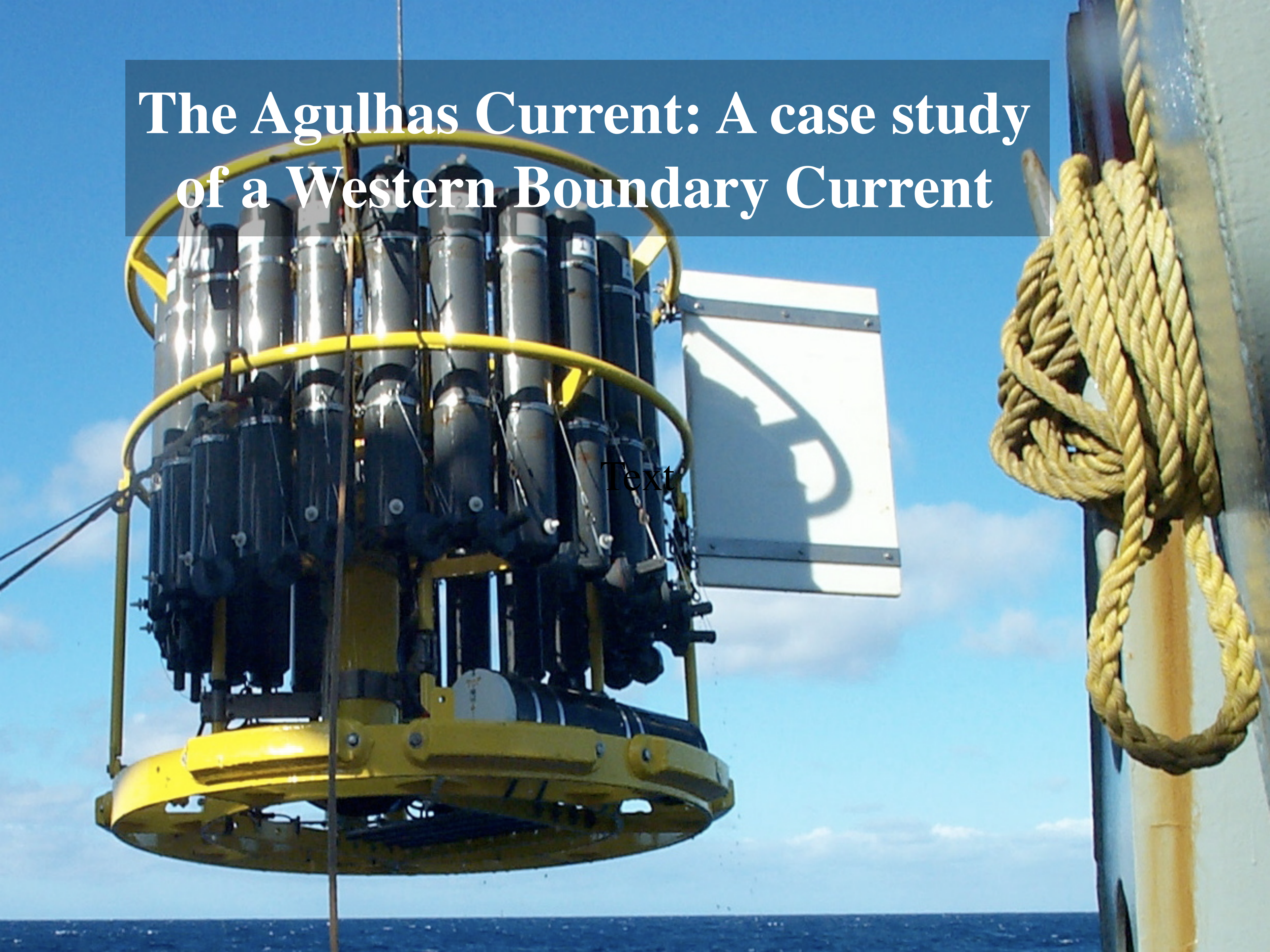
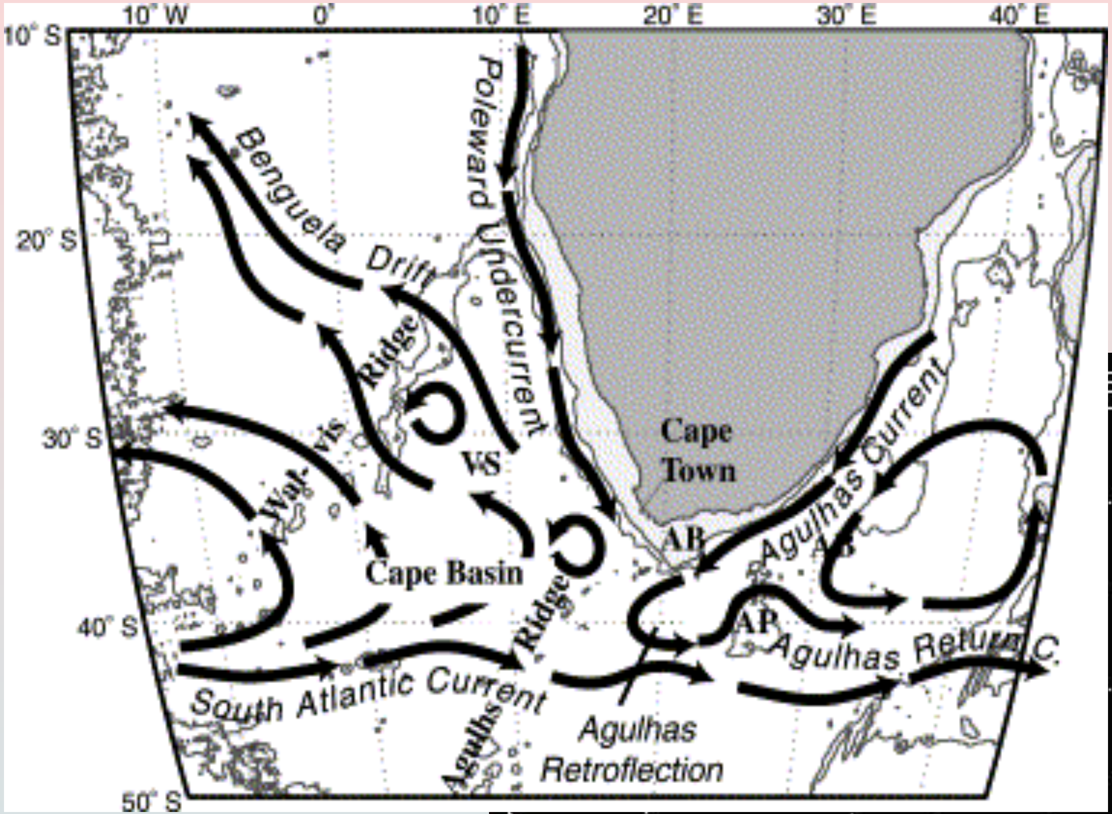
The Agulhas Current: A case study of a Western Boundary Current



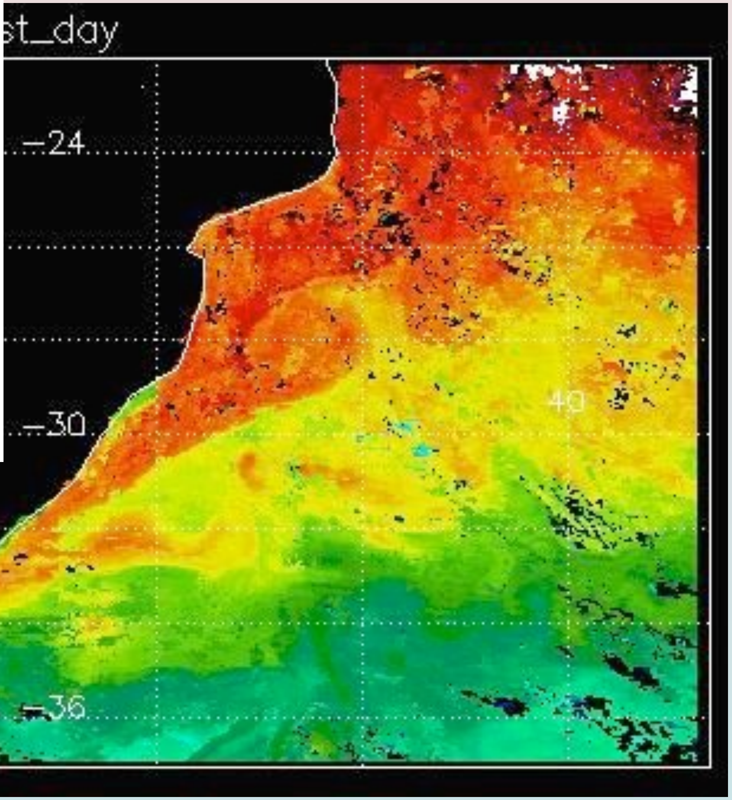
Text

Where is the Agulhas Current?



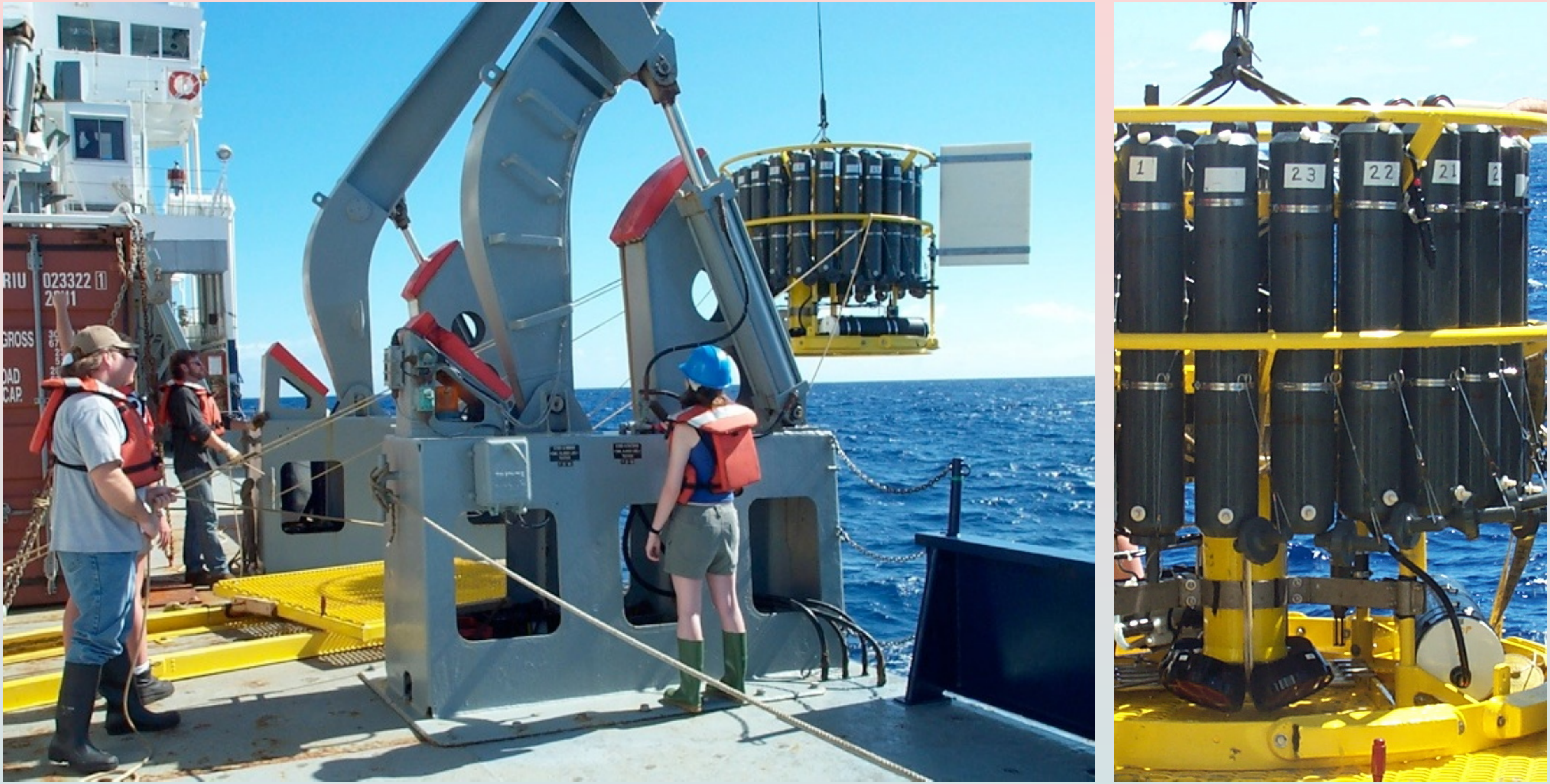
From Boebel et al., (2003)

MODIS SST courtesy of
Warner Baringer

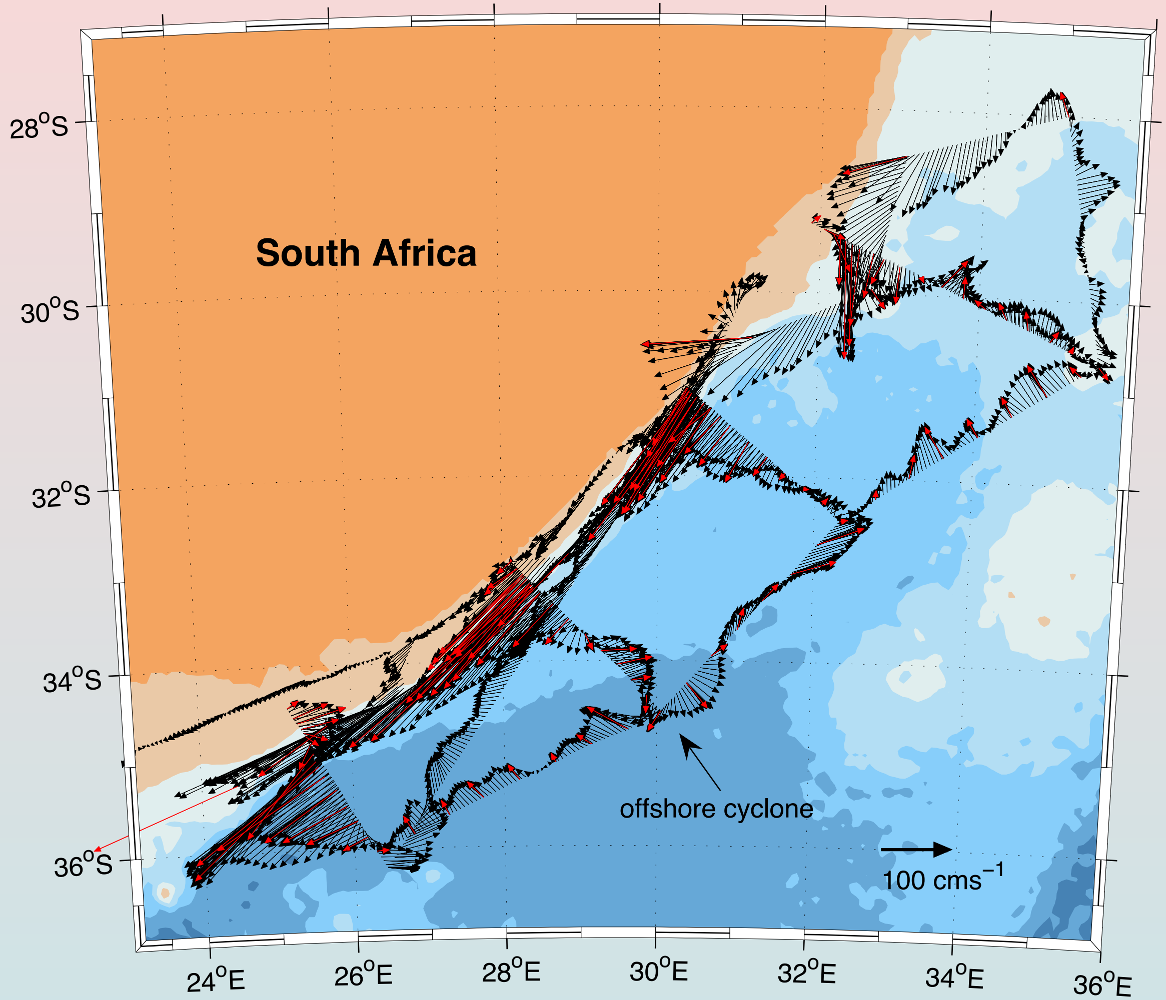


Ship

Instrumentation: CTD and ADCPs



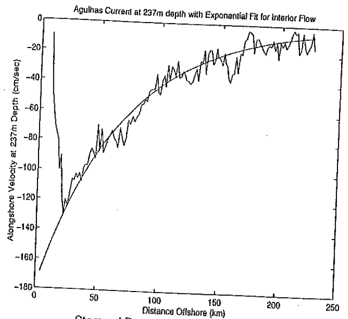
Currents (25-75 m)



