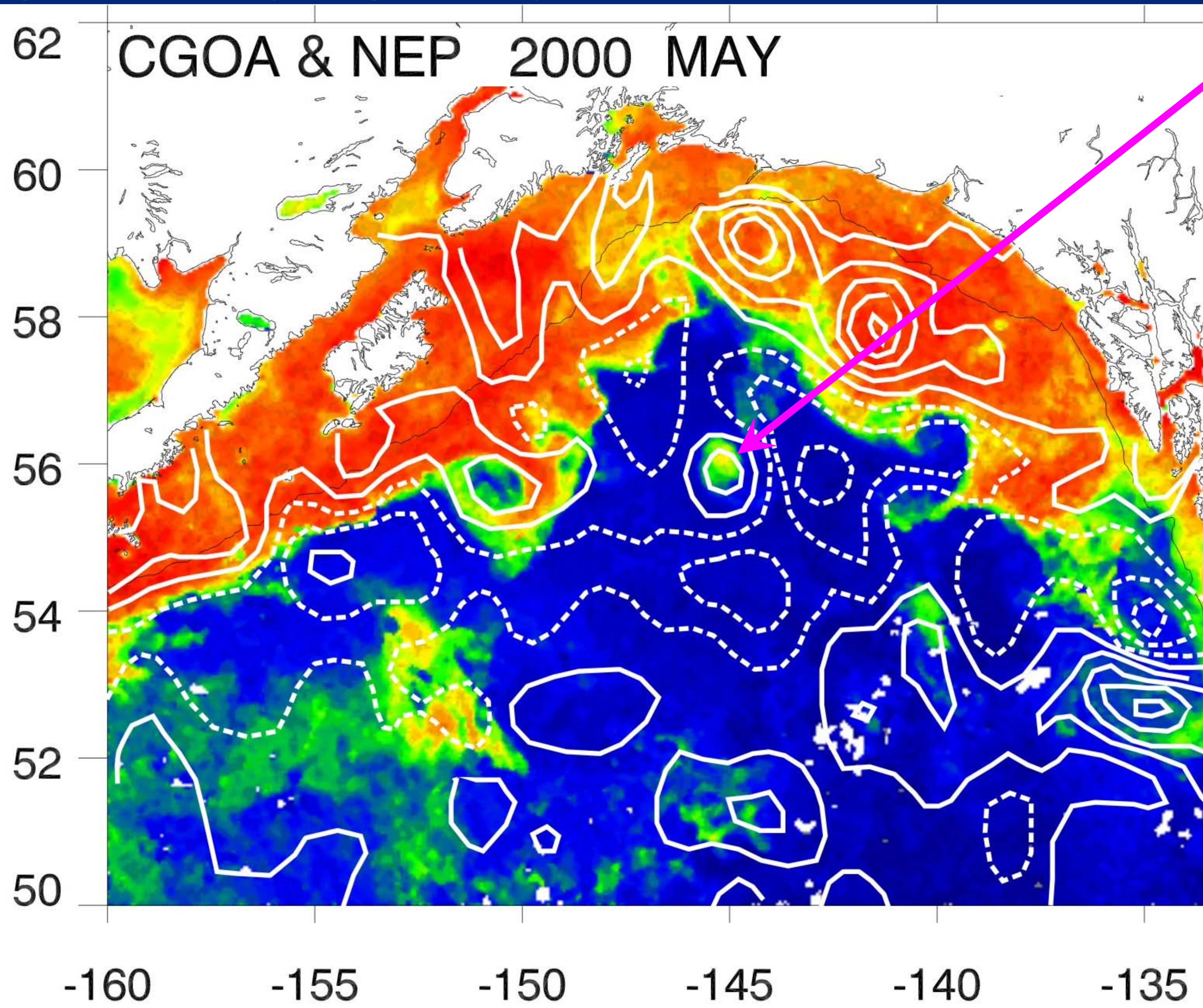
By April and May, Sitka and Haida Eddies define the seaward extent of phytoplankton blooms. High phytoplankton biomass can be in central waters, or in coastal waters entrained into outer rings of eddies and carried out to sea. Deep-sea waters can be carried toward and onto the shelf by this same advective process.

