Diapycnal heat fluxes in tropical upwelling regions

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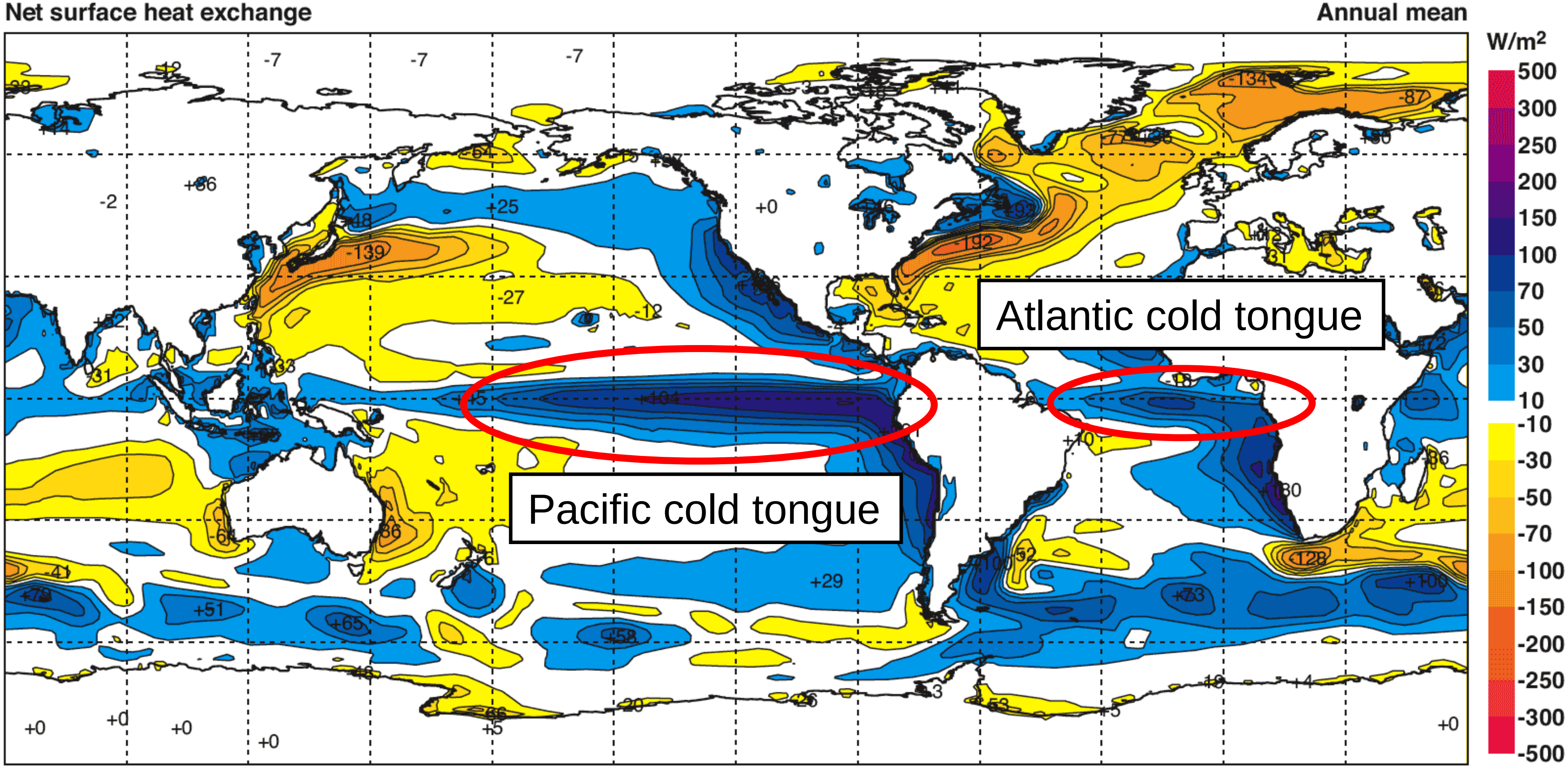
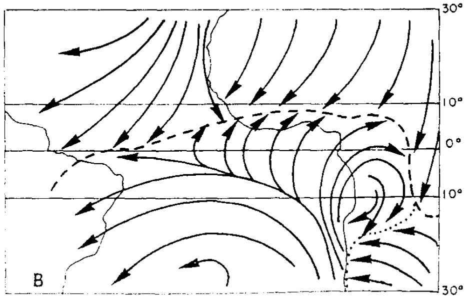
Roadmap

- Motivation: Tropical Atlantic Climate and mixed layer heat balance
- Mixing and diapycnal heat flux in the equatorial Atlantic
- Mixing and diapycnal heat flux on the shelf off Angola
- Conclusions

