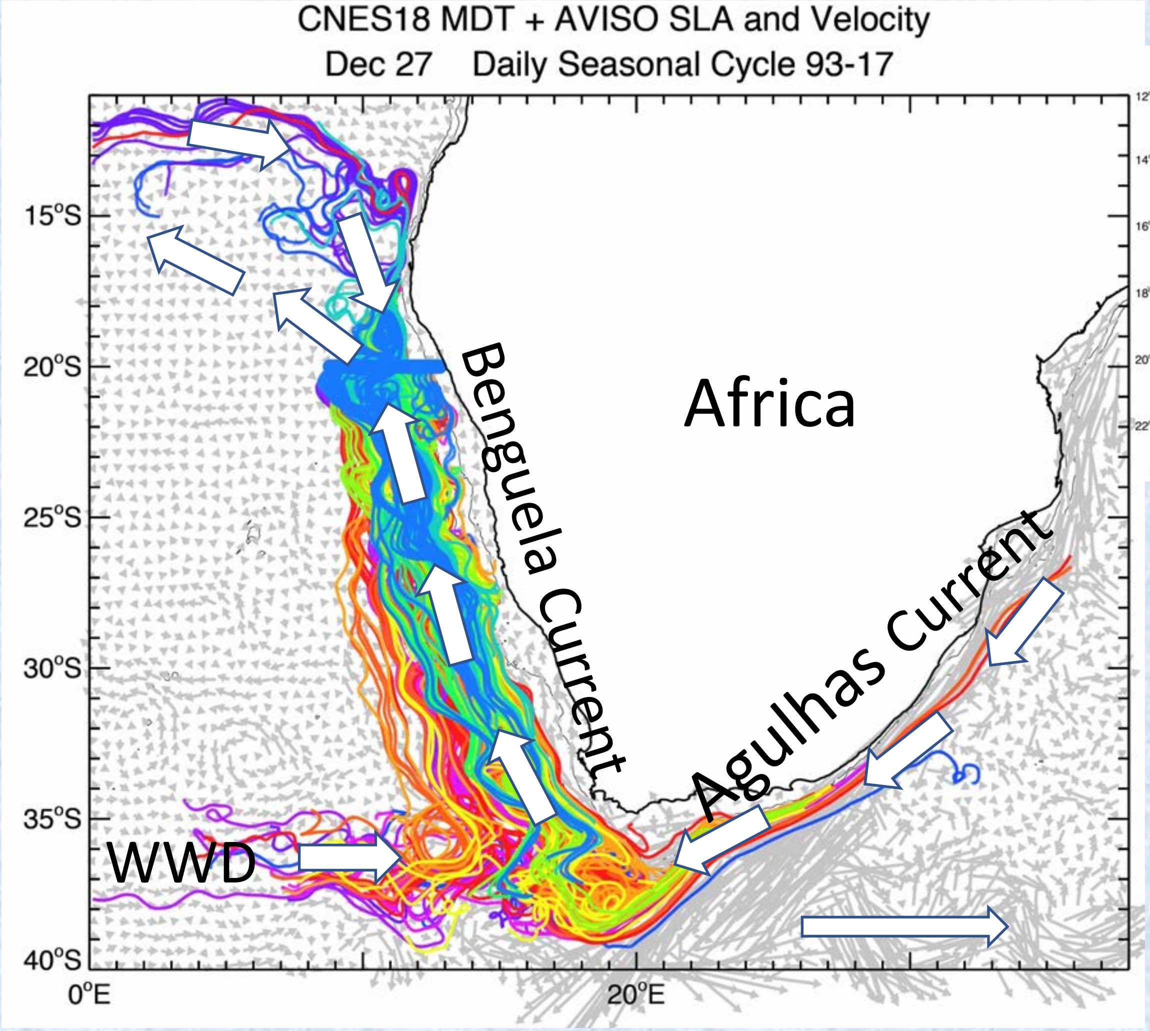
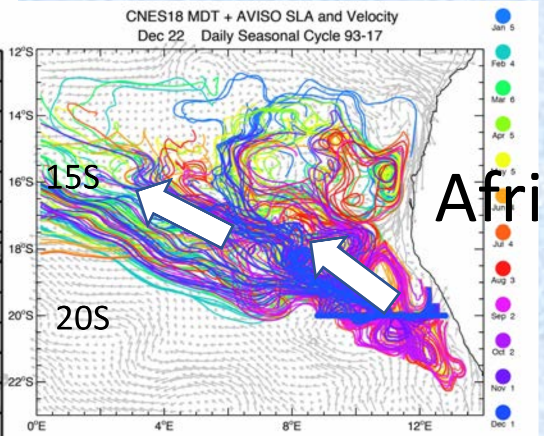
Altimeter Analysis of Eulerian Velocities & Lagrangian Trajectories In the Interactions of South Africa's Agulhas & Benguela Current Systems

P. Ted Strub, Corinne James, Ricardo Matano, Vincent Combes
College of Earth, Ocean, and Atmospheric Sciences; Oregon State University





<u>Altimeter-Derived Trajectorie</u>s

(Above): We trace water parcels forwards for two years from 20°S.

(Left): We trace water parcels backwards for two years from 20°S.

The result is a Lagrangian view of the Benguela and Algulhas Currents, but missing the trajectories of parcels that retroflect south of the Agulhas Current.

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A Unique Property of the Benguela Current:

- **An EBC Connects to a WBC**

Satellite Determination of:

1) **Seasonal Surface Forcing by Wind Stress**
2) **Long-Term Mean Surface Geostrophic Currents (from CNES-CLS18 MDT)**
3) **Altimeter-Derived Lagrangian Trajectories – Pathways from the Agulhas to the Benguela: How the WBC actually connects to the EBC**
4) **Altimeter-Derived Seasonal Eulerian Surface Velocity Anomalies – Enabling Trajectories/Opposing Winds**

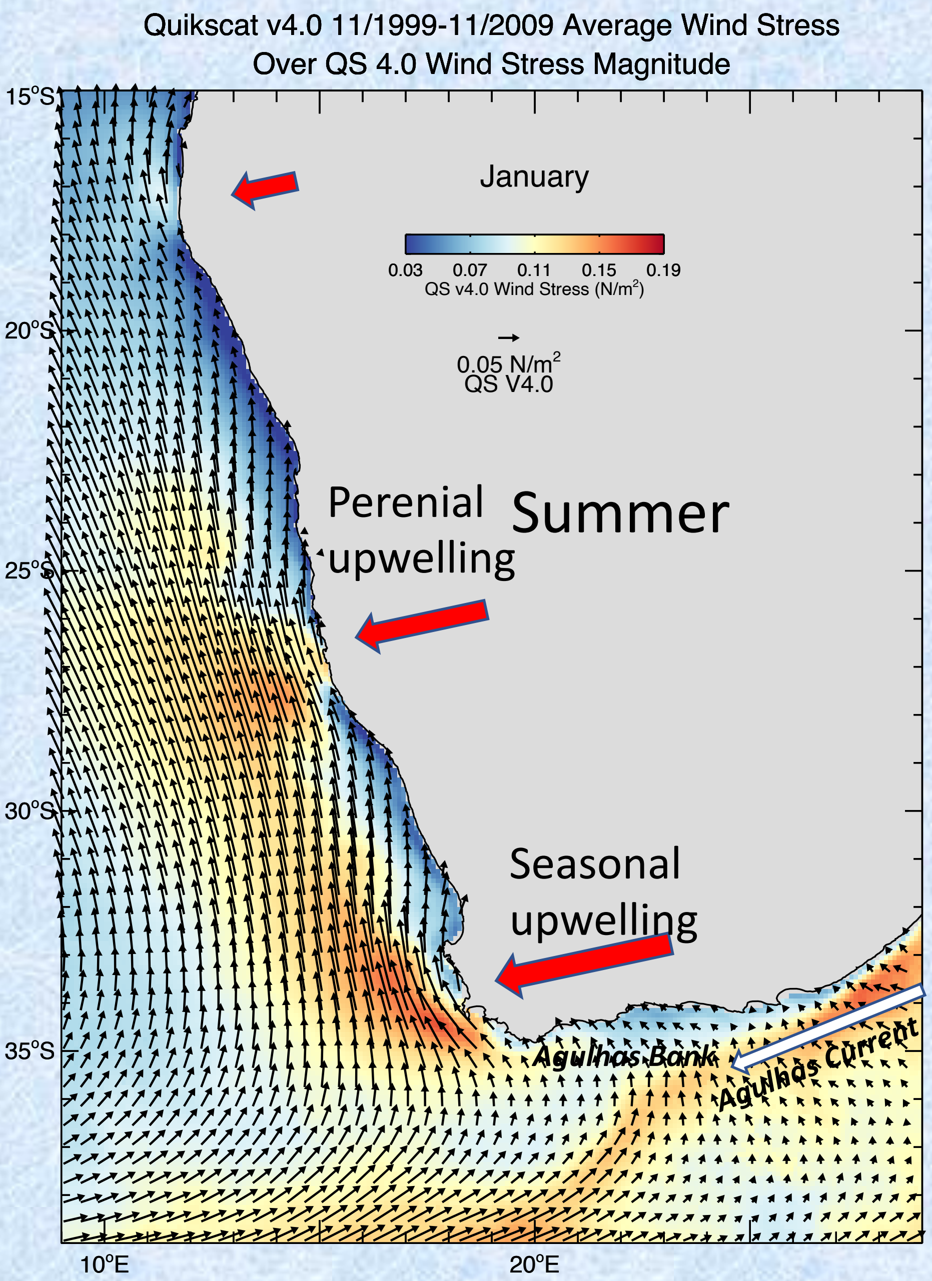
***** See the presentation of complementary model results by Matano et al. (in the Large-Scale Circulation session)***

“The Benguela is the only EBC with connections to a WBC.