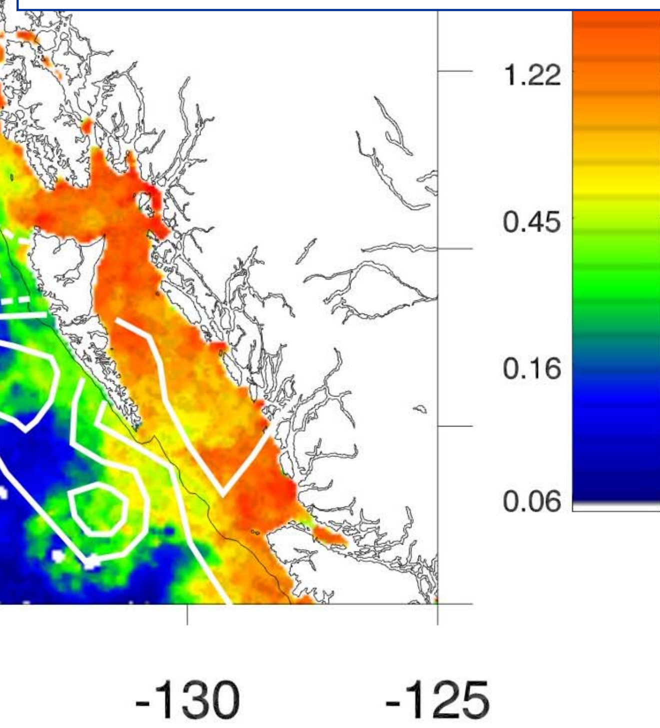


C: Upwell core nutrients toward surface as eddy decays.

Isopycnals must rise as these baroclinic eddies decay, lifting sub-surface nutrients up to euphotic zone. The bloom in a 16-month-old eddy in mid-gulf in May 2000 was likely due to this process during the preceding winter. See also: next slide