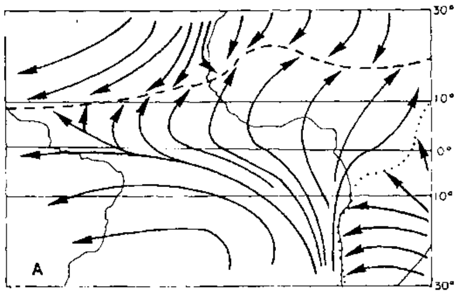
Motivation: Net surface heat fluxes

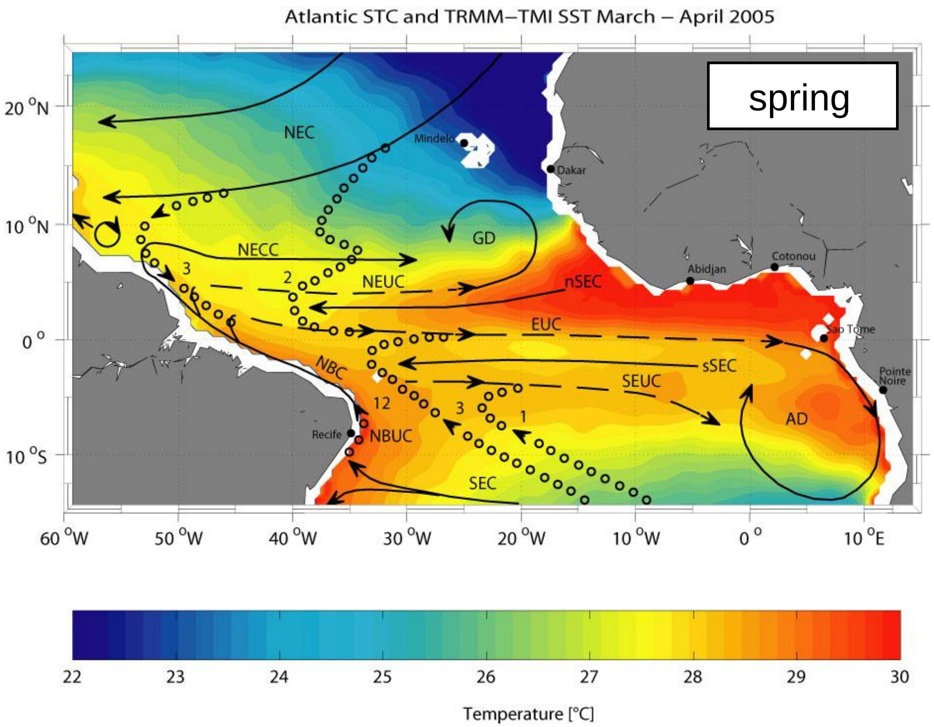


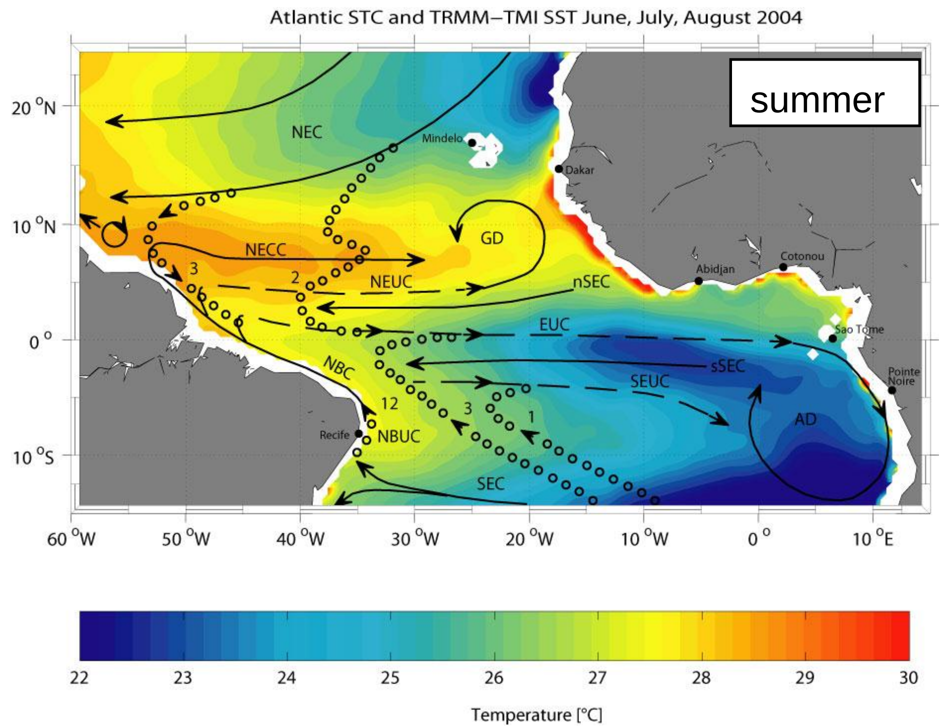
Annual-mean heat flux *Q* through the sea surface in Wm^{-2} calculated from the ECMWF 40-year reanalysis (Kallberg et al., 2005)



