Altimetric Studies of the Oceanic Pathways in the Northeast Pacific Ocean

or

Characteristics of Poleward Pathways Between the Southern and Northern CCS: The Role of Ekman Transports *and the Inshore Countercurrent*

Ted Strub, Corinne James, Vincent Combes, Melanie Fewings, Ricardo Matano
CEOAS, OSU

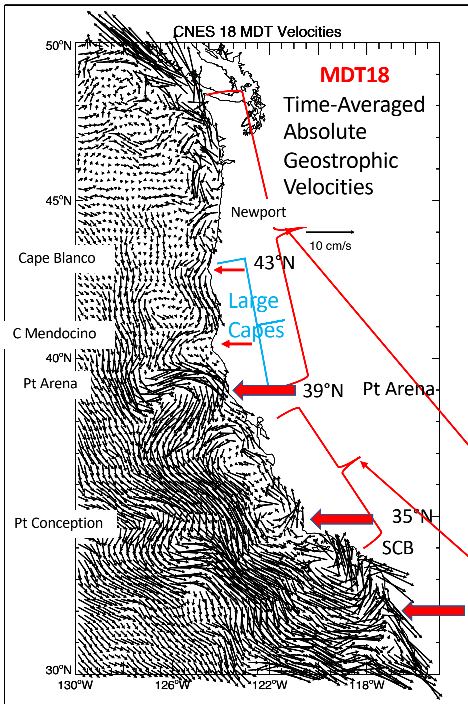
Motivation

- Observations of "tropical/subtropical" species of zooplankton and water properties off Oregon have been used to infer transports from far to the south during some years, especially El Niño warm events (especially 1982-83, 1997-98).

Questions:

- Can passive water parcels reach Oregon (44°N) from the Southern California Bight (32-35°N)? How far can passive water parcels be transported poleward in the equatorward CCS?
- What are the seasonal and spatial characteristics of trajectories that reach Oregon?
- How does the wind-driven Ekman transport modify the geostrophic transport found beneath the upper Ekman layer?
- Does the region of large capes (Pt Arena, Capes Mendocino and Blanco, 39°N-43°N) act as a barrier to poleward transport of passive water parcels?
- Does northward transport increase during the 1997-2020 24-year record?

In our present OSTST project we are creating Lagrangian trajectories from the daily gridded geostrophic surface velocities (with and without an additional Ekman transport component), showing the pathways the taken by passive water parcels. The present focus is on the few pathways that move water parcels from the southern to the northern regions of the California Current, answering the questions shown in the slide. We ignore the 1993-1996 period, during which ERS-1 was moved between several different orbits.



Methods

- We calculate daily Lagrangian trajectories
  - Using the "Parcels" software
- We use two daily altimeter-based data sets:
  - Absolute geostrophic velocity from SLA + CLS CNES MDT18 (Mulet et al., 2021).
  - "OSCAR": Absolute geostrophic velocity + Ekman transports in the top 30m.

The California Current System – Features of Interest

Region of the seasonal reversal of the CCS currents to northward in autumn-winter, often called the poleward "Davidson Current (DC)"

ICC = The poleward Inshore Countercurrent, minimum/absent in spring.

Large red arrows show the latitudes of release, 32°N, 35°N and 39°N

Trajectories are created from the purely geostrophic absolute velocities, created from "AVISO" SLA + MDT18 (identified as "geostrophic" trajectories) and from the OSCAR velocities, which include the effects of wind-driven Ekman transport in the upper 30 meters ("Ekman" trajectories).

The MDT18 velocity field shows the main characteristics of the California Current System:

- A meandering equatorward offshore current that connects back to the West Wind Drift;
- A coastal current that meanders around the large capes and alternates in direction north of ~39°N from equatorward in spring and summer to poleward in fall and winter (the "Davidson Current", DC); At its southern end, it enters the SCB.
- A poleward coastal "Inshore Countercurrent (ICC)" between ~33°N-37°N, which is weak or reversed to equatorward in spring but poleward the rest of the year;
- The cyclonic gyre in the Southern California Bight (SCB, 32°N-35°N), which is also weakest in spring.
- A region of large capes between ~39°N—43°N.