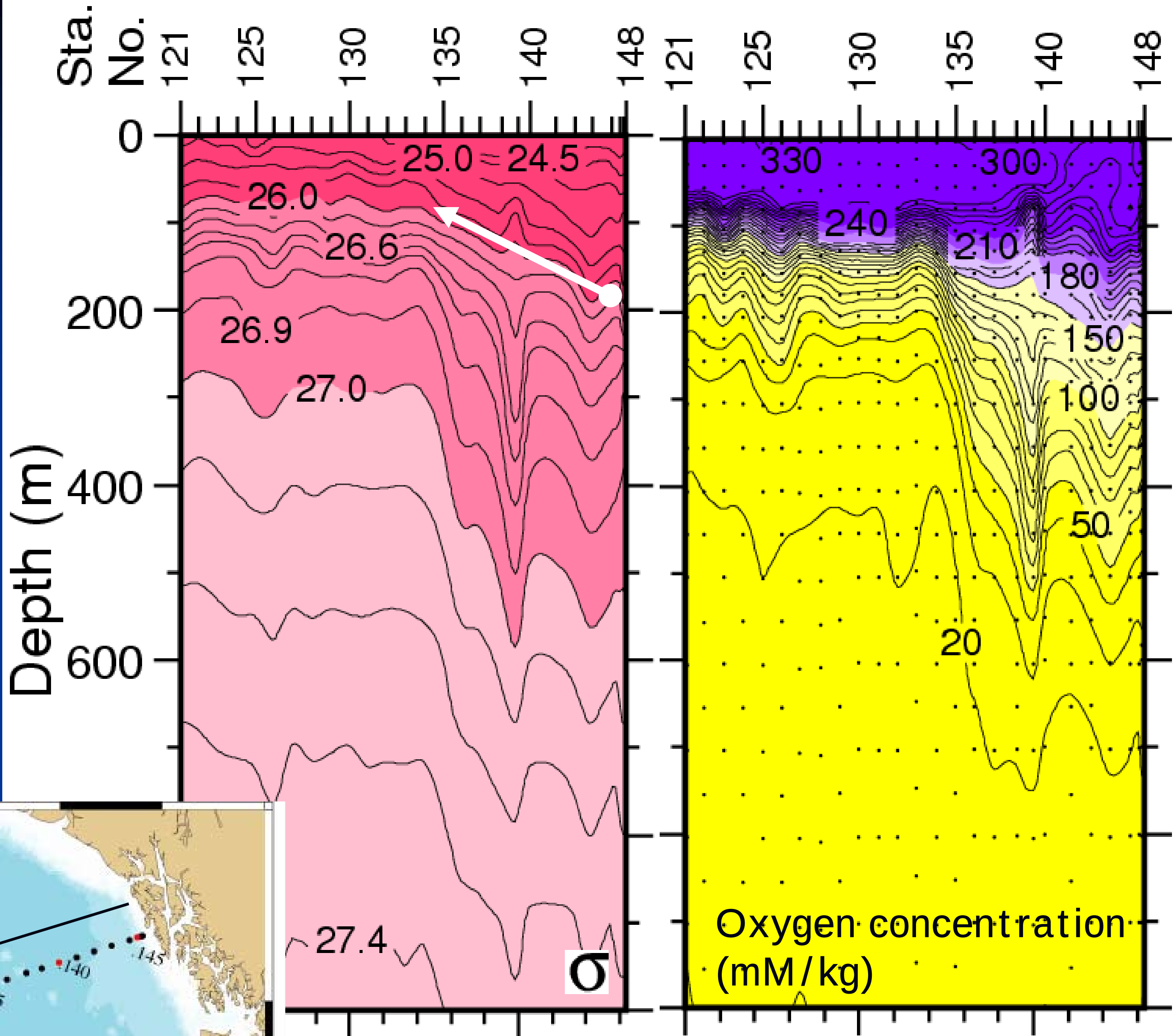


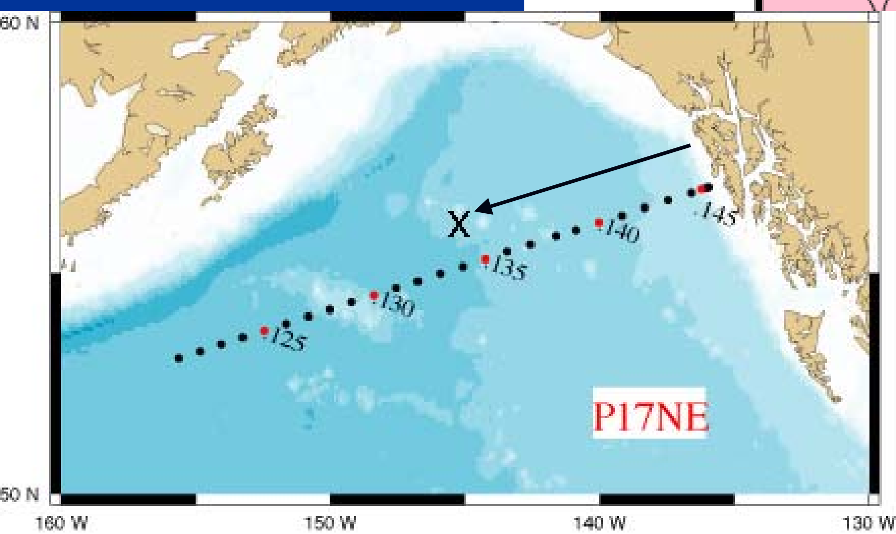


D: Upward advection along isopycnals as eddies drift from the continental slope toward mid-gulf.

Note how isopycnals shoal toward mid-gulf.

The x and arrow below show track of eddy in previous slide.





