Equatorial subthermocline circulation driven by intraseasonal variability

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In the beginning...

Deep-Sea Research, 1976, Vol.23, pp. 999-1001. Pergamon Press. Printed in Great Britain.

EQUATORIAL UNDERCURRENTS*

JAMES R. LUYTEN** and J.C. SWALLOW[+]

(Received 16 August 1976)

During the latter part of May and June, 1976, the R.V. Atlantis II occupied a section along 53°E in the western Indian Ocean extending from 0°45'S to 5°N latitude. The observations consisted primarily of time series of vertical profiles of horizontal velocity, extending from the ocean surface to the bottom. A number of the results from these measurements, although not completely unexpected, are novel.

Nine velocity profiles that changed the world...

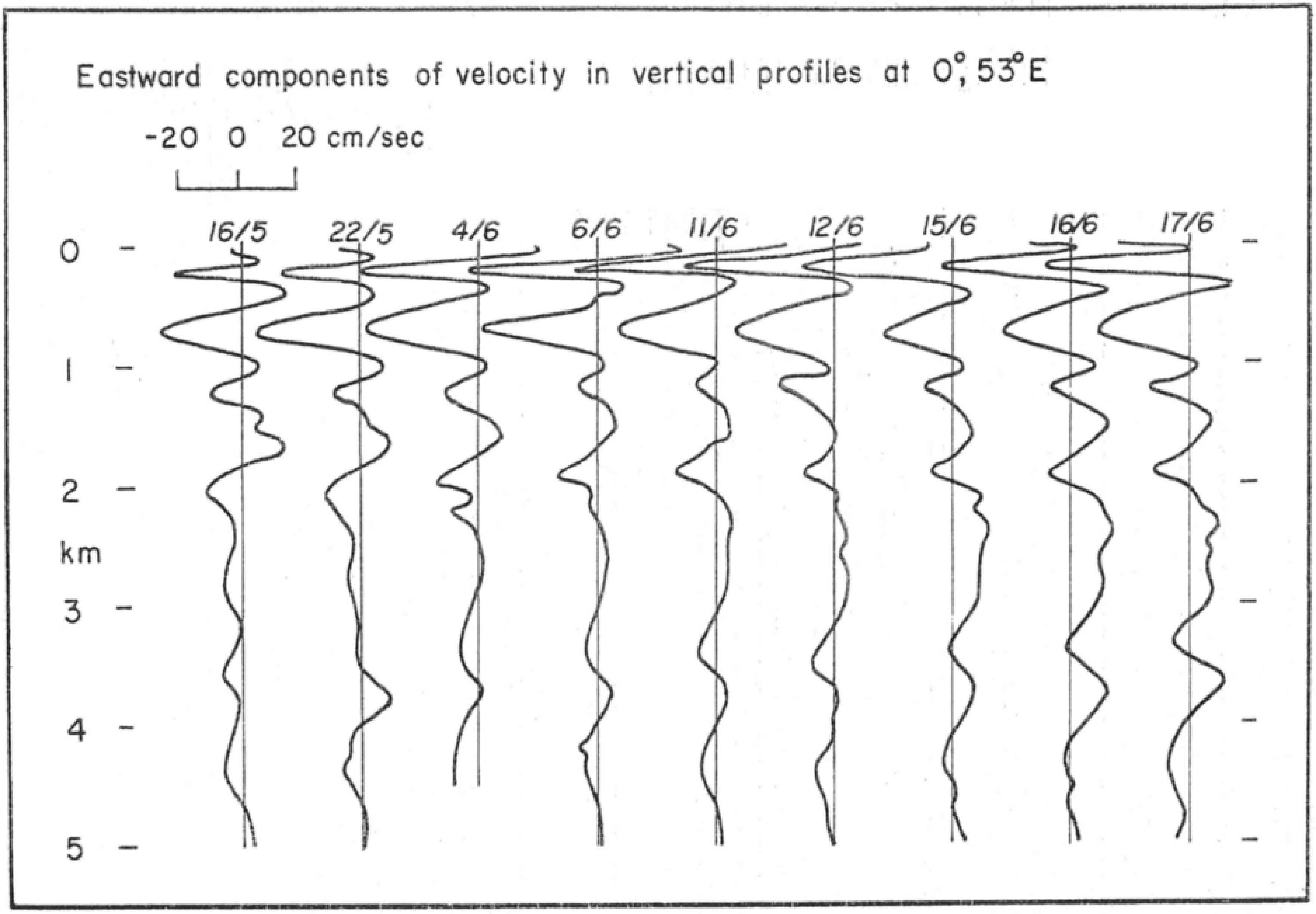


Figure 1

1976 zonal velocity profiles analyzed by O'Neill and Luyten (1984)

- One month, two latitudes
- One section, 6 latitudes

- Small vertical scale near the equator
- Persistent in time
- Larger vertical scale at higher latitudes

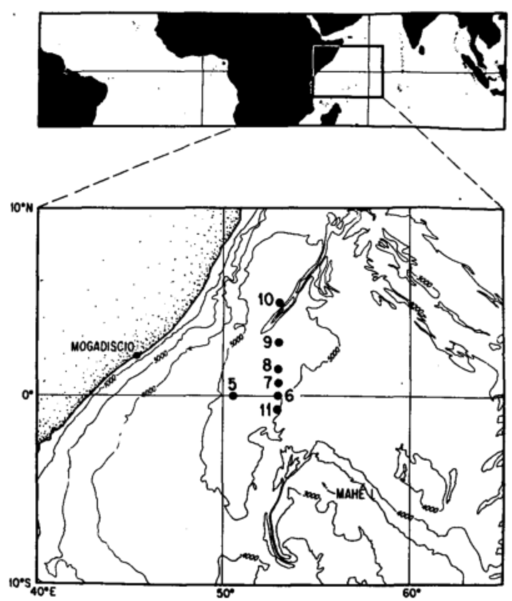


FIG. 1. Bathymetric map of the western equatorial Indian Ocean, showing the location of the 1976 White Horse profiling stations.

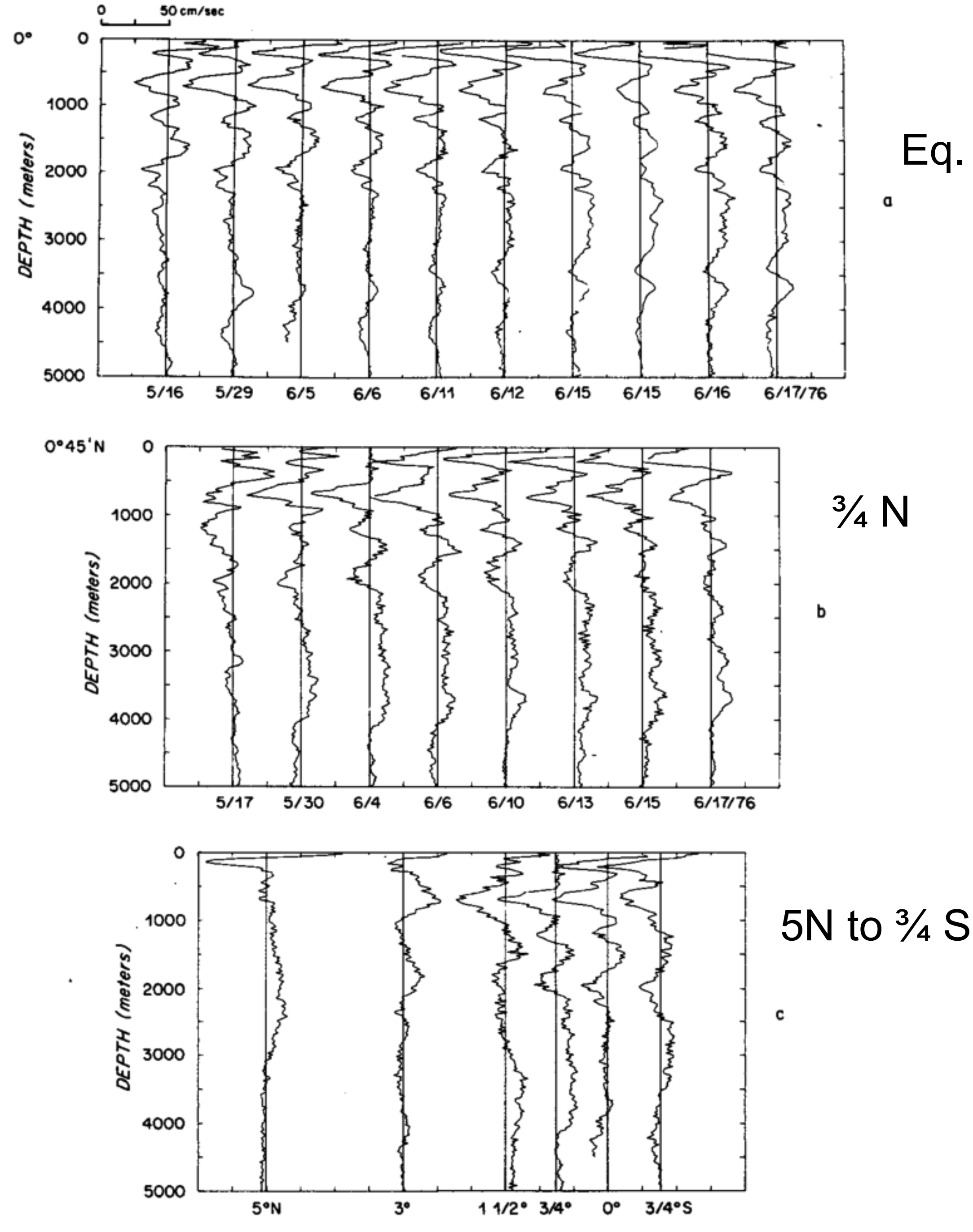


FIG. 1. (a) Time series of zonal velocity profiles from 0°, 53°E spanning 16 May–17 June 1976; (b) time series of same from 0°45'N, 53°E spanning 17 May–17 June; (c) latitudinal section of zonal velocity from a transect along 53°E from 0°45'S to 5°N.