Winds and Seasonal SST Variability

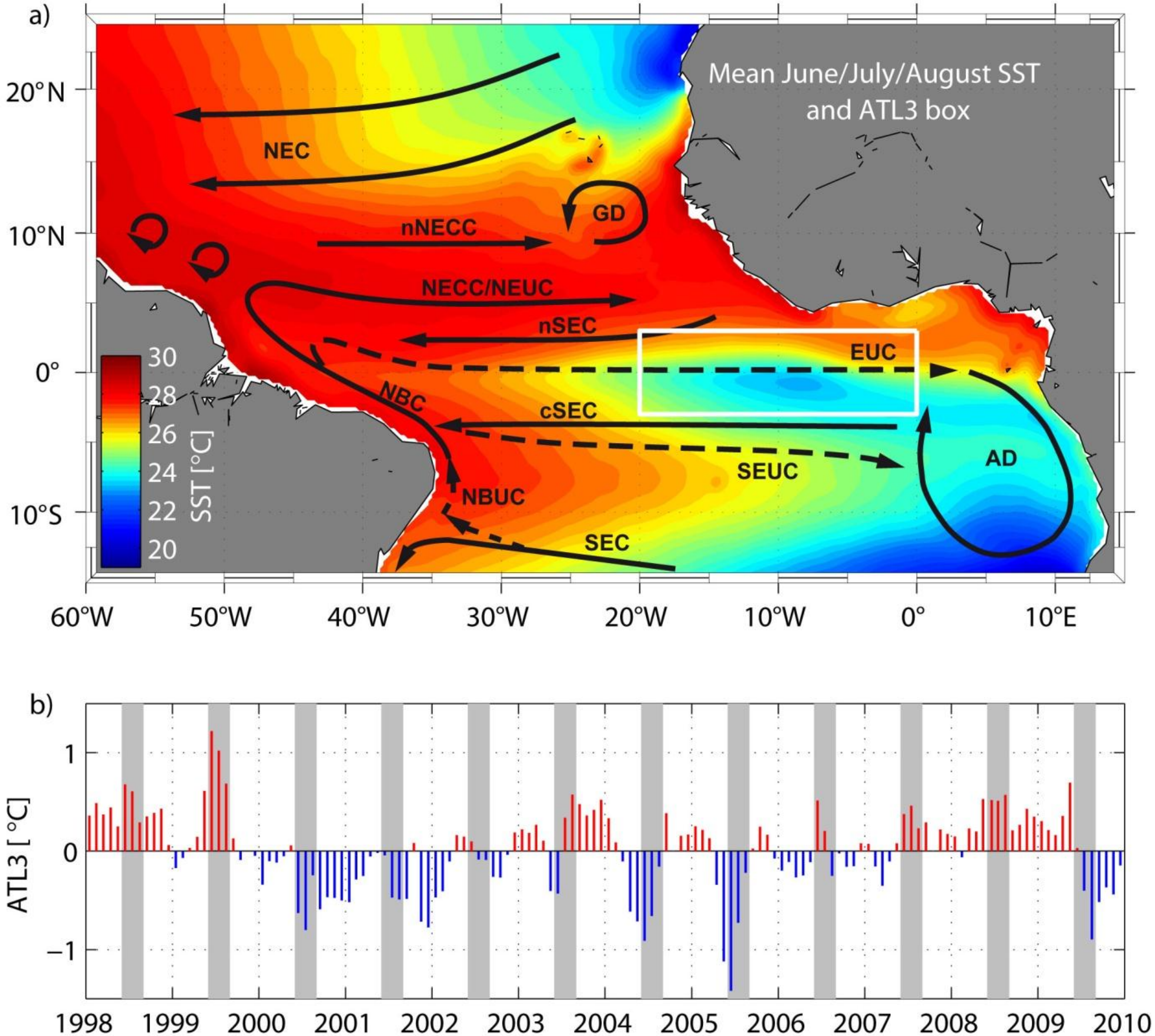






- Seasonal migration of the intertropical convergence zone causes seasonal variability of the sea surface temperature in the eastern upwelling regions
- Eastward undercurrents (EUC, SEUC, NEUC) supply recently subducted waters from the western boundary to the upwelling regions.

Interannual SST Variability



Equatorial Cold Tongue

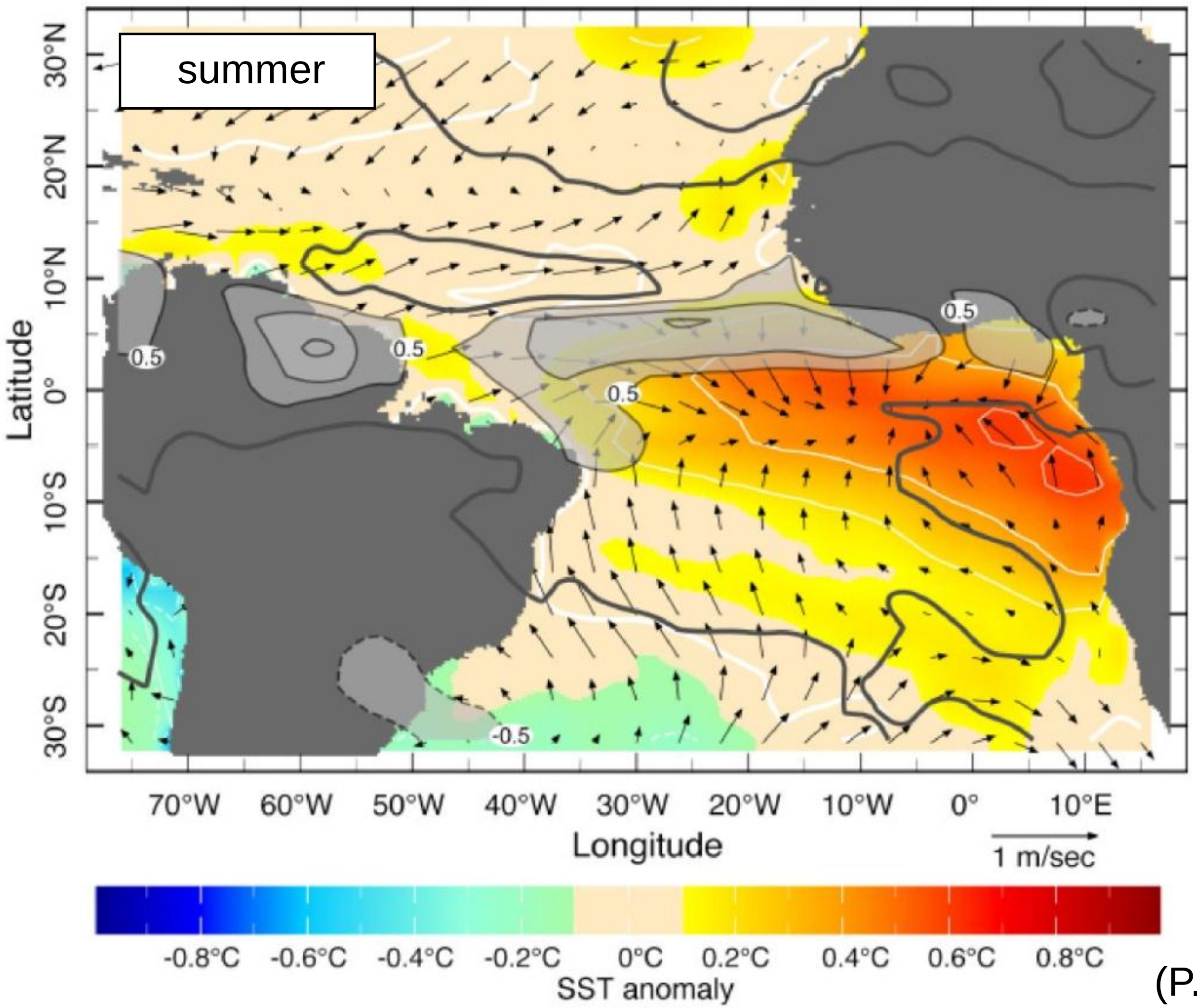
Cold SSTs develops during boreal summer in the eastern equatorial Atlantic

Strong interannual variability and long term warming trend

ATL3 annual cycle:
Max in April ~29°C
Min in Aug. ~24°C

(Brandt et al., 2011)

Interannual SST and Climate Variability



Zonal Mode - „Atlantic Nino“

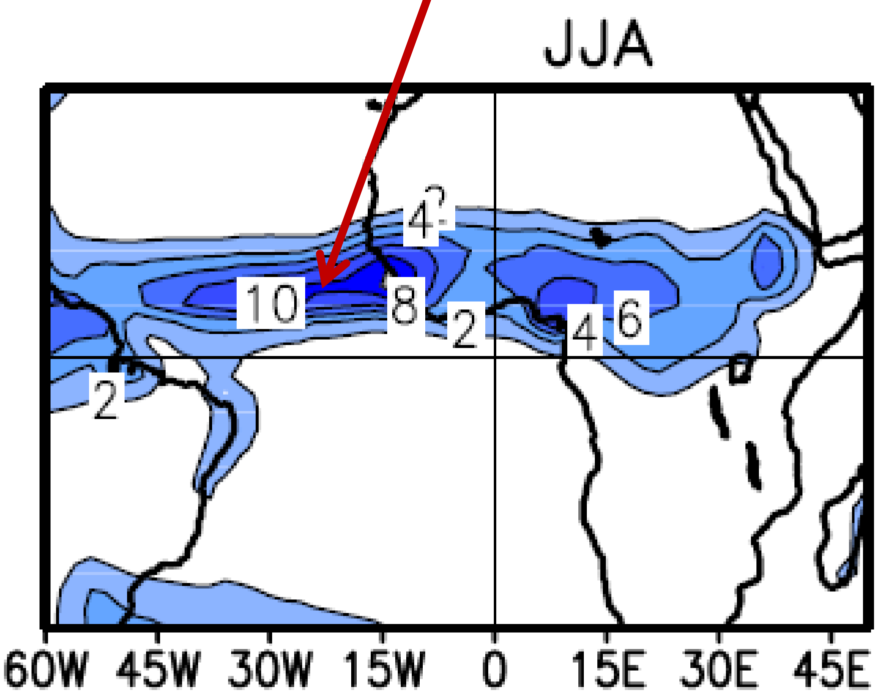
Increased precipitation (grey shaded, mm/day) during warm events