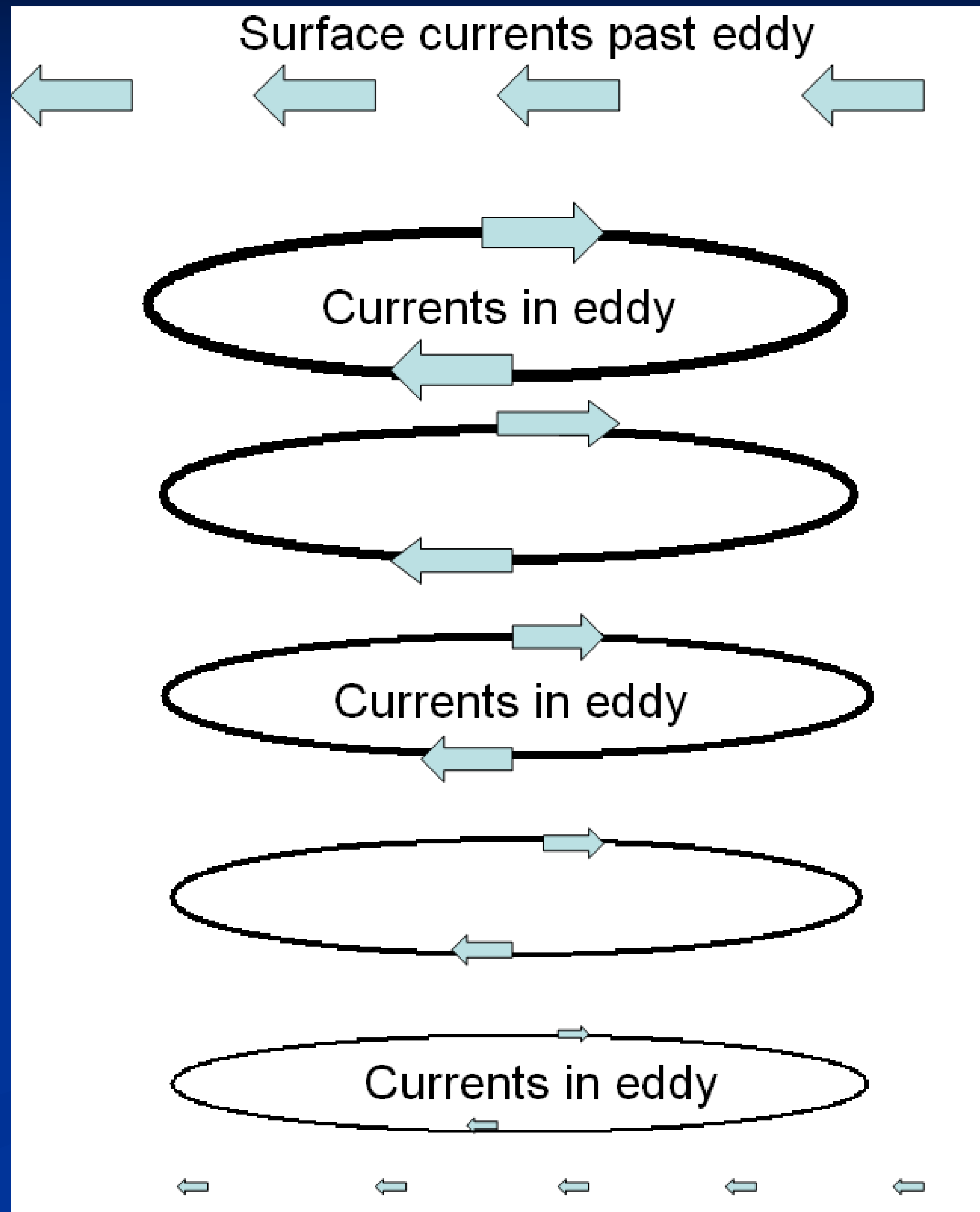
Data from WOCE cruise along P17NE.
(D. Musgrave and T. Royer.
Contours from WOCE Web site of L. Talley.

E: Turbulent diapycnal mixing in eddies, due to higher current speeds in rotating eddies.

Potential energy in depressed isopycnals → Kinetic energy of rotating eddy → turbulence → turbulent dissipation and diapycnal mixing. (About 15% goes to mixing)