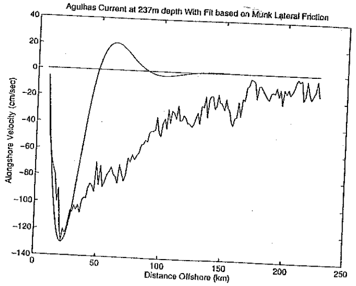
Beal, 2006

Boundary Layer model for the Agulhas Current

Stommel BL

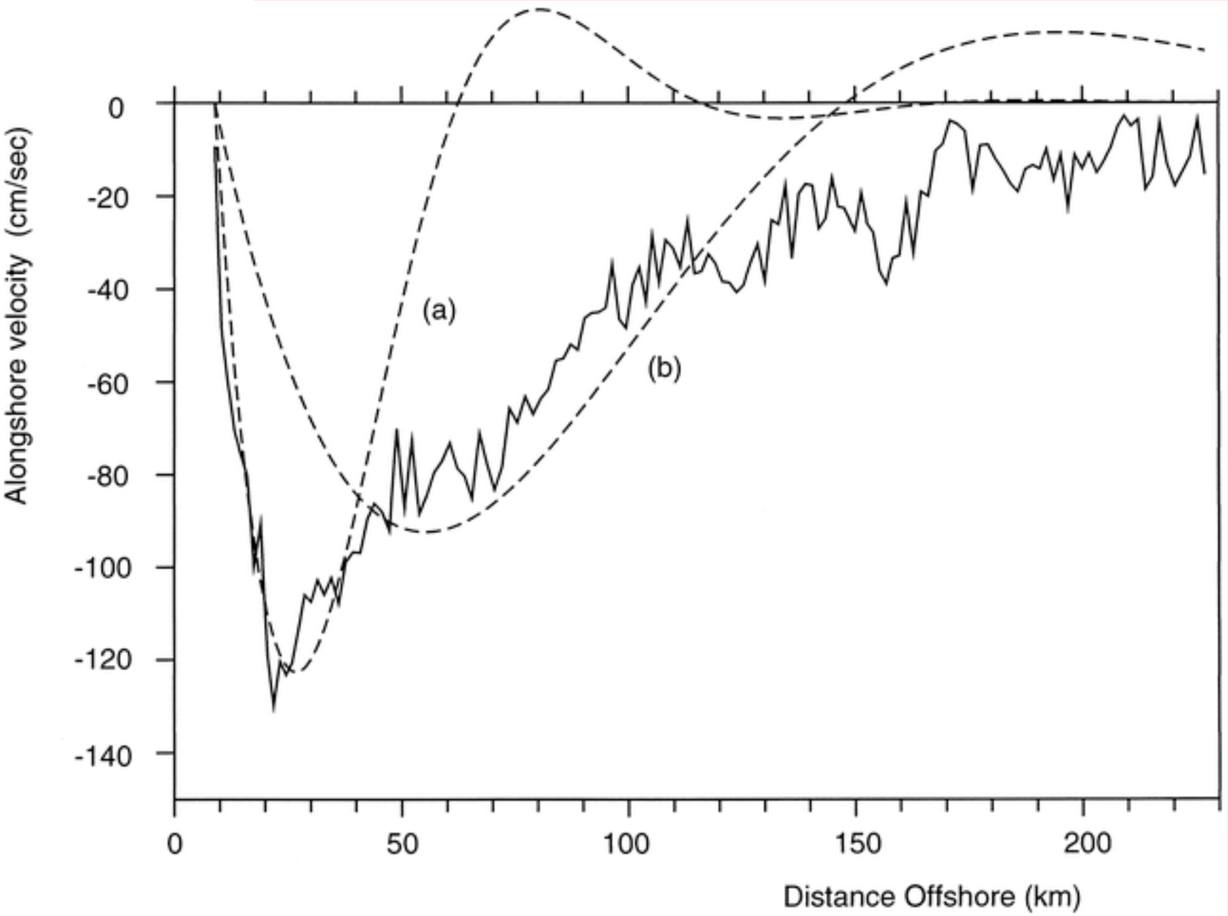


Stommel Boundary Layer (Bottom Friction)



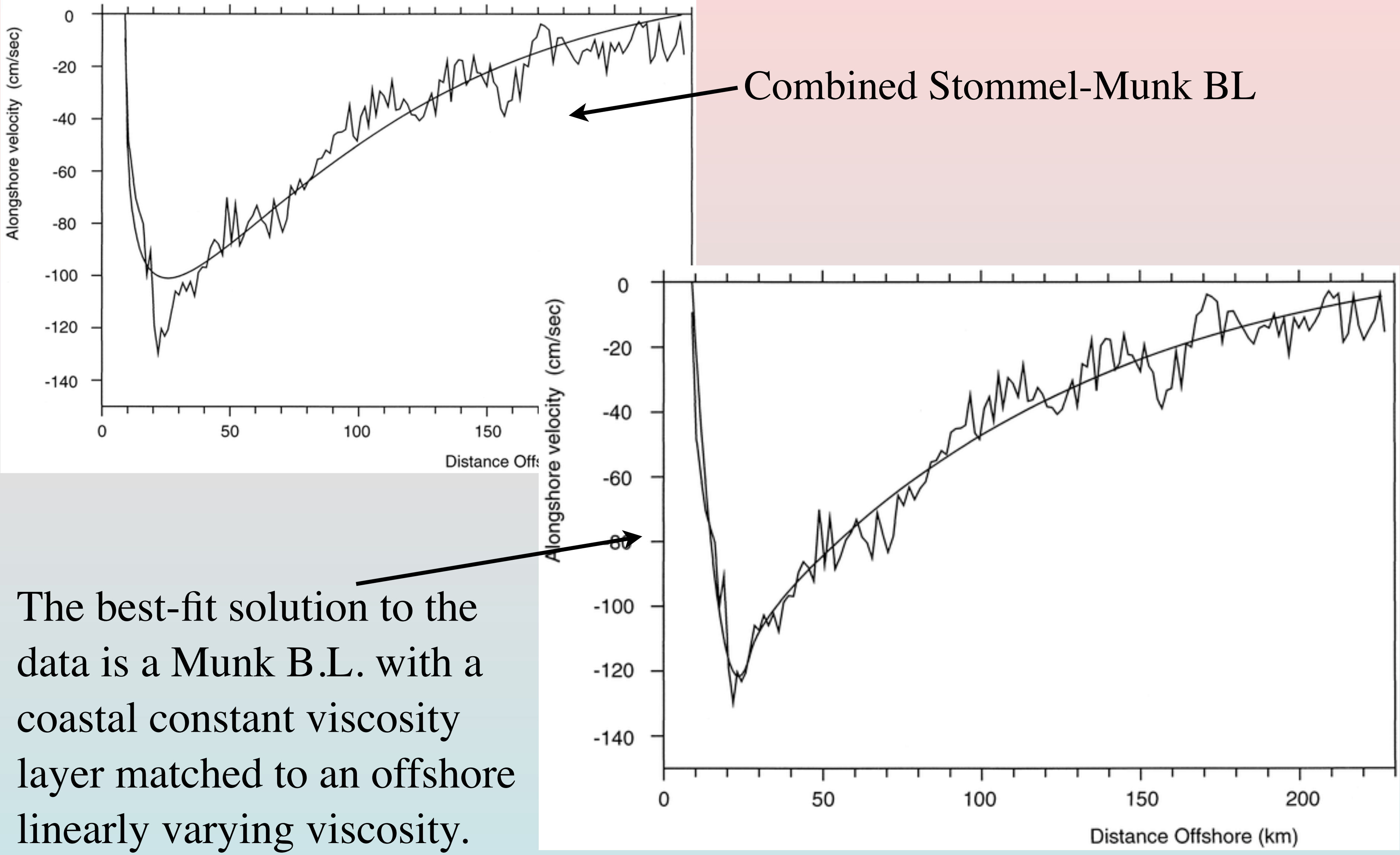
Munk Boundary Layer (Lateral Friction, Zero Velocity - no slip - on side wall)

Munk BL



Solid curve is the ADCP current data at a depth of 237 m for a section crossing the Agulhas Current, at an angle of 130° relative to true north near 31.5°S. At this depth the edge of the continental slope is 8.6 km from the coast. Dotted curves are the best-fit Munk solutions to (a) data between 9 and 43 km, (b) data between 9 and 227 km.

Boundary Layer model for the Agulhas Current



Combined Stommel-Munk BL

The best-fit solution to the data is a Munk B.L. with a coastal constant viscosity layer matched to an offshore linearly varying viscosity.

Webb (1999)

Measuring full-depth velocity with a Lowered ADCP

LADCP - Lowered Acoustic Doppler Current Profiler, 150 kHz, ↓6000 m

Once at >100 m depth, moves independently of ship.

Can measure attitude in the water, so vector properties of measured velocity are known.

But, instrument cannot measure the component of velocity due to its own motion.

$$U_{meas} = U_{ocean} + U_{adcp}$$

Measuring full-depth velocity with a Lowered ADCP

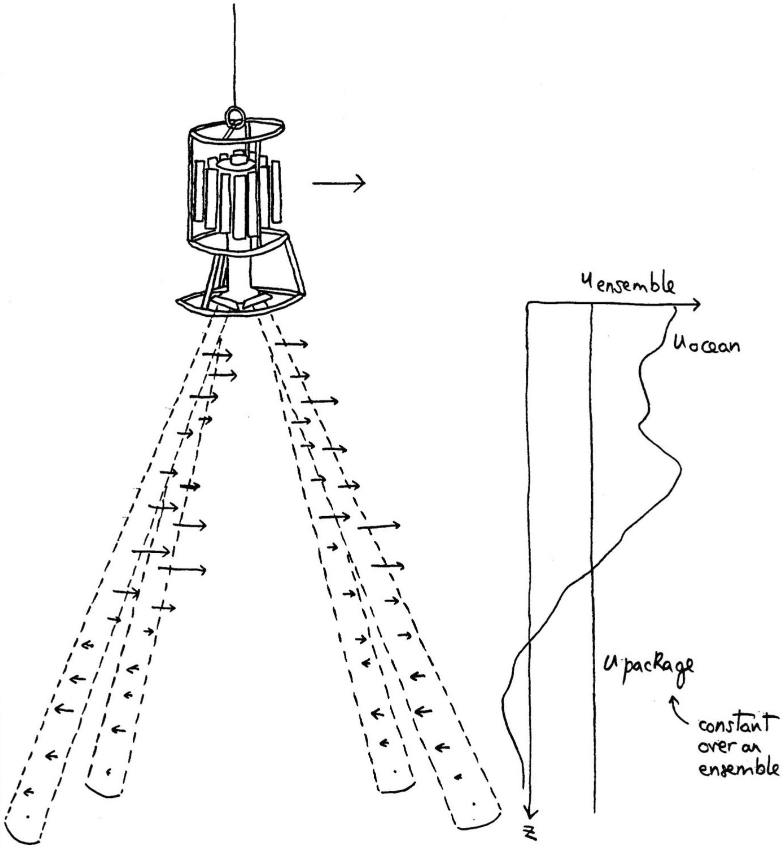


Figure 2.3 A cartoon showing what the LADCP is measuring on each ping. The instrument profiles about 300m of the water column on each ping; this is an ensemble. The velocities are collected in bins of length 16m and each velocity contains a component from the ocean current plus a component from the motion of the instrument itself. The component of velocity due to the motion of the instrument must be the same in each bin of an ensemble, therefore by differentiating the measured velocities over an ensemble the motion of the instrument is removed. The ensemble shears are then strung together, demeaned and integrated up over the complete depth of the cast to give relative velocities.

U_{adcp} is constant throughout a profile (or ping) with n bins.