⇒ SST in the equatorial cold tongue important for regional climate prediction

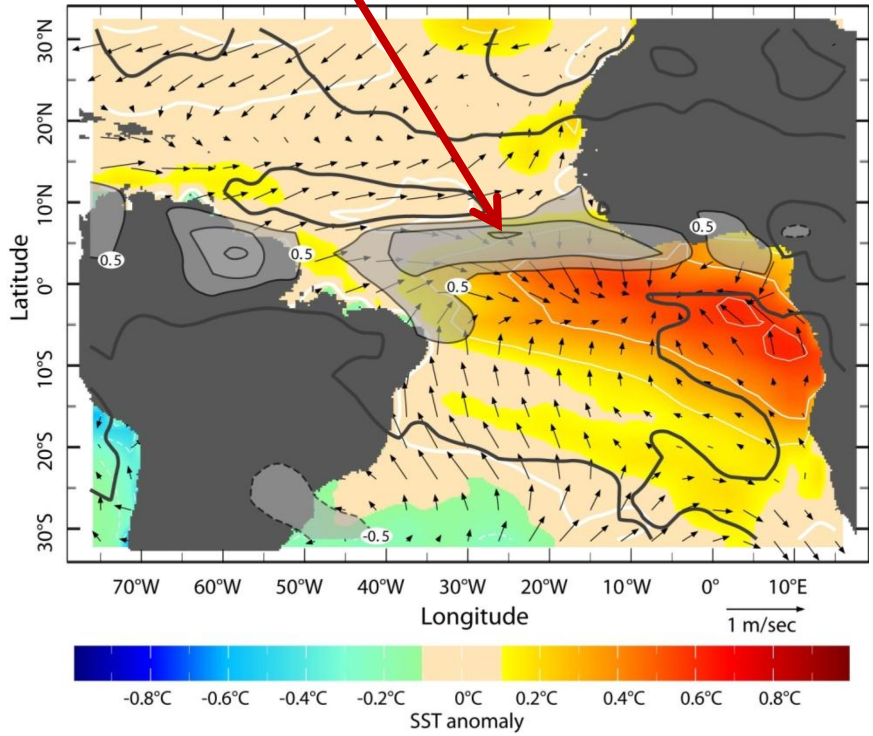
(P. Chang et al., 2006)

Interannual SST and Climate Variability

Average precipitation [mm/day] during boreal summer



First EOF of interannual variability of boreal summer precipitation [mm/day]



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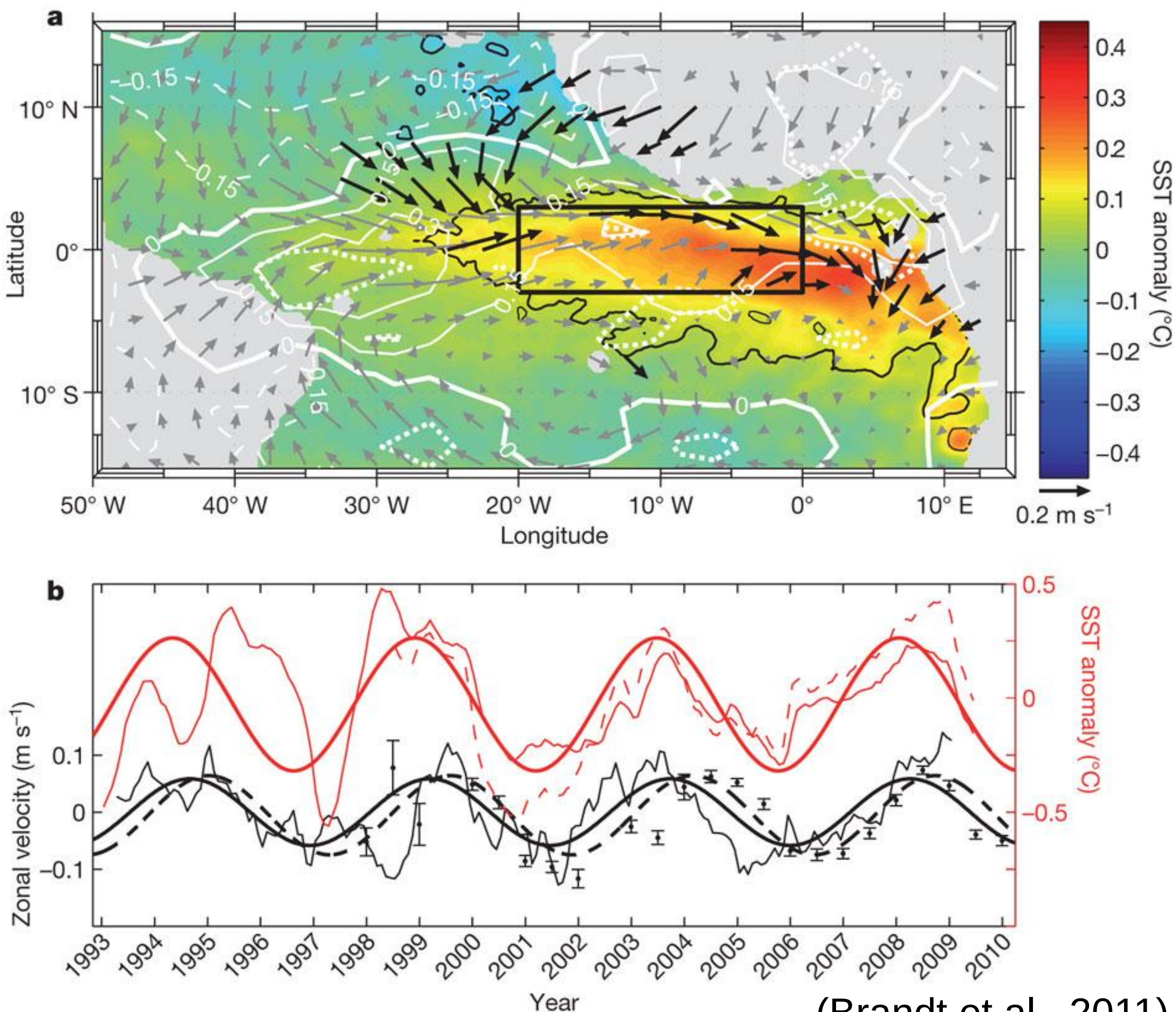
4.5-year Climate Cycle in SST and Currents



Correlated wind anomaly

Hadley Center SST

Satellite SST

4.5y SST harmonic

Surface zonal velocity anomaly (Satellite Alt.)