We release water parcels at the three latitudes shown by red arrows: 32°N in the SCB; 35°N just north of the SCB; and 39°N at the southern end of the Large Capes Region.

Initial Strategy

- Release 40 passive water parcels at the beginning of each 30-day "month."
- On E-W transects. 4° wide, every 0.1°.
- Start at April 1 each year and continue each trajectory for 360 days.
- Start from transects at 32°N, 35°N and 39°N.

Data Sets

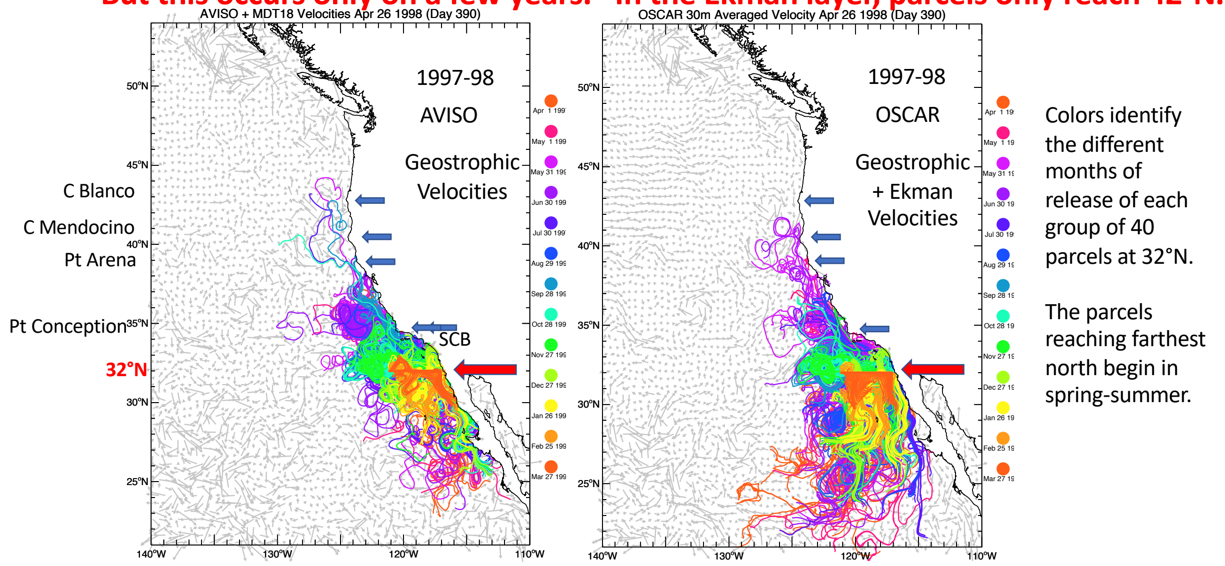
- "AVISO" (CMEMS, Copernicus Marine Service) Altimeter-derived trajectories represent the geostrophic pathways of parcels beneath the Ekman layer but above the Poleward Undercurrent (PUC).
- "OSCAR" (from ESR in Seattle) Trajectories represent changes made by wind stress to the altimeter's geostrophic velocities in the surface (30m) Ekman layer.

We release parcels at the three latitudes along 4° E-W transects. Starting April 1 of each calendar yea. Releases occur at the beginning of twelve 30-day "months" and each set of parcels is followed for 360 days. Most of the parcels go south but we focus on those that travel north.

The geostrophic velocities create trajectories typical of the flow beneath the surface Ekman layer.

The OSCAR velocities create trajectories typical of the flow within the surface Ekman layer.