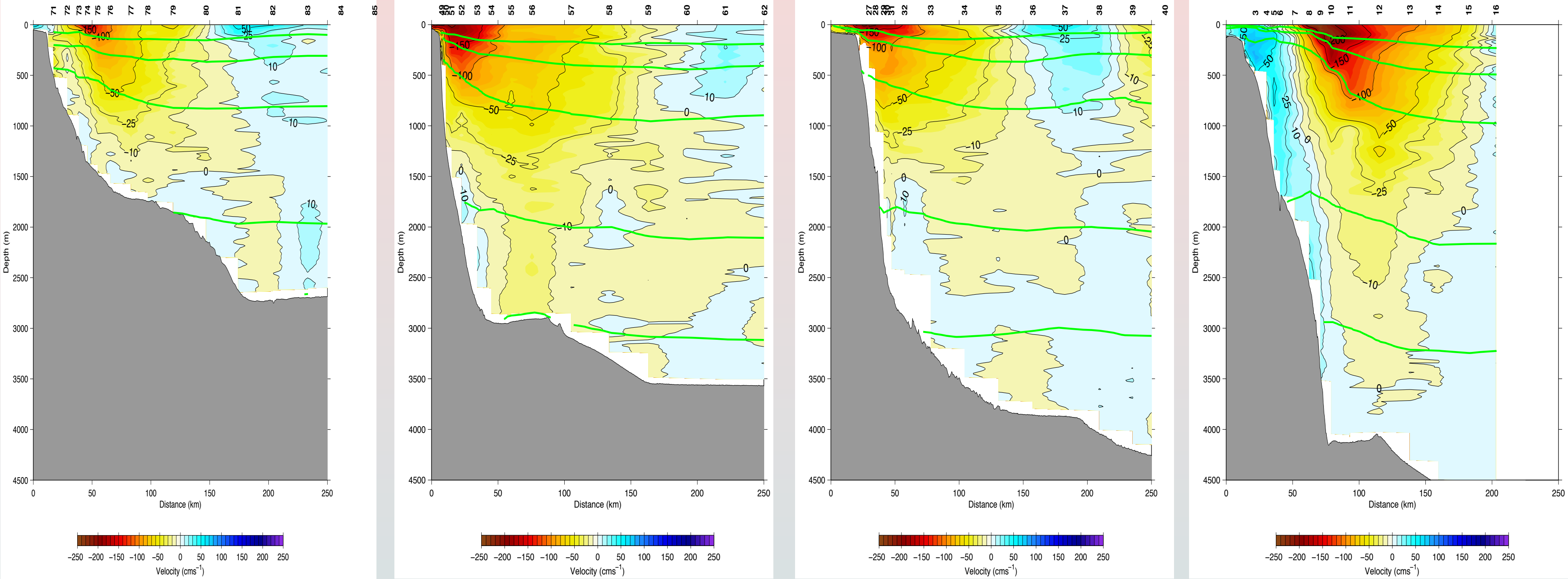
Ocean velocity can be split into U_{bc} (measured shear over 2 bins) and U_{bt} (unknown const. for profile).

Then, with minimum 2 bins, can solve for U_{bt} and U_{adcp}.

In practice, single ping data is very noisy - use additional constraints where possible: ship velocity, ADCP velocities, bottom-track velocities.

Beal, 1997; Firing, 1998; Visbeck, 2002

Direct velocity sections across Agulhas Current collected during AUCE, March 2003



~30°S
Richards Bay

~32°S
Port Shepstone

~34°S
East London

~36°S
Port Elizabeth

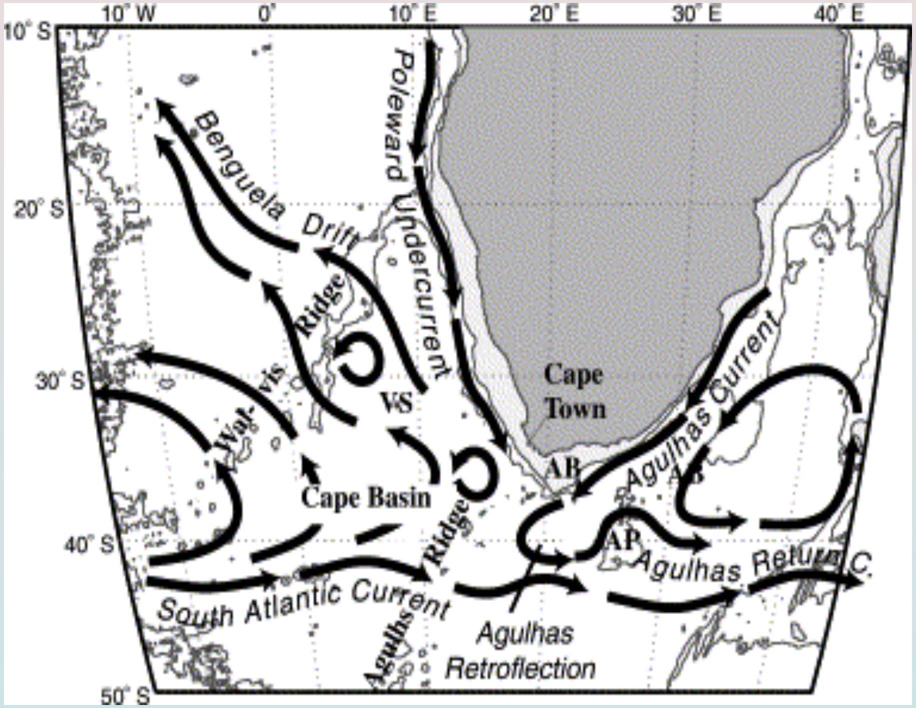
Geostrophic versus Direct Velocities

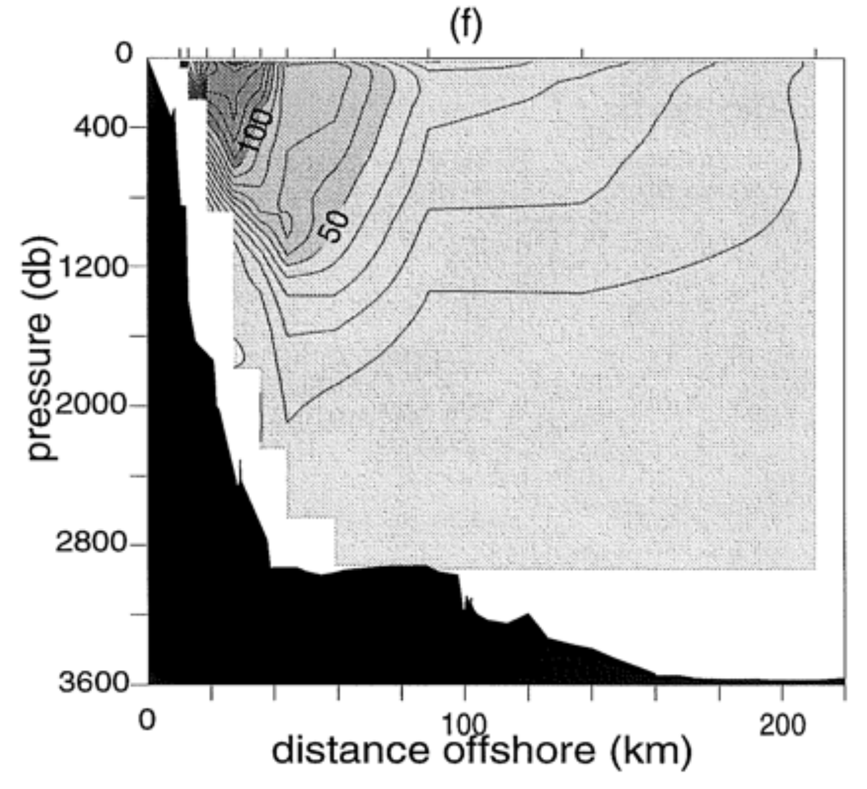
Use **thermal wind equations** to obtain geostrophic velocities from CTD measurements......

- Using equation of state for seawater can obtain density from measurements of temperature and salinity.
- Differentiating and eliminating pressure from the geostrophic equations, we obtain the thermal wind equations, from which we can use our measured density gradients to calculate **geostrophic shear**.
- Why can we not measure the absolute pressure gradient and obtain geostrophic currents?
- How do we obtain a reference velocity?
  - ⇘ assume bottom velocity is zero
  - ⇘ use water mass properties
  - ⇘ direct measurement with current meter (what depth?)
  - ⇘ use mass conservation (e.g. set up an "inverse model")

Agulhas Current off South Africa

- Geostrophic velocity integrated from *v=0* at the sea bed from 11 stations measuring (p, T, S), giving 10 profiles of geostrophic shear *dv/dz*





Geostrophic versus Direct Velocities

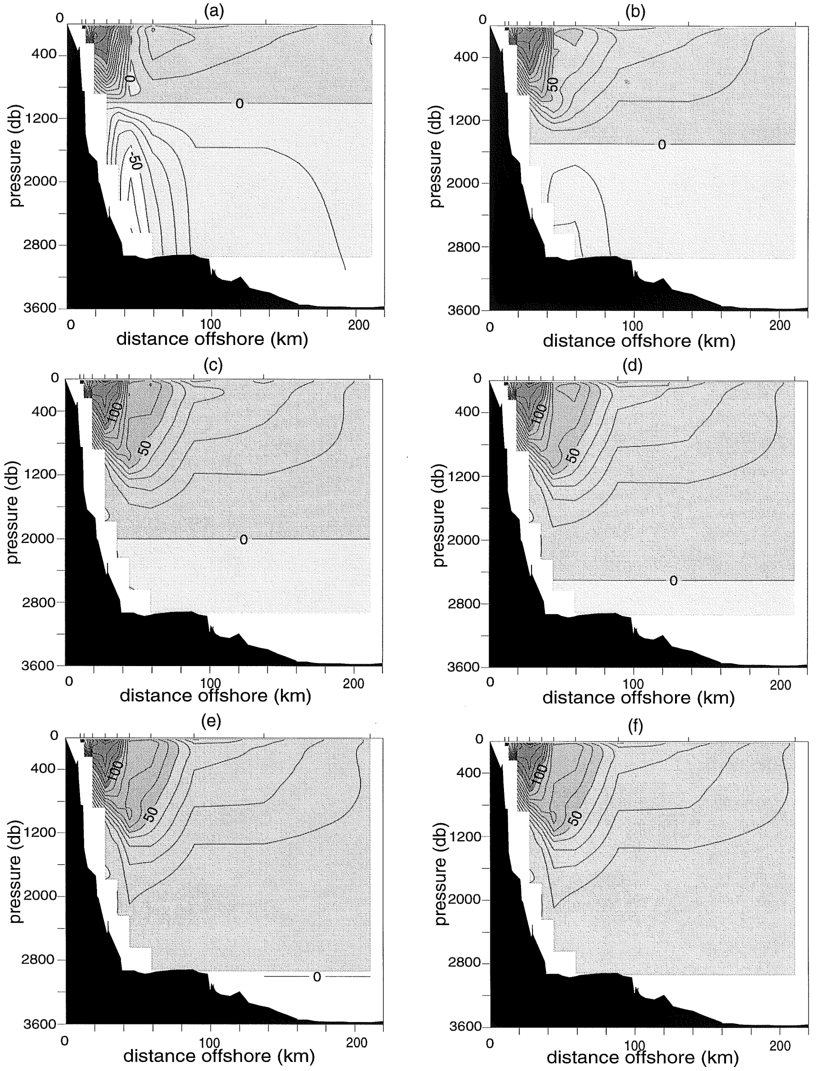


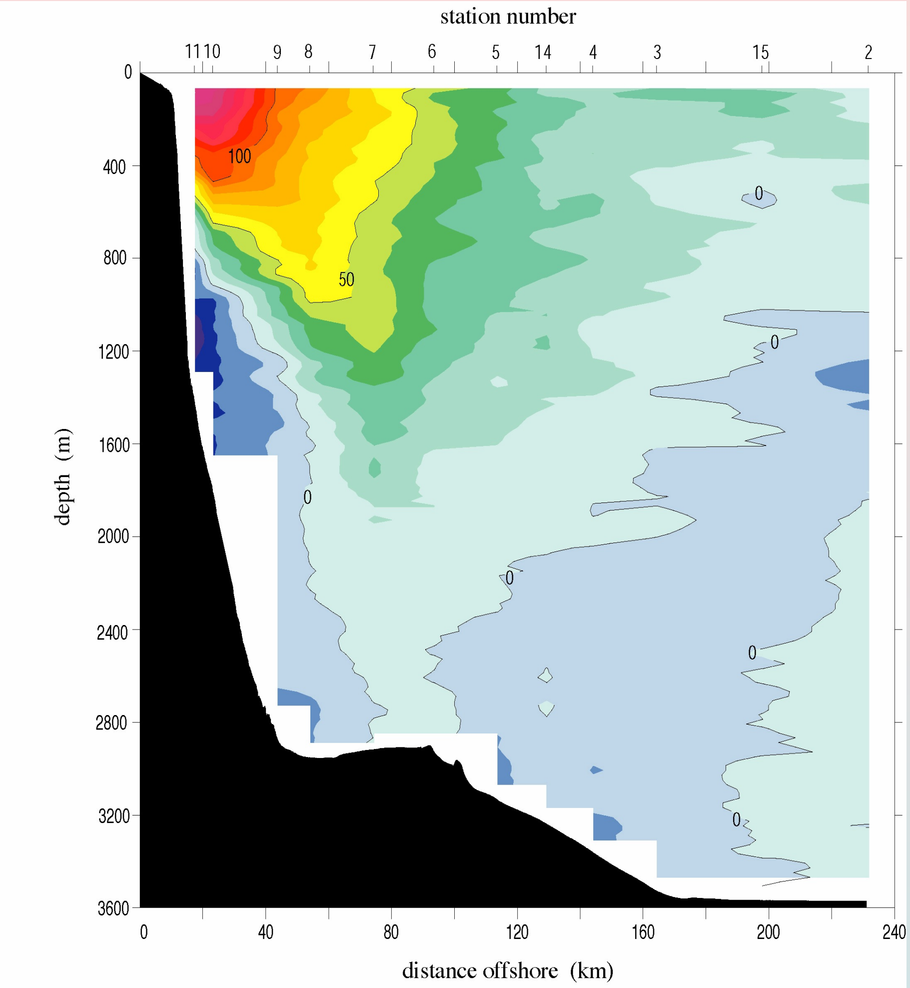
Figure 1.6 Geostrophic velocity of the Agulhas Current at 32°S in November 1987. Isotach intervals are every 10cms^{-1} and the grey scale changes every 50cms^{-1}, the lightest shade represents speeds of more than 50cms^{-1} north-eastward and the darkest represents speeds greater than 100cms^{-1} to the south-west. The position of each station pair is marked along the top axis. Absolute geostrophic velocities are referenced to a zero velocity surface at (a) 1000db, (b) 1500db, (c) 2000db, (d) 2500db, (e) 3000db, and (f) 3500db.

- Where is the reference level?
  Is there a reference “level”?