4.5y surface velocity

1000m velocity (ARGO)

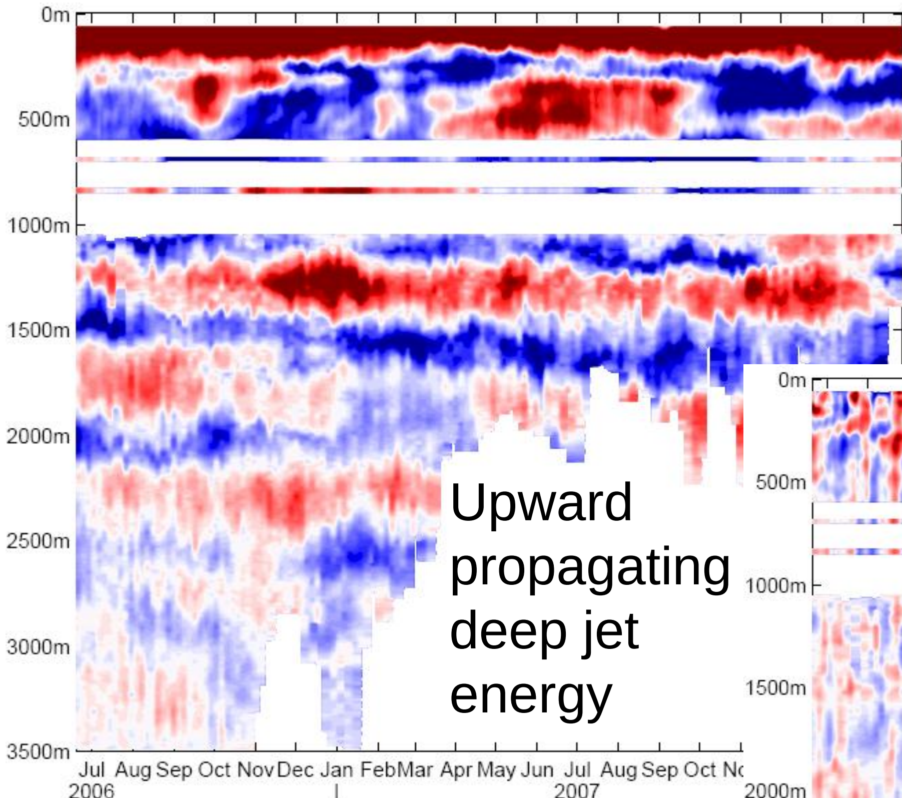
4.5y 1000m velocity

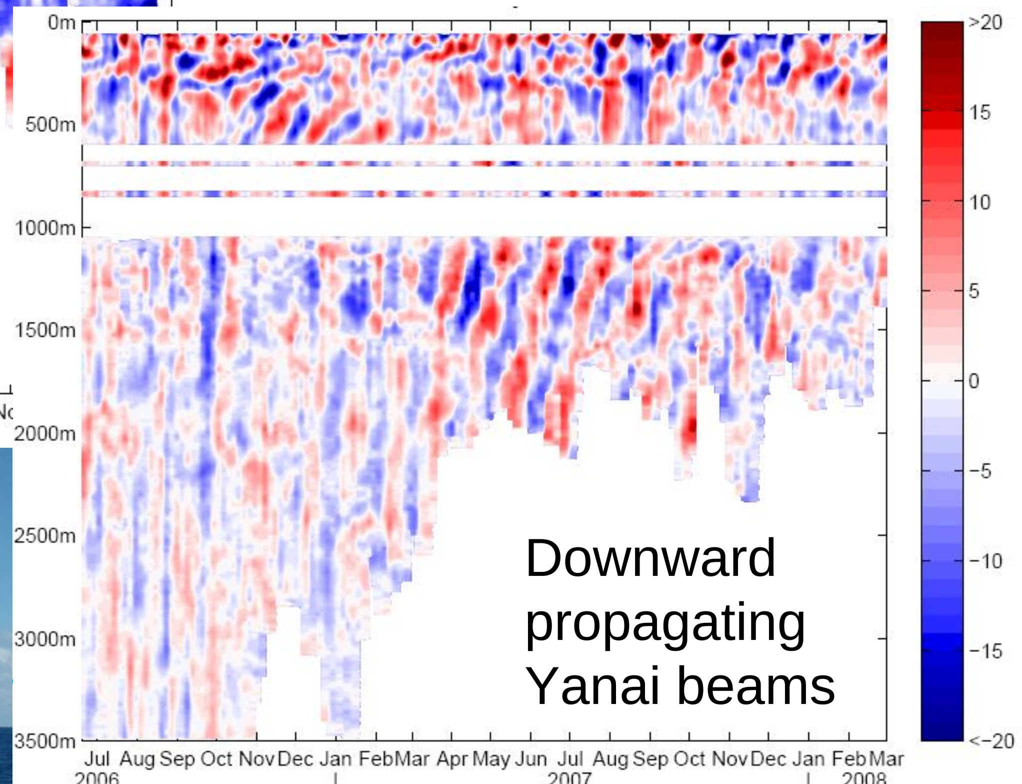
(Brandt et al., 2011)