What type of connections are expected? ”

- Anticyclonic ‘Agulhas Rings’ from the Retroflection interact with the coastal ocean off SW Africa (this is old news, not repeated here).
- Deep water is brought onto the Agulhas Bank during the passage of Natal Pulses within the Agulhas Current and moved into the Benguela Current and out into the South Atlantic. The satellites can’t see the deep pathways but ocean circulation models can – see the presentation by Matano et al. in the Large-Scale Circulation session.
- **Water is transported directly (‘leaking’) by surface currents from the westward Agulhas Current into the equatorward Benguela Coastal Current. This is important for the transport of fish eggs and larvae from spawning regions to the western nurseries. We look at this using altimeter-derived trajectories and maps of the seasonal changes in surface currents.**
- **First the wind stress forcing.**

Seasonal Wind Stress Forcing



West Coast: **Upwelling centers at ~33°-34°S, 26°-27°S, 16°-17°S**

Summer Upwelling:
Stronger in the south.

Winter Upwelling:
Stronger in the north,
Absent in the south.

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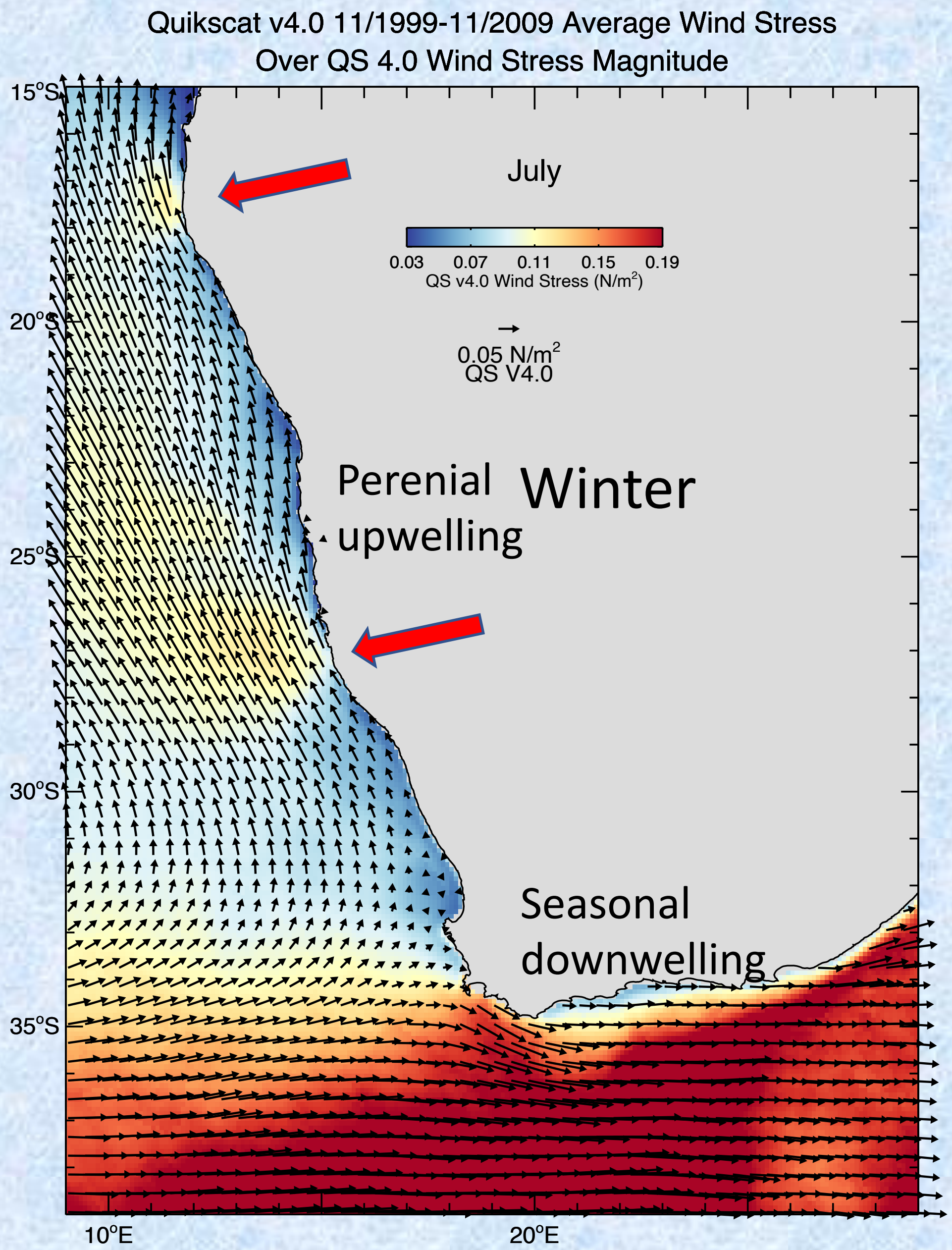
South Coast:

Summer: Weak, intermittent upwelling next to the coast;
Stronger wind stress over warm and opposing flow in the Agulhas Current.

Winter:
Strong downwelling due to westerlies in the 'Roaring 40s'



Seasonal Alongshore Wind Stress Forcing

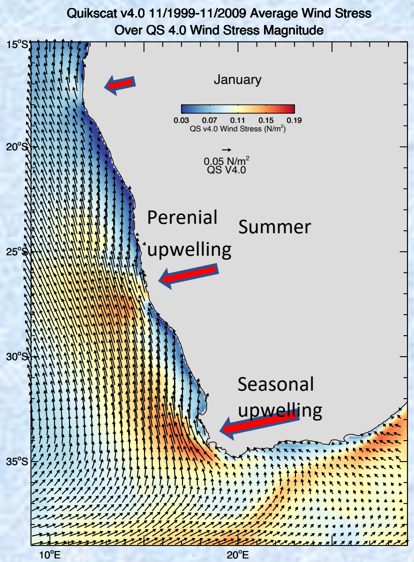
Looking at seasonality more closely

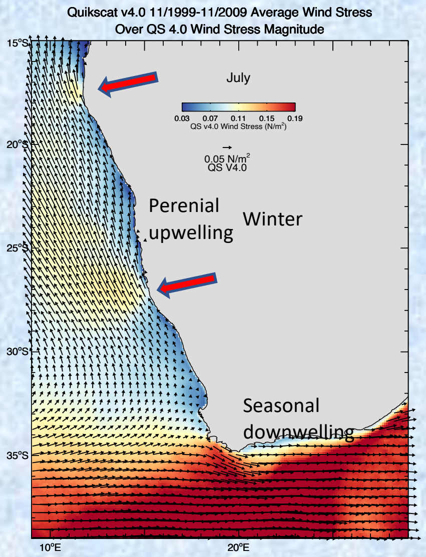
West Coast North: Max upwelling: Autumn & Spring

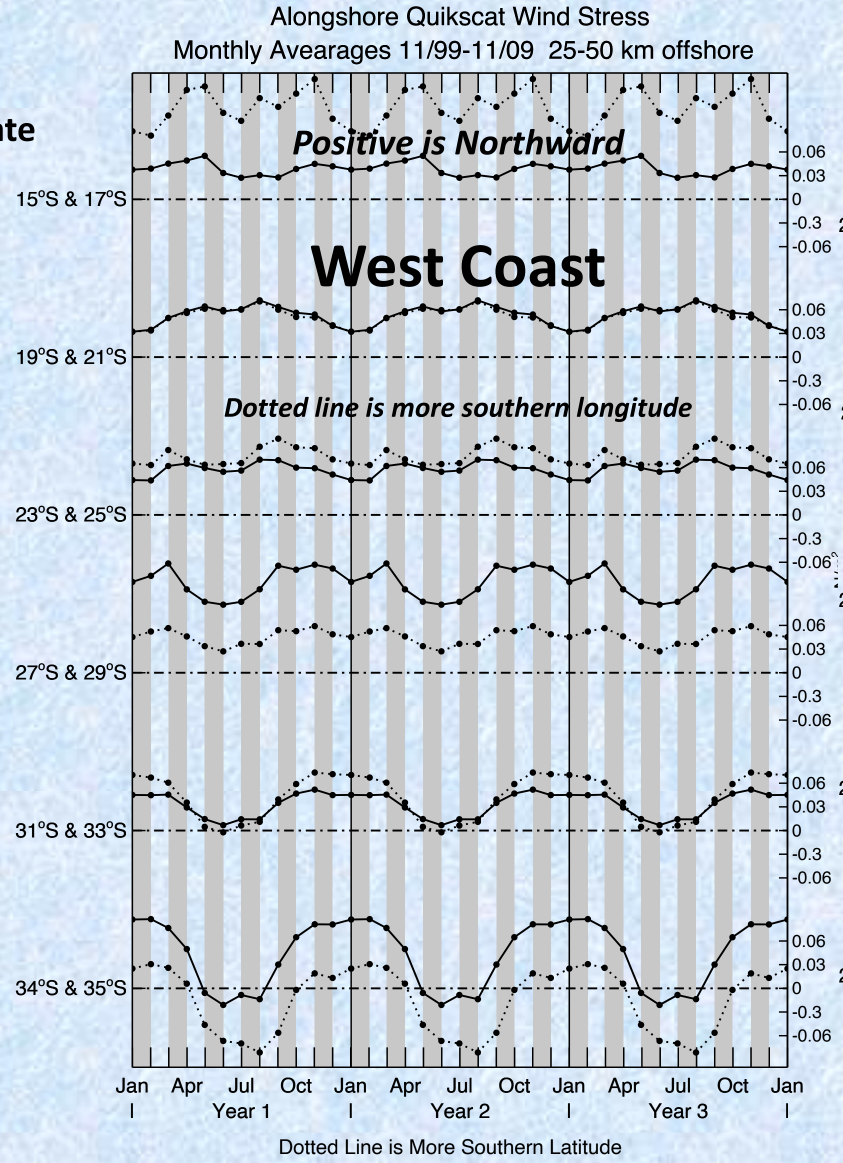
West Coast Center: Max upwelling: Late Winger & Late Summer