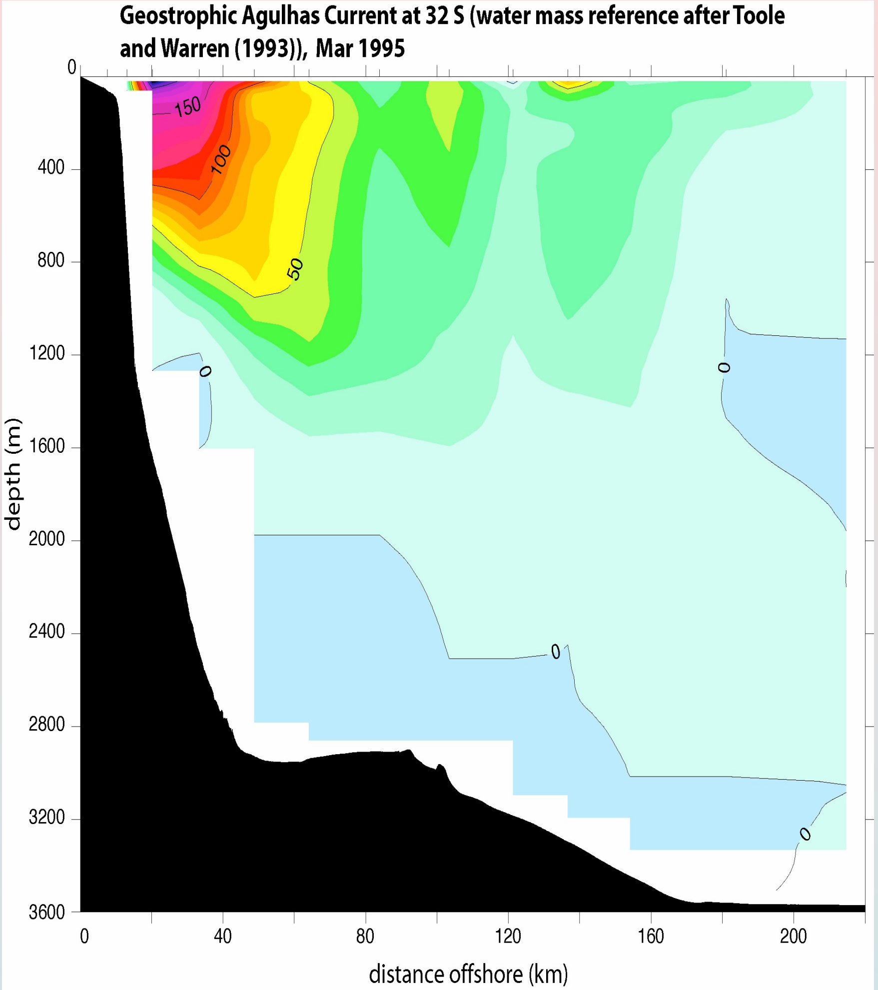
Reference Level (dbar)	Geostrophic transport (Sv)	Transport above 1000
1000	-31	30
1500	42	56
2000	75	66
2500	88	71
3000	89	74
3500	90	74

Beal, 1999

Geostrophic versus Direct Velocities



LADCP

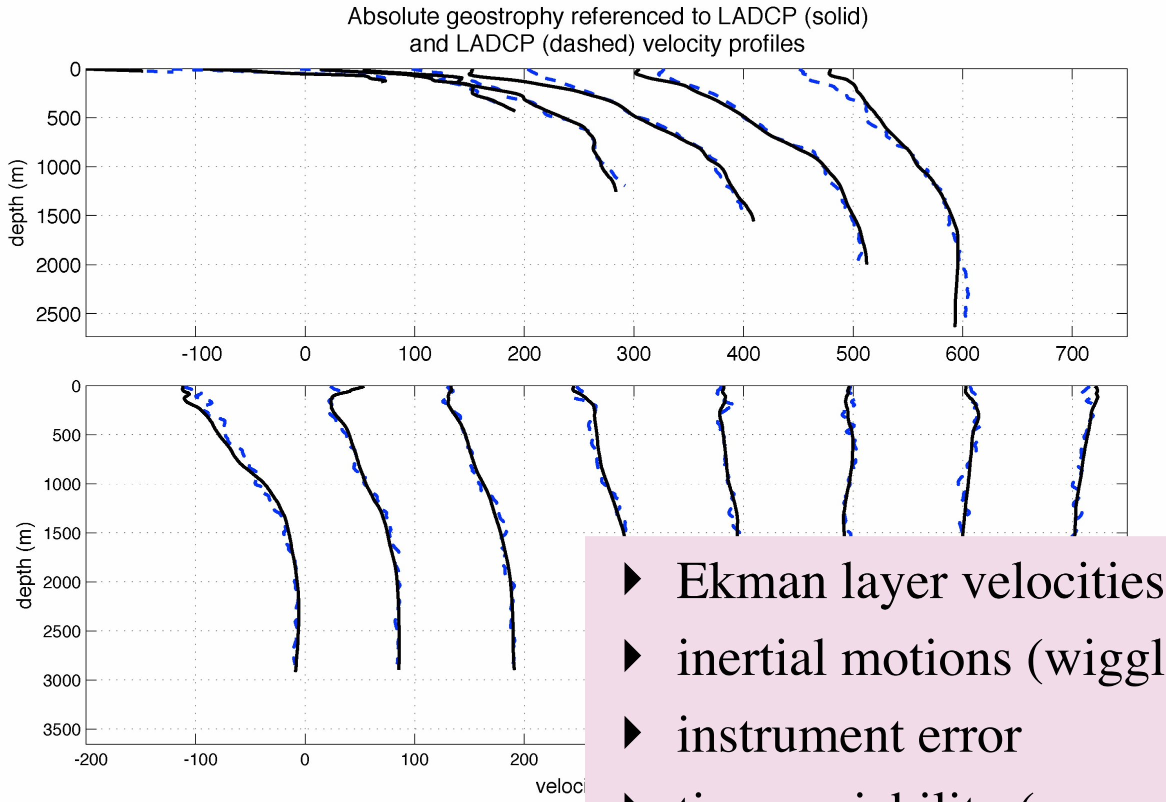


Geostrophic Agulhas Current at 32 S (water mass reference after Toole and Warren (1993)), Mar 1995

Geostrophy

Beal, 1999

Geostrophic versus Direct Velocities

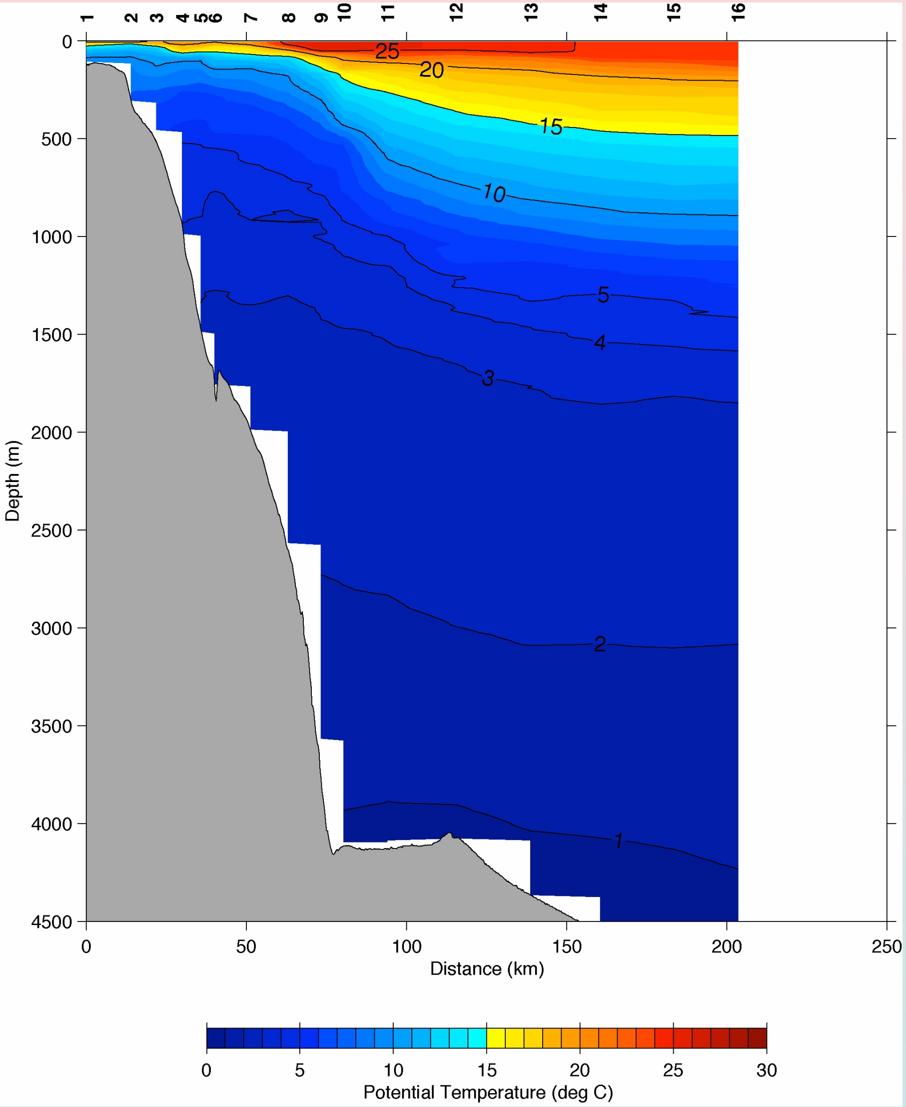


Absolute geostrophy referenced to LADCP (solid)
and LADCP (dashed) velocity profiles

- Ekman layer velocities (surface)
- inertial motions (wiggly bit)
- instrument error
- time variability (measurements are not synoptic)

- what makes the difference?

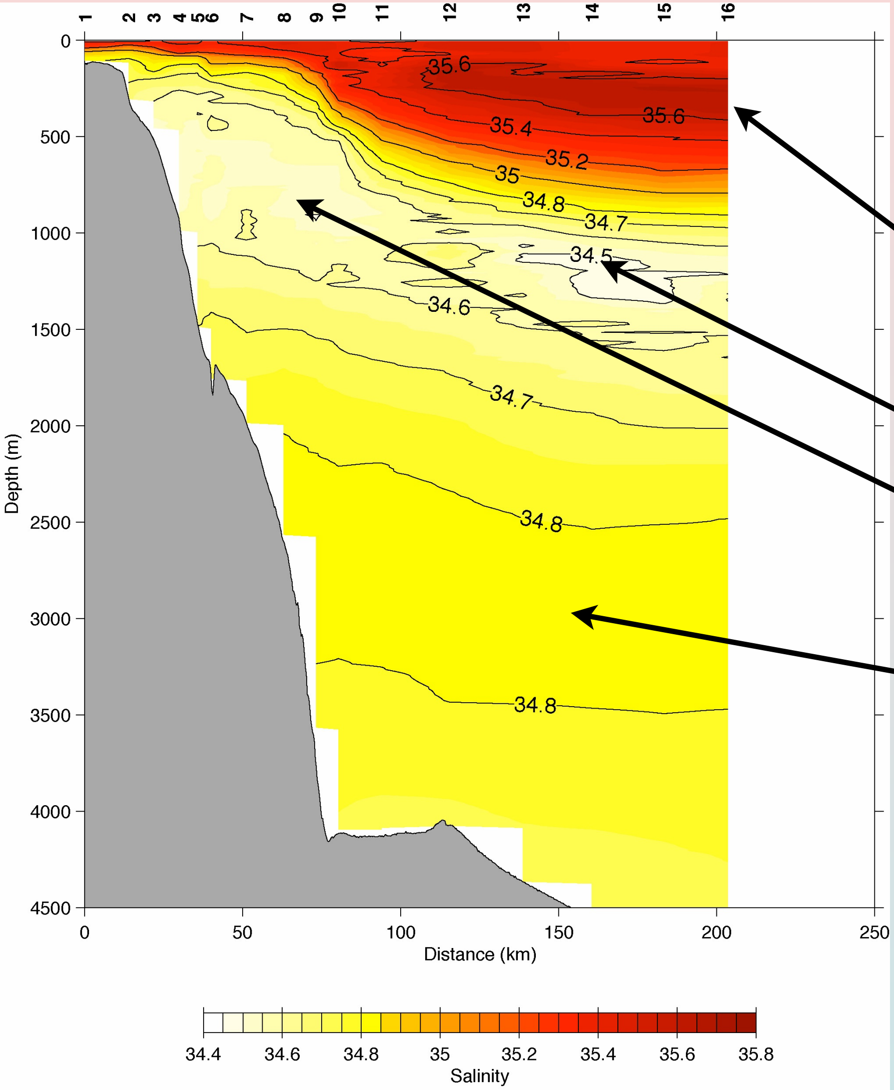
Temperature, Salinity, and Oxygen distributions



Potential Temperature (ºC)

- Isotherms slope upwards towards coast
- Neutral density layers thin towards coast
- On this section 15ºC isotherm outcrops

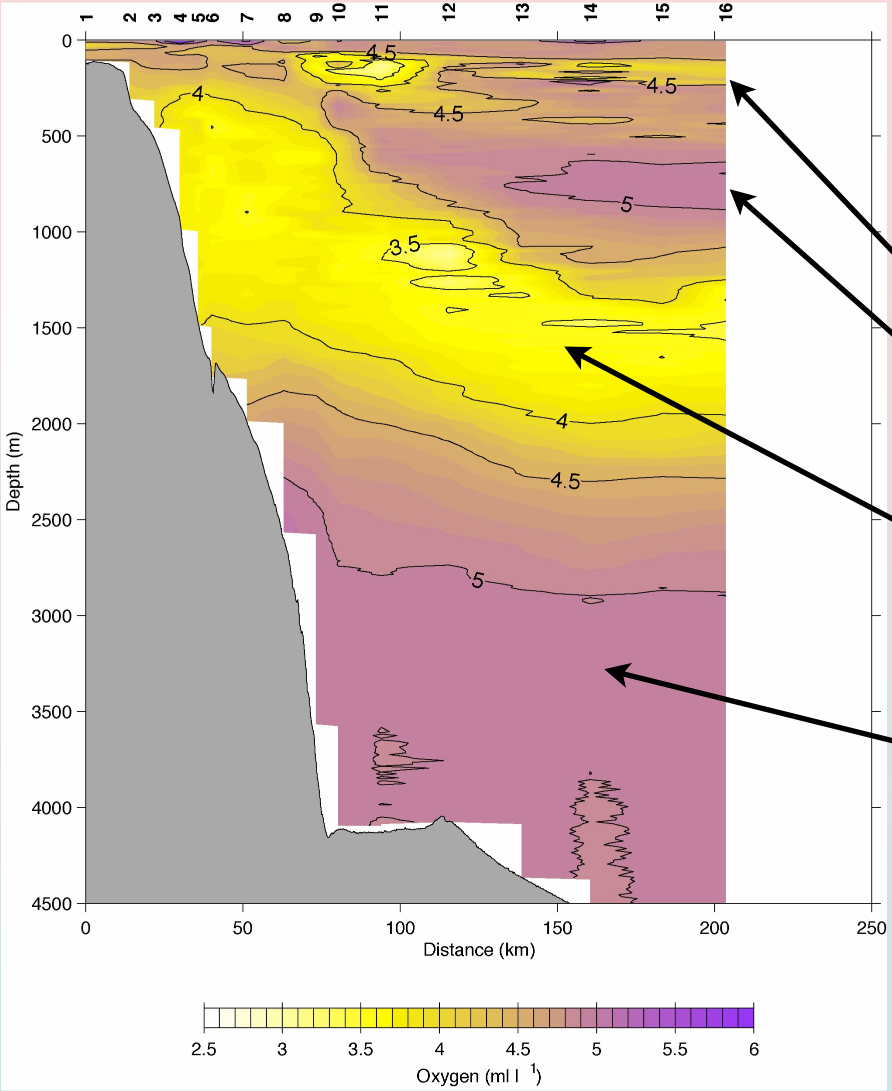
Temperature, Salinity, and Oxygen distributions