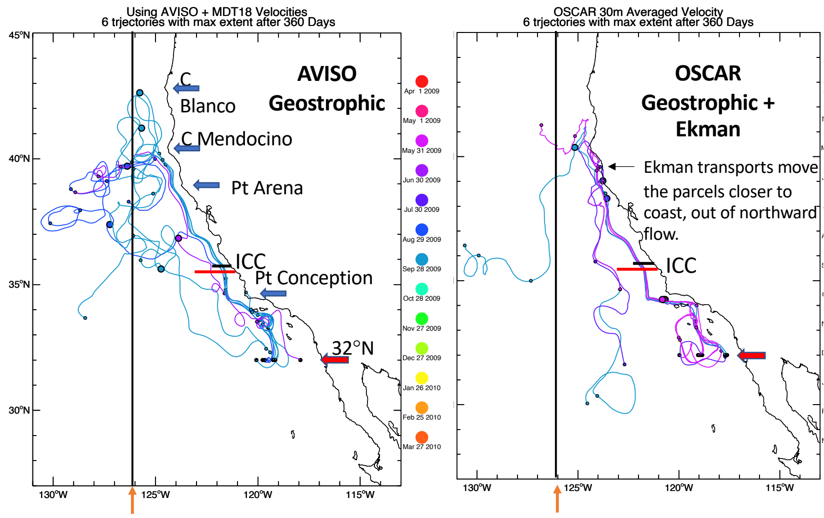
1997-98 (Strongest El Niño in our record). Release parcels along 32°N.
It is possible for "geostrophic" parcels from the SCB to travel north of 43°-44°N.
But this occurs only on a few years. In the Ekman layer, parcels only reach 42°N.



Here we show trajectories of all parcels released from 32°N during the 1997-98 "year", the strongest oceanic El Niño in our record.

- Some of the geostrophic trajectories reach Cape Blanco (42.8°N) or farther north;
- Ekman trajectories only reach ~ 42°N;
- Trajectories from 32°N only reach this far north on a few years;
- Colors show the month of release;
- The parcels reaching farthest north from 32°N are released in spring-summer.

360-Day Trajectories for the Six Parcels that Travel Farthest North from 32°N
Starting April 1 2009 – a "Moderate El Niño"



Next, we show the most northern extent of all parcel trajectories for all years, but only for parcels in the region east of 126°W (dark vertical lines).

Characteristics of "Successful Parcels"

- **Travel in the ICC, connecting to the DC.**
- **Most travel north of Pt. Conception occurs in autumn-winter.**
- **Of parcels released at 35°N (north of the SCB), 50% of those that reach 39°N and 41°N are released within 1° of the coast; 80% are released within 2° of the coast (black and red horizontal lines near 35°N).**

What Stops Parcels?

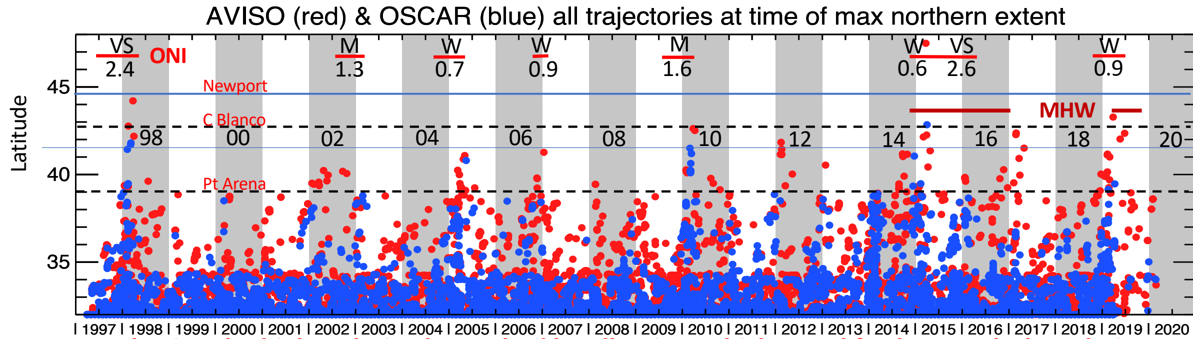
- **Detrainment from the poleward coastal current by offshore jets at the capes.**
- **Ekman drift toward the coast, where currents are slow or form small eddies.**

Characteristics of the parcels that travel farthest north are revealed by plotting the trajectories of the six parcels that travel farthest north each year. We have examined these for all years and releases at all three latitudes. This example is for 2009-2010, a moderate El Niño, with releases from 32°N. Circles on the trajectories are every 2 months and the large circles show the parcel location after 6 months.

