# The response of the surface circulation of the Arabian Sea to monsoonal forcing

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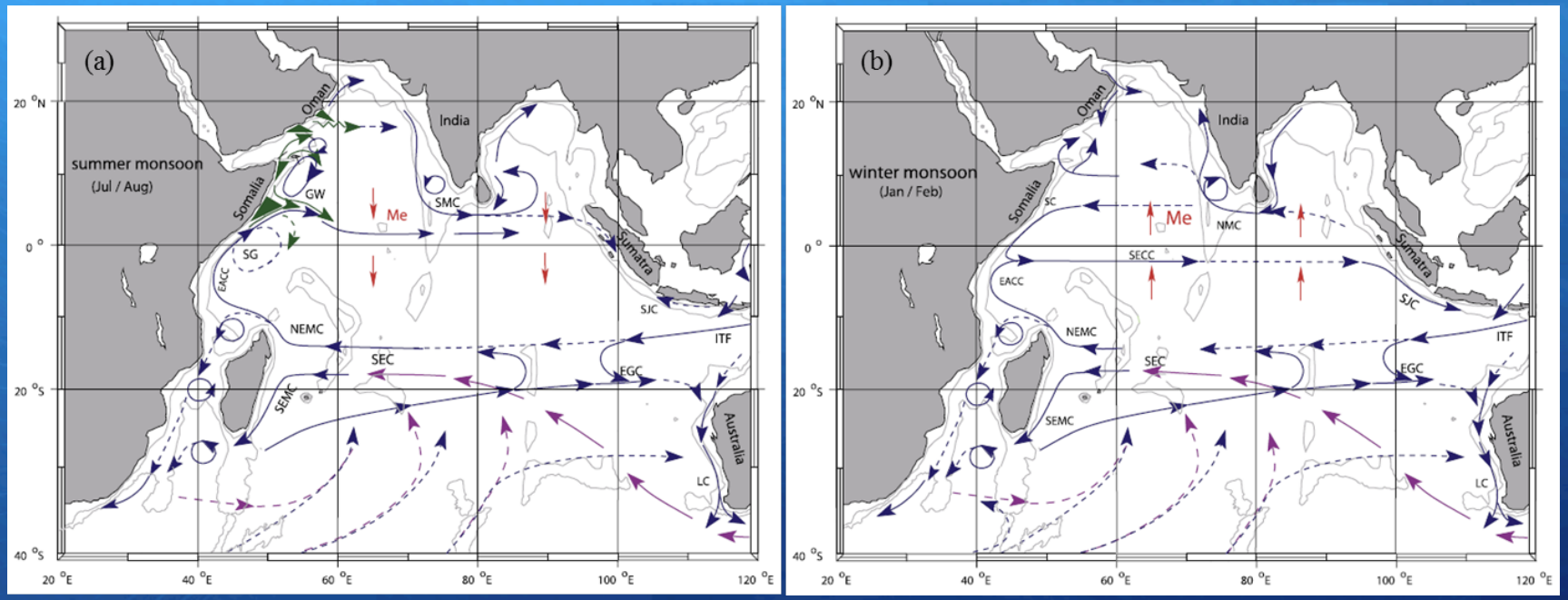
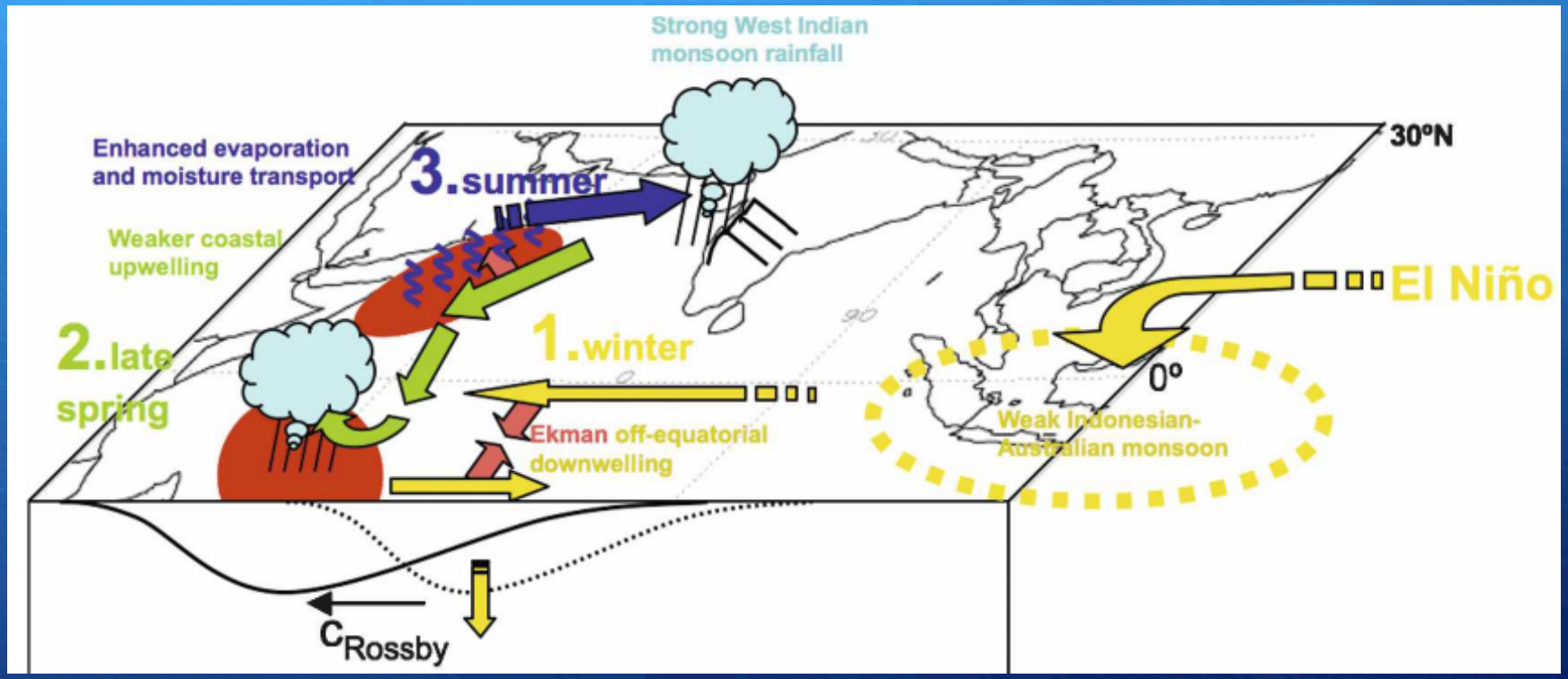
# Monsoon circulation of the Indian Ocean