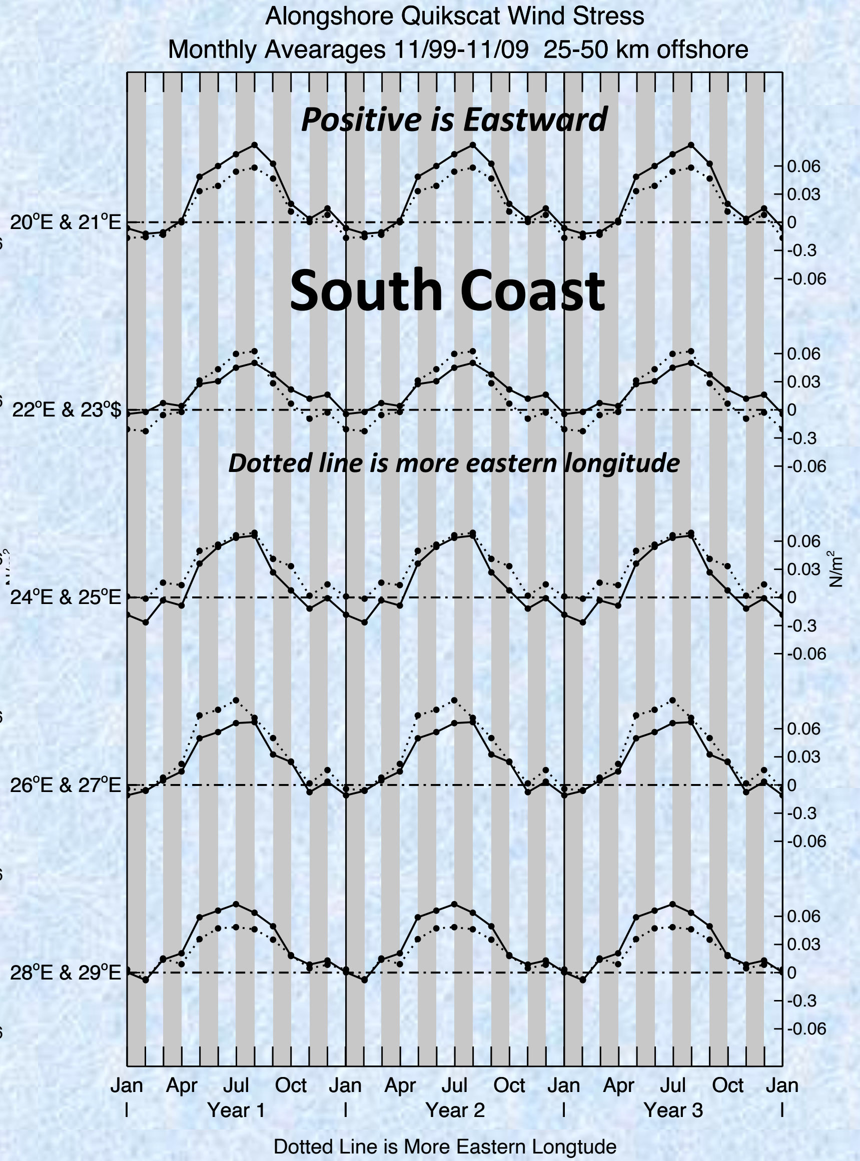
West Coast South: Max upwelling: Spring-Summer – Note strong upwelling January-March

South Coast: Max downwelling: Autumn-Winter

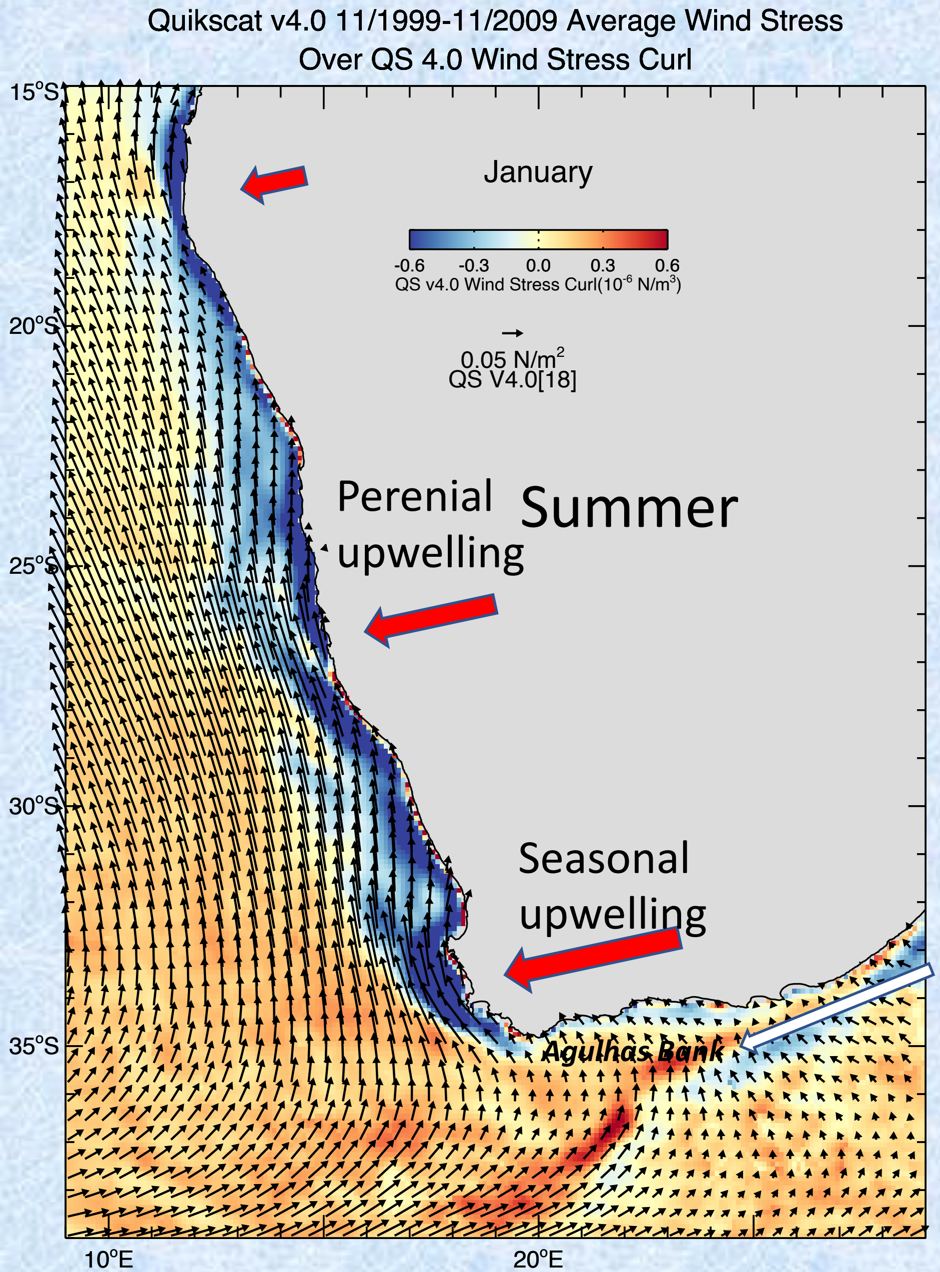








Seasonal Wind Stress Curl (WSC) Forcing



West Coast: **Upwelling centers at ~33°-34°S, 26°-27°S, 16°-17°S**

Summer Upwelling:
Strongly negative WSC along the west coast increases upwelling away from the coast.

Winter Upwelling:
Negative WSC confined to the north.