The importance of the ICC is highlighted. The most successful parcels travel 500-600 km over 2-month periods (~10 cm/s), usually in autumn-winter. Ekman transports toward the coast during fall-winter move the parcels into slower water and reduce their northward extent. Offshore flow in jets and filaments at the northern end of the cyclonic meanders also remove parcels from the strong poleward flow.

50% of the parcels that reach 39°N and 41° from 35°N (just north of the SCB) are released in the 1° next to the coast (black line at 35°N). 80% of the parcels that reach those latitudes are released in the 2° next to the coast (red line at 35°N), showing again the importance of the ICC.

32°N Release: Maximum 1-Year Northward Displacements



- **Plotting the highest latitude reached by all points which travel farther north than their release latitude from 32°N**
- Plot at the month of maximum northern extent. Most parcels reach their northern maximum in winter. **Parcels in the Ekman Layer do not reach as far north.**
- There is some correspondence between El Niño years and northward transport (?MHW too?)
- There appears to be more northward transport in the second half of the record. Is this due to the use of the "All Satellite" data set?

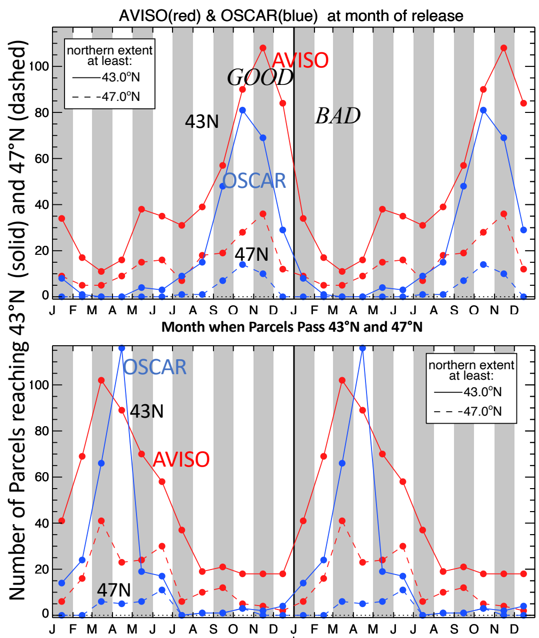
Here we show the maximum northward latitude (y-axis) reached by all parcels for both the geostrophic (red) and Ekman (blue) trajectories, for all years (x-axis). The month during which the parcels reached their maximum extent is indicated by placement along the x-axis.

Periods of positive ONI index (Niño 3.4 index) are indicated by horizontal red lines at the top, showing the maximum ONI index value and indicating Very Strong (VS), Moderate (M) or Weak (W) for the El Niño. The period of the Marine Heat Waves (MHW) at the end of the record are also identified.

El Niño years tend to experience greater northward transports, but other years also have strong transports and the strong 2015-16 El Niño event does not produce extreme northward trajectories.

Are there greater northward extents of the trajectories (more northward transports) during the second half of the record?

Seasonal timing of parcels released at 39°N that pass 43°N and 47°N



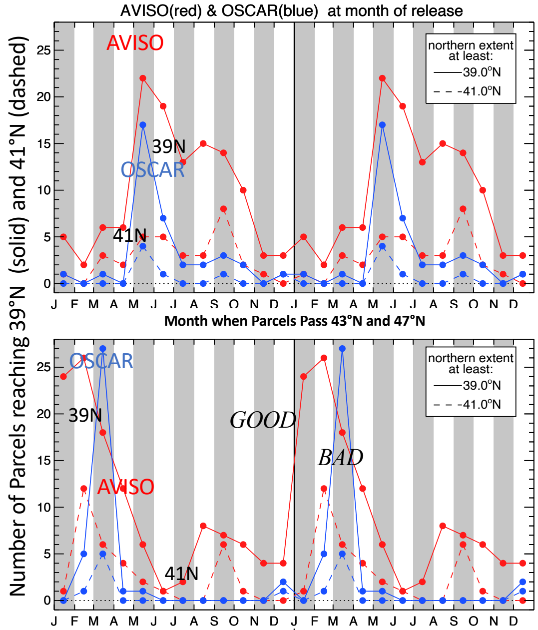
- Parcels near 39°N in autumn are favored for northward travel
- Including Ekman transports narrows the window of opportunity to autumn, strongly reduces northward travel in winter, spring and summer.