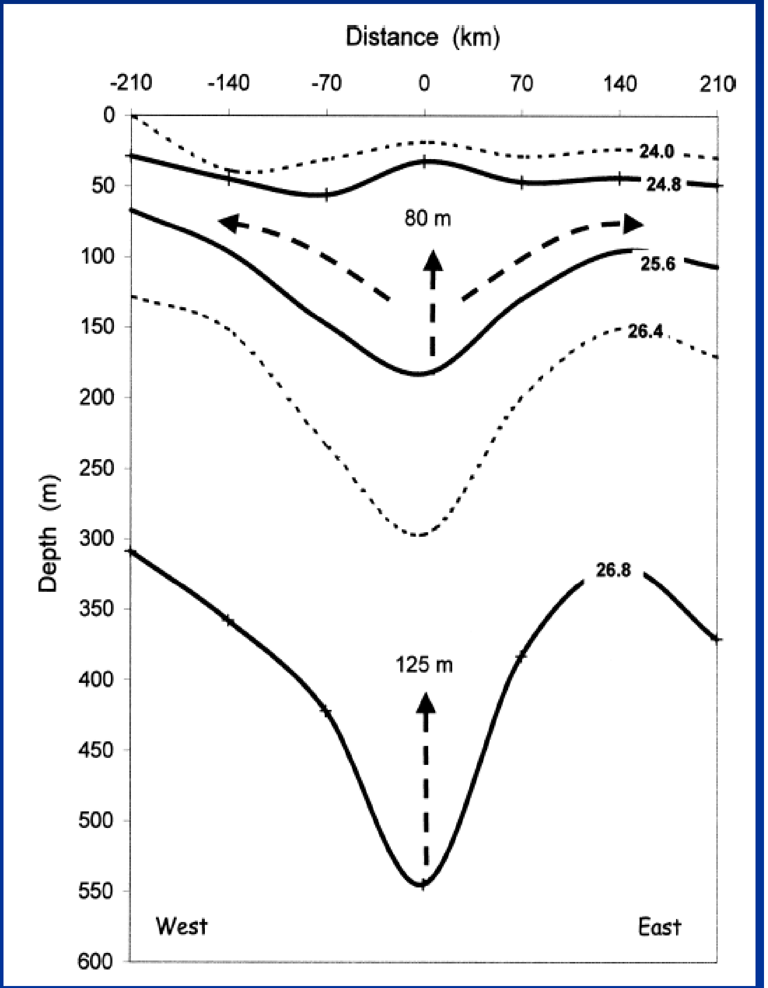
Potential energy stored in eddies is converted to kinetic energy, then dissipates due to turbulent stirring and mixing. This mixing will mix nutrients toward regions of lower concentrations, such as the surface euphotic zone. This energy source is very large, but it is not clear how this mixing is vertically distributed.

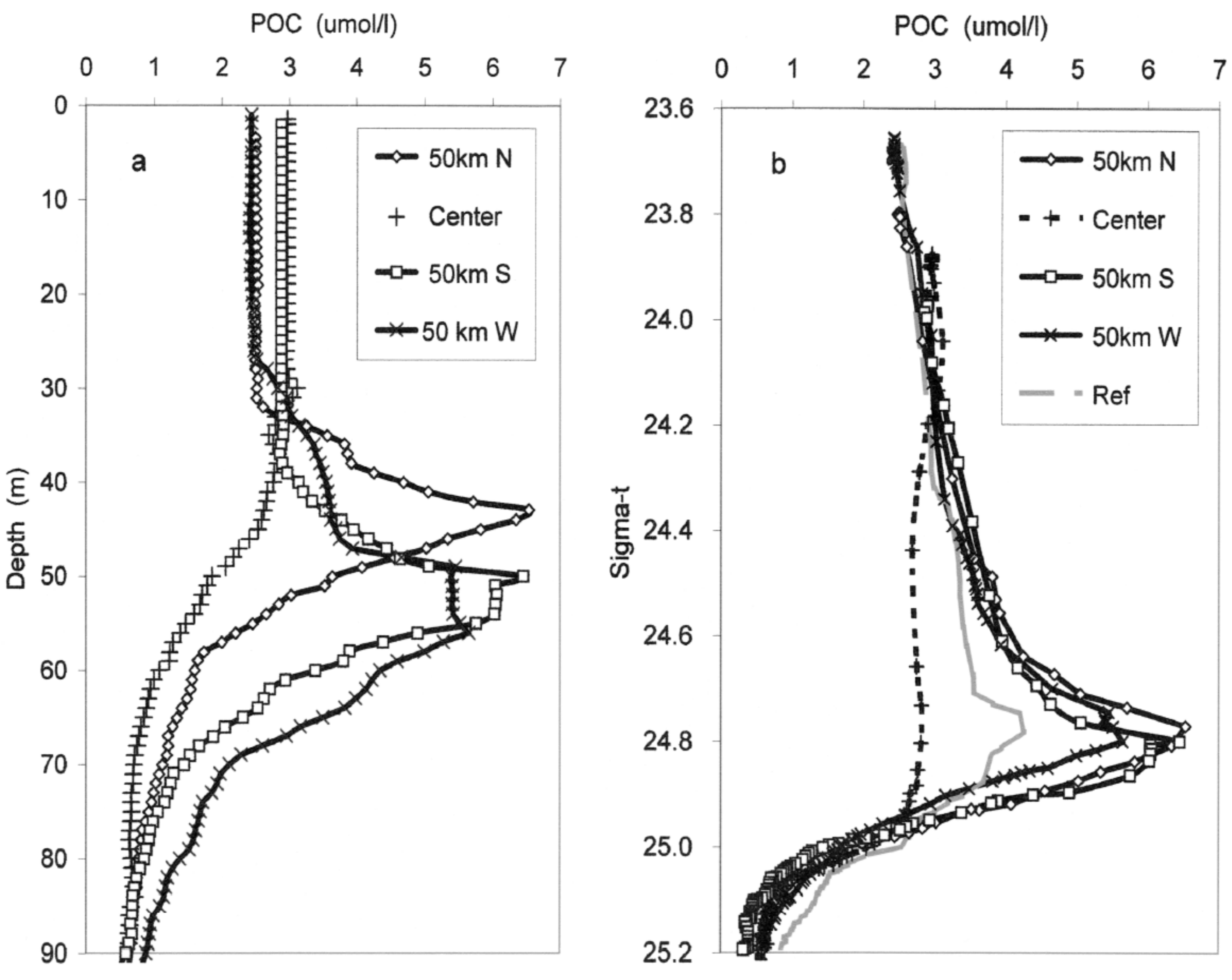
Ref: Mackas, Tsurumi, Galbraith & Yelland, 2005 for more details of this effect at the base of the mixed layer in winter.