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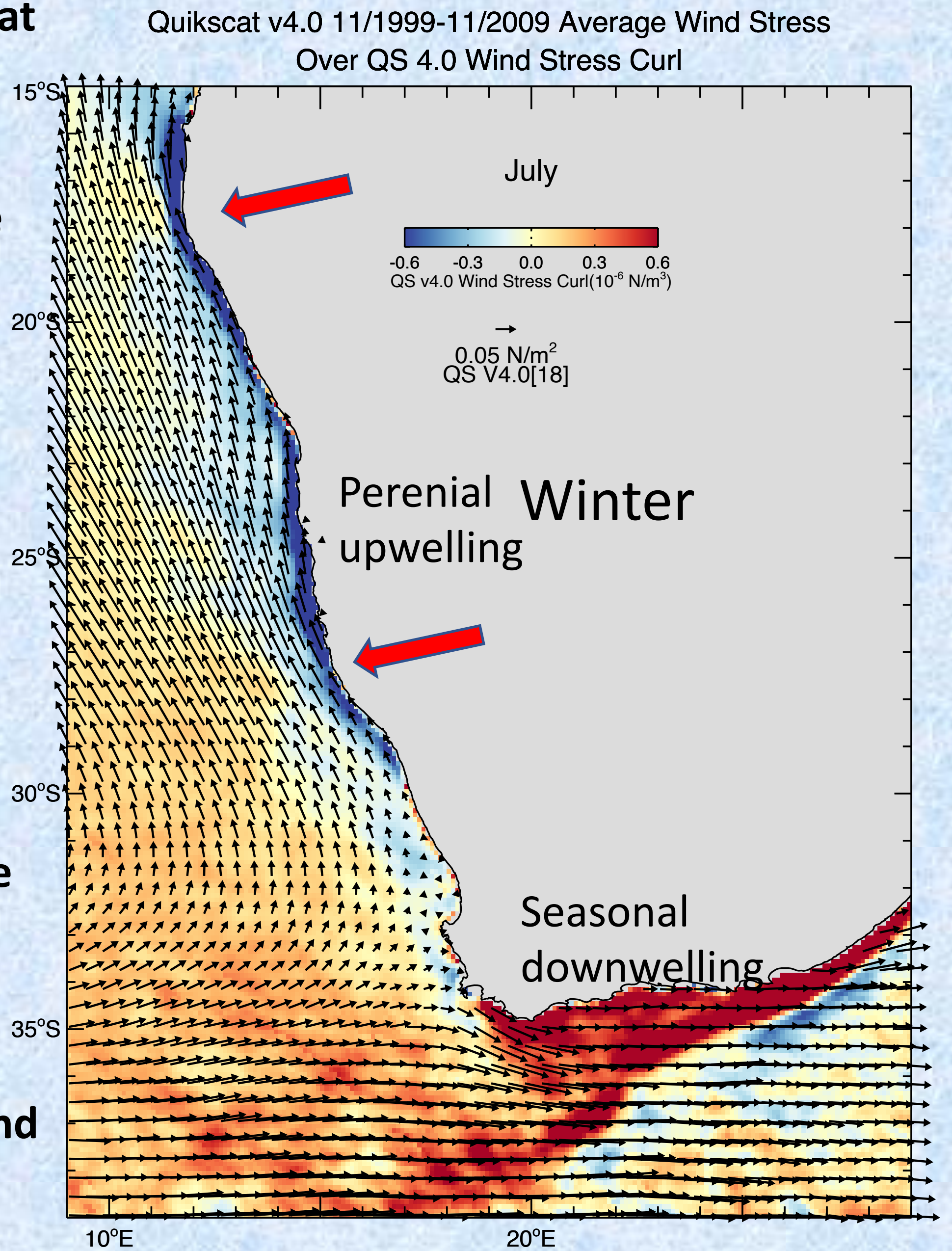
South Coast:

Summer:
Weakly negative coastal WSC; positive/negative bands over the Agulhas Current;

Winter:
Strongly positive WSC over the Agulhas Bank. Negative WSC band offshore of Agulhas C. center.

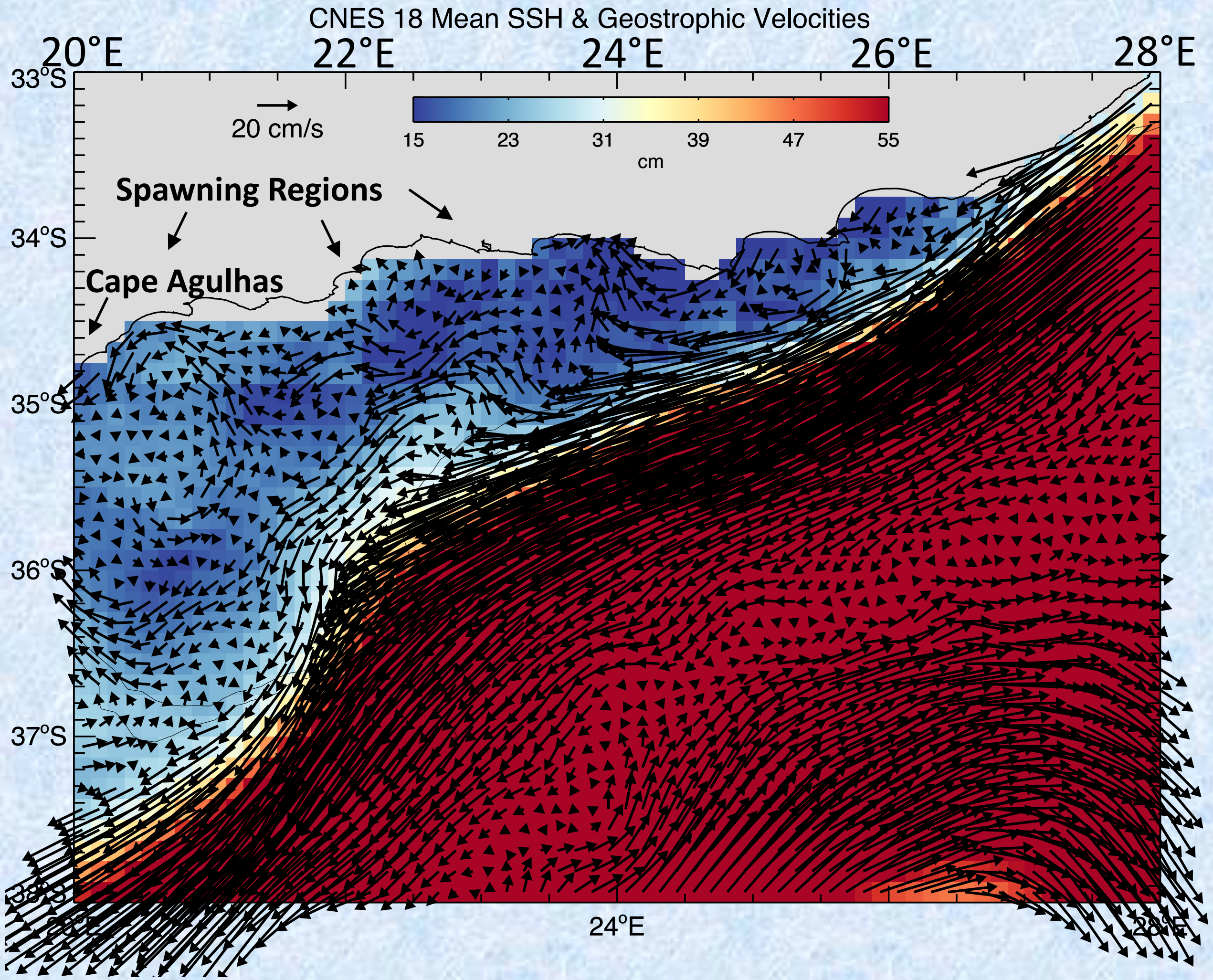


Mean Dynamic Topography & Surface Currents: Agulhas Bank

Concentrating on the Southern Benguela's Connection to the Agulhas Current/Bank

Although there may still be some 'artifacts' in the mean SSH and associated geostrophic currents in the CLS18 MDT, a number of features agree with previous modeling and observational studies.

- **The edge of the southwestward Agulhas Current (AC) borders the shelfbreak along the Agulhas Bank, before turning ccl and retroflecting west of 20°E.**
- **A band of slightly lower SSH extends from near the coast east of 22°E to the southwest over the mid-Bank region. This corresponds to the "cool ridge" of domed subsurface isotherms. It is suggested that there should be cyclonic flow around this ridge and that is seen over some SW parts of the ridge.**
- **Flow from the inner AC between 22°-24°E connects to the coast between 20°-22°E. The westward coastal current feeds into the inner Benguela C. (next slide).**
- **A feature that the satellite can not see is the onshore flow in a bottom Ekman layer driven by the strong flow to the southwest along the edge of the Bank. This feeds upwelling over the Bank (see Matano et al presentation).**