- Parcels leaving 39°N pass 43°N and 47°N in winter and spring.

Seasonal timing is important.
(Top panel): After release at the southern boundary of the Large Capes Region (39°N), the number of parcels that move north past 43°N (solid lines) and 47°N (dashed lines) are shown on the y-axis as a function of the month of release, repeating the annual pattern twice. For geostrophic parcels (red), successful parcels are released from May-January. Fewer Ekman trajectories (blue) extend past these limits than geostrophic trajectories. More importantly, **for Ekman trajectories, parcels must be at 39°N during late-summer and autumn (August-December) to have any chance of traveling north of 43°N. Parcels released after December do not reach that latitude.**

(Bottom panel): This shows the same data but plotted as a function of the months during which the parcels pass the above limits. These are primarily in winter-spring-summer for the geostrophic trajectories; and for winter-spring for the Ekman trajectories. **The window of opportunity for parcels in the Ekman layer to reach Oregon is very much narrower than for the parcels beneath the Ekman layer. Winter winds push the parcels toward the coast and trap them in slower water in the Ekman layer.**

Seasonal timing of parcels released at 32°N that pass 39°N and 41°N



- "Geostrophic" parcels leaving 32°N in spring, summer and early fall are favored to get past 39°N and 41°N.
- Including Ekman transport greatly reduces northward travel during summer through winter, leaving a narrow window of opportunity in May-June. Few "Ekman" parcels reach 41°N.

- Some "Geostrophic" parcels arrive at 39°N in autumn, in time to continue past 43°N. Most arrive in winter.
- Almost all "Ekman" parcels arrive in February or later, too late to continue past 43°N.

- (Not shown) Releases at 35°N, north of the SCB: When Ekman transports are included, most parcels released from 35°N still arrive too late at 39°N to continue past 43°N. More parcels beneath the Ekman layer reach 39°N and 43°N.

Seasonal timing is important.
(Top panel): After release in the Southern California Bight (32°N), the number of parcels that move north past 39°N (solid lines) and 41°N (dashed lines) are shown, similar to the previous figure, showing the month of release. For the geostrophic trajectories beneath the Ekman layer, parcels released during May-October are favored. For the trajectories within the Ekman layer, only parcels released during May-June have much chance.

(Bottom panel) **This shows the problem in moving north of the Large Capes Region.** The months during which the parcels from the south reach 39°N (solid lines) are primarily during January-April (geostrophic, red) and Feb-March (Ekman, blue). This is too late for parcels at 39°N to travel past 43°N, as shown in the previous slide. Some of the geostrophic parcels beneath the Ekman layer (red) reach 39°N during August-December and have a chance to travel north of 43°N.

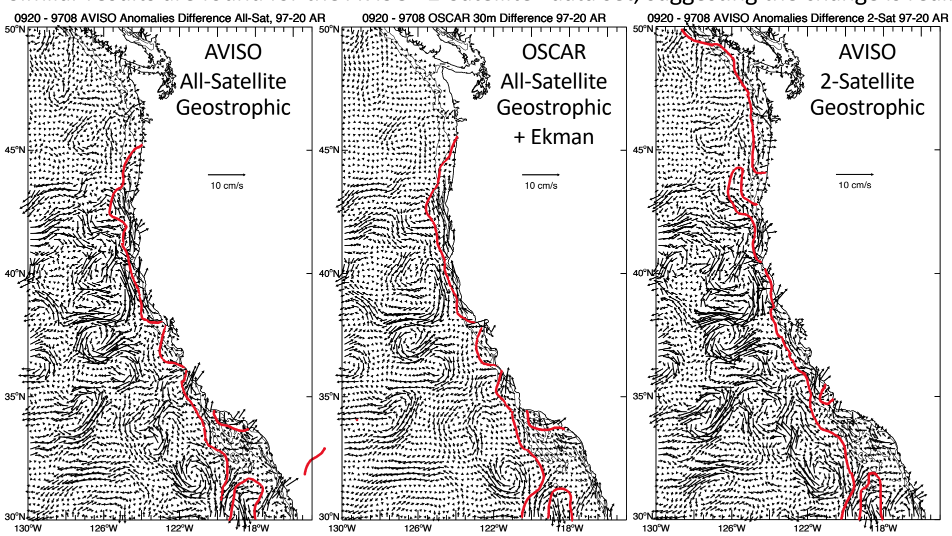
(Not shown) When parcels are released from 35°N, more of the geostrophic trajectories reach 39°N in summer and autumn, with a better chance of extending past 43°N. However, the Ekman trajectories still do not reach 39°N until winter, too late to get past the capes.