- Circulation of the Arabian Sea switches direction annually under the influence of strong monsoon winds
- Upwelling wedges associated with eddy structures in the western Arabian Sea connected to changes in the wind field [Vecchi et al., 2004]

Schott et al., 2009

# Indian monsoon rainfall

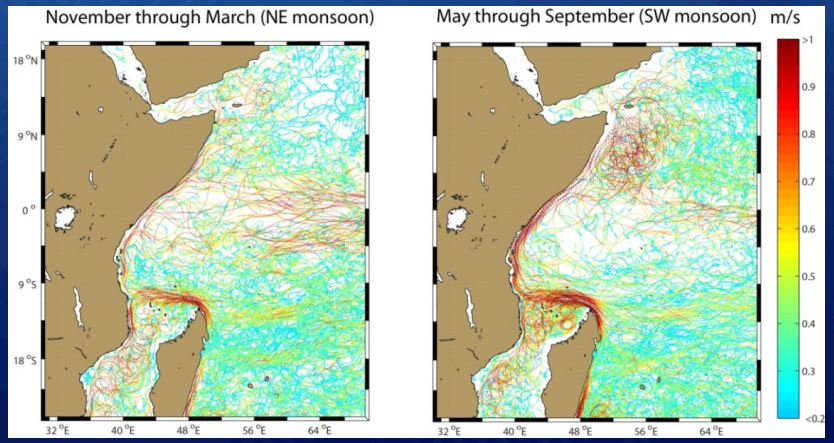



- Horizontal advection, coastal upwelling, wind-driven mixing, and Ekman pumping all affect sea surface temperature (SST) in the Arabian Sea [Lee et al., 2000]
- Beside the winds, SST feeds back on rainfall over India

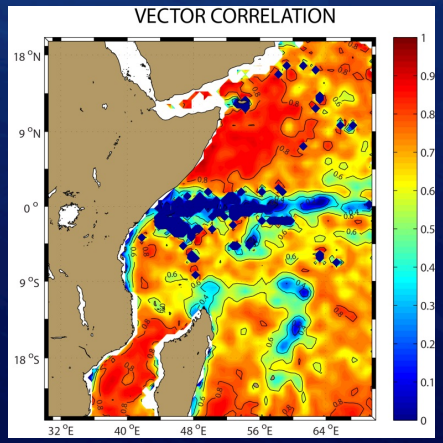
Izumo et al., 2008

# Data

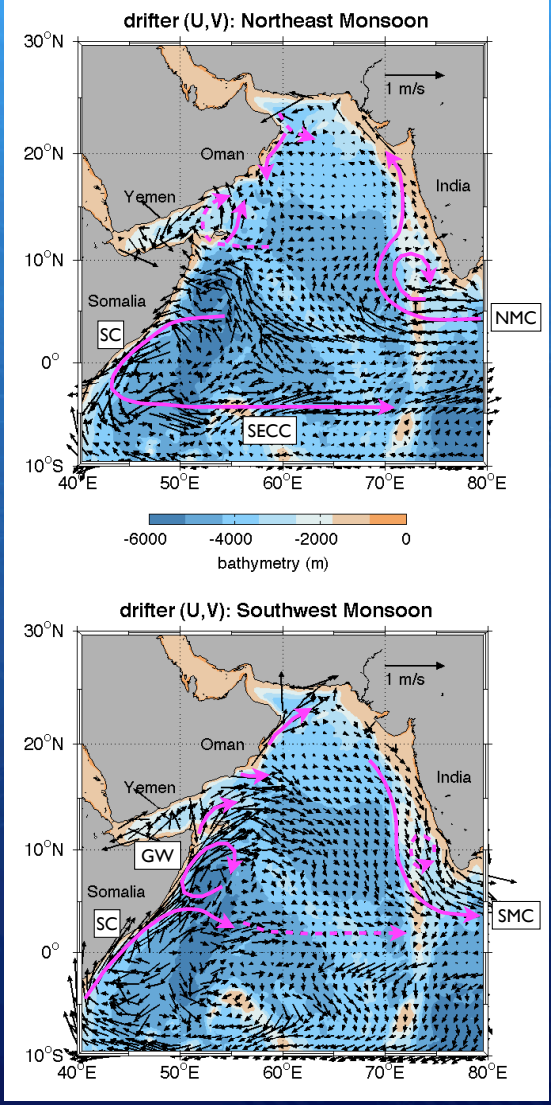
- Large amounts of data required to resolve the evolution of the flow in a region with no steady circulation
  - Monthly-mean scatterometer winds (QuickSCAT)
  - Monthly-mean circulation from a global drifter climatology of absolute near-surface currents [Lumpkin and Jonson, 2013]
  - Weekly maps of geostrophic flow from a drifter-altimeter synthesis [Lumpkin and Garzoli,2011; Hormann et al., 2012]
  - Satellite altimeter data from AVISO [Le Traon et al., 1998]