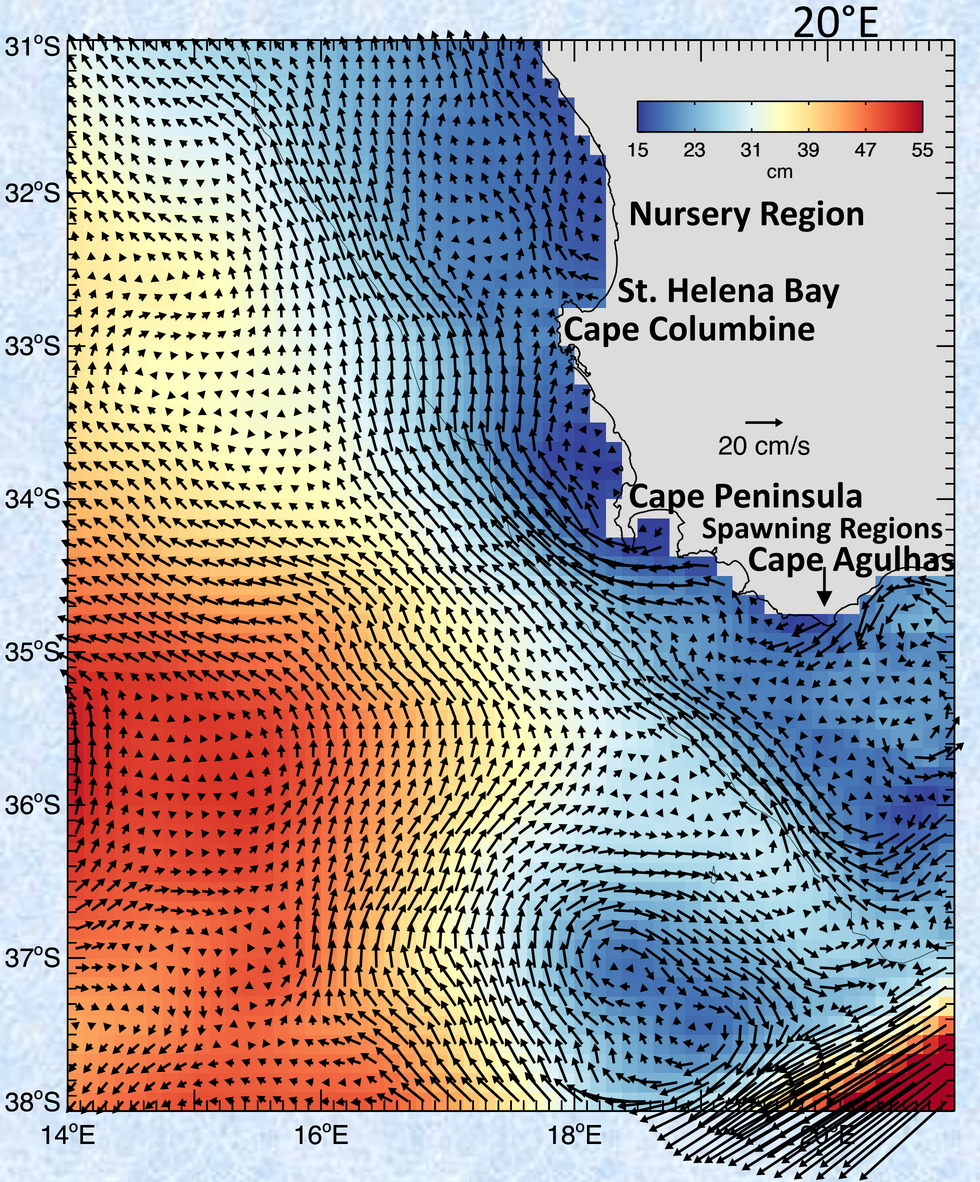
Mean Dynamic Topography & Surface Currents: Agulhas Bank

Concentrating on the Southern Benguela's Connection to the Agulhas Current/Bank

As over the Agulhas Bank farther east, major features in the CLS18 MDT geostrophic currents agree with previous studies.

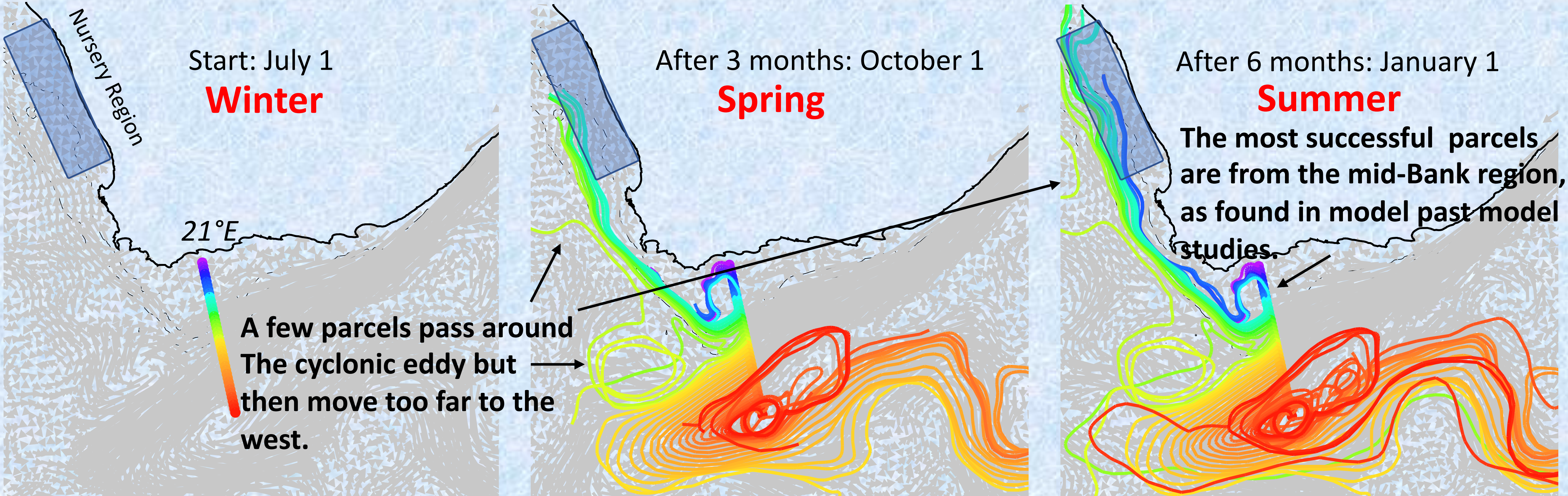
- **The coastal flow east of 20°E (Cape Agulhas) continues to the northwest, over the western region of the Agulhas Bank that extends from Cape Agulhas to the Cape Peninsula, where the Bank/shelf becomes very narrow.**
- **At the Cape Peninsula, the flow continues to Cape Columbine but bifurcates into branches that flow to the northeast along the coast past St. Helena Bay and to the northwest, joining the warm, shelf-edge jet found about 100km west of the coast between 33°-35°S.**
- **Some flow from the inner edge of the Agulhas bypasses the retroflection and travels around the west side of the cyclonic eddy (18°-20°E, ~37°S) into the offshore shelf-edge jet.**
- **Other westward flow from the southern side of the "Cool Ridge" between 36.0°-36.5°S, 20°-21°E (previous slide) also flows into the shelf-edge jet.**
- **Small pelagic fish eggs and larvae must move passively from the Agulhas Bank (east and west of Cape Agulhas) to the nursery area over the shelf north of St. Helena Bay.**
- ***How do they reach the nursery from east of Cape Agulhas?***

CNES 18 Mean SSH & Geostrophic Velocities



Altimeter-Derived Lagrangian Pathways: Agulhas Bank to Benguela Current

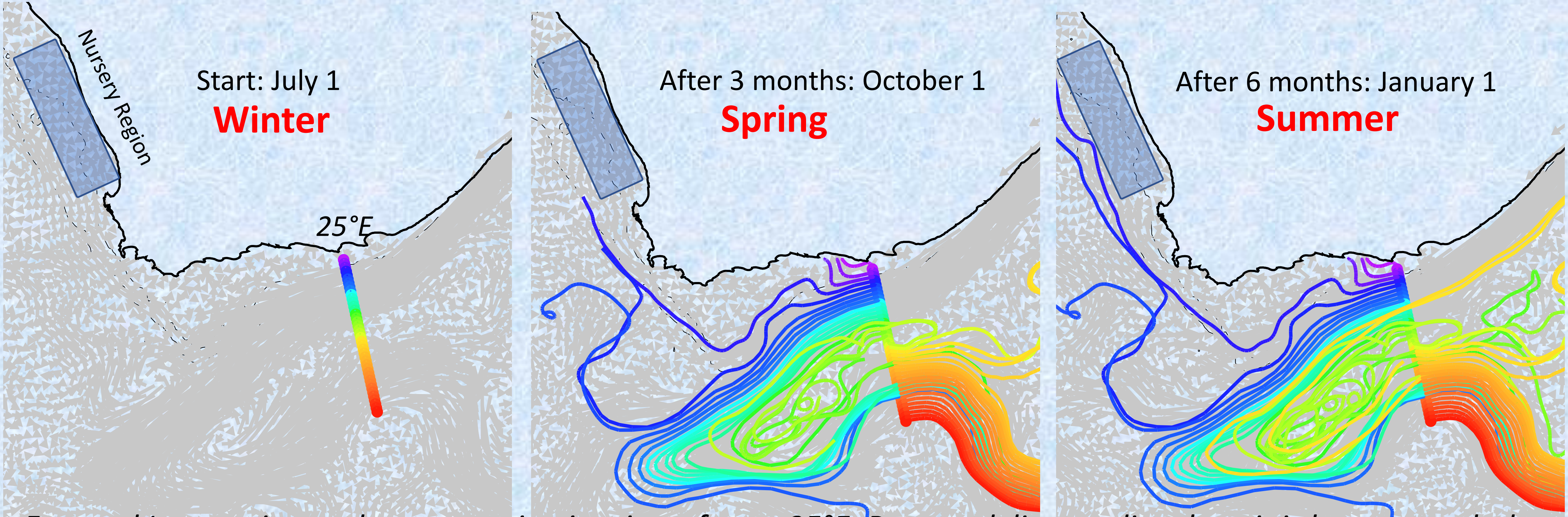
Gridded surface geostrophic velocities from the daily AVISO fields are averaged to form a daily seasonal cycle,then combined with the CLS18 MDT surface velocity fields. These provide input to the OceanParcels software (http://oceanparcels.org/index.html), which calculates Lagrangian trajectories.



Forward Lagrangian pathways starting in winter from ~21°E; Past modeling studies show it is best to reach the nursery by the end of December. After that the offshore Ekman transports move water parcels to the west.