F: Advect nutrients (including iron) up along isopycnals into euphotic zone, to support sub-surface phytoplankton growth.

Several observations indicate that plankton accumulate in sub-surface waters around Sitka-type eddies. The diagram below indicates how advection along isopycnals in eddies can lead to upwelled nutrients. The POC at lower right is an indicator of higher production in eddy rings than in central waters.





Left: Sigma-t contours in Haida-1998, August 1998, showing suggested path of nutrients along isopycnals. Right: POC concentrations in and near the centre of Haida 1998-in late August 1998. POC is estimated from light limitation data using the formula of Bishop (1999). Figures from Whitney and Robert, 2002.

G: Inject nutrients into the Alaskan Stream and North Pacific Current, which then flow into the SE gulf.

Eddies in the Alaskan Stream divert their own waters and coastal waters seaward well into the gulf. These waters can be entrained into the North Pacific Current or Alaskan Gyre and carried back into the gulf, carrying lots of nutrients.

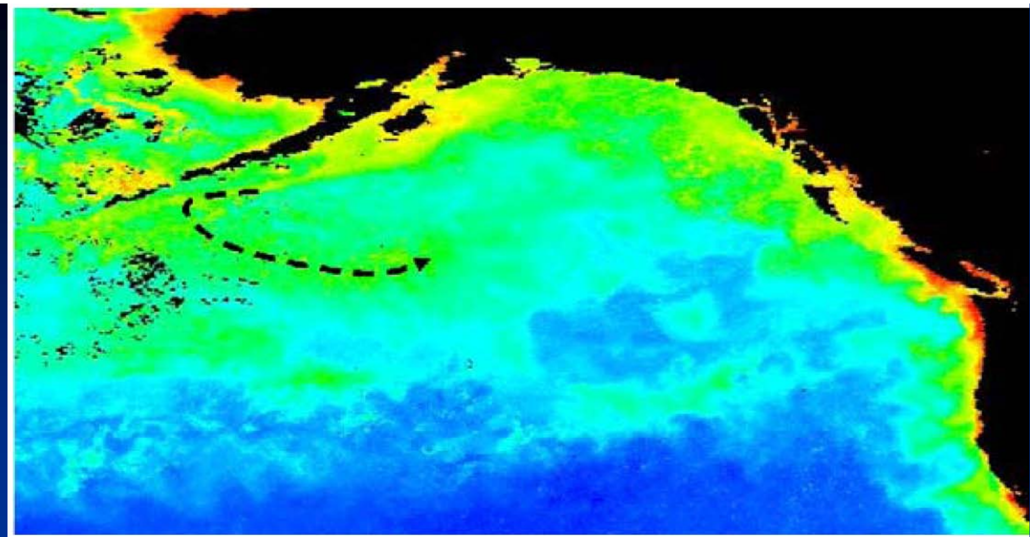
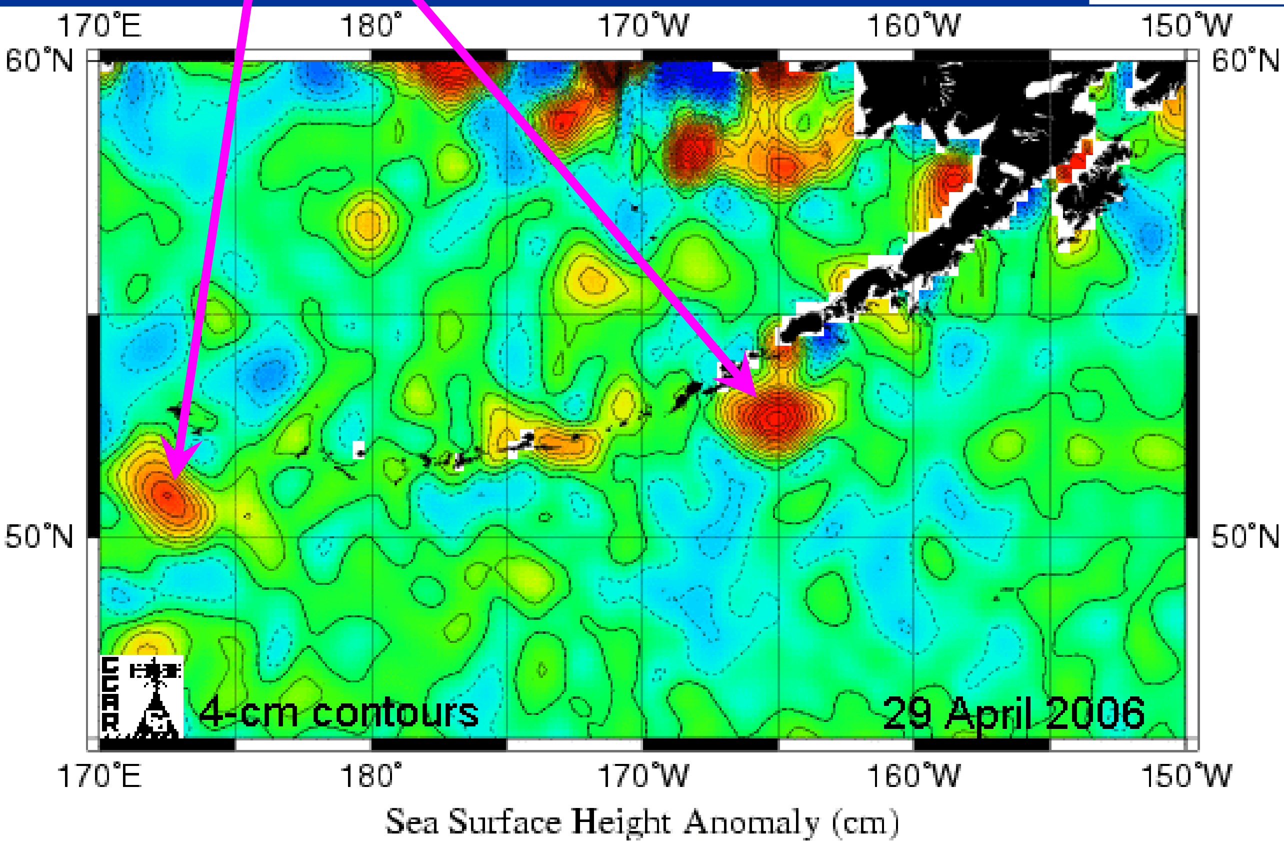


Figure 17, Whitney, Crawford and Harrison (2005)

Fig. 17. Seasonal composite SeaWiFS image, showing chlorophyll distribution for summer 1999. The dashed line indicates the possible route of coastal waters being recirculated around the Alaska Gyre.



Most eddies in the Alaskan Stream are Sitka-class eddies that carry their high sub-surface nutrient levels into the Alaskan Stream. These eddies can inject their own nutrients into the N Pac Current and AK Gyre, or advect coastal nutrients into these flows.

There are usually one to three such eddies in the Alaskan Stream.

Eddies participate in almost all processes that provide nutrients and iron to the deep-sea surface waters of the Gulf of Alaska.