Drifter array in the western Arabian Sea (left) and correlation with currents from altimetry (right)



# Monsoons as static circulations

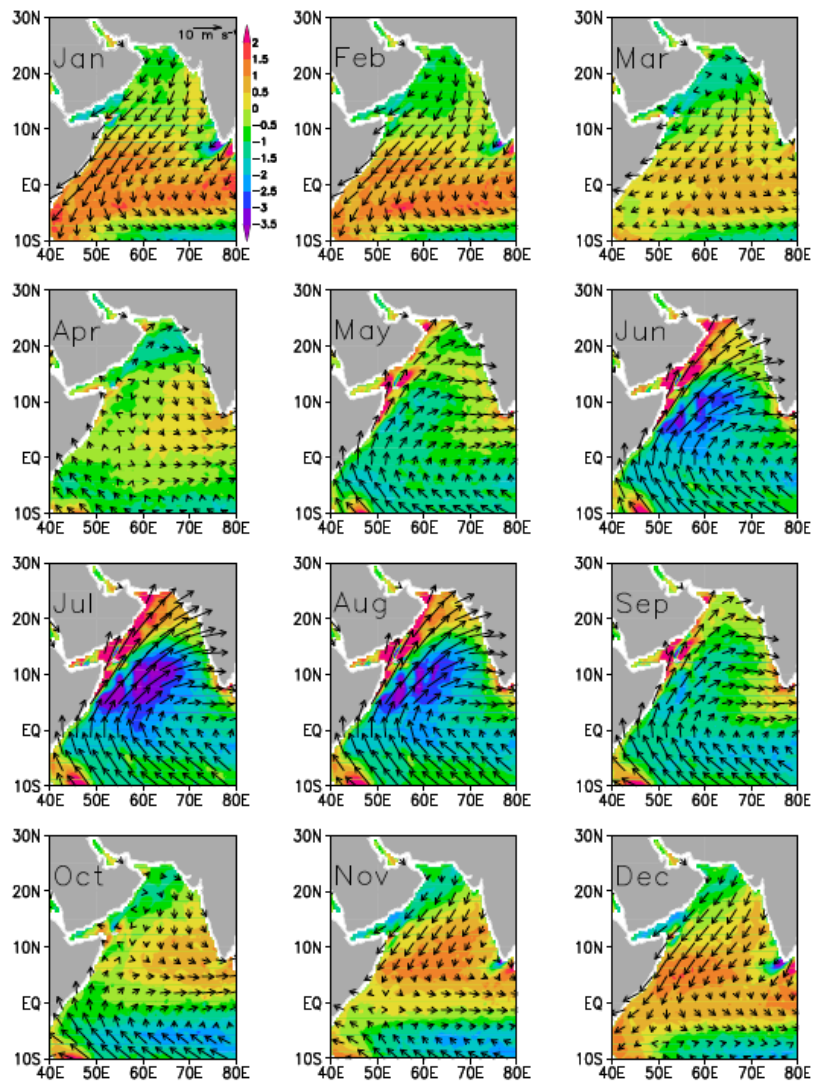



- Seasonally-averaged circulations can show currents and connections that do not actually exist
  - Northeast Monsoon Current appears to feed into southward Somali Current
  - Northward Somali Current appears to feed into Southwest Monsoon Current
  - South Equatorial Counter Current appears to be lacking during the southwest monsoon

Magenta arrows are schematics of identified currents after Schott and McCreary [2001].