Salinity

- Subtropical surface water, salinity maximum
- AAIW salinity minimum
- RSW modified intermediate waters
- NADW salinity maximum

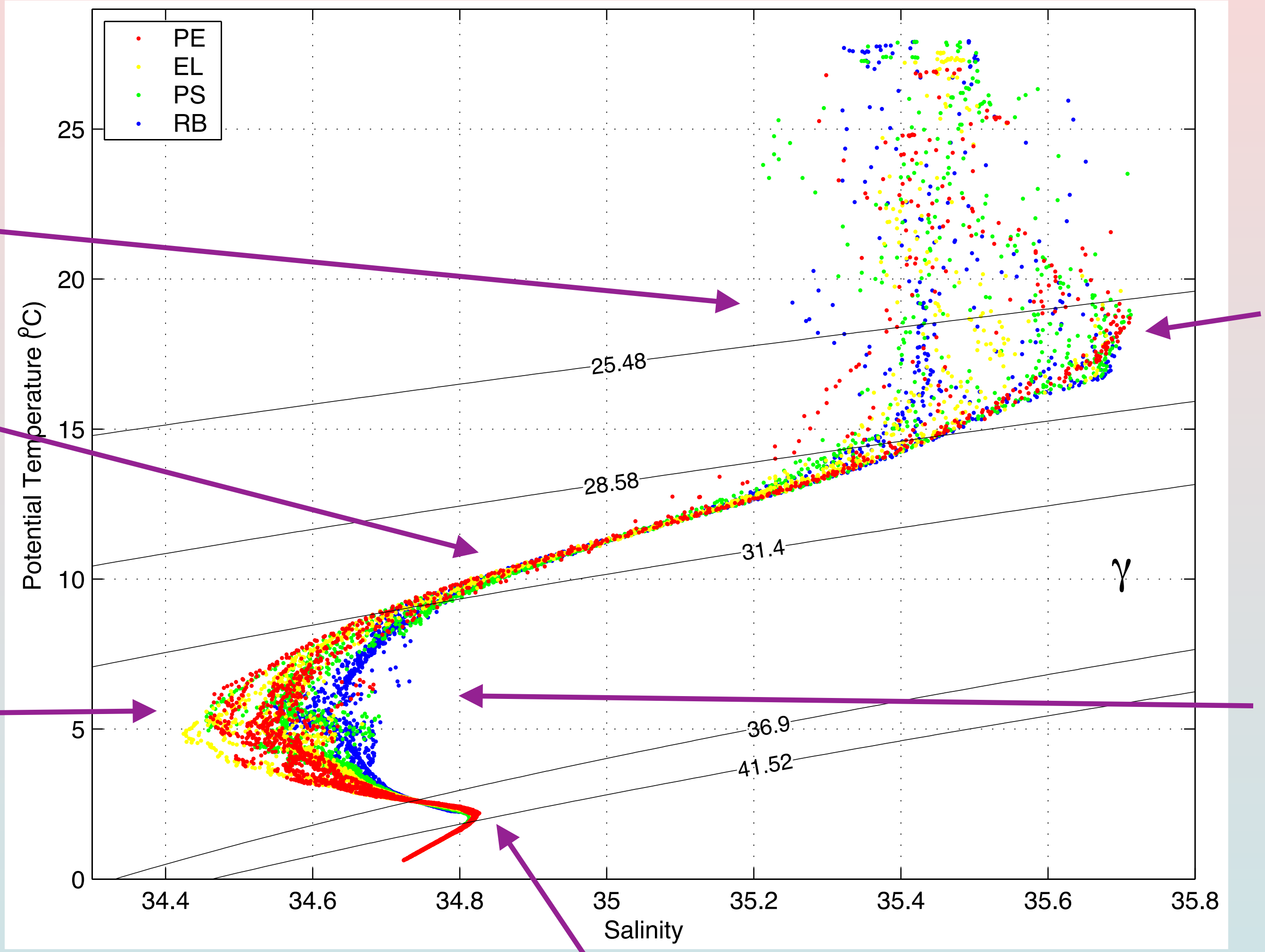
Temperature, Salinity, and Oxygen distributions



Oxygen ml/l

- STSW oxygen minimum
- SubAntarctic Mode Water, oxygen maximum
- Intermediate oxygen minimum originating in Arabian Sea
- NADW oxygen maximum