Altimeter-Derived Lagrangian Pathways: Agulhas Bank to Benguela Current

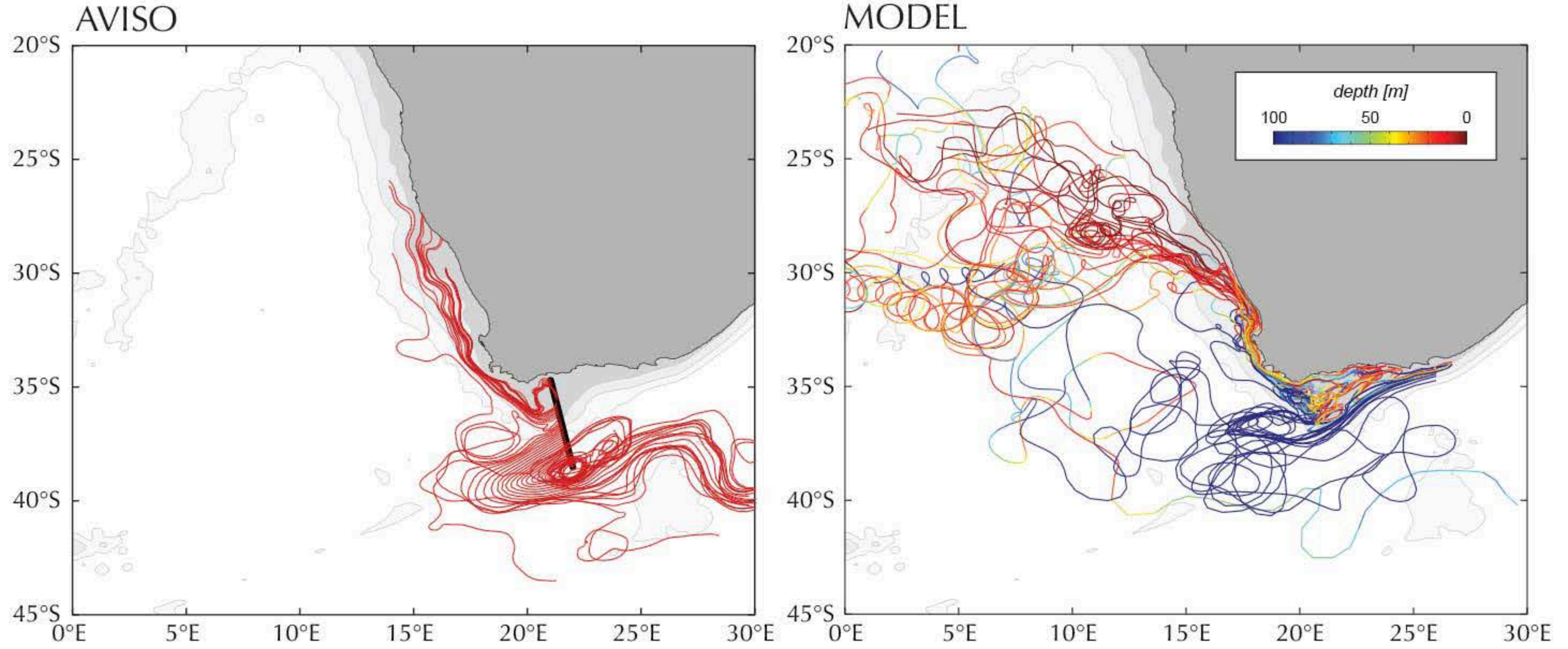
The success of parcels reaching the nursery area is much less for those leaving the more eastern Agulhas Bank spawning region. Many retroflect, some go around the cyclonic eddy, only a few travel past the nursery region. If these represent vertically migrating larvae, they may still reach the nursery in the onshore flowing compensating flow under the offshore Ekman transport of the upwelling system.



Forward Lagrangian pathways starting in winter from ~25°E; Past modeling studies show it is best to reach the nursery by the end of December. After that the offshore Ekman transports move water parcels to the west.

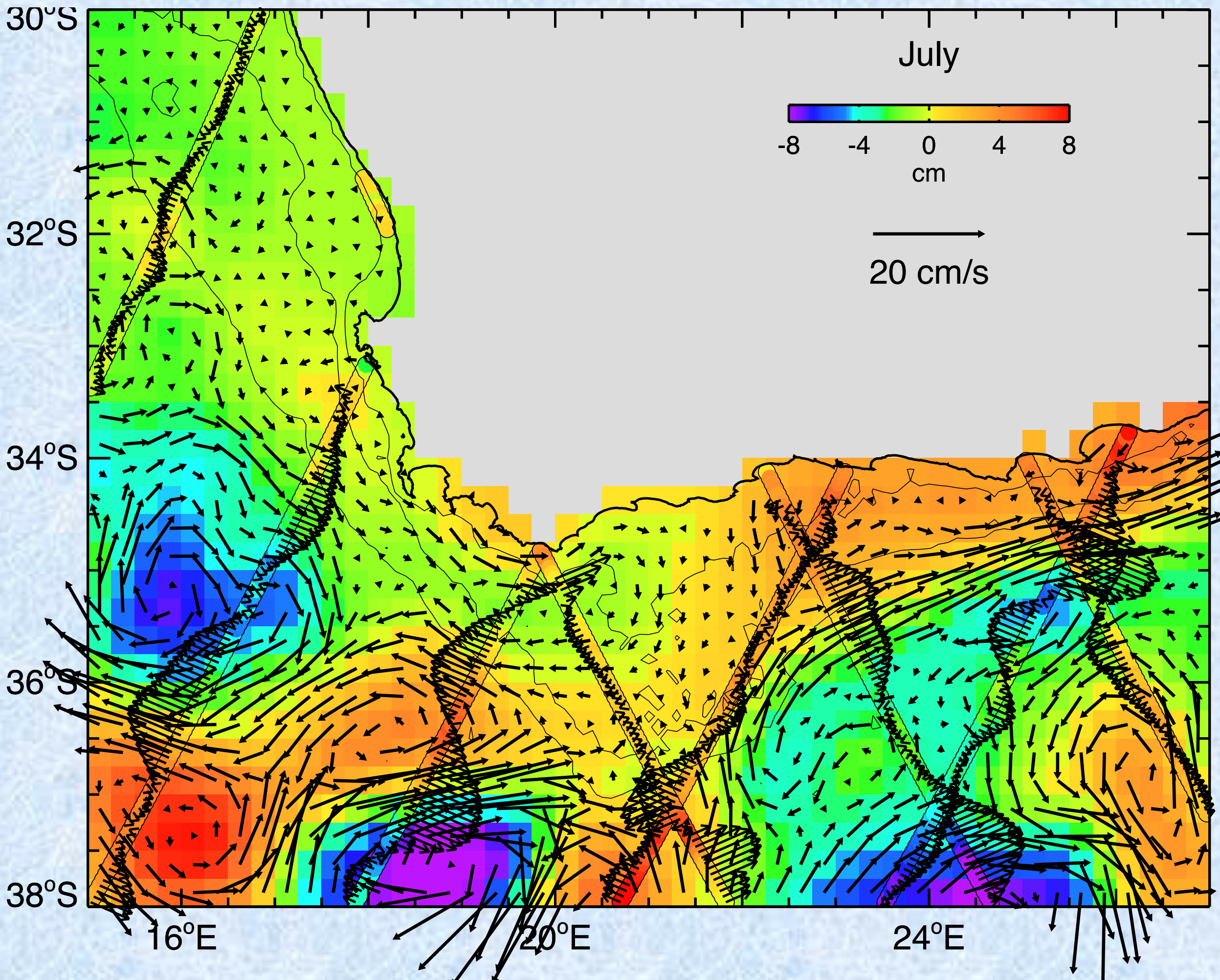
Model vs Altimeter Lagrangian Pathways: Agulhas Bank to Benguela Current