Beal, Hormann et al., 2013

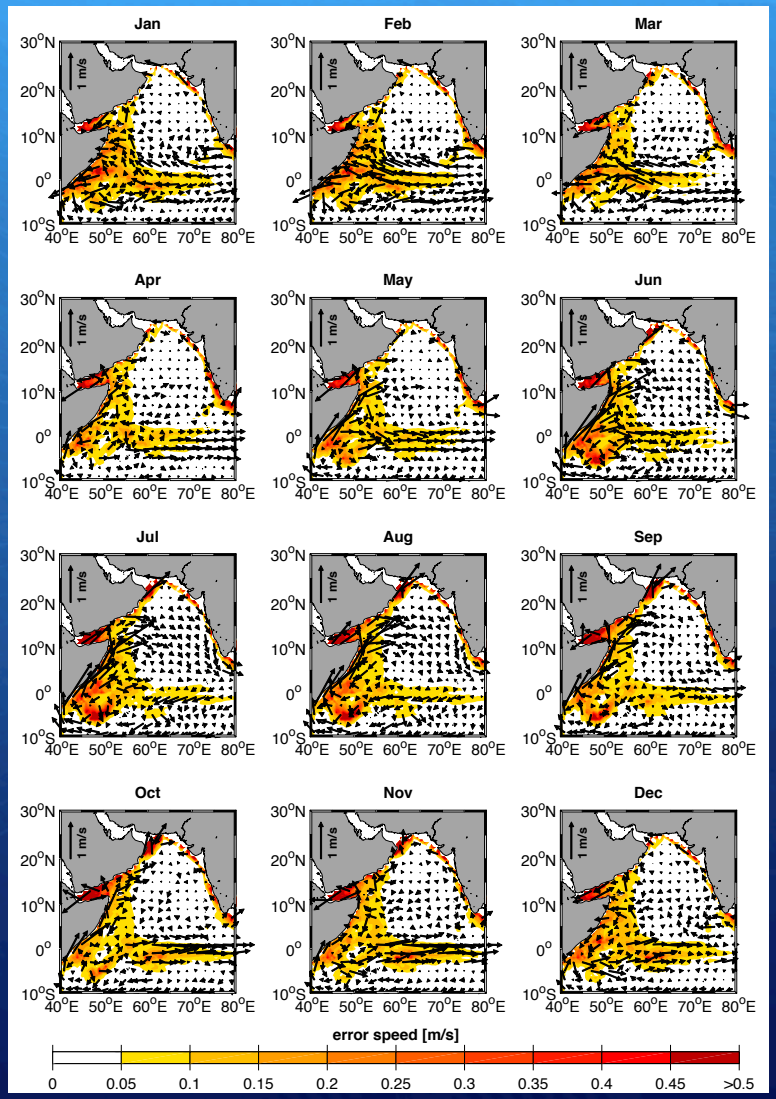
# Monthly winds and curl




- Nov. – Mar.: prevailing northeasterly winds and positive curl
- May – Sep.: prevailing southwesterly winds and negative curl, with strong positive (upwelling) curl along the Somali, Yemeni, and Omani coasts
- Weakest winds in the intermonsoon months of April and October

Beal, Hormann et al., 2013

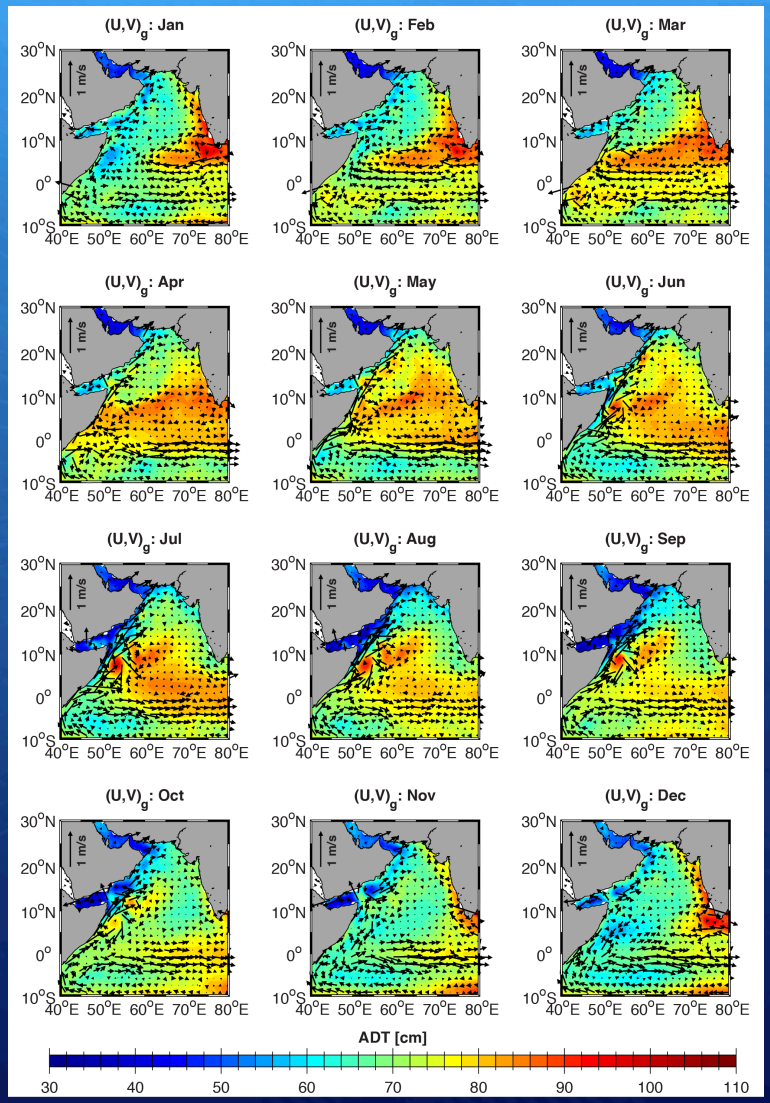
# Absolute near-surface currents




- Few observations combined with high variance typically lead to large errors, with maxima in the west and along the equator
- Eastward Wyrtki Jets along the equator in Apr./May and Oct./Nov. (>1 m/s)
- Indications of closed Southern Gyre during the southwest monsoon