T-S Diagram



TSW

STSW

central or
thermocline
waters

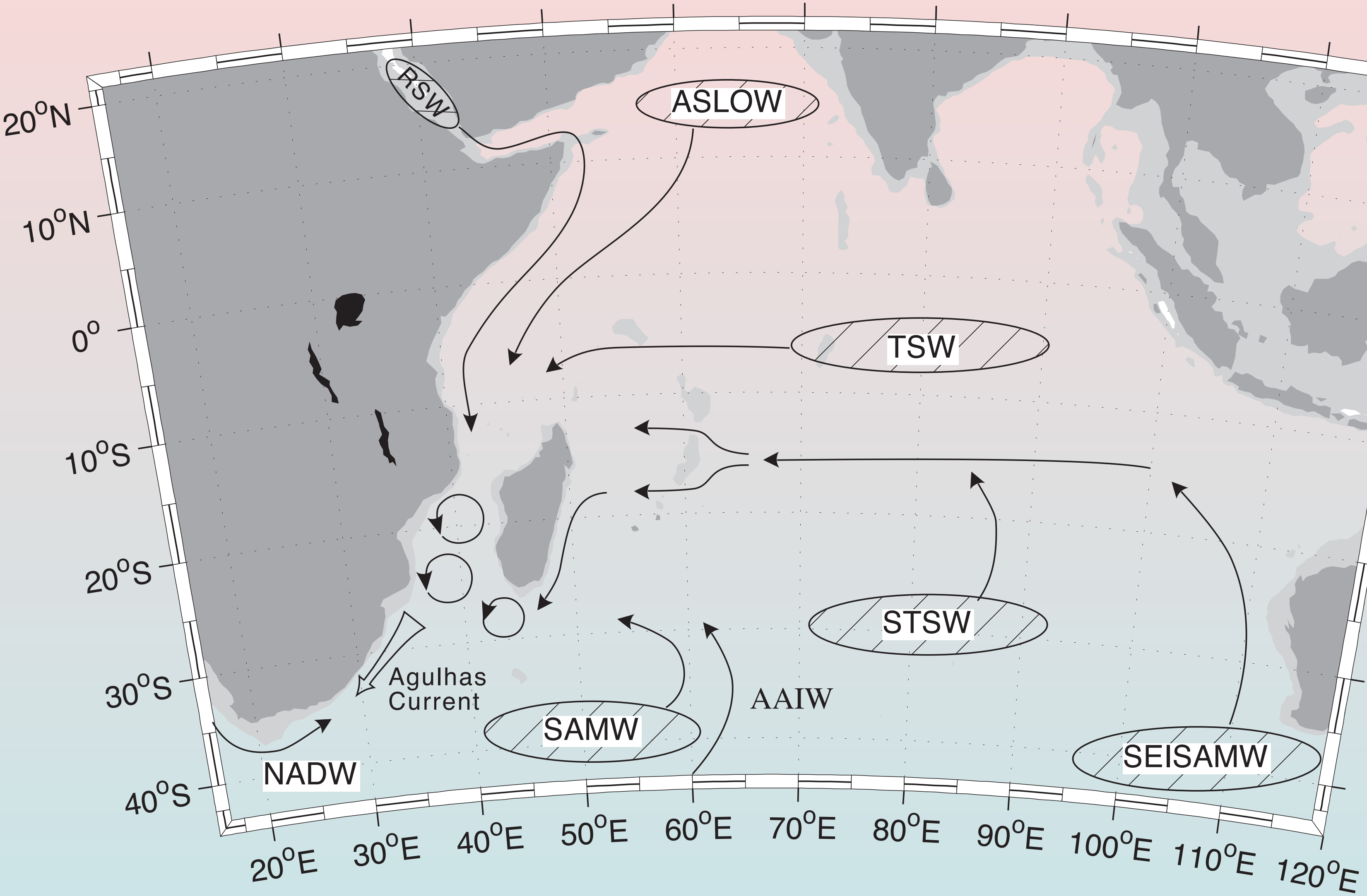
AAIW

RSW

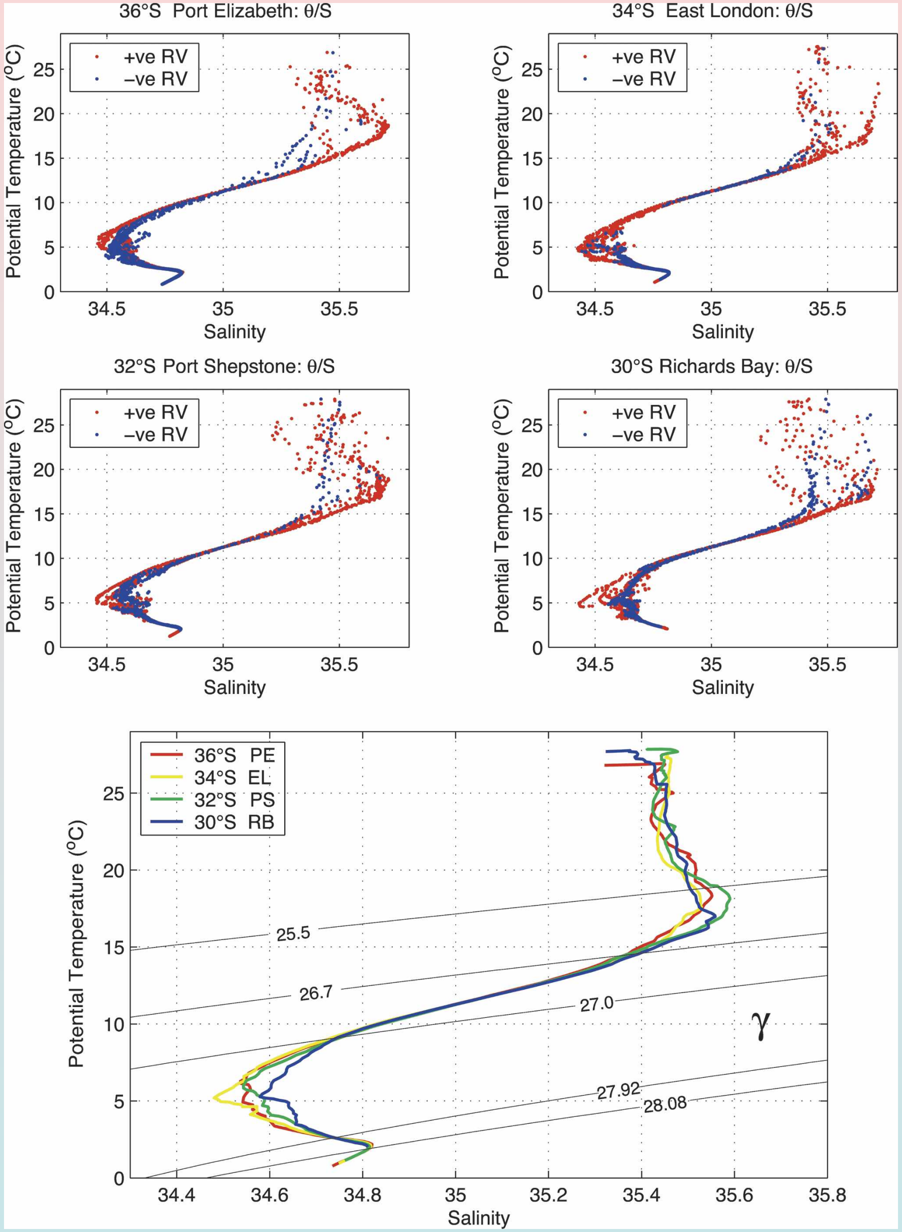
NADW

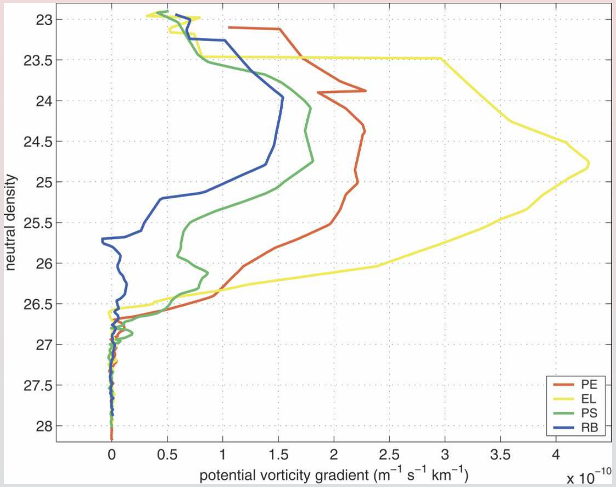
Beal, 2006

Water mass sources of the Agulhas Current



Cross-stream water mass separation due to vorticity and kinematic steering

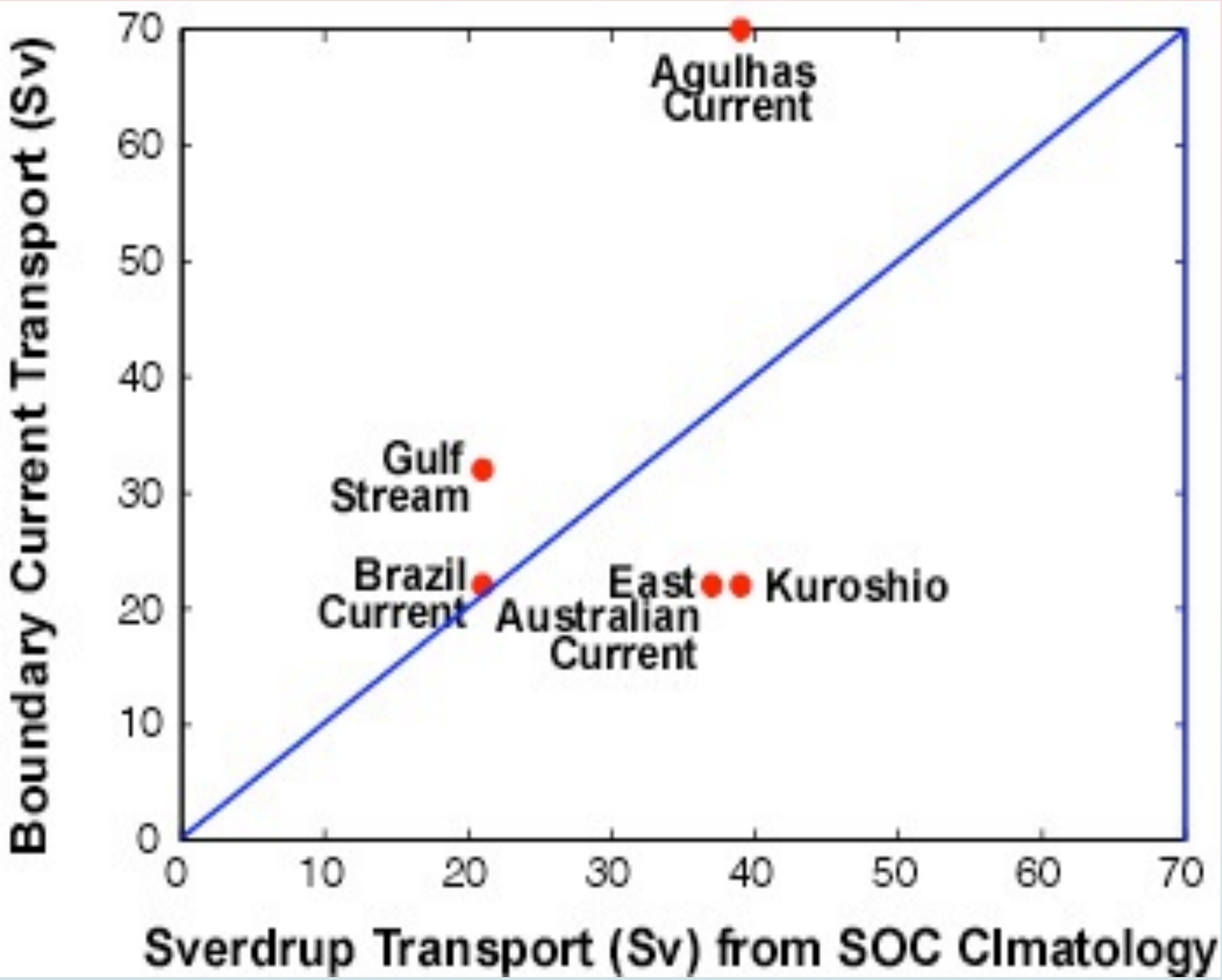




Potential vorticity gradient across front

Beal, 2006

Measured WBC transport versus predicted Sverdrup transport

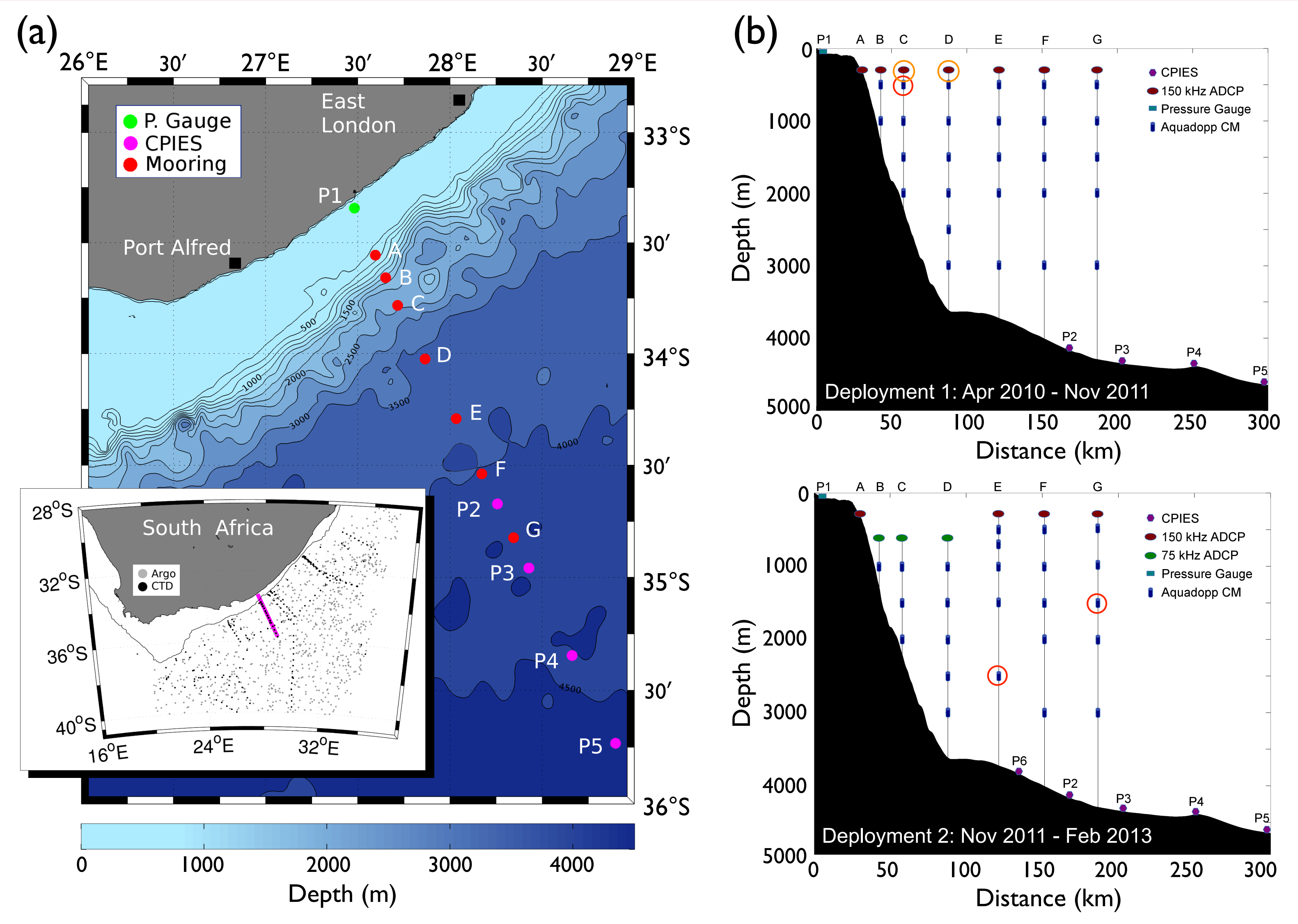


$$V = \frac{1}{\rho\beta} curl \tau$$

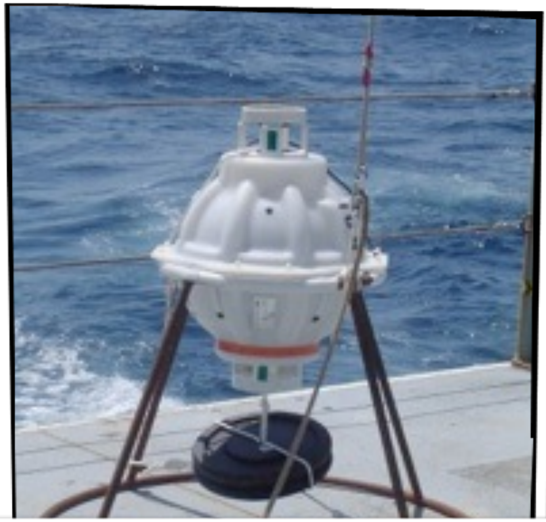
-why is the Agulhas Current so much larger than Sverdrup Balance predicts?

Downstream gain in transport is equal to Sverdrup transport

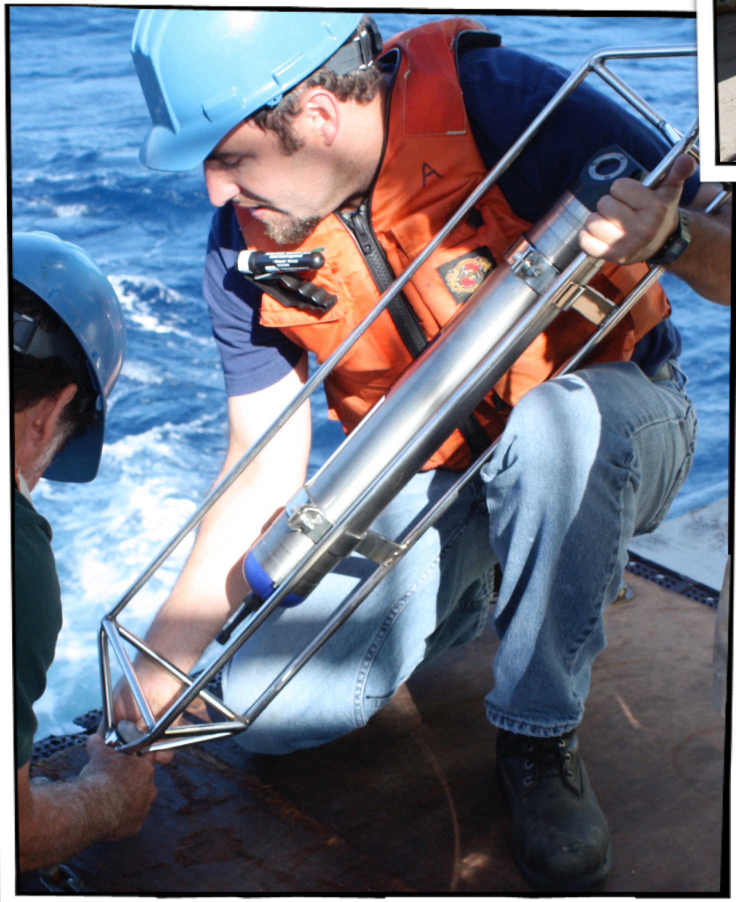
Agulhas Current Time-Series,
April 2010 - February 2013