1979: More profiles in the western IO

Mentioned by Luyten, Fieux, and Gonella (1980)

Analyzed by Ponte and Luyten (1990)

Variation with longitude, two-month interval between sections

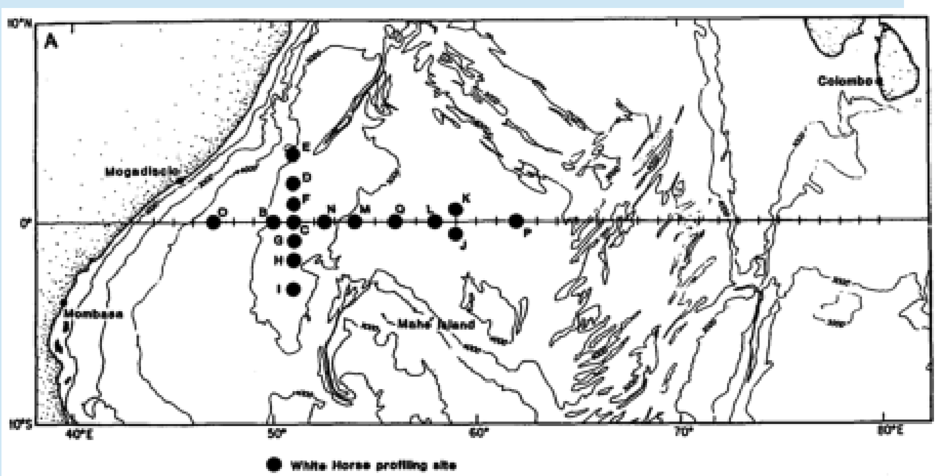


FIG. 1. Location of the sites occupied during INDEX 79, in the western Indian Ocean.

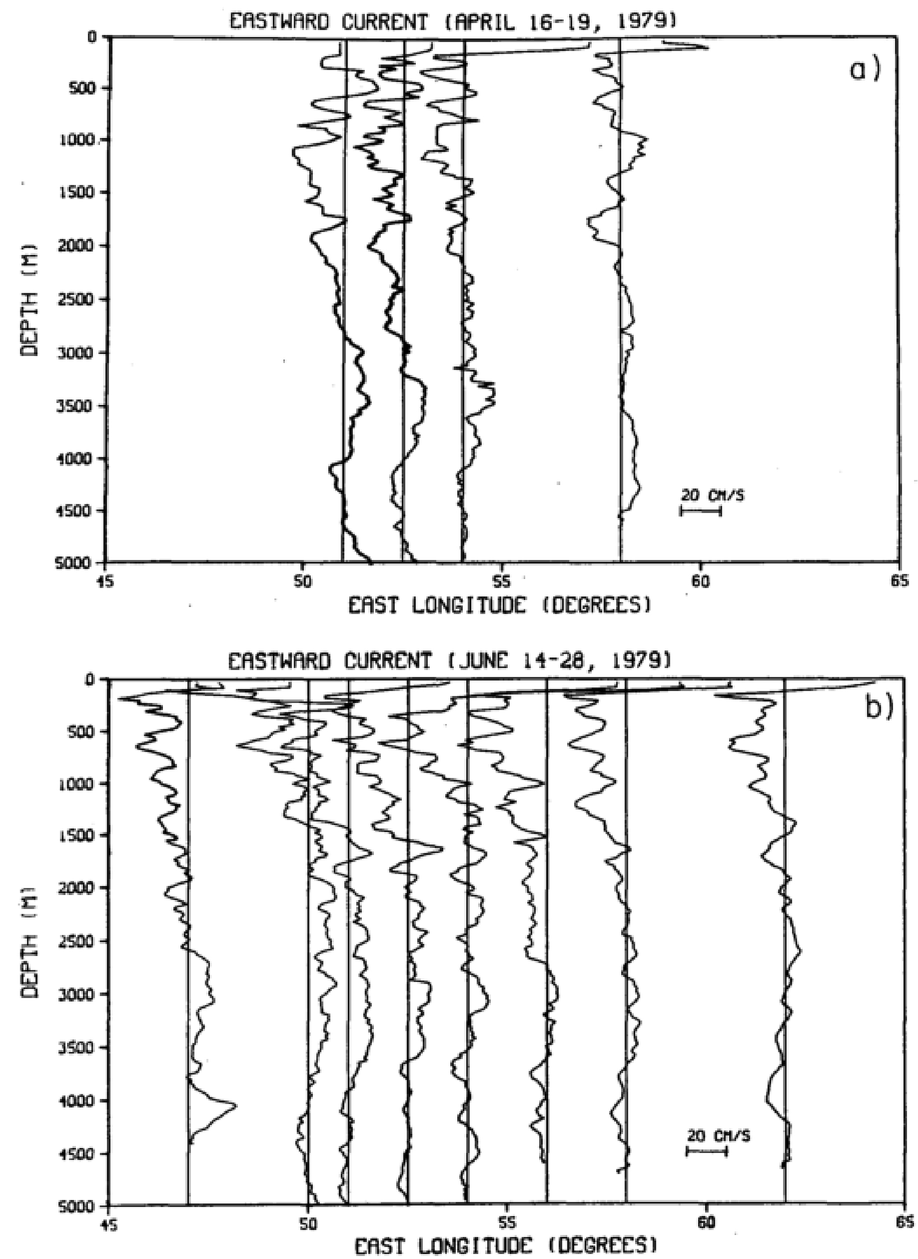
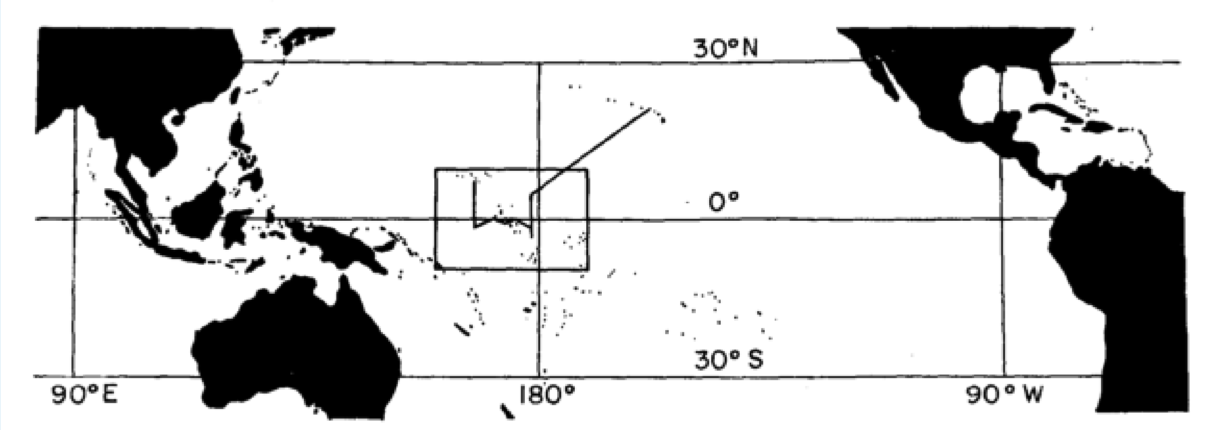
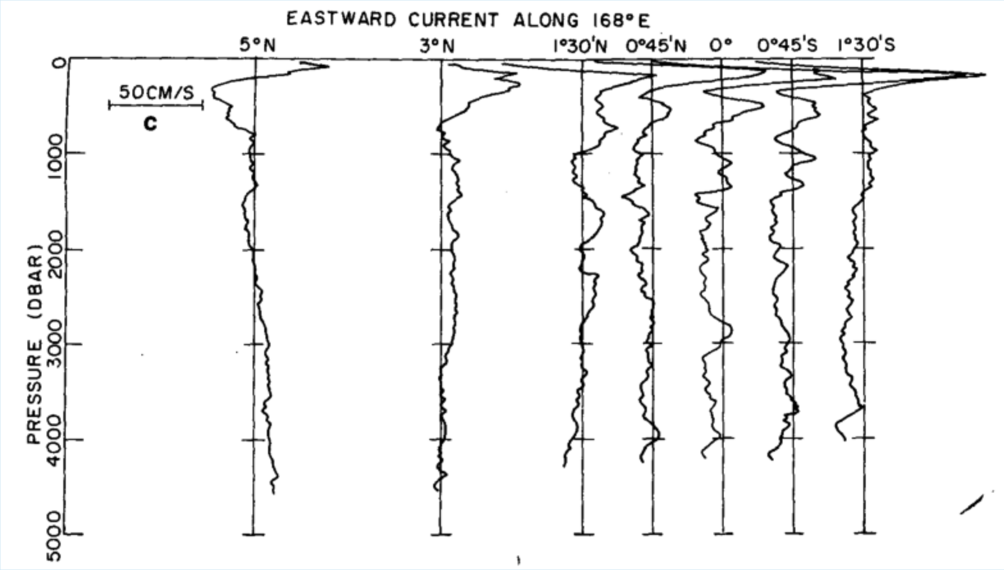


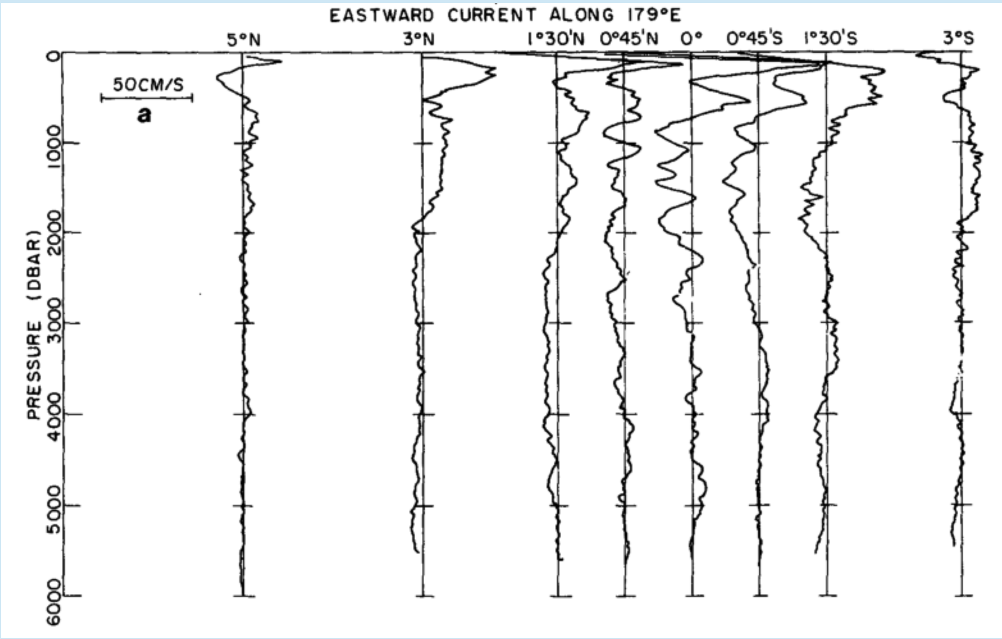
FIG. 2. Zonal velocity along the equator, measured during (a) April 1979 and (b) June 1979.

Meanwhile, in the Western Pacific...

1978, 25 profiles
168°E and 175°E
Sparse latitude sampling
Eriksen (1981)







And in the Eastern Pacific...