Beal, Hormann et al., 2013

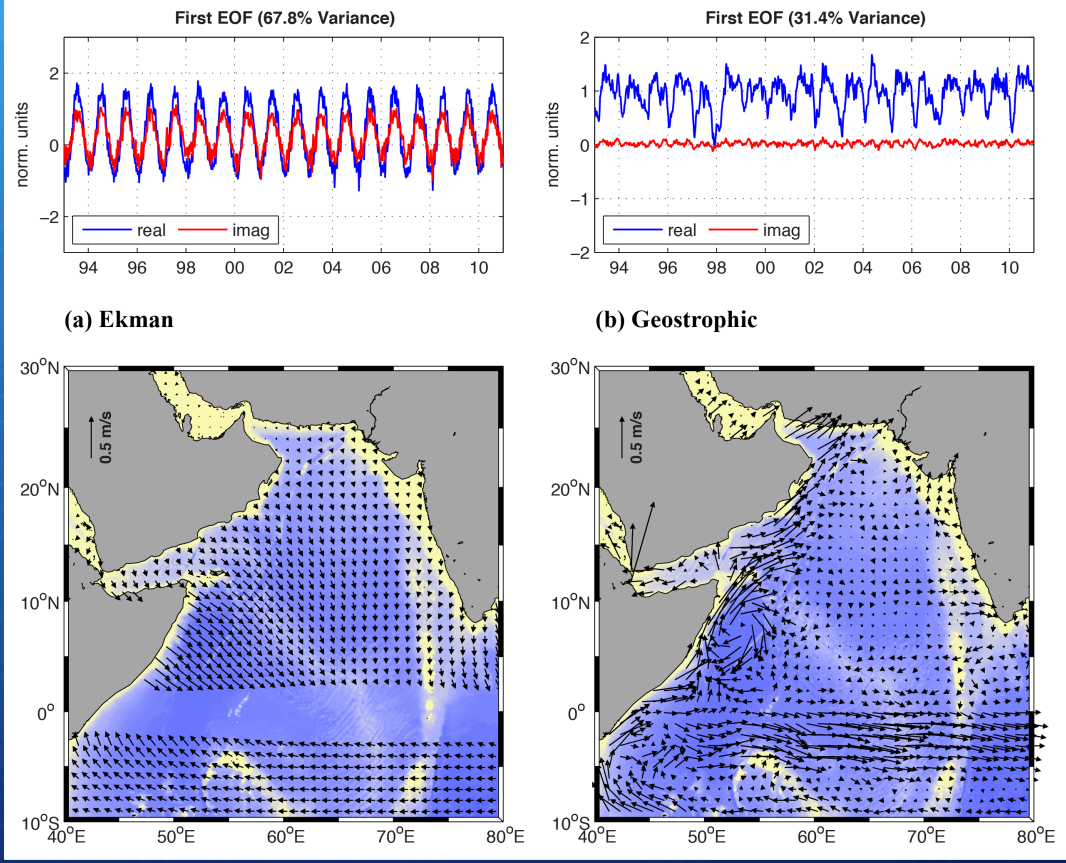
# Geostrophic surface currents




- Early appearance of northward Somali Current and Great Whirl in April
- Year-round South Equatorial Counter Current, fed by the East African Coastal Current
- Southern Gyre appears to be retroflection of the EACC
- Monsoon currents not connected to western boundary circulation

Beal, Hormann et al., 2013

# Dominant modes of variance

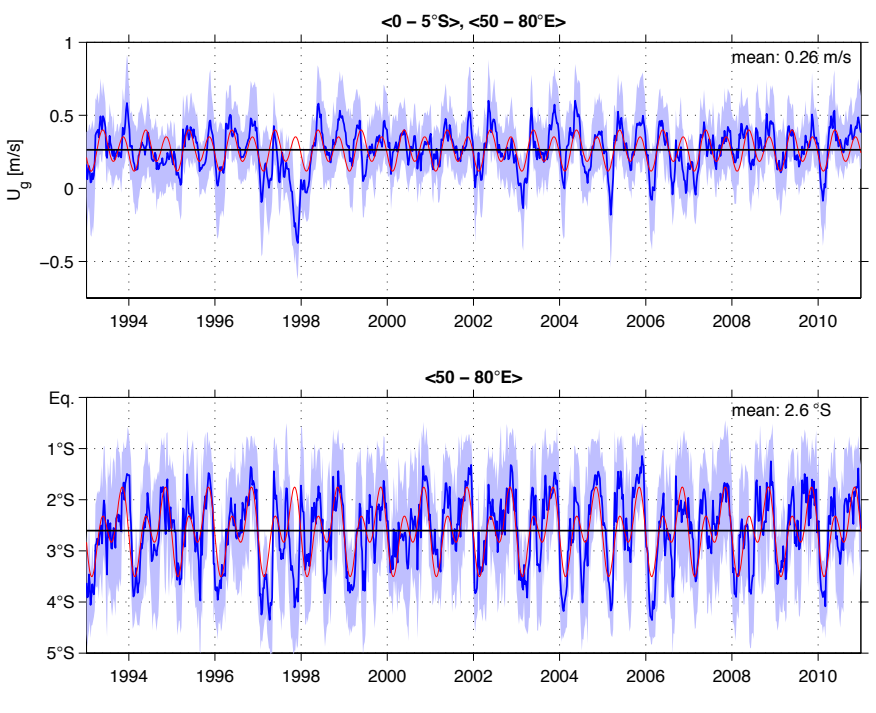


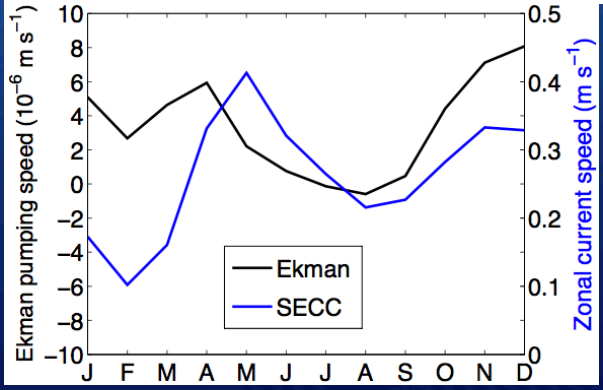

- Strongest Ekman currents are normal to the Somali coast in boreal summer
- Geostrophic mode dominated by northward flow along the western boundary, the Great Whirl and South Equatorial Counter Current