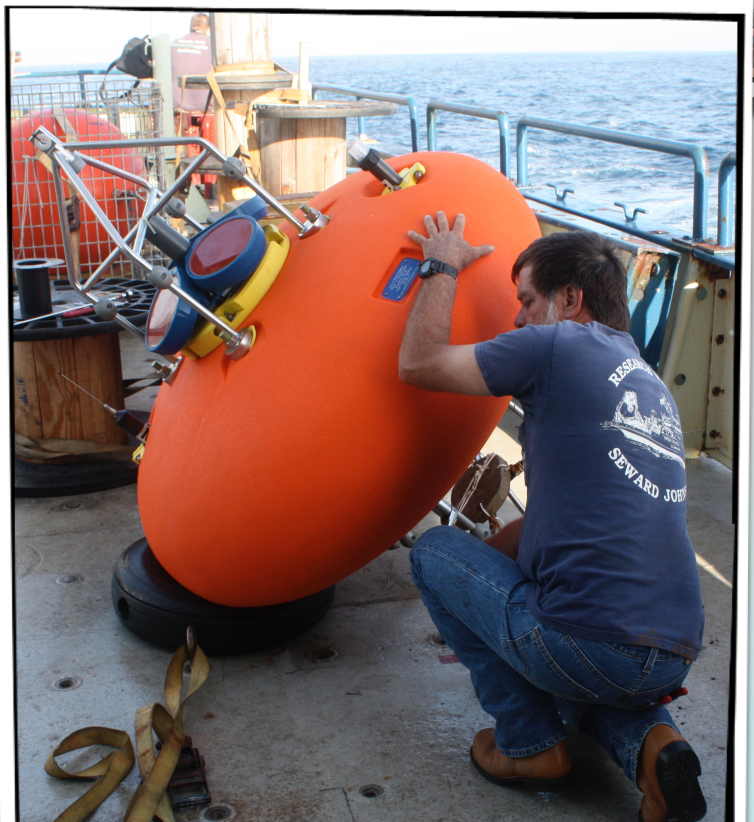


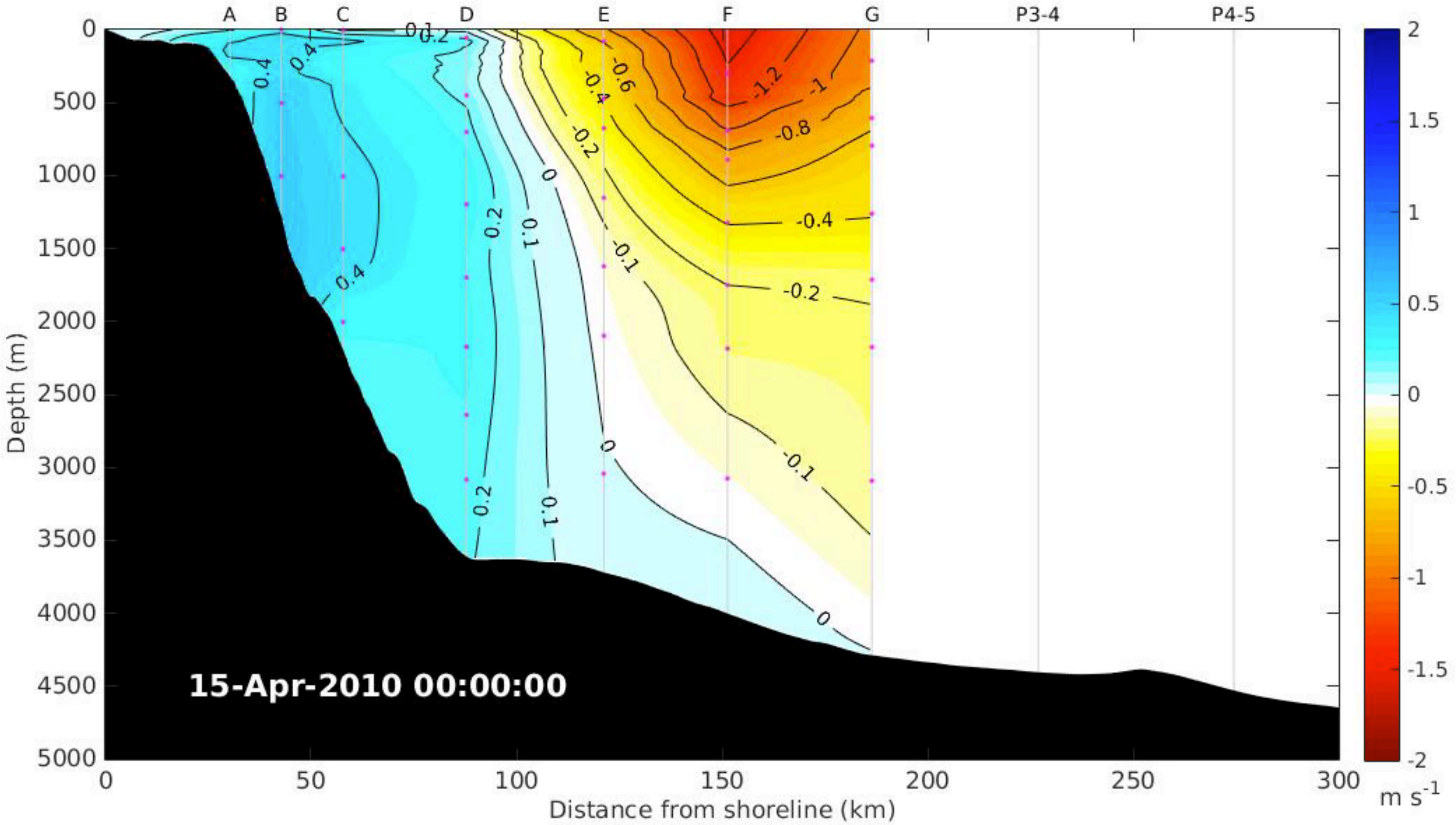
Beal et al, 2015

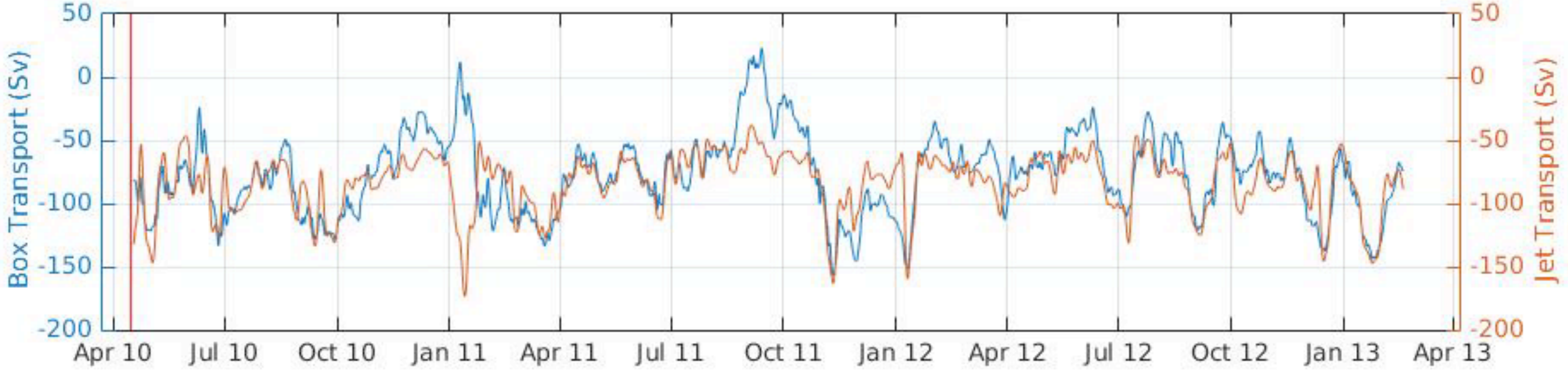



RELEASE
DISABLE (A)
ENABLE (A)
University of Miami
Ocean Technology Group
M/N-8242 RELEASE S/N-33822
Miami
RELEASE
DISABLE (A)
ENABLE (A)
University of Miami
Ocean Technology Group
M/N-8242XS RELEASE S/N-33826
INT. XPNDR (A)= 11.0 KHZ
REPLY XPNDR (A)= 12.0 KHZ
TRANSPONDER
INT. XPNDR (B)= n/a KHZ
REPLY XPNDR (B)= n/a KHZ
227430
211005
210770
RSMAS

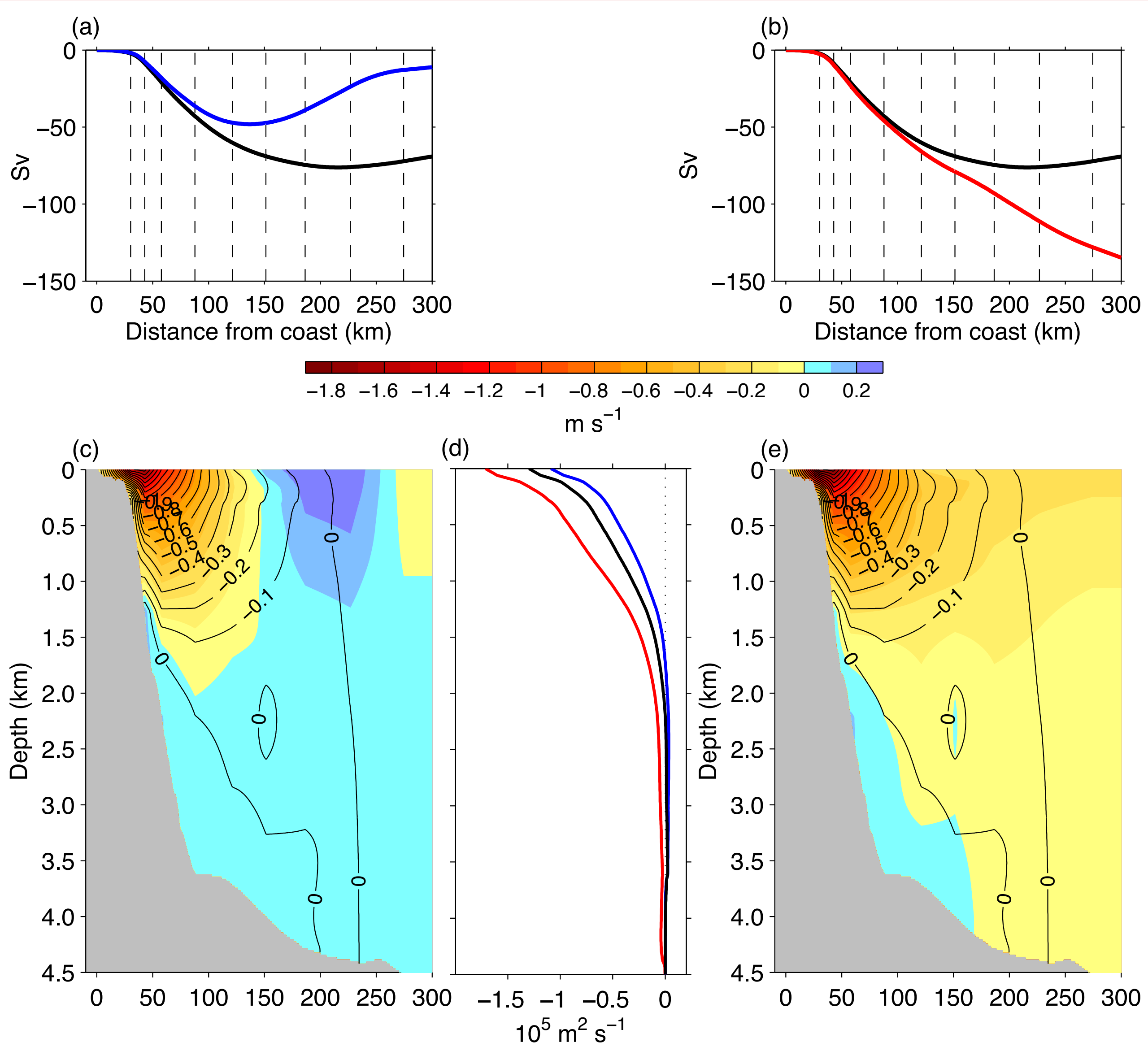



SEWARD JOH


A
B
C
D
E
F
G
P3-4
P4-5
Depth (m)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance from shoreline (km)
0
50
100
150
200
250
300
0.1
0.2
0.4
0.4
0.4
0.2
0.1
0
0.2
0.1
-0.4
-0.6
-1.2
-1
-0.8
-0.2
-0.4
-0.1
-0.2
0
-0.1
0
15-Apr-2010 00:00:00
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
m s^-1


Box Transport (Sv)
Jet Transport (Sv)
50
0
-50
-100
-150
-200
Apr 10
Jul 10
Oct 10
Jan 11
Apr 11
Jul 11
Oct 11
Jan 12
Apr 12
Jul 12
Oct 12
Jan 13
Apr 13

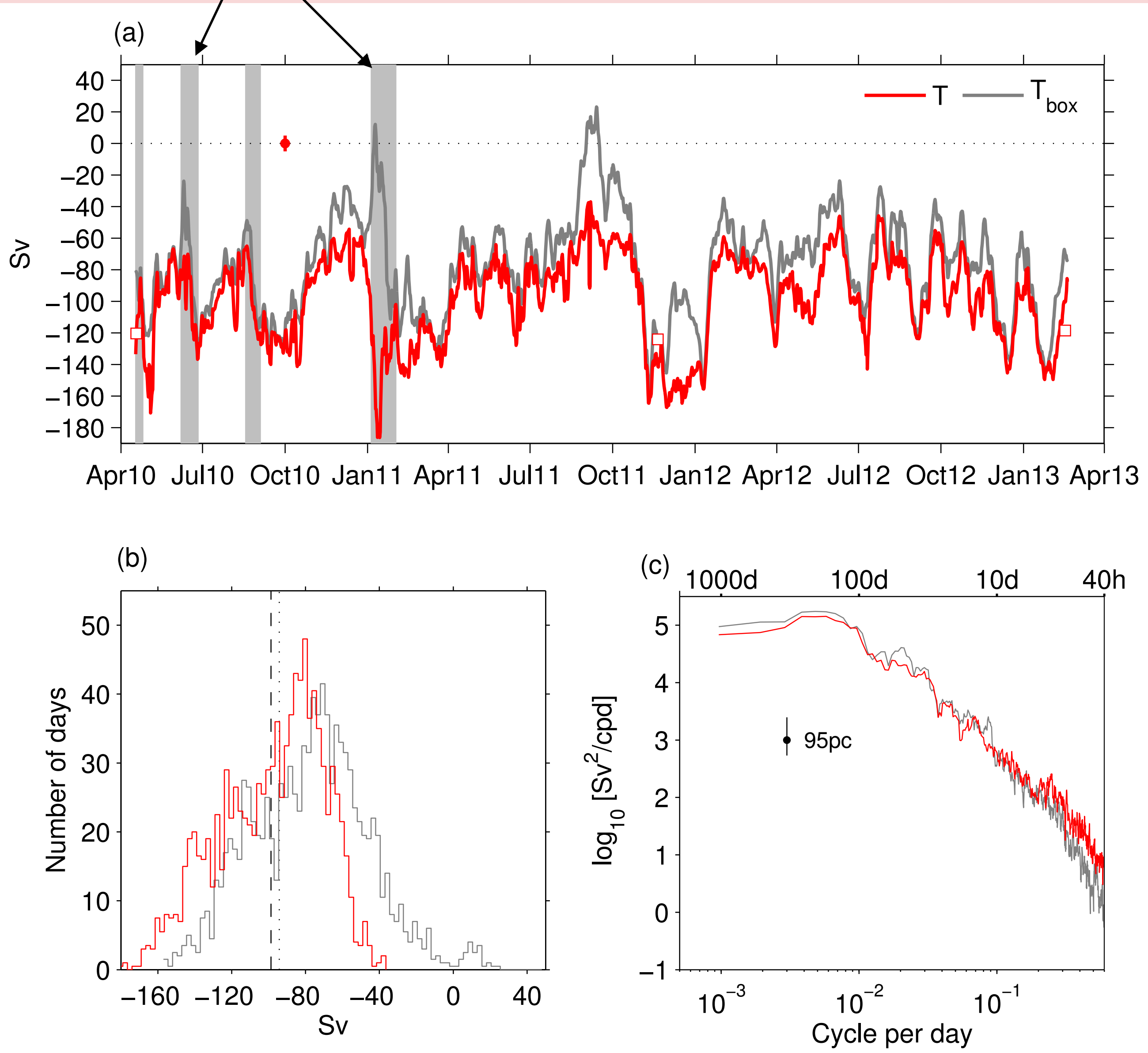
Agulhas Current velocity and transport for mean, 10% weakest, and 10% strongest transports



Beal et al, 2015

Agulhas Current Transport

meanders

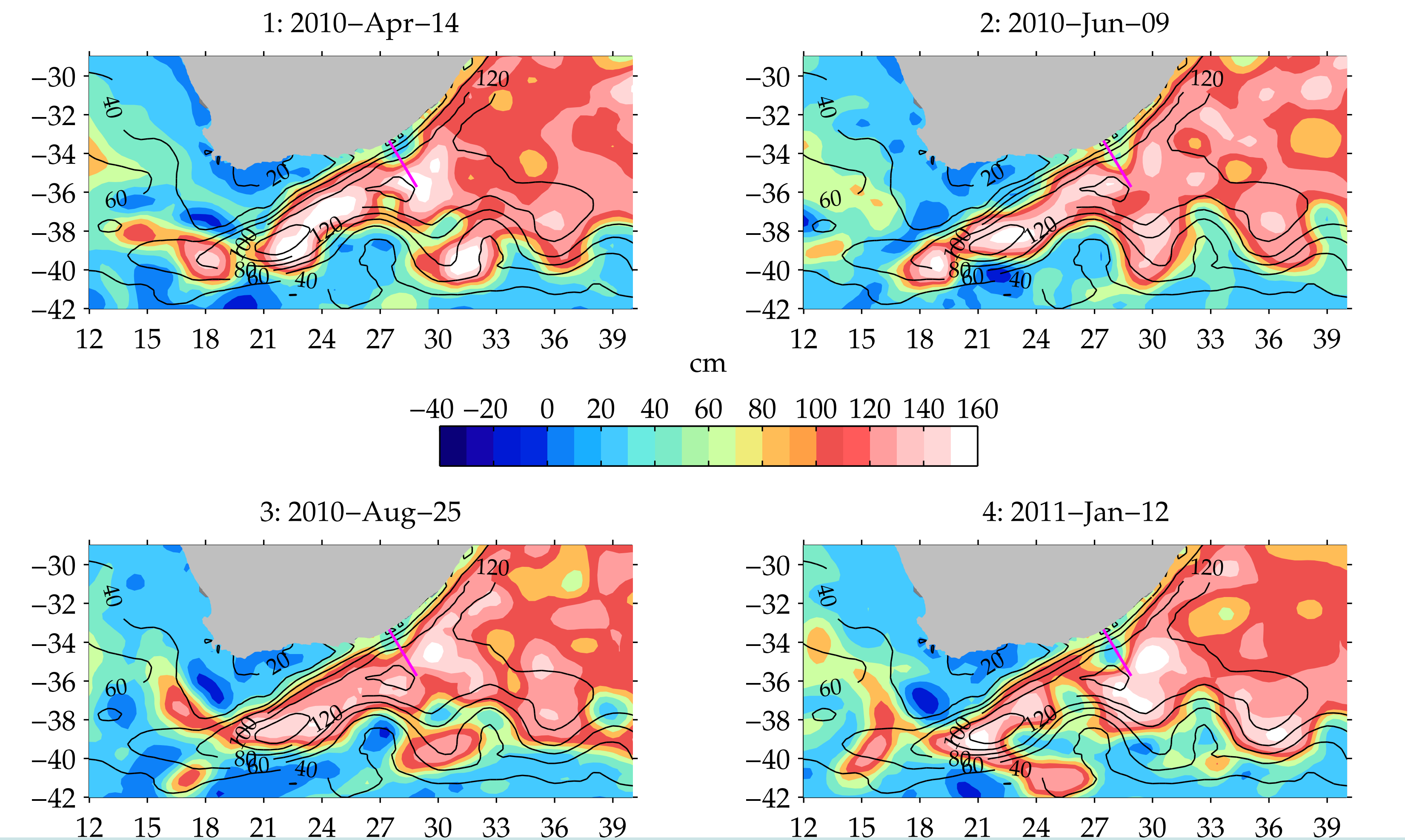


T = SW transport integrated to first cumulated transport minimum (different limit of integration every time step)