1979
4 profiles at 110°W, Equator
Hayes and Milburn (1980)

V U

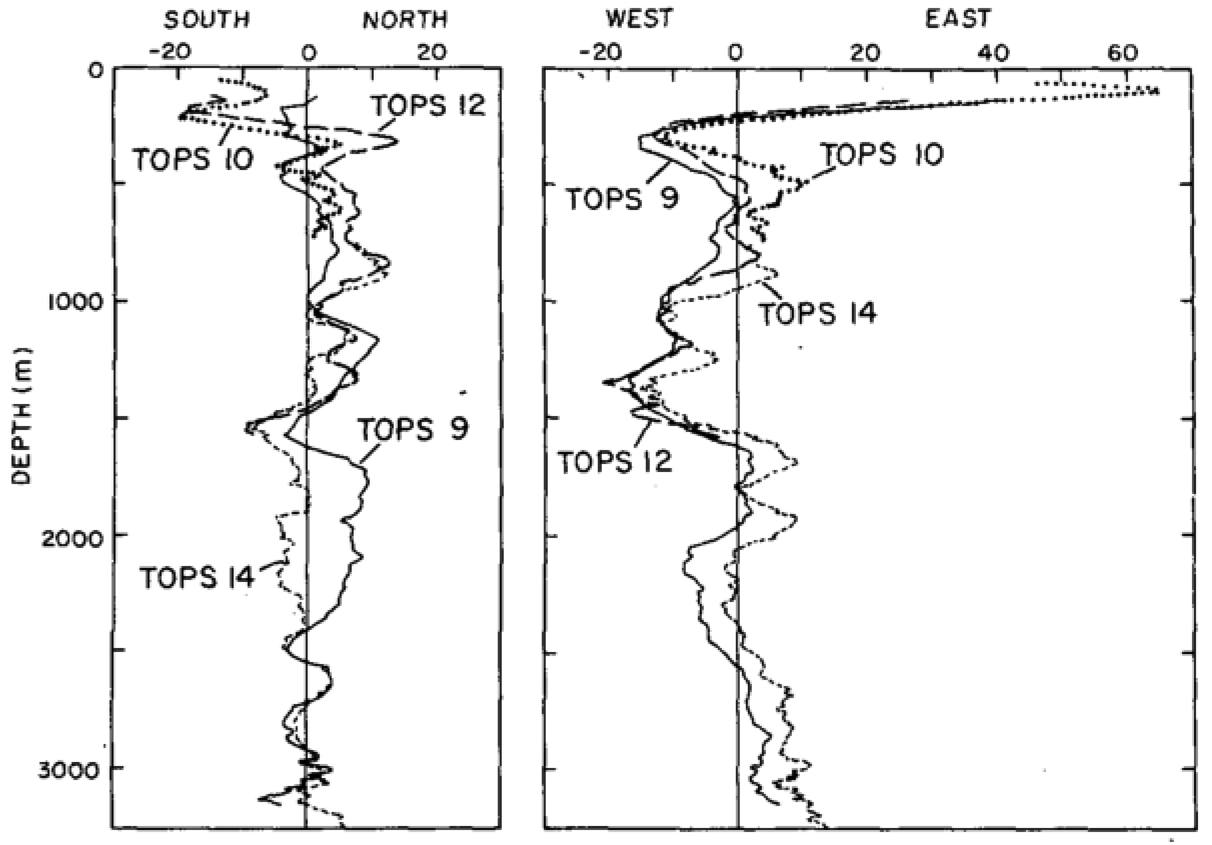


FIG. 1. Four vertical profiles of horizontal velocity at 0°2.5′N, 109°58′W collected over a 27 h period. Total water depth was 3800 m.

Eastern and Central Pacific, a transect along the Equator

7 profiles in 1980
159°W to 125°W
Leetmaa and Spain (1981)

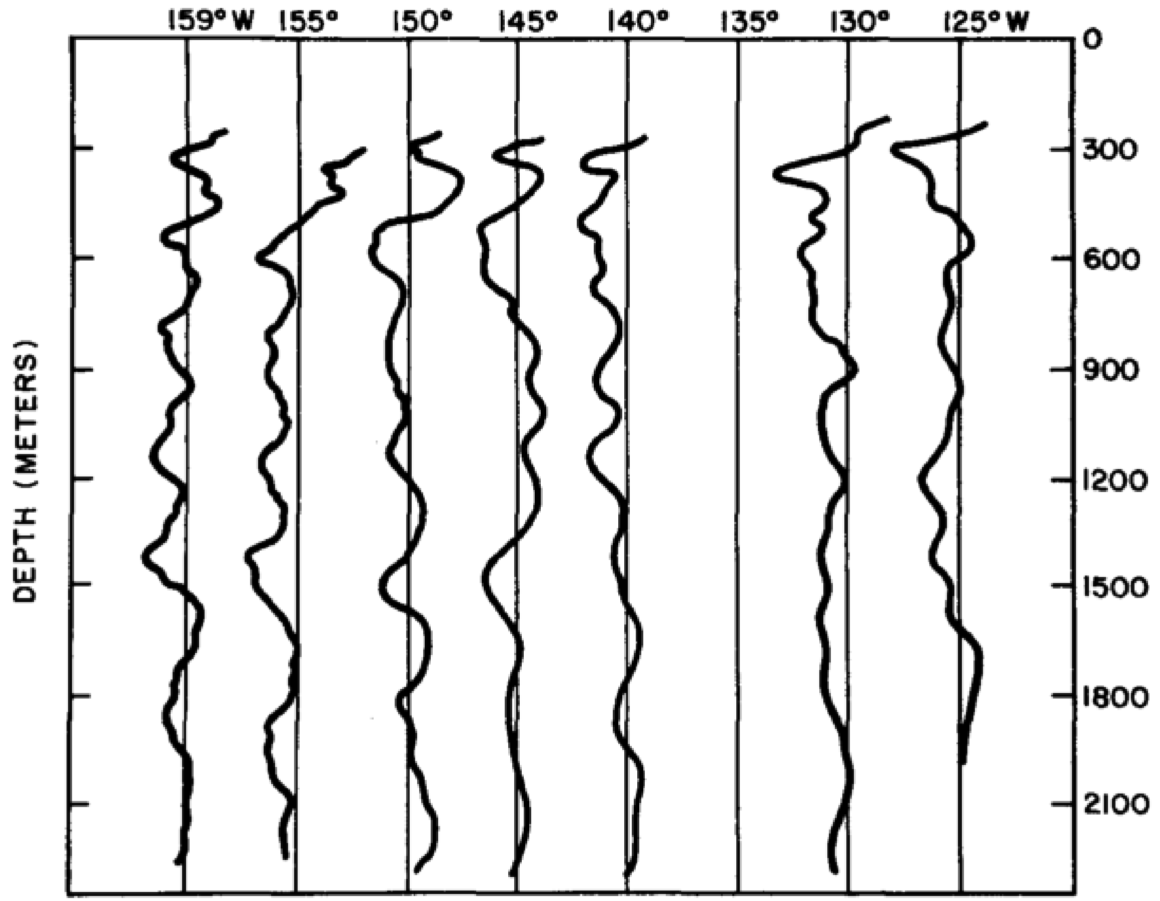


FIG. 4. Zonal velocity profiles between 159 and 125°W. The velocity scale is 50 cm s^{-1} between 5° of longitude, i.e., between vertical lines. Velocities in the top 200 m were omitted because of the large values in the undercurrent.

Central Pacific: a 16-month time series

21 cruises, 41 sections
3°S to 3°N, every 0.5°
Complicated by 82-83 El Nino

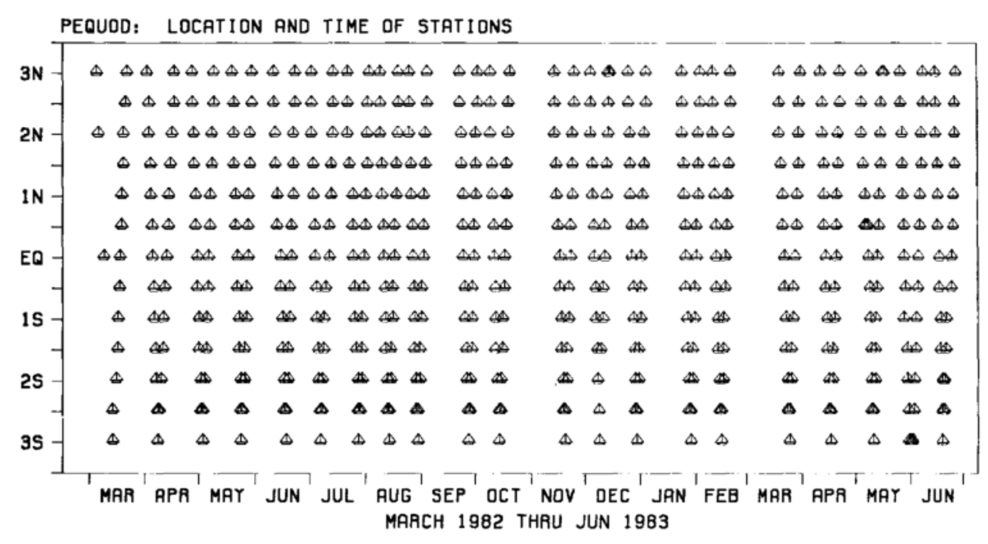


Figure 2. Pegasus current profile times and latitudes.