The Deep Jets and the 4.5-Year Climate Cycle

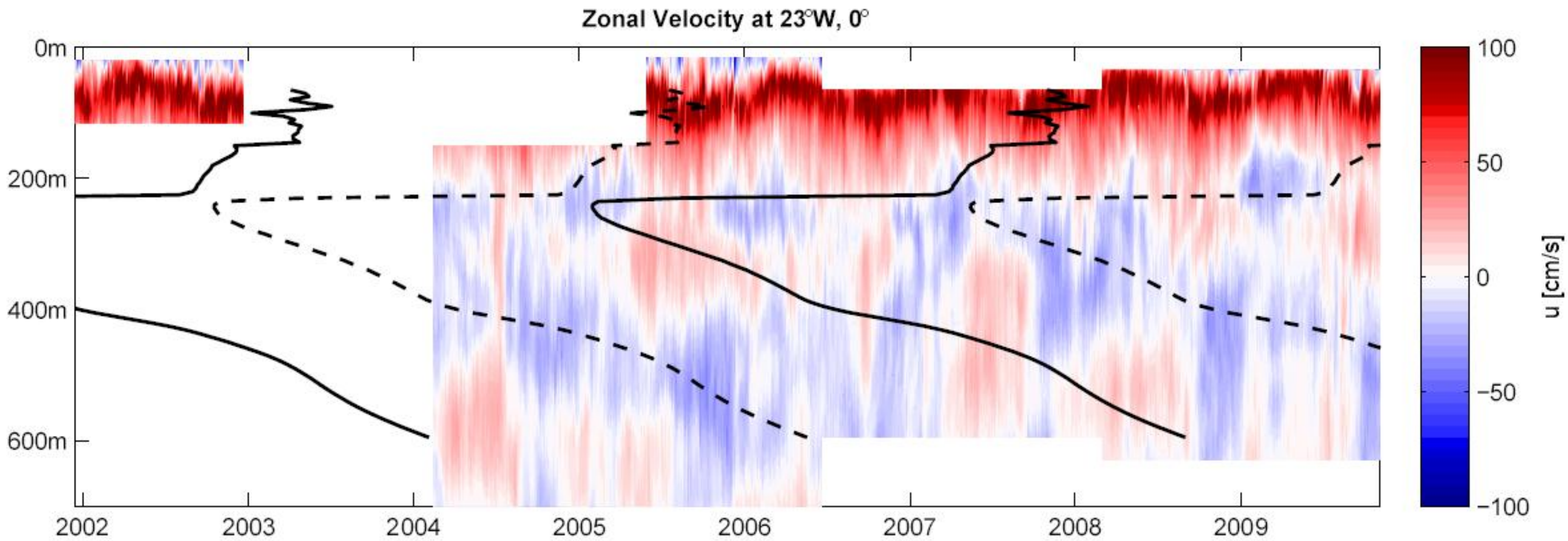
Zonal (left) and meridional (right) velocity [m/s] measured at 23°W, 0°N with ADCP and moored profiler

(Brandt et al., 2011)





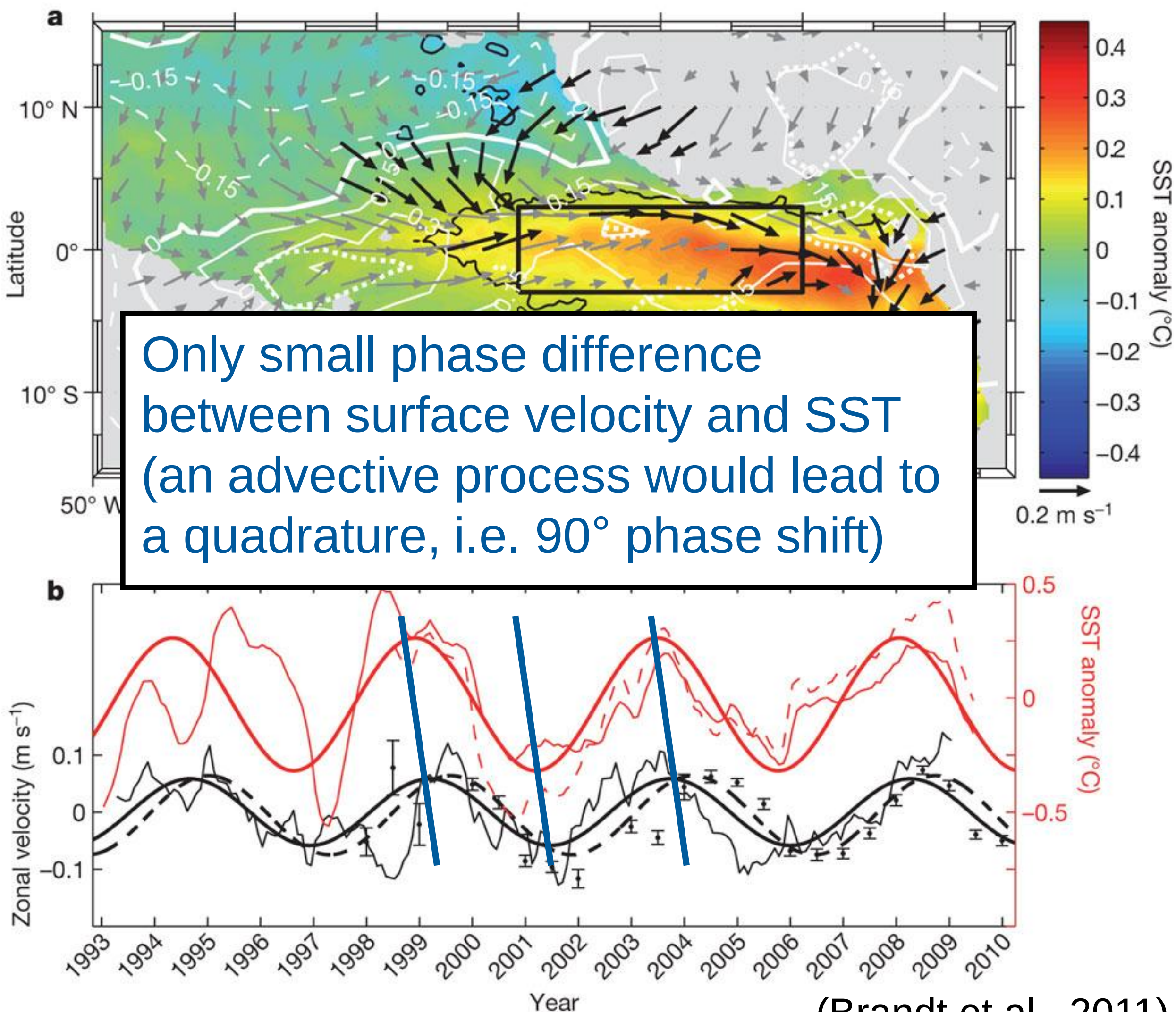
The Deep Jets and the 4.5-Year Climate Cycle



(Brandt et al., 2011)

- Consistent downward phase propagation below the EUC
- 4.5-year cycle also within the EUC
- Phase jump at about the critical level (Kelvin wave speed equals the background flow speed)

4.5-year Climate Cycle in SST and



Only small phase difference between surface velocity and SST (an advective process would lead to a quadrature, i.e. 90° phase shift)

Correlated wind anomaly

Hadley Center SST

Satellite SST

4.5y SST harmonic

Surface zonal velocity anomaly (Satellite Alt.)