Tbox = SW transport integrated to offshore distance of mean zero crossing (fixed area of integration)

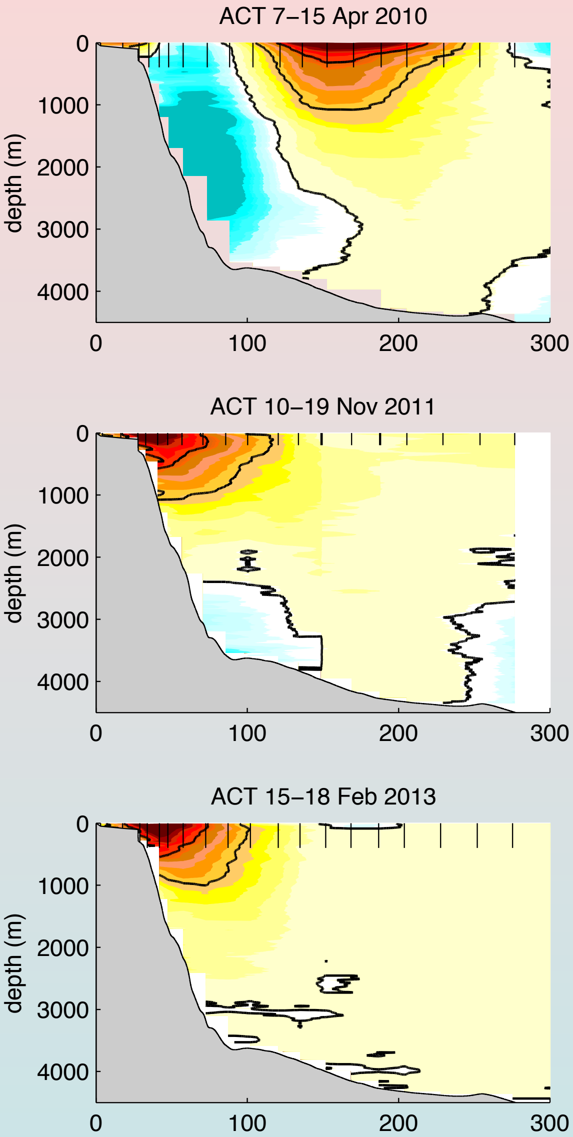
Beal et al, 2015

Four Agulhas meander events during ACT (and 14 ring-shedding events)



Elipot et al, 2015

In situ sampling of meander during ACT, April 2010



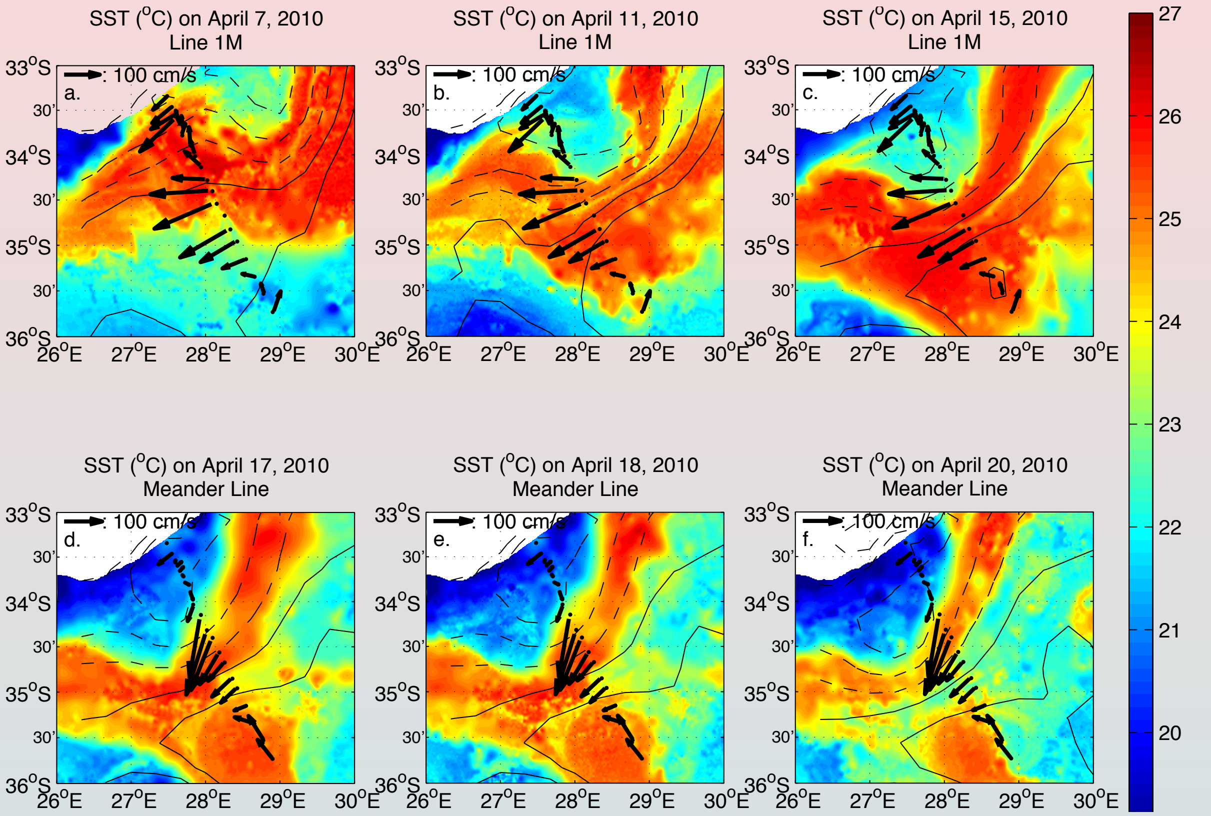
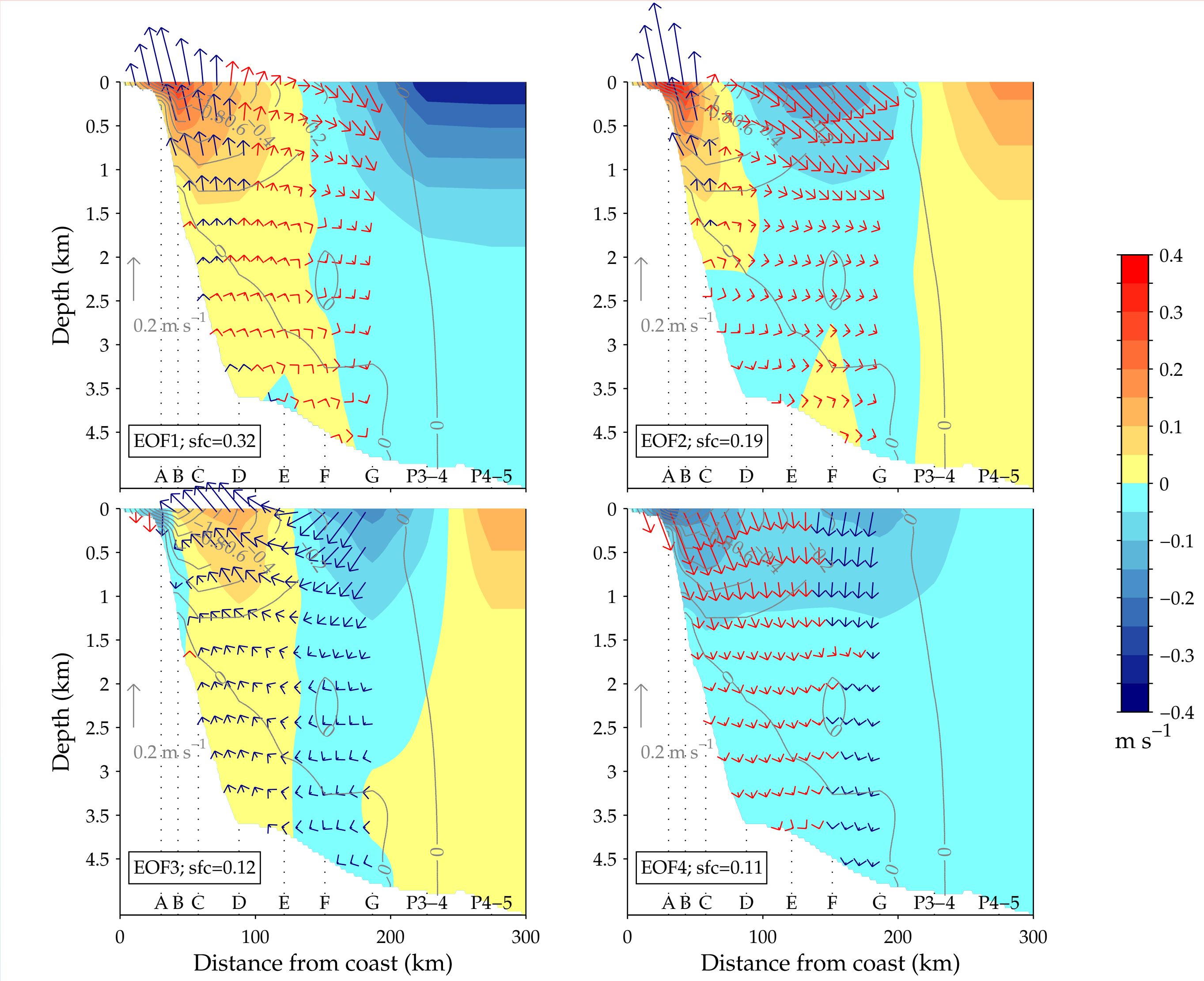


Figure 3: Six panels showing the progression of the solitary meander during the first cruise, from 7th April 2010 (a) through 20th April 2010 (f). Colors show SST (°C) from GHRSST, with the color scale shown on the right. Black contour lines represent MADT (mapped absolute dynamic topography, cm) from AVISO. Dashed contours show the 50 cm, 75 cm and 100 cm isopleths, and solid contours show the 125cm, 150 cm, and 175 cm isopleths. Bold vectors show LADCP velocities averaged over the top 200 m of the asynoptic meander line (a-c) and the meander line (d-f; with velocity scale given by the arrow at the top left of each panel).

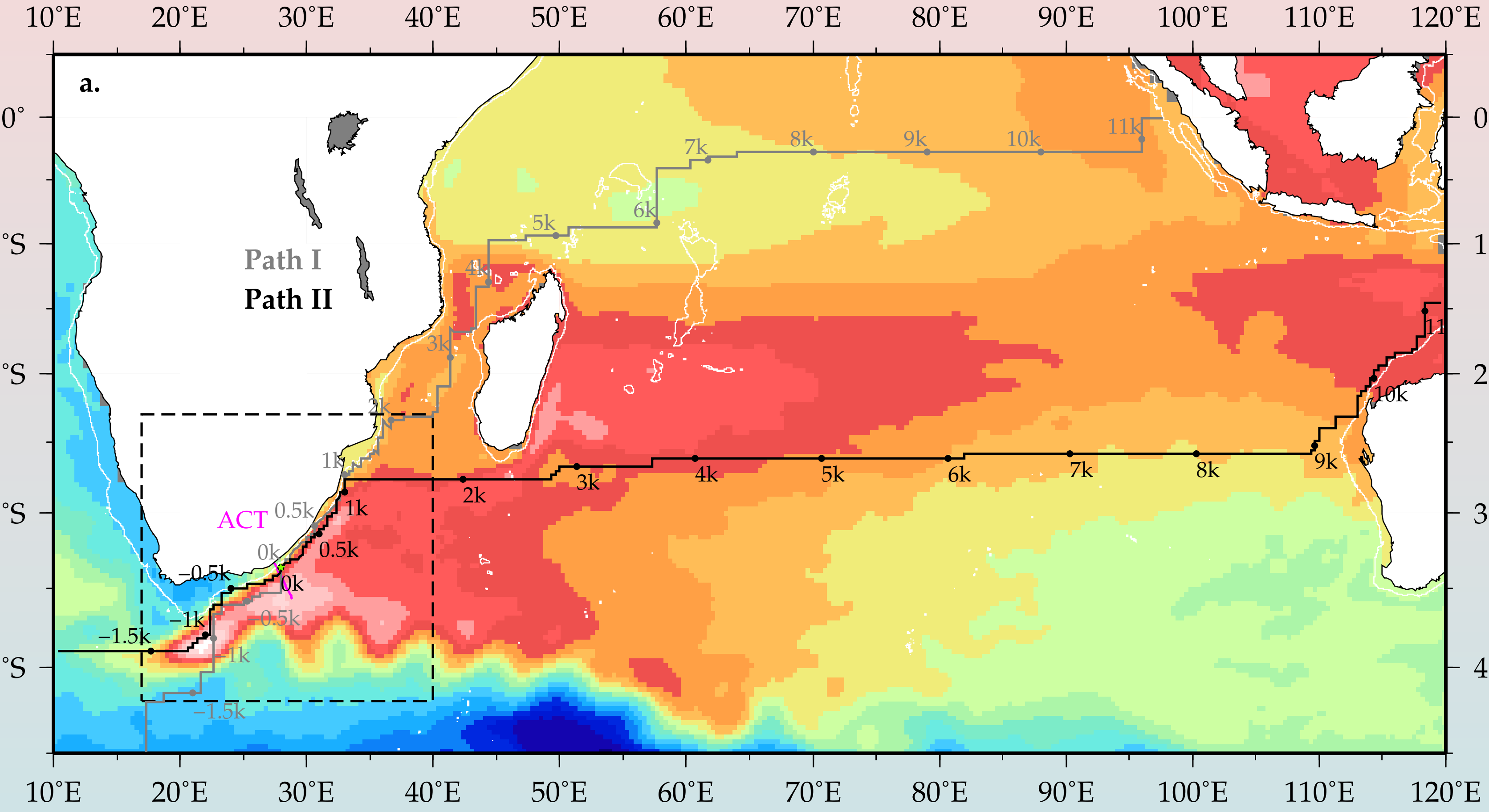
Leber & Beal, 2013

Dominant modes of velocity variance = meanders
Dominant mode of transport variance = pulses



Elipot et al, 2015

Mesoscale meanders can be traced up and downstream



Elipot et al, 2015

In Summary

- The horizontal structure of the Agulhas Current, as measured by shipboard ADCP, is most closely modelled by a Munk boundary layer with linearly varying viscosity offshore.
- Two decades ago the first full-depth, direct velocity measurements of the Agulhas Current were made with a Lowered ADCP. Uncertainties order 10cm/s due to instrument motion and noise.
- Different geostrophic reference level choices influence the structure and transport of the flow and can lead to misunderstandings.
- Geostrophy is smoother than direct velocities, because inertial motions and Ekman flows are disregarded
- The water masses in the Agulhas Current are from disparate sources.
- For the most part, water masses remain distinct and separated either side of the Current axis, due to vorticity and kinematic mixing barrier.
- It matters how you measure transport.
- Dominant mode of variability in Agulhas Current is solitary meanders
- The measured transport of the Agulhas Current is considerably larger than its predicted Sverdrup transport.