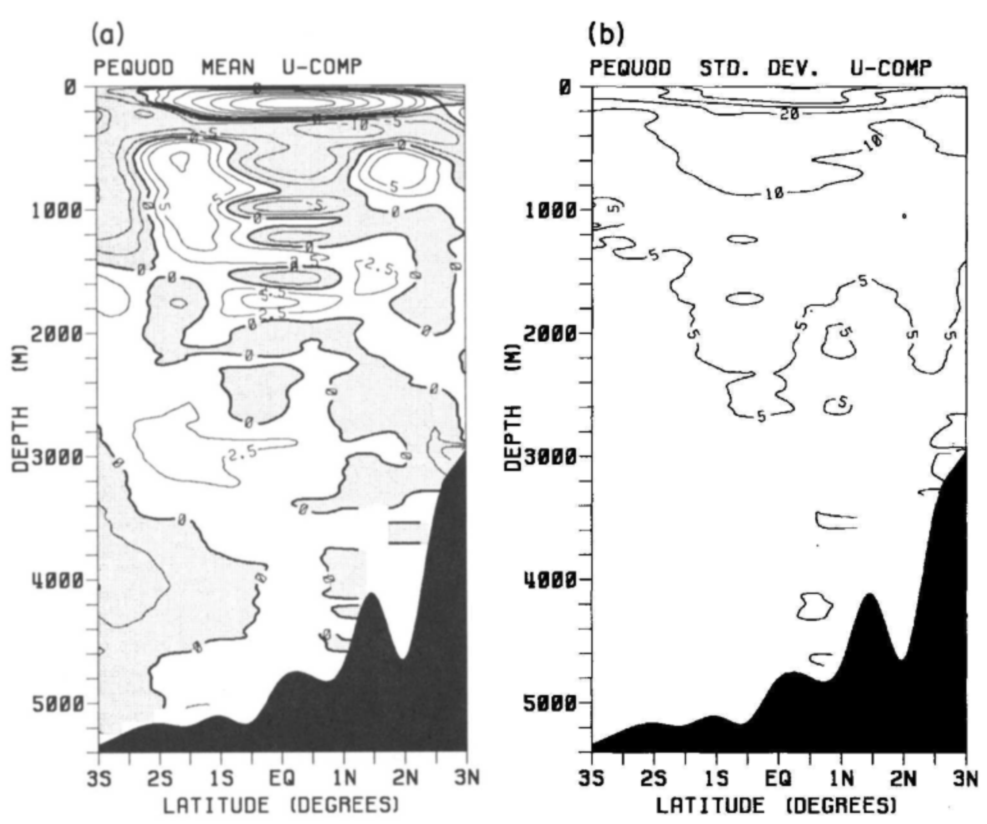
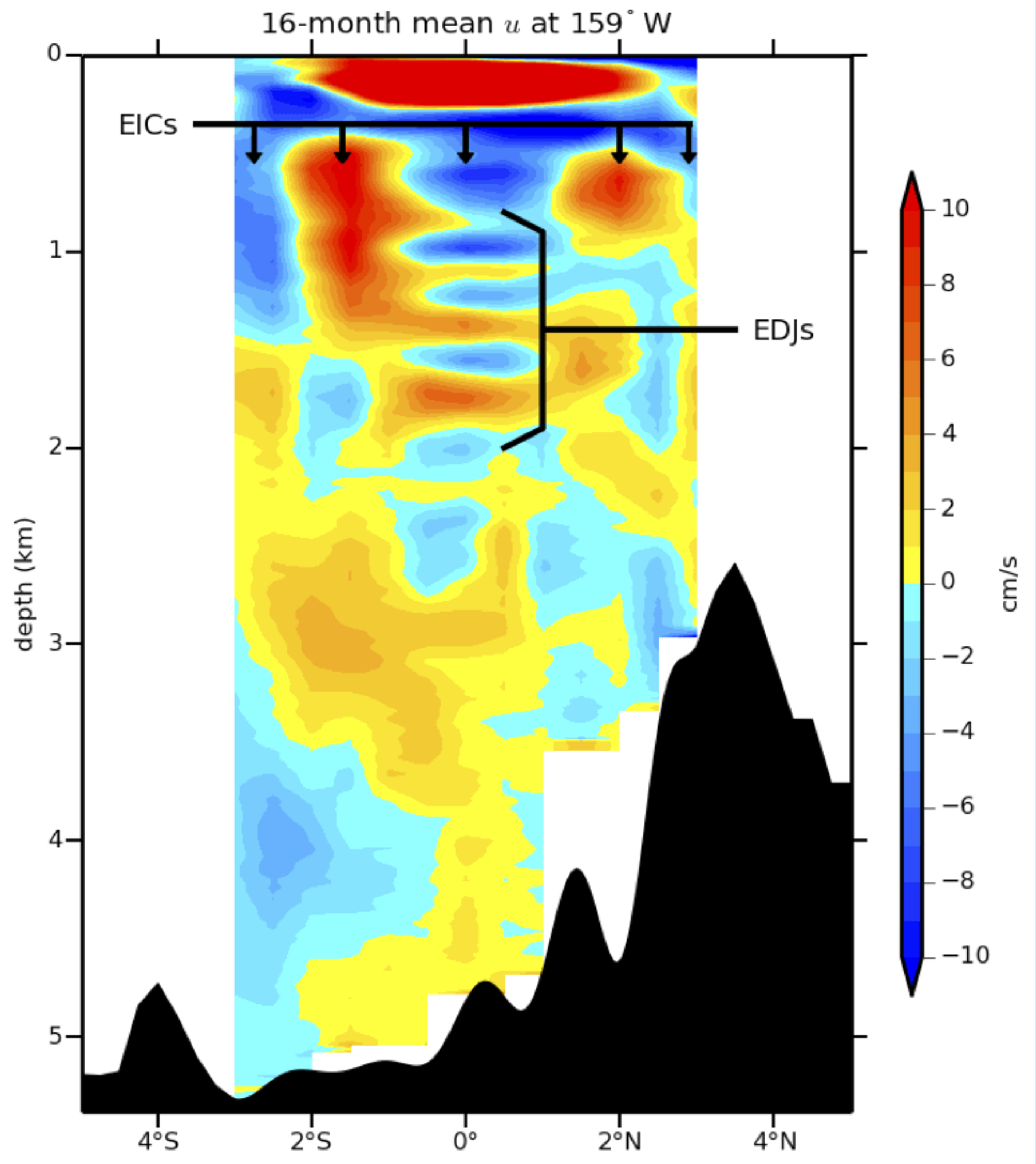


Figure 3. Average (a) and standard deviation (b) of the zonal current component during the 16 months of observations. Contours are on integral multiples of 10 cm/s, and there are additional contours at ±2.5 and ±5 cm/s. Westward flow is shaded.

Described by Firing (1987, 1989)
Lack of unambiguous EDJ vertical propagation.
Directed attention to the off-equatorial currents with larger vertical scale.


16-month mean u at 159˚ W
EICs
EDJs
depth (km)
0
1
2
3
4
5
4°S
2°S
0°
2°N
4°N
10
8
6
4
2
0
−2
−4
−6
−8
−10
cm/s

Atlantic: observations lagged

Eriksen (1982) inferred the existence of EDJ structure from sparse CTD data (GEOSECS program).

Ponte, Luyten, Richardson (1990) reported EDJ structure from a single Equatorial velocity profile.

What we knew in 1990 from observations:

- Small vertical scale zonal flows (“Equatorial Deep Jets” or EDJs) are found in Indian, Pacific, Atlantic
- Central Pacific: Larger vertical scale zonal flows alternate with latitude (“Equatorial Intermediate Currents” or EICs)
- Central Pacific: EDJs and EICs persist over 16 months
- EDJ zonal scale: at least 10° in central Pacific

Notice how much we *didn't* know.

Theory in 1990:

- Mainly focused on EDJ
- Based on linear equatorial wave dynamics
  - Kelvin wave, speed c_n to the east
  - Long Rossby wave, speed <= $c_n/3$ to the west
  - Low frequency → energy propagation is nearly horizontal

What makes the waves?

Direct periodic wind forcing?

- Wunsch (1977)
- McCreary (1984)
- McCreary and Lukas (1986)

Thermohaline forcing?

- Kawase (1987)
- Ponte (1989)

Direct periodic wind forcing?

- Wunsch (1977)
- McCreary (1984)
- McCreary and Lukas (1986)

No good:
very low (but unknown) frequency of EDJ
→ very shallow ray angles,
→ too many boundary reflections
→ too much dissipation

Gent and Luyten (1985) overstated the importance of energy reflection by thermocline?
See Rothstein, Moore, McCreary (1985)

Thermohaline forcing?

- Kawase (1987) fundamentals in reduced gravity model
- Ponte (1989) specific to EDJ generation

Questionable: would require very small vertical scales in WBC.

Theory in 1990:

What about the EICs?

The relevant section from our proposal:

> 2.2.2 Deep extra-equatorial currents
>
> The situation is simple: there are no models, analytic or numerical, of the deep extra-equatorial currents.

Lien's plunge into the equatorial depths:

NSF proposal with Lien, Dennis Moore, and me (UH), and Lew Rothstein (URI), in 1990

Hypotheses:

- Thermohaline, driven from the western boundary
- *Indirectly* wind-driven via nonlinear interaction of high-frequency motions excited by the wind or by instabilities of the mean wind-driven currents

Lien's first approach: inertial instability

Presented in Hua, Moore, and Le Gentil (1997)

Initial value problem
2-D, latitude-depth
Detailed analytic treatment, Couette flow context

High-res nonlinear, nonhydrostatic numerical solution

Subsequent work by Lien et al. on EDJ, EICs:

- 3-D

- Unstable mixed Rossby-gravity (MRG) waves and short Rossby waves from the western boundary.

d'Orgeville, Hua, and Sasaki (2007)

Hua, d'Orgeville, Fruman, Menesguen, Schopp, Klein, Sasaki (2008)

Menesguen, Hua, Fruman, and Schopp (2009): simultaneous generation of EDJ and EICs in a numerical model.

What have we learned from observations since 1990?

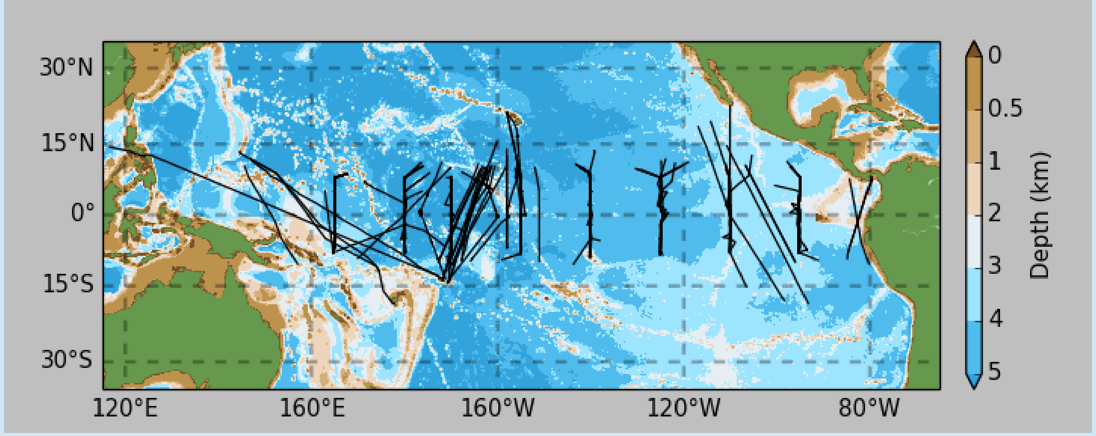
EICs are basin-scale in Atlantic and Pacific.