The large capes are not an absolute barrier but seasonally they are a barrier to parcels that do not arrive at 39°N by autumn.

Increased Poleward Transport? 2009-2020 vs 1997-2008

Average the first and second half of the records, then subtract: 2009-2020 minus 1997-2008.

Increased poleward flow is found next to the coast for both AVISO (left) and OSCAR (middle) data sets. Is this because they both use the “All-Satellite” altimeter data set, with more altimeters in the second half of the record? Similar results are found for the AVISO “2-Satellite” data set, suggesting the change is real.



Impacts

Increased transport into the northern CCS may bring more “warm-water zooplankton” to the PNW, which are lower in fat content than “cold-water zooplankton”. Young salmon entering the ocean in spring do better with fat cold-water zooplankton.

Above, we raised the question of whether there has been an increase in the number of trajectories that reach the highest latitudes during the second half of our record. Has there been an increase poleward surface transports during 1997-2020? Could this be caused by the increase in the number of altimeters in the All-Satellite fields we are using, resulting in stronger mesoscale transport features? The OSCAR fields are also constructed using the All-Satellite fields.

Here we average the Eulerian velocities during the first and second halves of the record (1997-2008 and 2009-2020, then subtract the former from the latter (2009-2020 minus 1997-2008). Results are shown for the All-Satellite (left), OSCAR (middle) and 2-Satellite data sets (right). The red line has been drawn to identify the increased poleward velocities to the right of the line, next to the coast, during the second half of the record.

Even in the more consistently created 2-Satellite fields, there does appear to be an increase in the poleward flow next to the coast.

We have also formed 1 degree averages of the velocities next to the coast and fit a linear trend to each. Especially in the ICC, but also around some of the capes, there are significant increases in the alongshore currents, with an average value over our domain of around 0.4 cm/s per decade. An increase of ~1 cm/s during these 24 years corresponds to increased northward movement over the course of a year of approximately 2.5 degrees. This increase would have ecological consequences for the system.

Oregon State University

Questions and Some Answers

- Can passive water parcels reach Oregon (44°N) from the Southern California Bight (32-35°N)? ***Yes, it is possible but only occurs on a few years. Parcels typically travel 300-1000 km from 32°N, 600-1000+ km from 35°N, 800-1200+ km from 39°N.***
- What are the seasonal and spatial characteristics of trajectories that reach Oregon from 32°N?
  - ***Parcels from 32°N need to reach 39°N by autumn, in order to pass 43°N by winter and spring.***
  - ***Parcels that reach farthest north use the poleward ICC and DC and often move most of the distance in a period of 2-4 months in autumn and winter.***
- How does the wind-driven Ekman transport modify the geostrophic transport found beneath the upper Ekman layer?
  - ***It reduces the distance travelled by moving the parcels toward the coast in fall-winter, out of the poleward jet.***
- Does the region of large capes (Pt Arena, Capes Mendocino and Blanco, 39°N-43°N) act as a barrier to poleward transport of passive water parcels?
  - ***Not a complete barrier but a seasonal barrier, especially to parcels in the Ekman layer.***
- Does northward transport increase during the 1997-2020 24-year record?
  - ***There appears to be stronger northward flow during 2009-2020 than during 1997-2008.***

Our conclusions at present are shown in this slide.