Leading modes correspond to largely annual variability

Beal, Hormann et al., 2013

# South Equatorial Counter Current



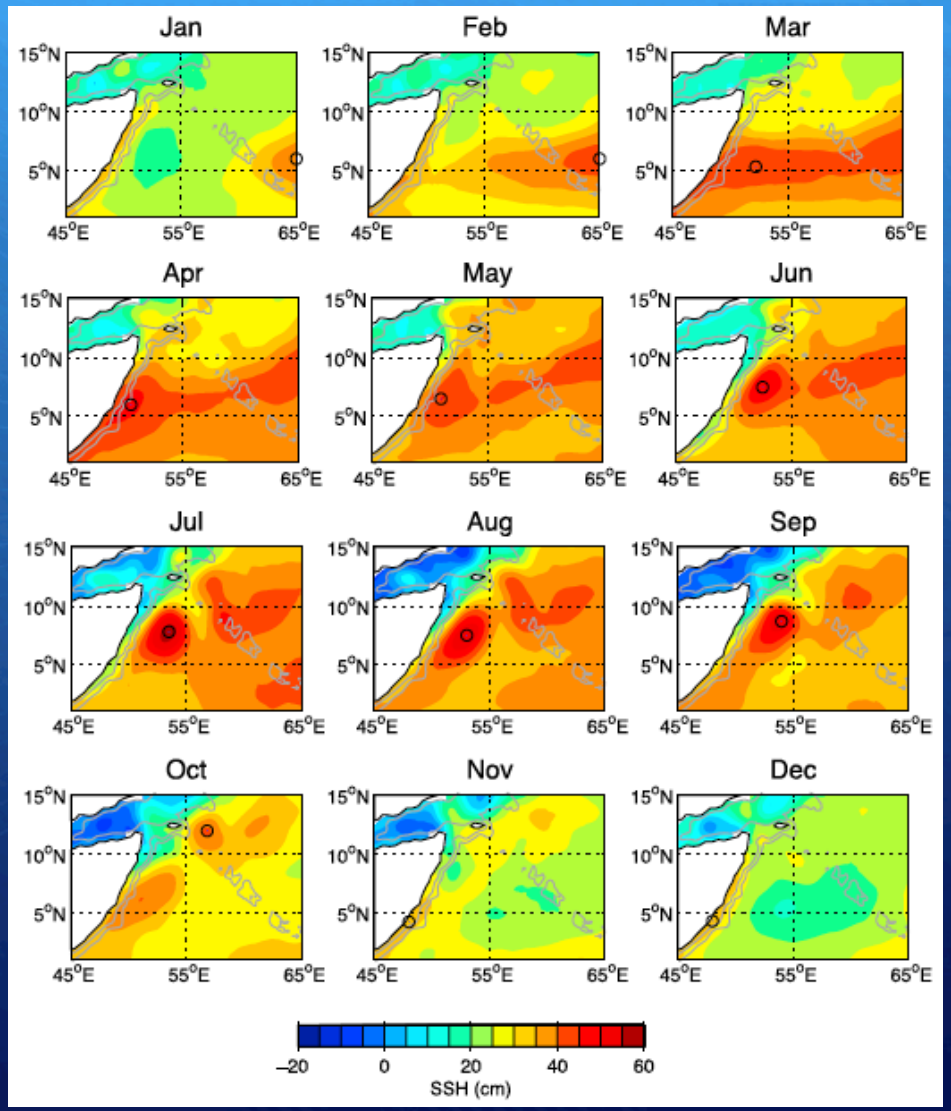




Ekman:
5 - 10°S,
50 - 80°E

- Eastward SECC obscured by strong Ekman currents during the southwest monsoon
- SECC shifted to the south/north when it is weakest/strongest
- Dominant semi-annual SECC variability tied to Ekman pumping over the tropical gyre

Beal, Hormann et al., 2013

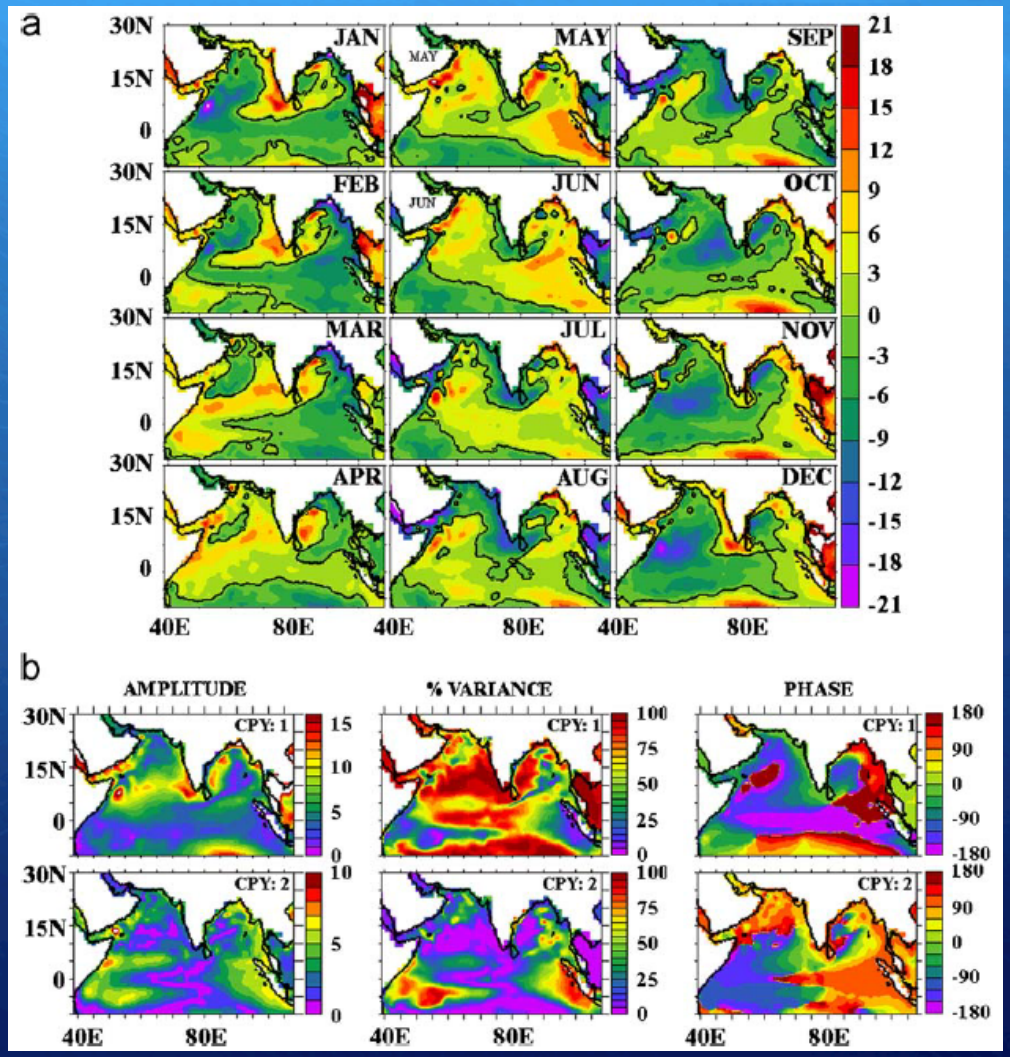
# Early initiation of western boundary flow