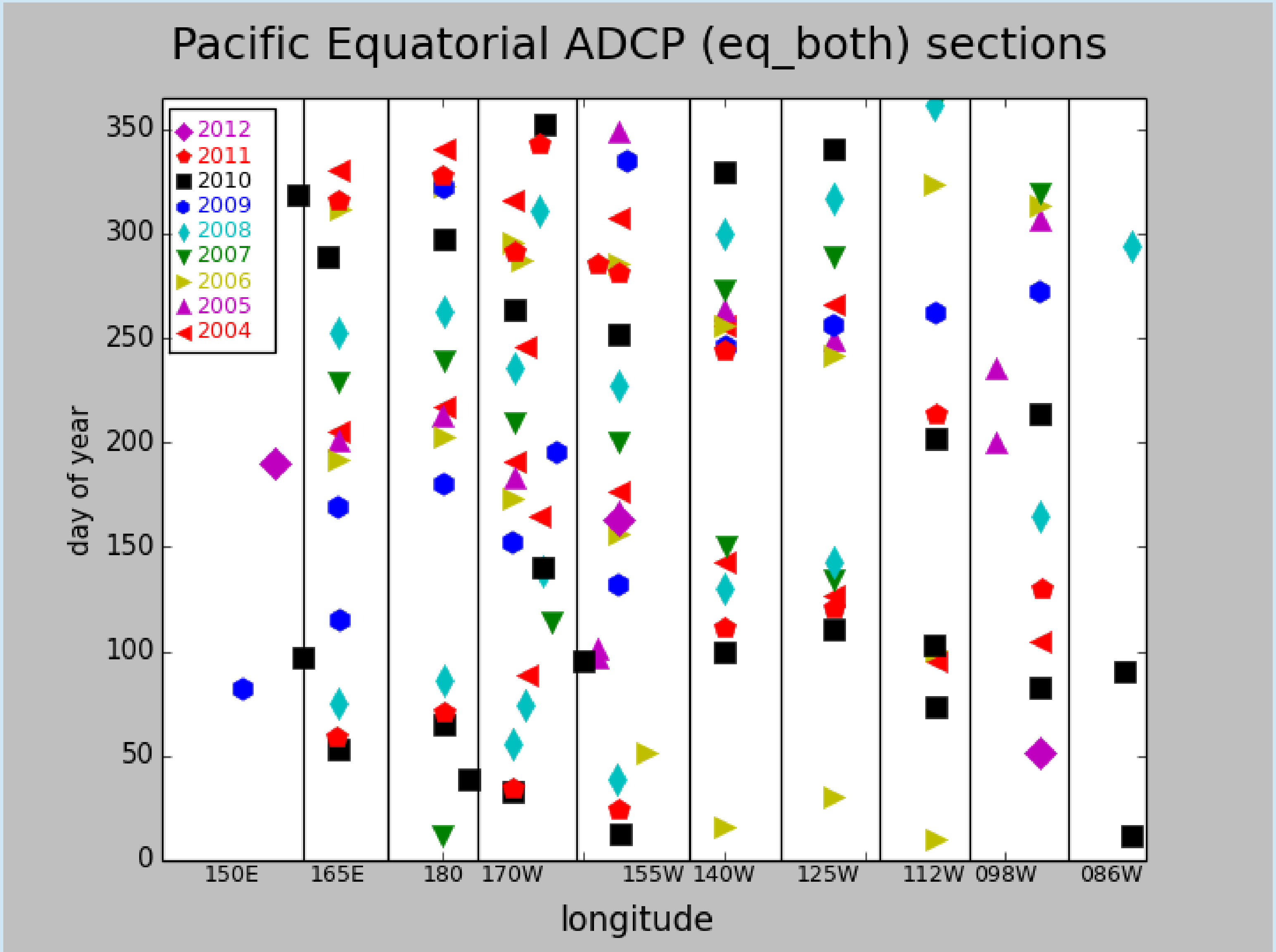
EIC-like alternating structure extends poleward 10° or more.

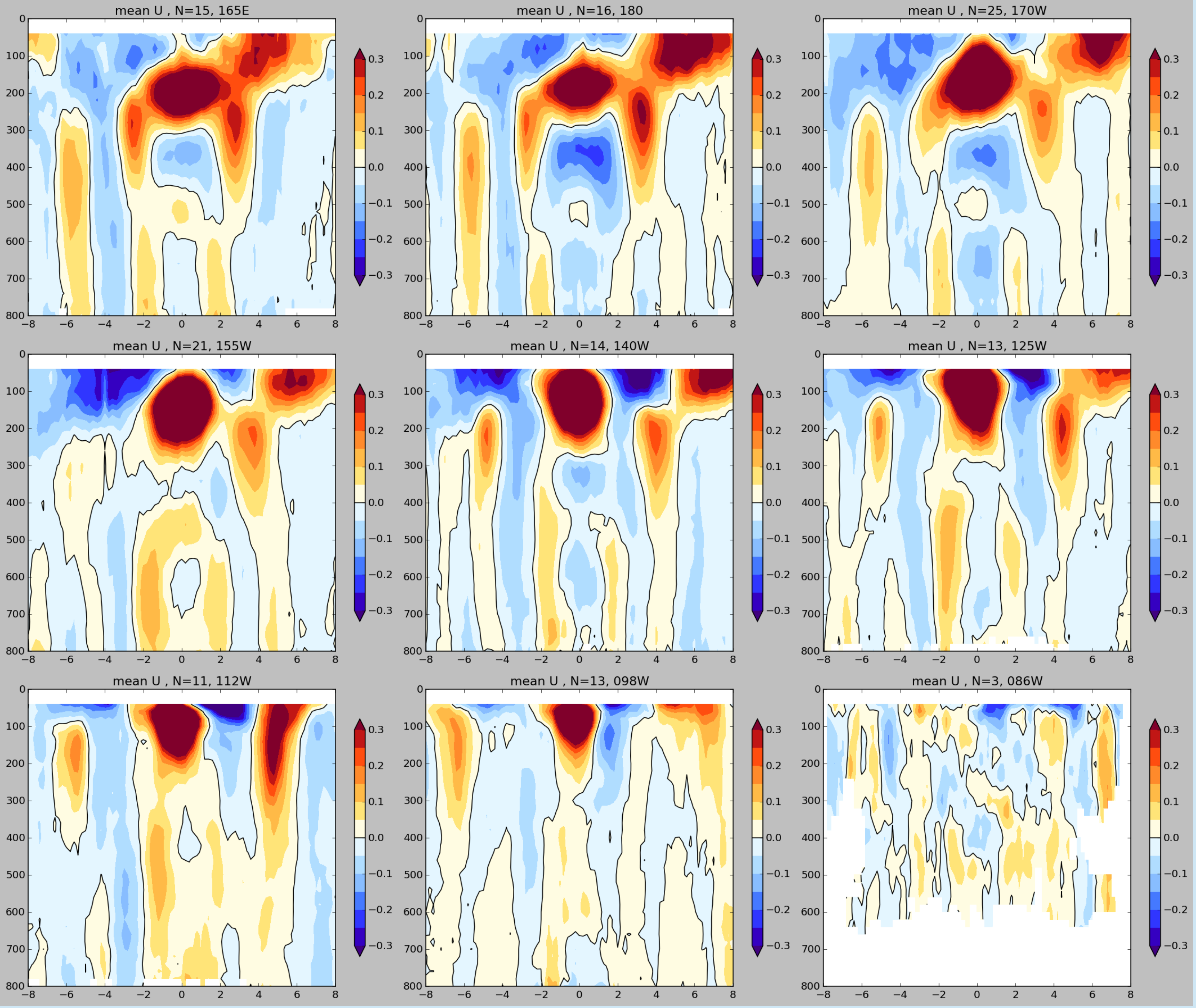
EDJs propagate phase downward in Atlantic (4.5-year period), probably also in the Pacific, but much slower (30-year period?).

The Indian Ocean is *very* different; but observations are few.

Shipboard ADCP
75 kHz, 38 kHz
2004-2012







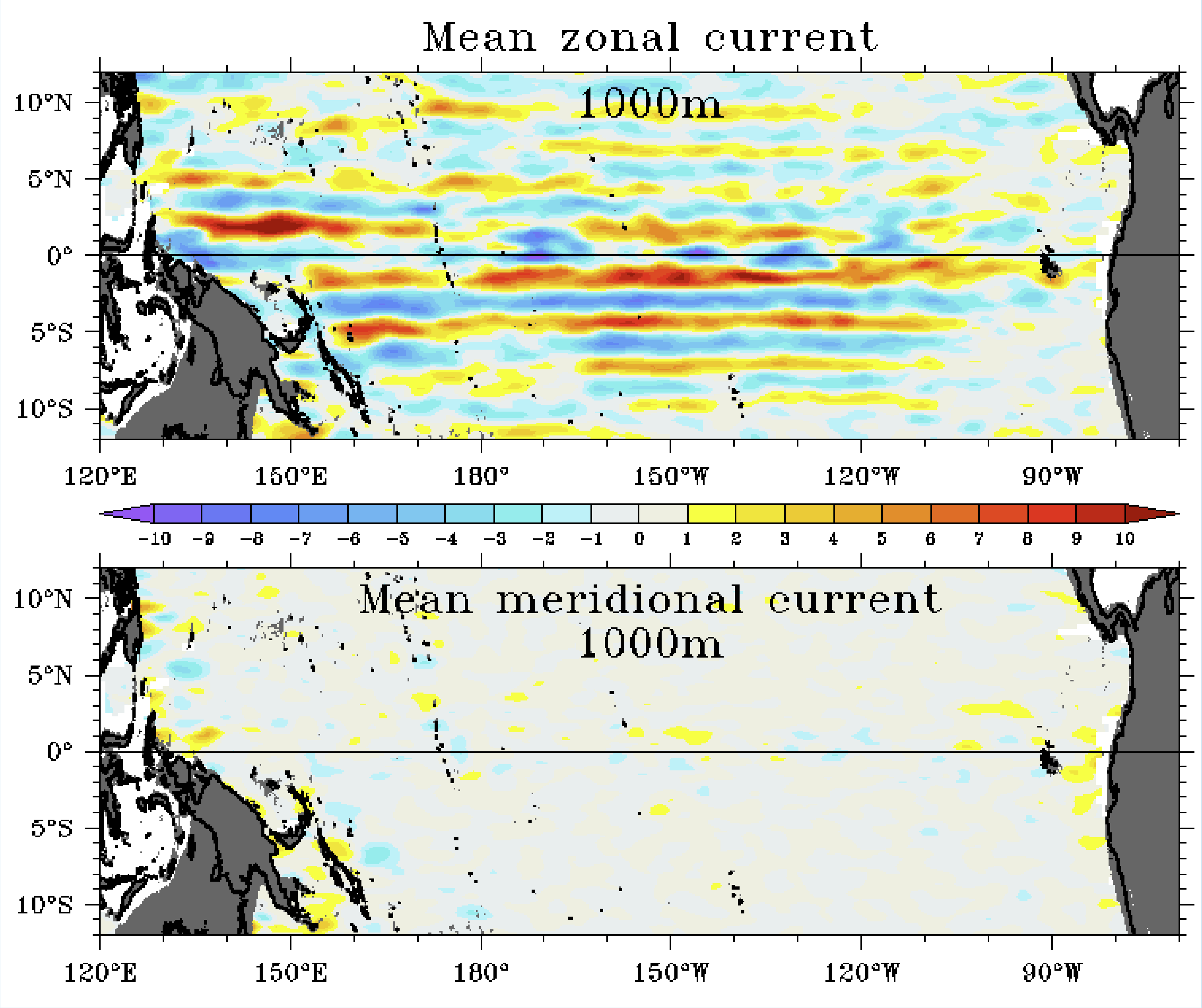
EICs:

Rise W-E

Die out E of about 110°W

Shipboard ADCP, 75 kHz and 38 kHz, last decade

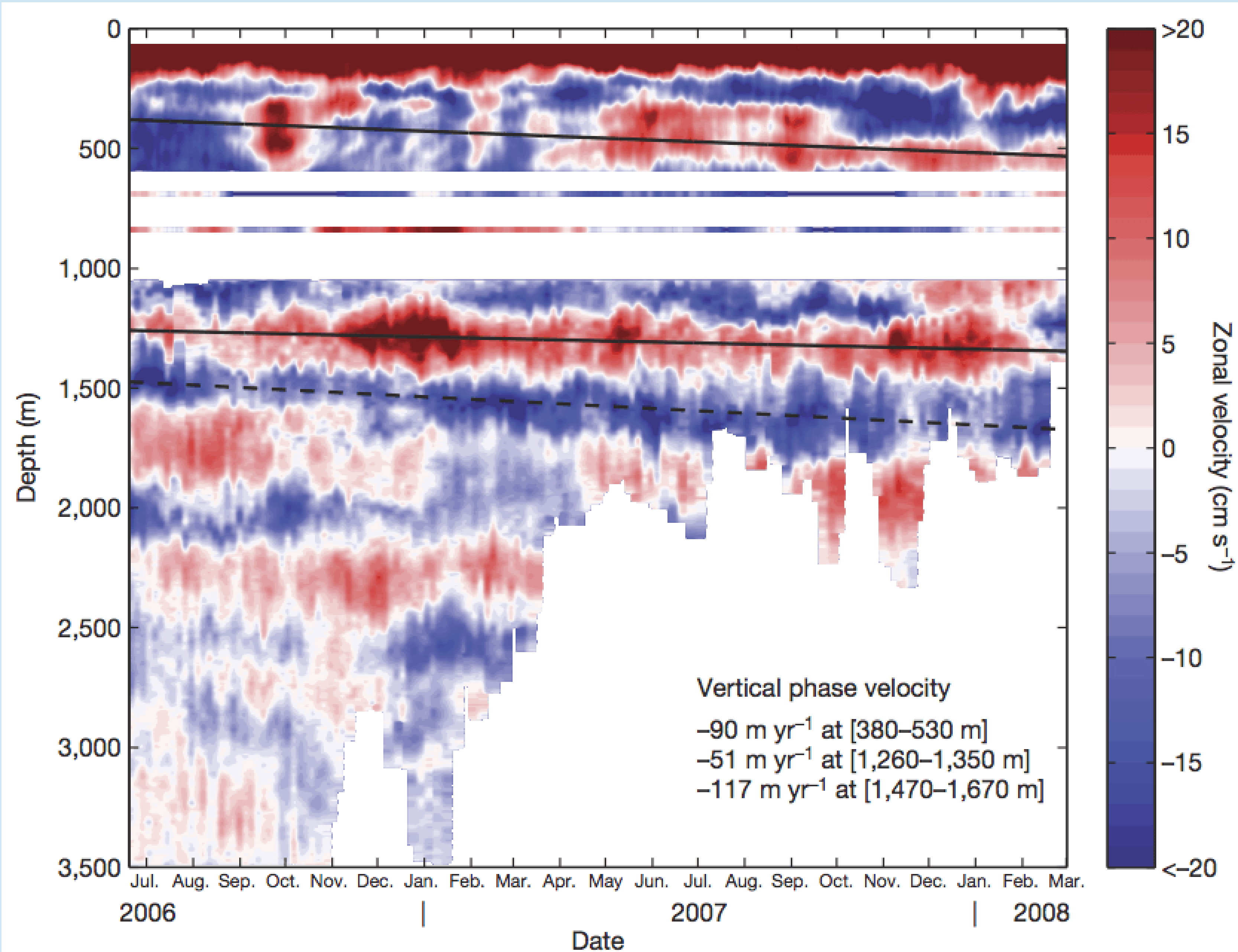
Global view: ARGO drift velocities



Cravatte, Kessler, Marin (2014)

Atlantic, 23°W
Moored profiler

Brandt et al., 2011



Indian Ocean:

ARGO: “no coherent zonal features” (Cravatte et al., 2014; also Brandt et al., 2011)

WOCE LADCP sections:

- Small scales on Equator have much shorter time scales than in Atlantic and Pacific
- No indication of mean EIC-type structure

Poor sampling compared to Atlantic and Pacific; dominant annual and semiannual variability.

Theory and modeling: other progress

EICs generated by Yanai beam (Ascani et al., 2010)

EDJ basin modes in a wind-driven model (Ascani et al., to be submitted soon)

In both cases, intra-seasonal variability (ISV) is central.

Emphasis:

- balance in quasi-steady state
- ISV from instability of wind-driven upper ocean mean circulation

Yanai (MRG) beam

- From Tropical Instability Waves
- Dissipation modifies PV: essential for zonal flow west of the beam

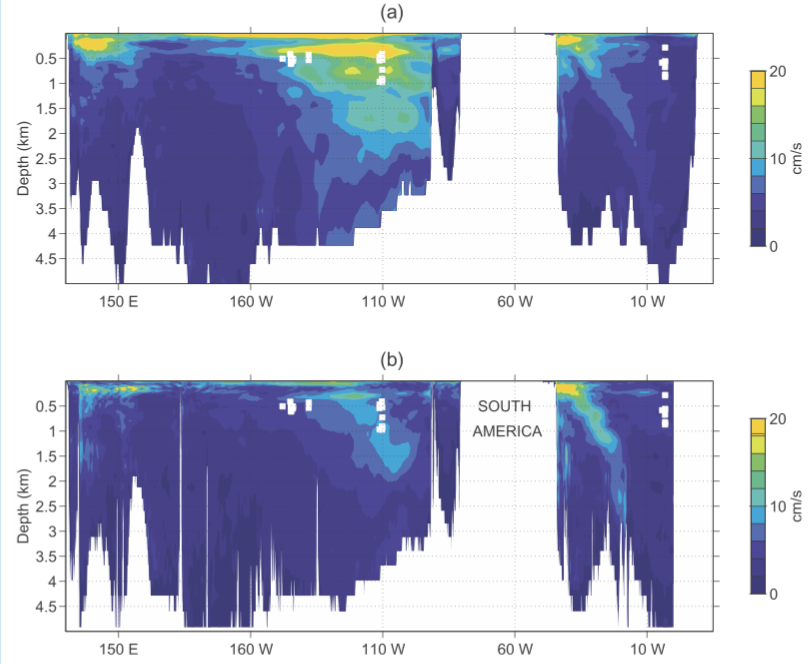
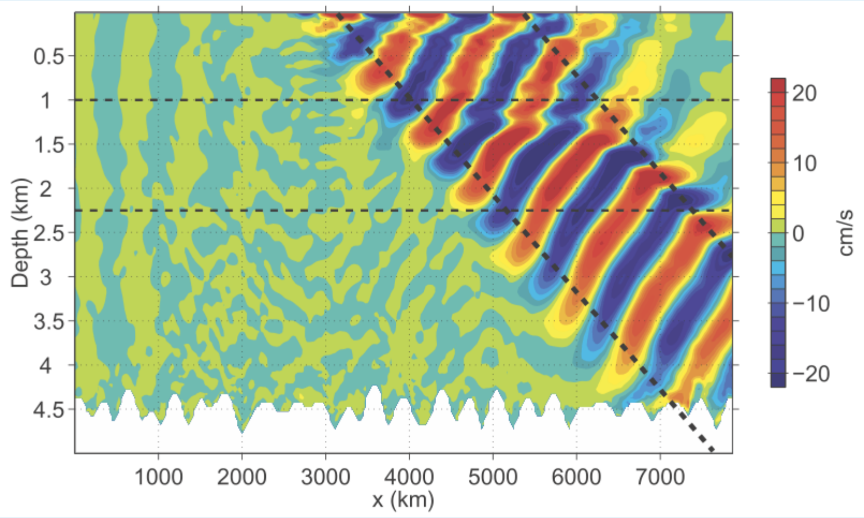
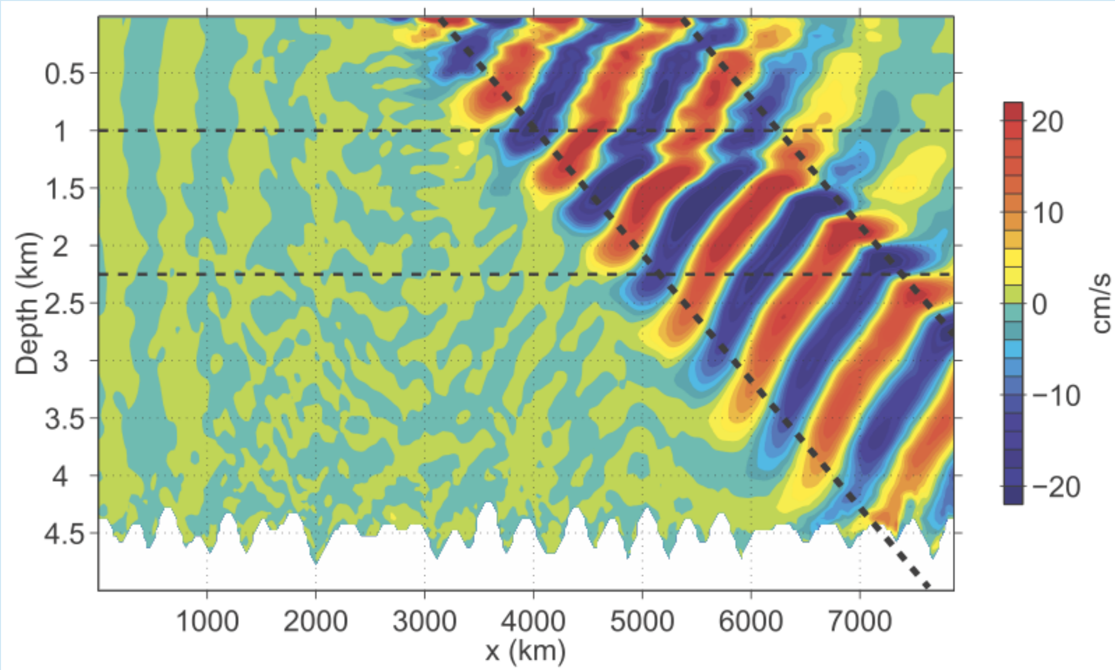
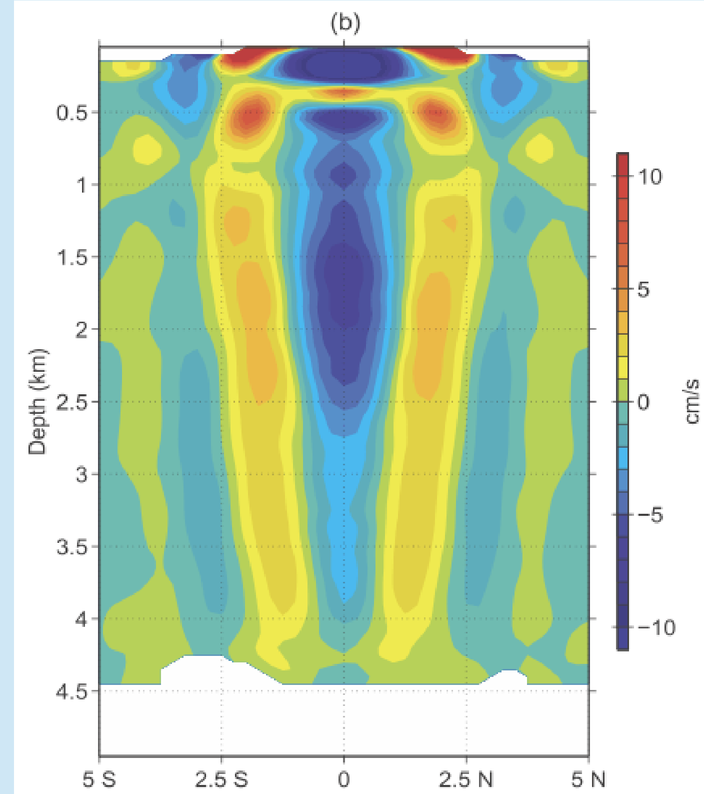
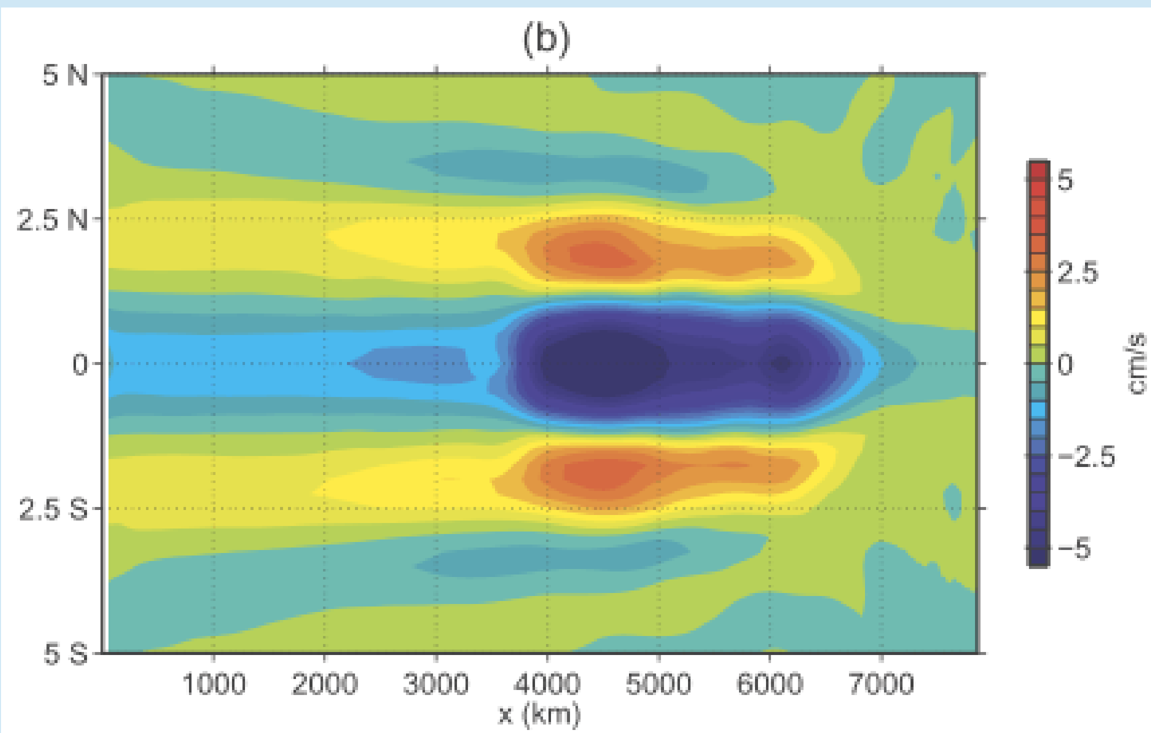