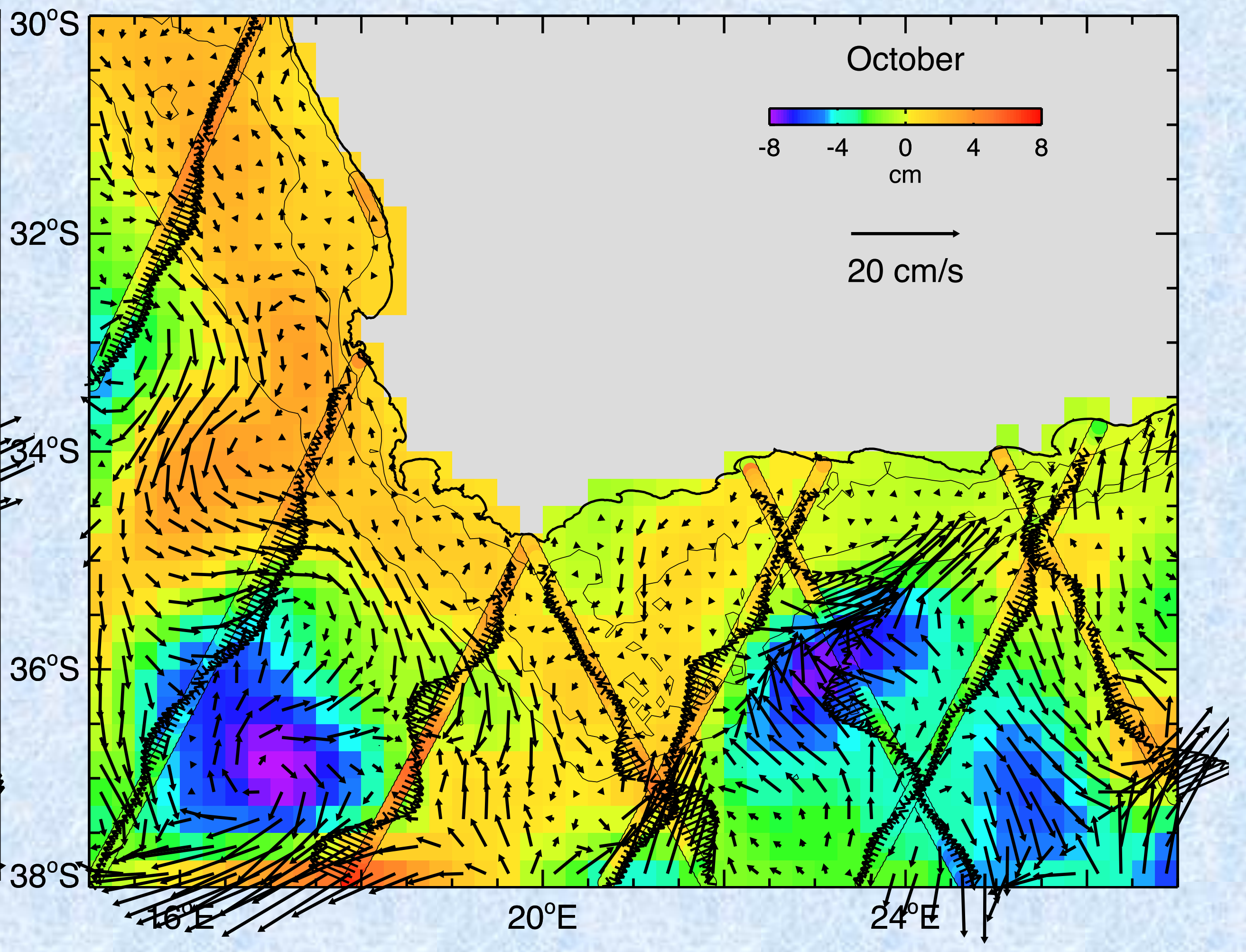
Are the altimelter-derived trajectories realistic, given their reliance on surface geostrophic currents. Below (right) are floats calculated within the ROMS model of Matano et al (this meeting), which move between 0-100m, compared to the altimeter-derived surface trajectories (left). Model floats that pass 20°E over the shelf at the surface and below follow similar paths to the satellite surface trajectories.



Seasonal Eulerian Current Fields: From SLA Anomalies (No MDT)

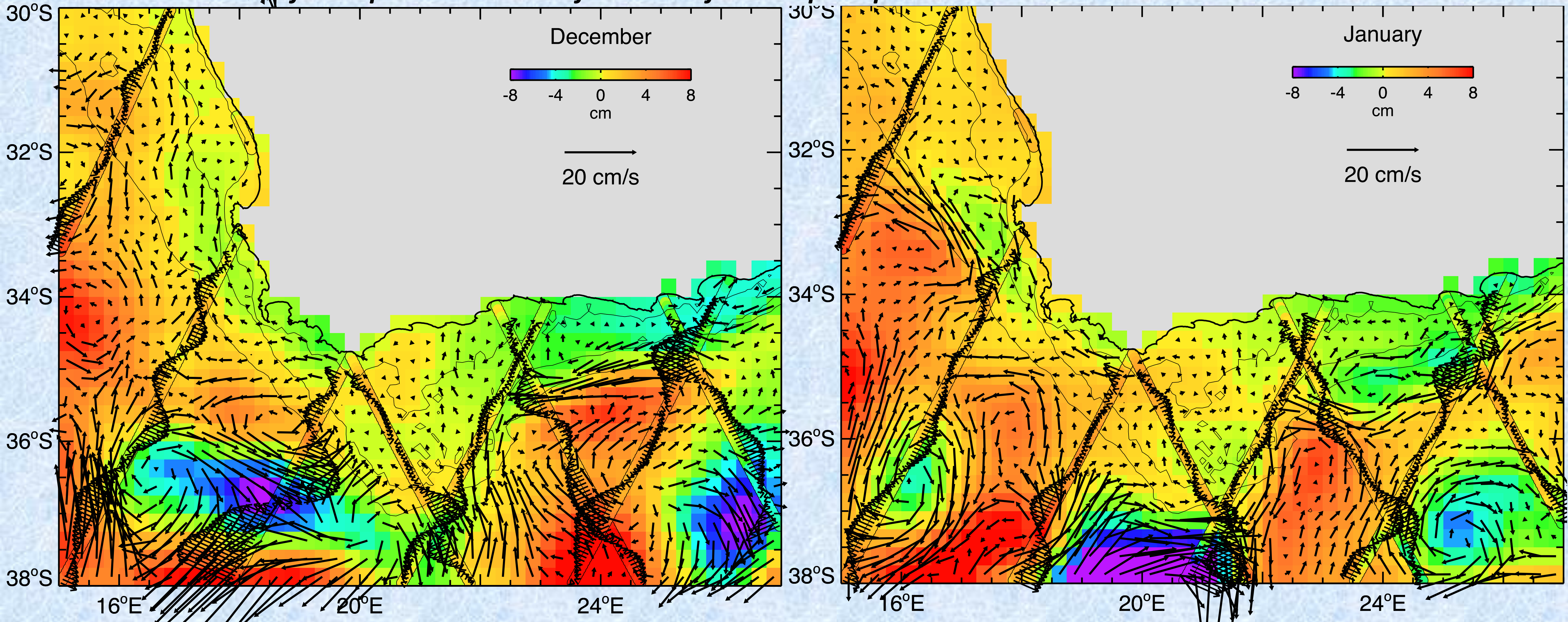
What governs the seasonally developing Lagrangian trajectories? The seasonal changes in mapped surface geostrophic currents (gridded and cross-track) are more easily seen in the anomaly fields (no long-term mean) from the SLA fields, in which we have the most confidence. **In July**, coastal current anomalies of ~7 cm s^{-1} near 20°E oppose the mean fields of 10-15 cm s^{-1} (above), slowing westward movement. Farther east near 25°E, much stronger eastward currents slow or reverse westward mean flow. These velocities decrease through **September** and reverse near 20°E, allowing the westward flow near the mean.





Seasonal Eulerian Current Fields: From SLA Anomalies (No MDT)

The coastal surface velocity anomalies toward the northwest continue to increase west of 20°E in November are maximum during **December** (below), augmenting the mean currents to create velocities of 20 cm s^{-1} or more (monthly displacements of 500 km or 5°), easily moving parcels far enough to reach the nursery latitude. But in **January**, current anomalies reverse north of 34°S, creating an additional barrier to northward flow, adding to the problem created by the continuing offshore Ekman transport. This pattern continues to April, when currents south of 34°S also reverse, leading to the July pattern (above). ***Thus December is the end of the optimum window for successful transport past 34°S.***



Summary

- Focusing on the southern Benguela (south of ~ 30°S) and its connections to the Agulhas Current and Agulhas Bank, the long-term mean surface heights (MDT) and their associated geostrophic velocities reproduce many of the known and hypothesized features of the circulation on the Agulhas Bank and the southern Benguela Current: the strong Agulhas Current located along the edge of the Agulhas Bank; the somewhat cyclonic currents around a tongue of low SSH that corresponds to the locations of the "Cool Ridge" described in the literature; coastal flow along in inner Bank west of 21°E that continues up the west coast for to the Cape Peninsula at 34°S; the cyclonic eddy west of the Agulhas Retroflection and pathways that lead from the Agulhas to the shelf-break jet to flows to the northwest north of 35°S.
- The southern Benguela is the region of strongly seasonal wind forcing, with equatorward wind stress between October and March. Coastal winds along the southern coast during this period are weak or intermittently westward.
- Lagrangian trajectories calculated from the daily seasonal altimeter data (SLA + MDT) are able to show the connection between the coastal locations along the Agulhas Bank and the nursery areas on the shelf to the north of 33°S. These reach the shelf area if released from around 21°E, but arrive later and stay off the shelf if released farther east. This agrees with previous modeling results, which found that most water parcels that reached the nursery region did this before the end of December.
- The mapped seasonal surface current anomalies show a period during October-December when velocities are most favorable for transport over the shelf from the Central Agulhas Bank to the shelf north of Cape Columbine. After this, the seasonal anomalies change direction to poleward between 33°-34°S, although wind stress continues to be strongly equatorwar. This may be similar to the creation of the "Inshore Countercurrent" along central California in summer.
- Hypotheses for the reversal of the seasonal current anomalies include:
  - (1) The offshore movement of the coastal low in SSH due to Rossby wave dynamics;
  - (2) The surfacing of the poleward undercurrent.
- The reasons for the reversal will be determined through the modeling efforts within our team.

Thank You!

NASA OSTST for ongoing support;
JPL, CNES, CLS, AVISO for quality data products.