4.5y surface velocity

1000m velocity (ARGO)

4.5y 1000m velocity

(Brandt et al., 2011)

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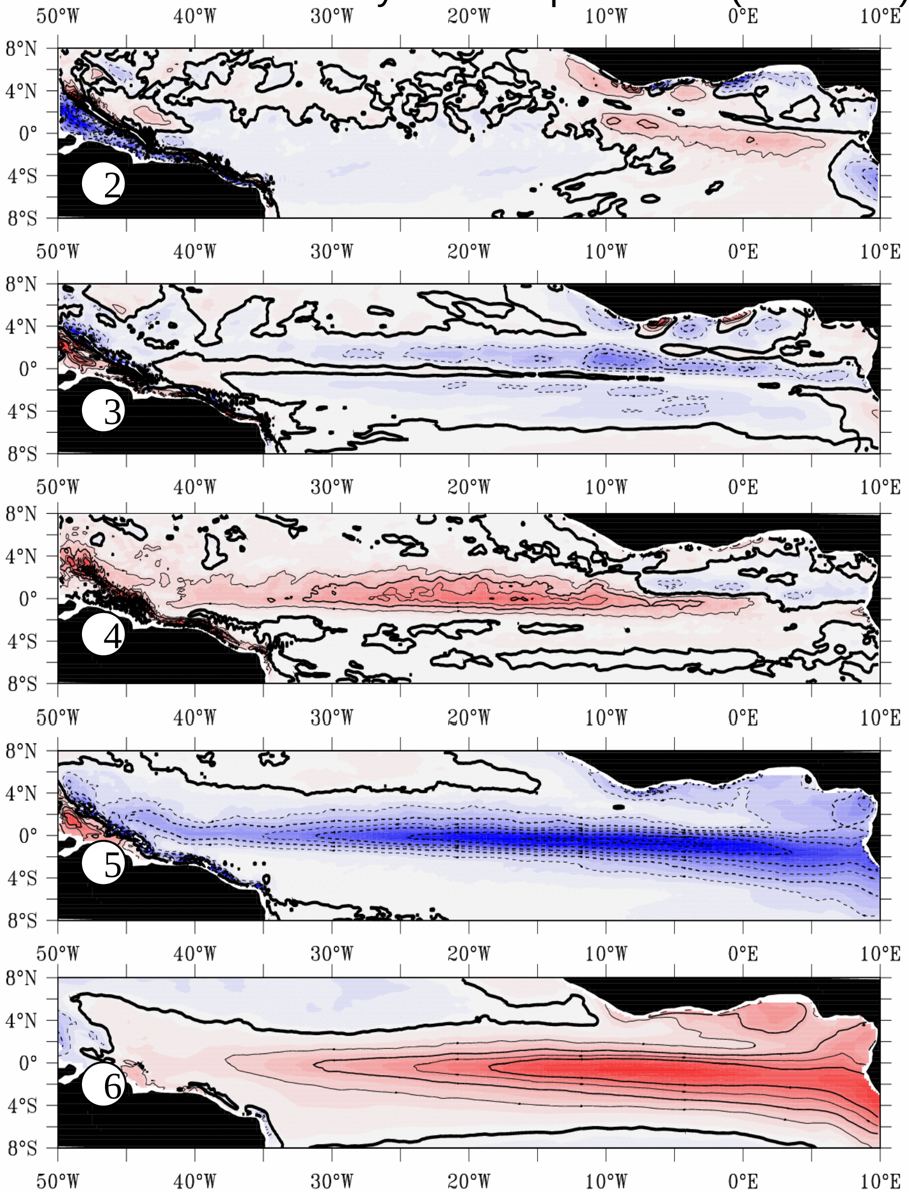
Which Processes Control SST Variability?

Mixed layer heat balance in from an OGCM

annual mean trends by different processes (°C/month)



zonal advection by
low frequency currents

$$\langle -\bar{u}\,\partial_x \bar{T} \rangle$$

meridional advection by
low frequency currents

$$\langle -\bar{v}\,\partial_y \bar{T} \rangle$$

high frequencies advection (<35 days)
effects of eddies

$$-\langle \overline{u'\partial_x T'} \rangle - h\langle \overline{v'\partial_y T'} \rangle + h\langle D_l \rangle$$

subsurface mixing (vertical advection,
entrainment and turbulent mixing)

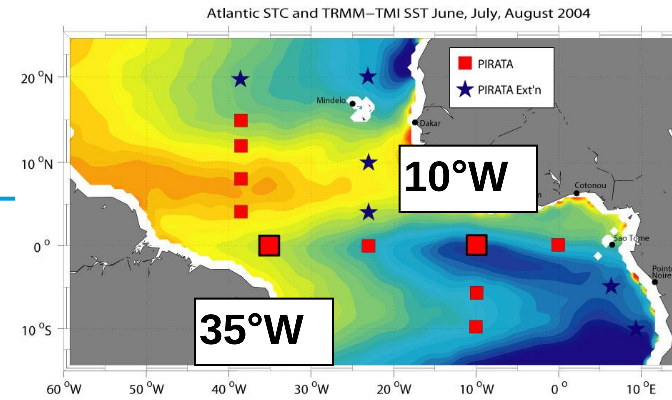
$$-\left(K_z \partial_z T\right)_{(z=h)} - \left(\partial_t h + w_{(z=h)}\right)\left(\langle T \rangle - T_{(z=h)}\right)$$