FIG. 5. Standard deviation (STD) of equatorial v in (a) the I98 model during years 20–22 and (b) OFES during year 46. White squares show the location of the moorings used in Fig. 4.









Idealized numerical model

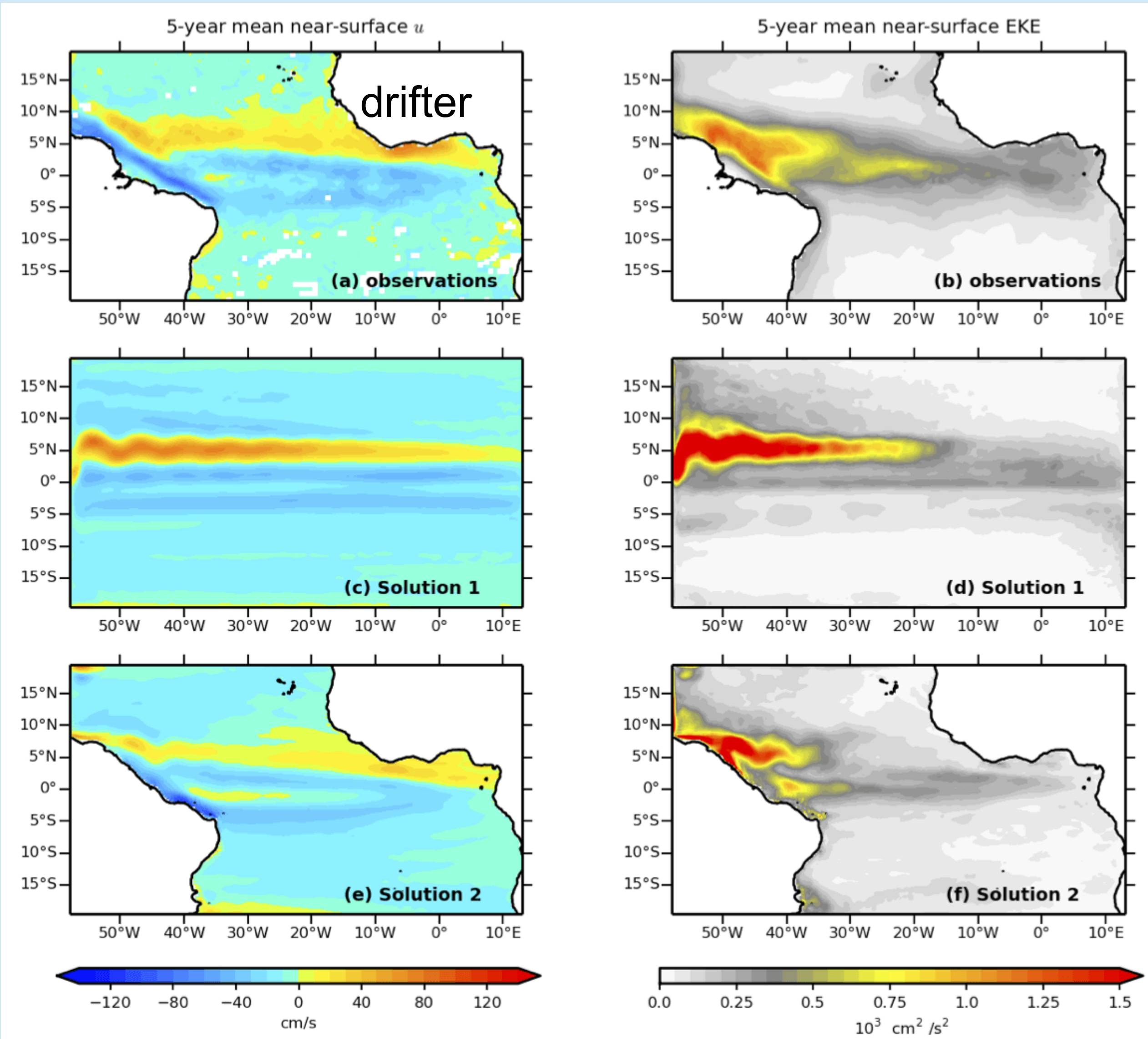
Yanai beam generated directly by surface forcing