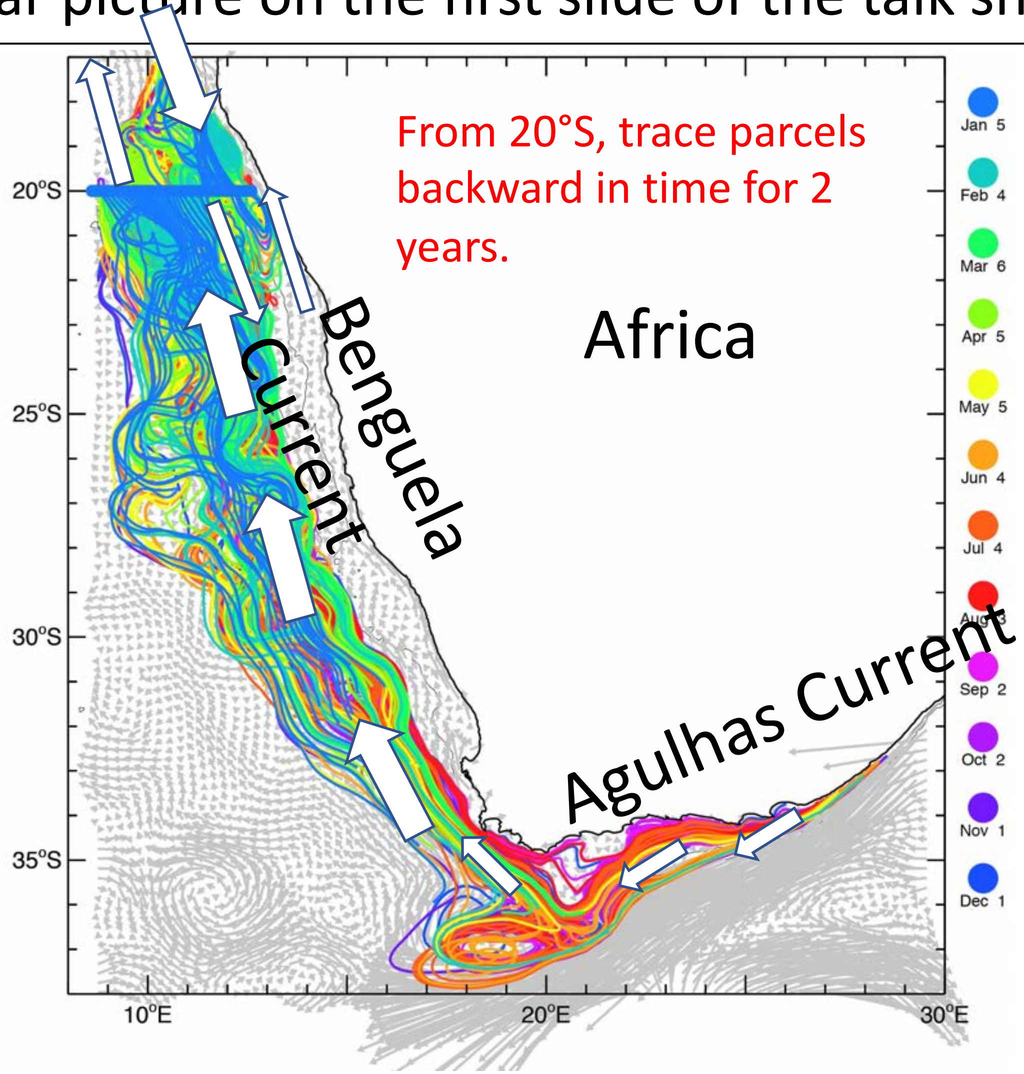
Oregon State University
College of Earth, Ocean, and Atmospheric Sciences

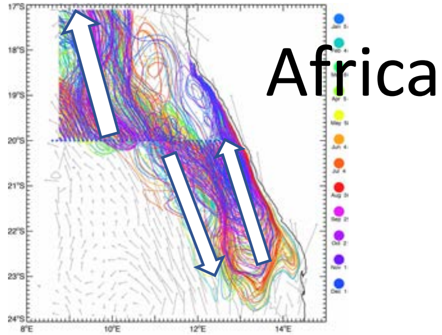
Extra Slides

For those who are still interested

Large-Scale Benguela/Agulhas Connection

20°S Lagrangian paths based on daily seasonal ROMS MODEL surface geostrophic velocities.
Compare to the similar picture on the first slide of the talk showing altimeter-derived pathways.





From 20°S, trace parcels forward in time for 2 years.

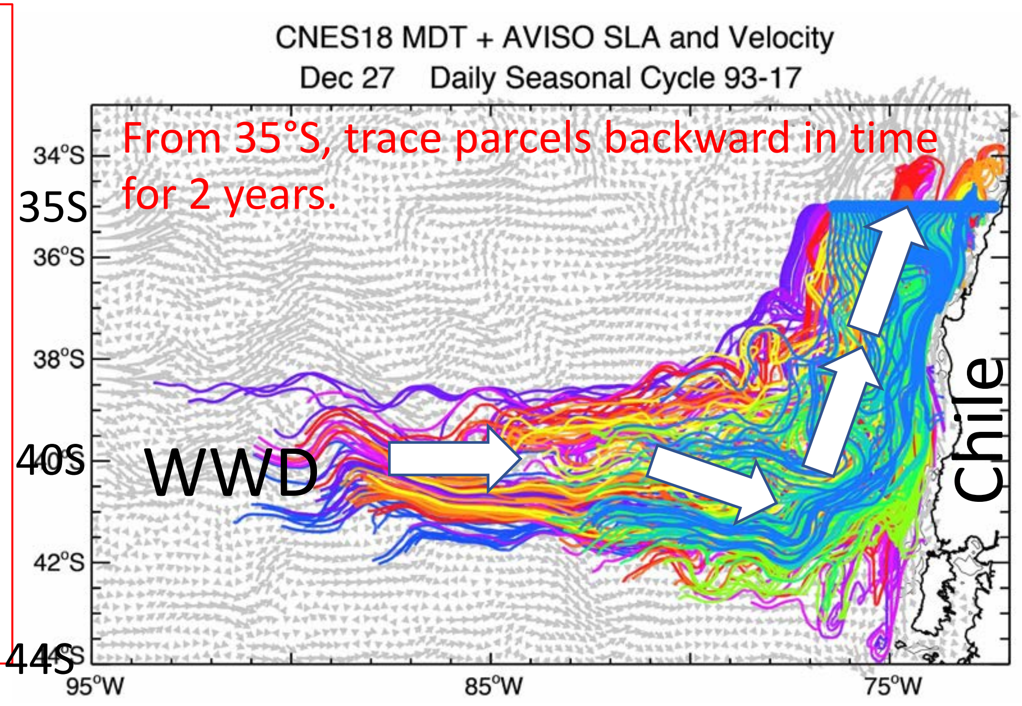
Starting at 20°S, release parcels and track them backwards and forward for 2 years. The model trajectories also show a clear connection between Benguela and Agulhas Currents, as do the altimeter trajectories.

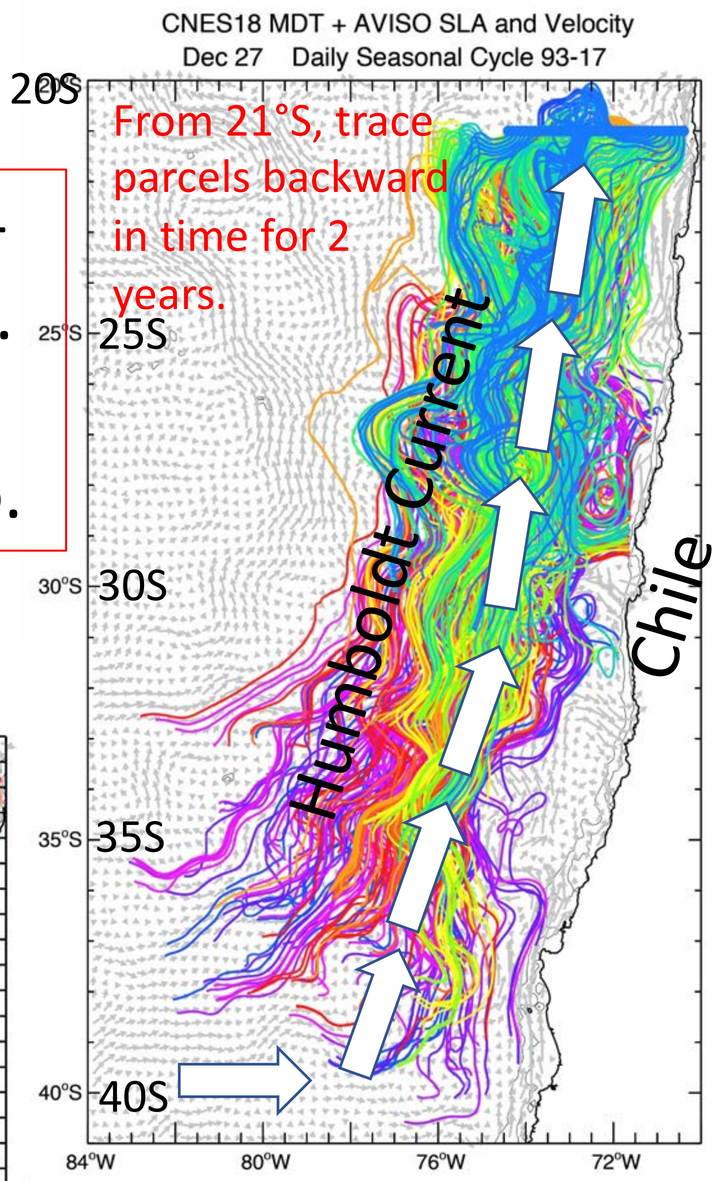
Comparative study in the Humboldt Current. 35°S & 21°S, backward integration in time.

Lagrangian trajectories based on daily seasonal (25-year mean) altimeter surface geostrophic velocities. Parcels move from the West Wind Drift into the equatorward boundary current. Colors=Release Mo.

"Ocean Parcels" software is used: http://oceanparcels.org/index.html

The most recent release is described in this ms: https://www.geosci-model-dev.net/12/3571/2019/gmd-12-3571-2019.html





Colors= Release Month