- Onset of northward Somali Current and Great Whirl one or two months before wind curl forcing
- Linear theory predicts 1-month lag [e.g., Lighthill, 1969]
- Early appearance of northward SC and GW coincident with arrival of annual Rossby wave [Brandt et al., 2002]

Beal and Donohue, 2013

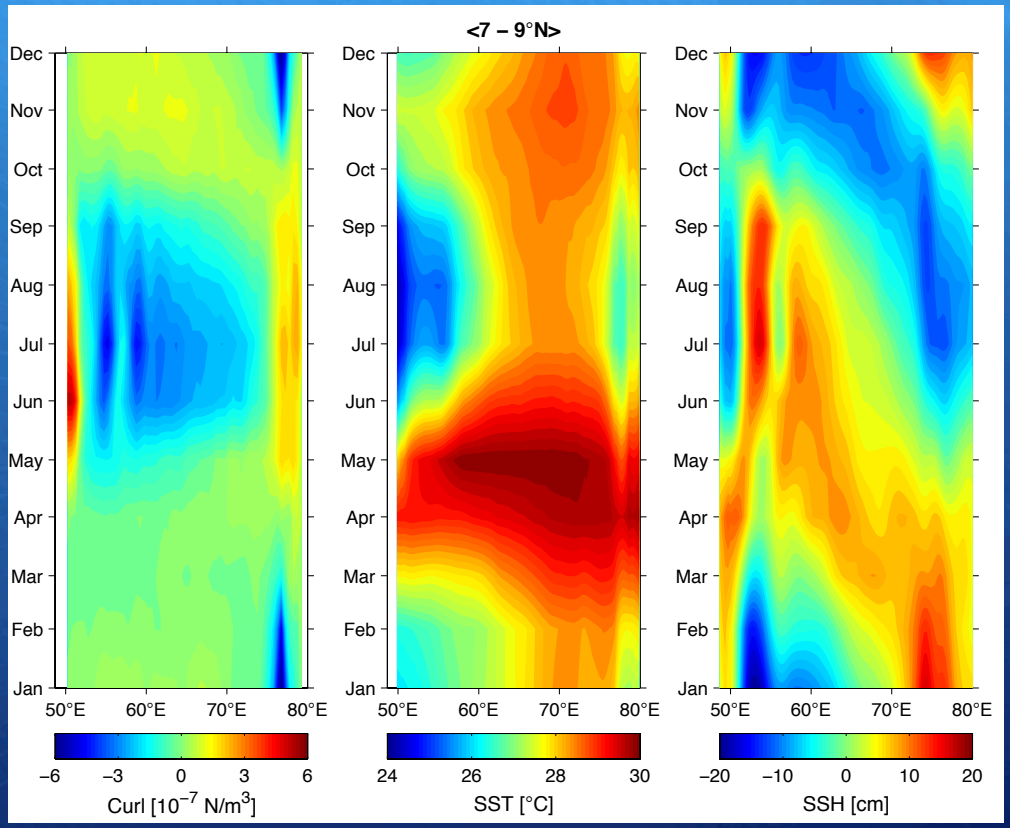
# Northern Indian Ocean waveguide




- Westward Rossby wave from wind curl region off the Somali coast, continuing as coastal then equatorial Kelvin waves to the east coast
- Kelvin wave around the rim of the Bay of Bengal, radiating Rossby waves back into the Arabian Sea
- time scale for wave processes: ~300 days [Shetye, 1998]