Ascani et al., 2010

Idealized wind-driven Atlantic with EDJ basin modes and EICs

U

EKE

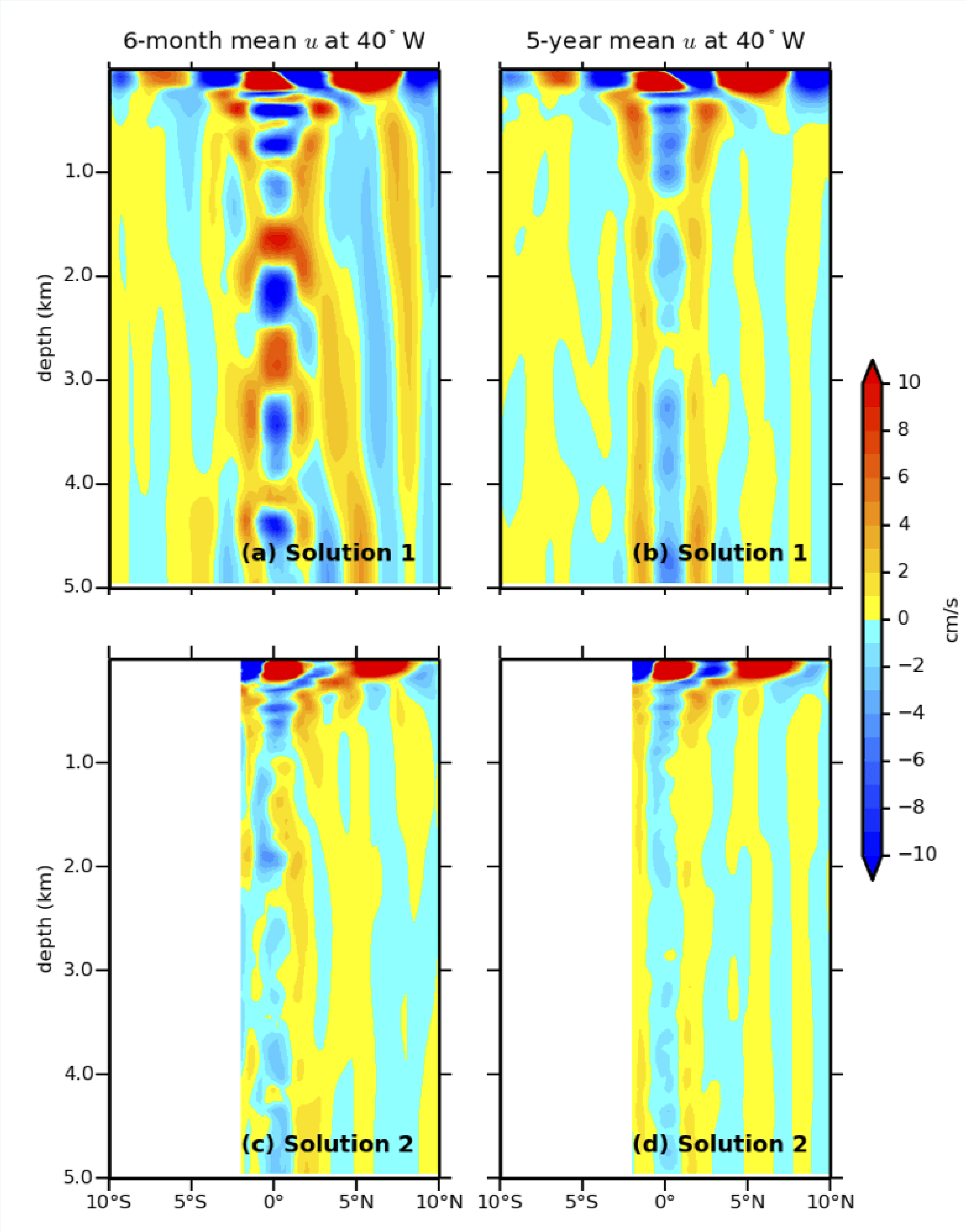


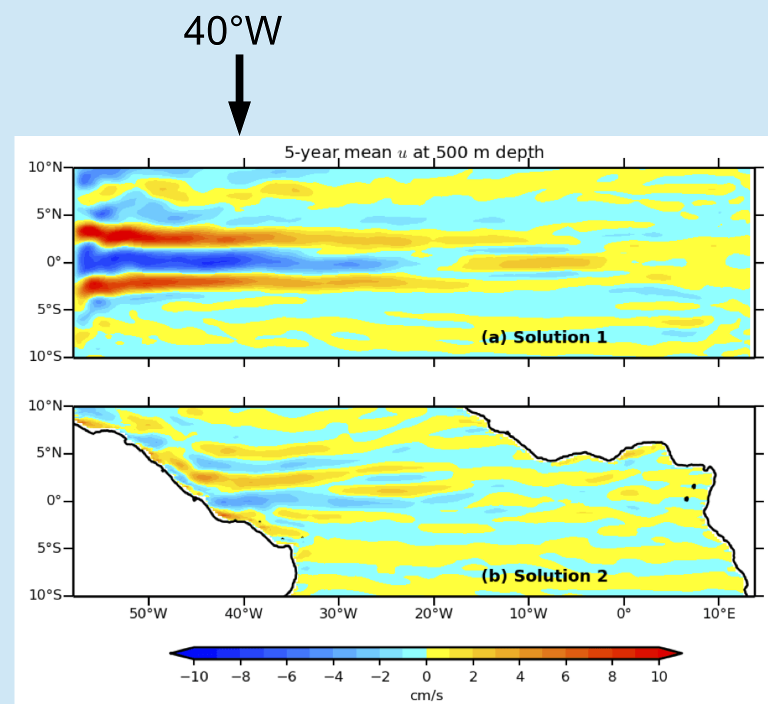
POP model, ¼ degree
100 levels
Biharmonic
PP81, 10^{-5} m^2s^{-1}

Wind: uniform in time and longitude

Wind: varying in longitude, mean annual cycle

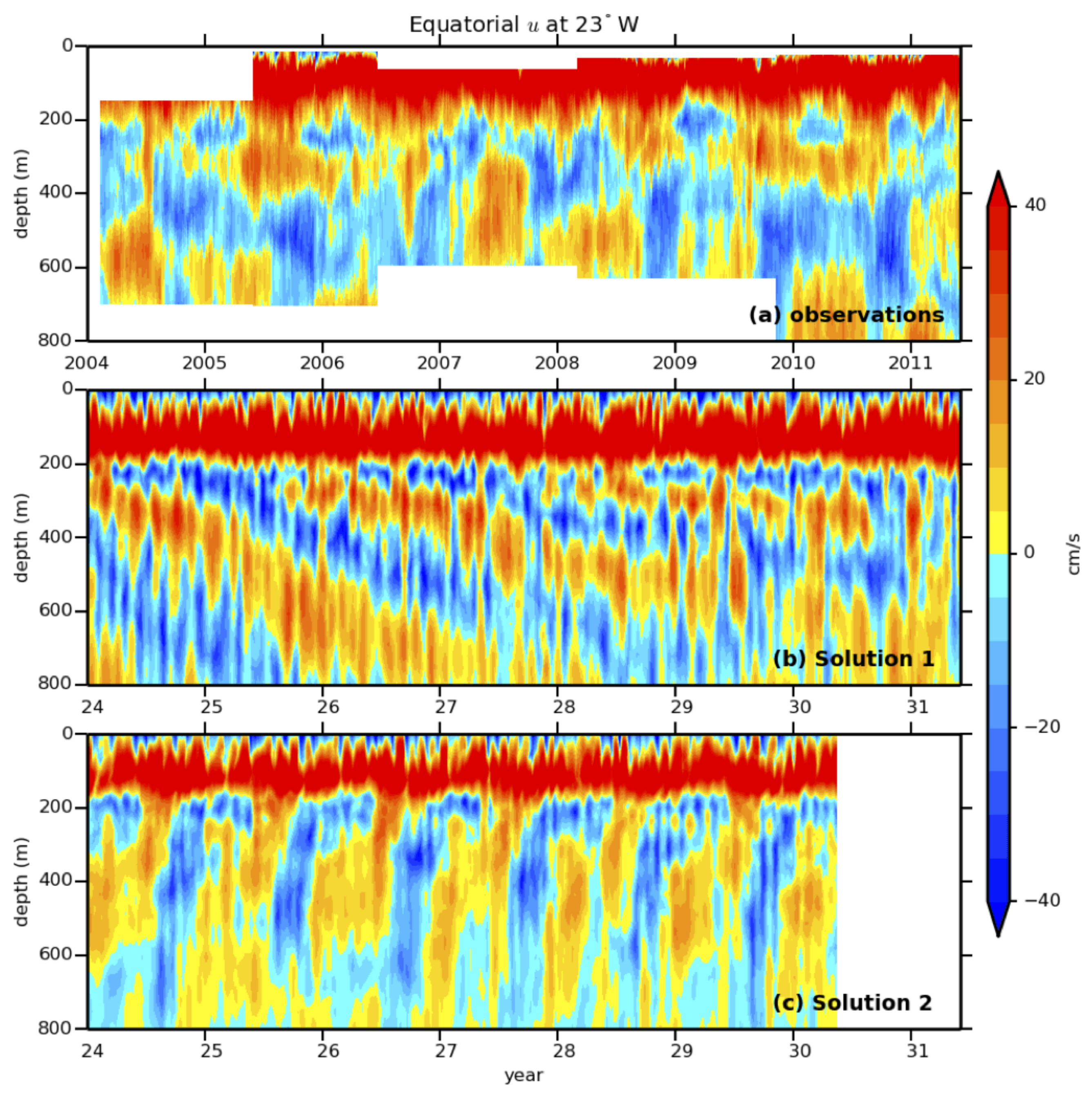
Ascani, Firing, McCreary, Brandt, and Greatbatch (2014)





Ascani et al. (2014)

Vertical propagation?



Observed U at 23°W
Brandt et al. (2011)

Model:
Rectangular basin
Steady winds

Model:
Atlantic coastlines
Annual cycle of wind

Ascani et al. (2014)

Observations compared to OGCMs: 2 examples

Observations:
16-month
Average

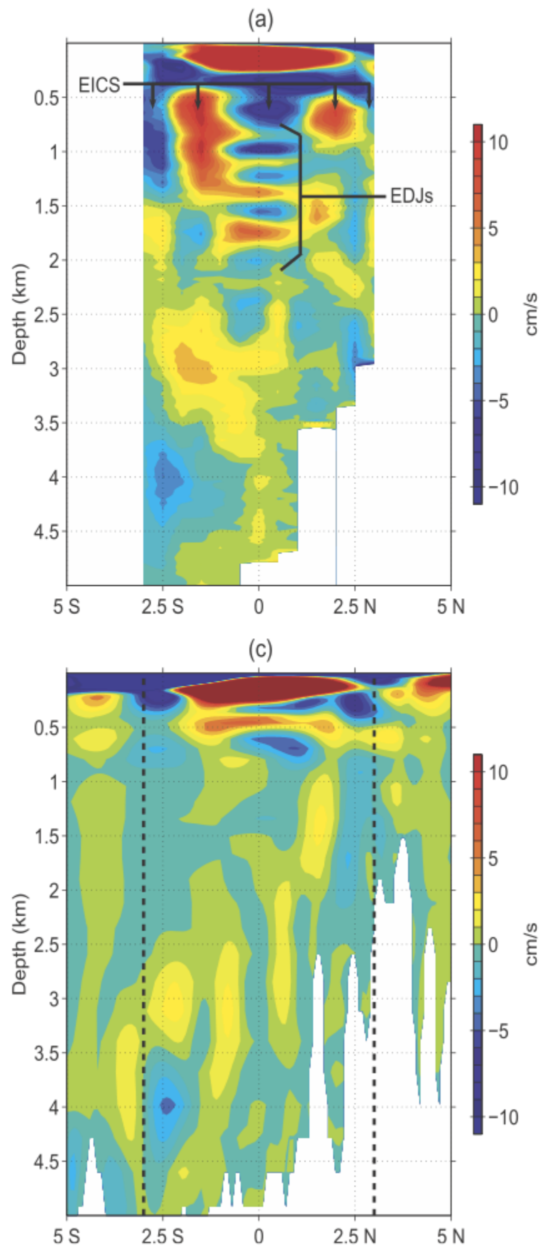


FIG. 1. Mean zonal velocity u at 159°W from (a) observations taken during the Line Island Profiling Project (LIPP; Firing 1987), (b) years 20–22 of the I98 model, and (c) years 41–51 of the OFES model. The two runs are forced by climatological winds. The I98 model has 1/4° resolution in the horizontal and 55 levels, whereas OFES has 1/10° resolution in the horizontal and 54 levels. Details of the runs can be found in I98 for their model and Masumoto et al. (2004) for OFES.

Model:
1/4°
55 levels
Hellerman & Rosenstein winds

OFES model:
1/10th°
54 levels
NCEP/NCAR Reanalysis winds

Ascani et al. 2010

Conclusions and questions:

1) Idealized models show how intra-seasonal variability can drive features resembling EDJs and EICs.

2) We still don't have adequate sampling of intra-seasonal variability or of the mean and low frequencies.

3) OGCMs still do not simulate observations well. Why not?

4) Why do models seem to need to be overdriven?

5) Why is there apparently net upward energy propagation of the EDJs?

6) Why do present simplified models fail to capture the full meridional extent of the system of EICs?

The equatorial subthermocline circulation remains a challenge!