Rao et al., 2008

# Evolution along 8°N

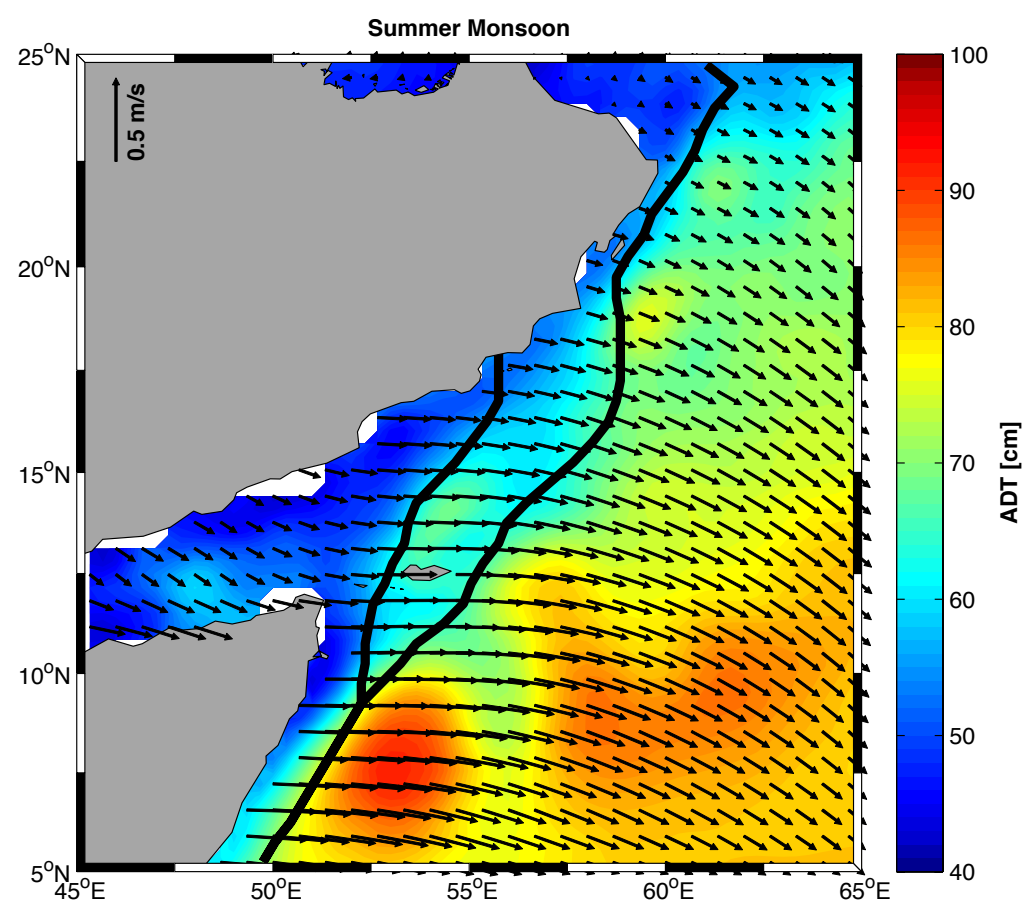



- Annual Rossby wave radiates off India in Oct./Nov., reaching the west coast in April
- Offshore gradient of SSH anomalies changes sign and coastal current switches from south- to northward
- Strong local wind curl obliterates Rossby waves in Jun. - Aug.

SSH: sea surface height

Beal, Hormann et al., 2013

# Flow off the Arabian Peninsula




ADT: absolute dynamic topography

- Strongest offshore flow between 10 - 18°N during the southwest monsoon
- Alongshore winds and double monsoon-jet maximum cause strong Ekman currents (vectors) and geostrophic flow (implicit via ADT) at the mouth of the Gulf of Aden

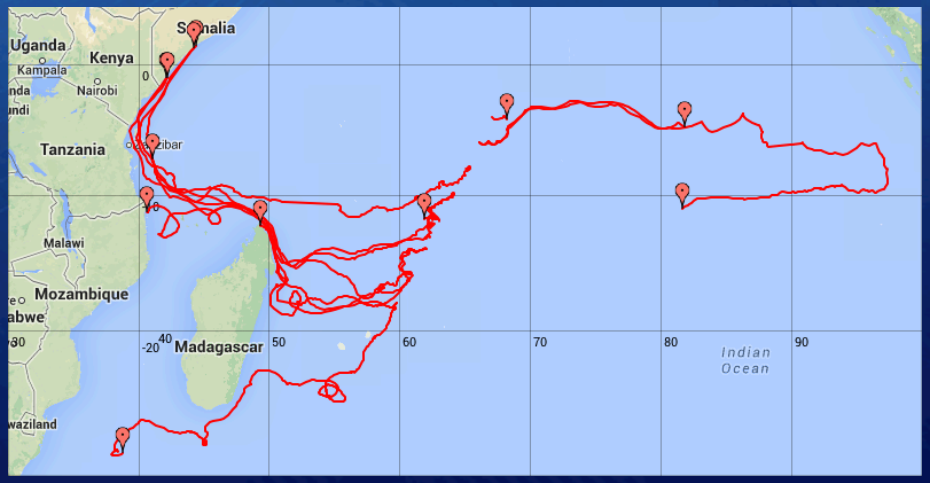
Beal, Hormann et al., 2013

# Conclusions

- Drifter and satellite data can resolve the seasonal circulation of the Arabian Sea
- SECC flows eastward year-round, fed by the EACC; semi-annual SECC variability governed by Ekman pumping over the tropical gyre
- EACC overshoots the equator during the southwest monsoon and Southern Gyre appears to be EACC retroflection
- Broad northward and offshore flow at the mouth of the Gulf of Aden coincident with alongshore winds and a switch in sign of the wind curl along the monsoon-jet axis
- Northward Somali Current and Great Whirl appear one or two months before the monsoon onset, driven by planetary waves initiated during the previous southwest monsoon; oceanic mechanism through which one monsoon may precondition the next?

# Perspectives

- Frequent piracy largely prevented in-situ observations in the Arabian Sea over the past 10 or 15 years, hampering the advancement of ocean-atmosphere research
- Lack of observations can be remedied by recent advances in technology of autonomous instruments
- Future investigations of phenomena in the Arabian Sea, like the annually reversing Somali Current system, will require optimal deployment locations




Drifters deployed in the western Indian Ocean during the Semester-at-Sea cruise in mid-March 2013