atmospheric
forcing

$$\frac{Q^* + Q_s\left(1 - f_{(z=h)}\right)}{\rho_0 C_p h}$$

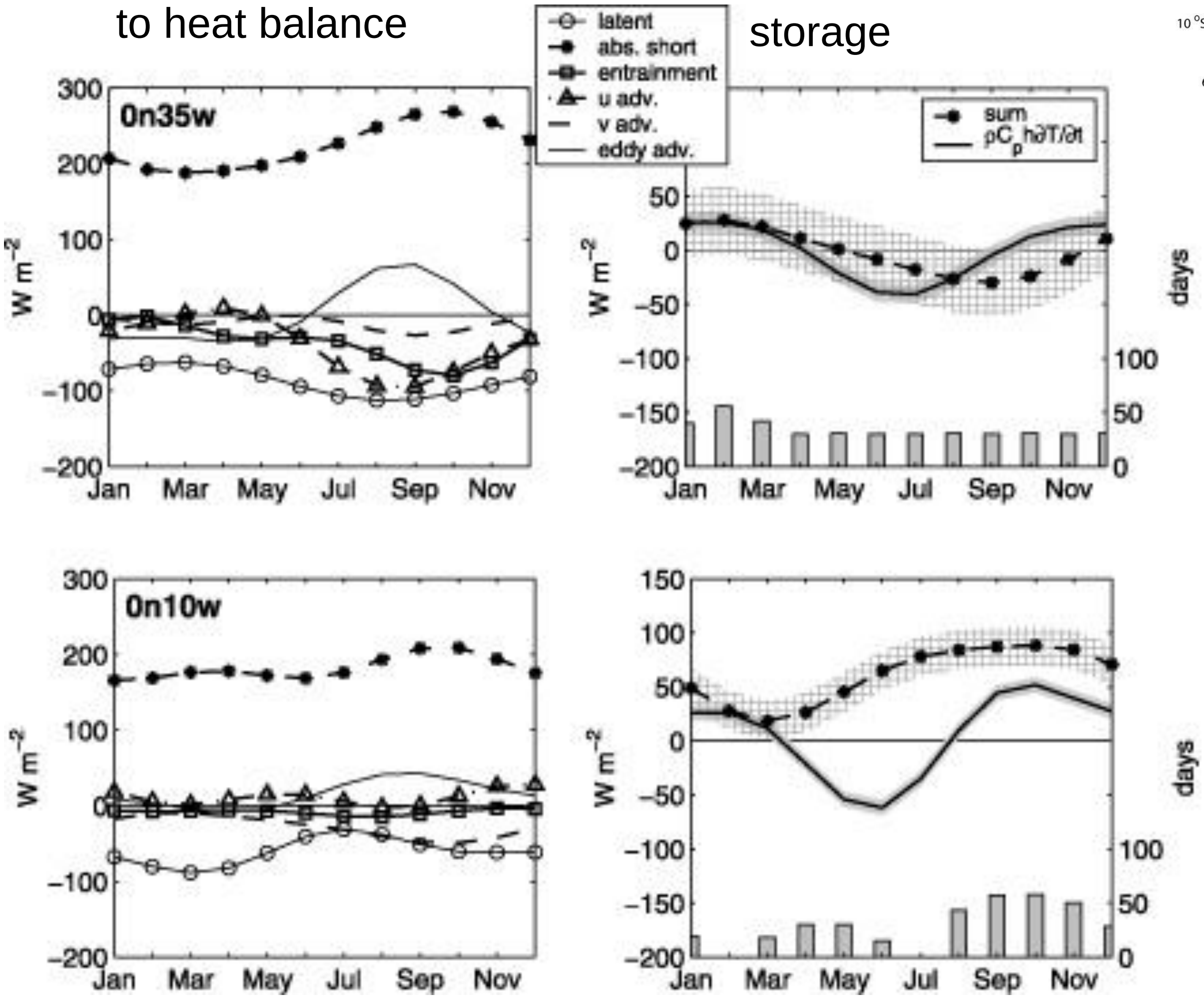
(Peter et al., 2006)

Mixed Layer Heat Balance from Observations



individual contributions to heat balance

sum and local storage



Heat balance within the region of the equatorial cold tongue could not be closed

Study did not include estimates of turbulent heat flux at the base of the mixed layer

(Foltz et al., 2003)

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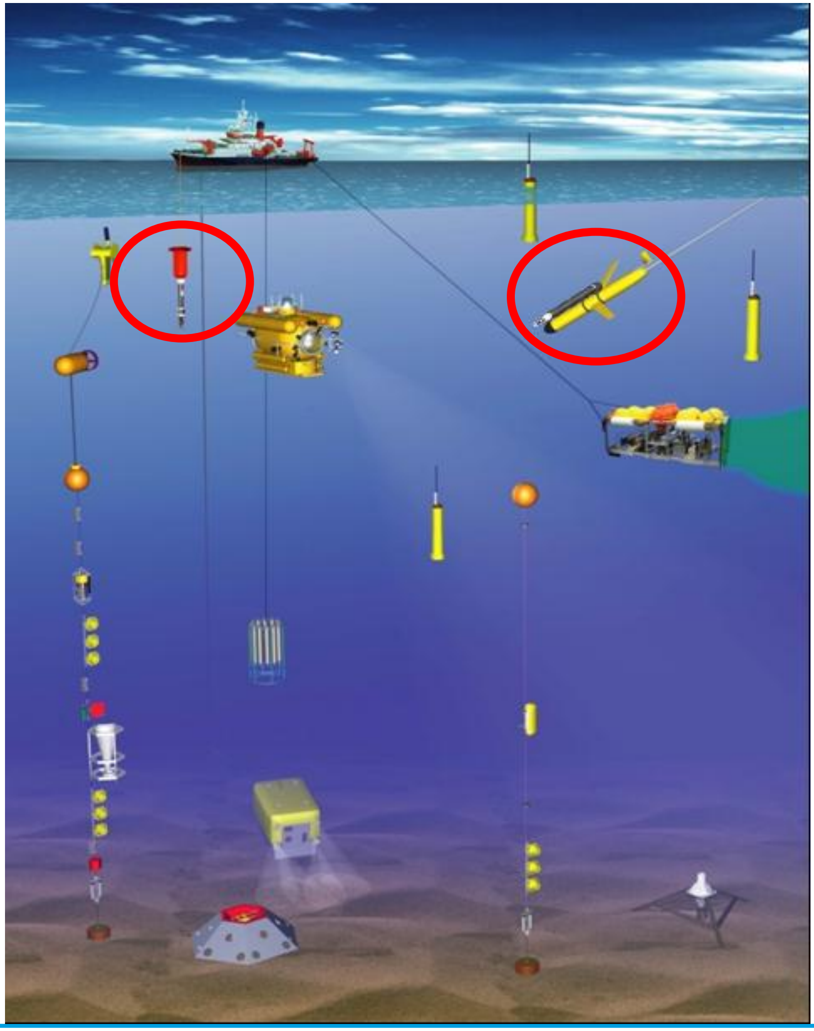
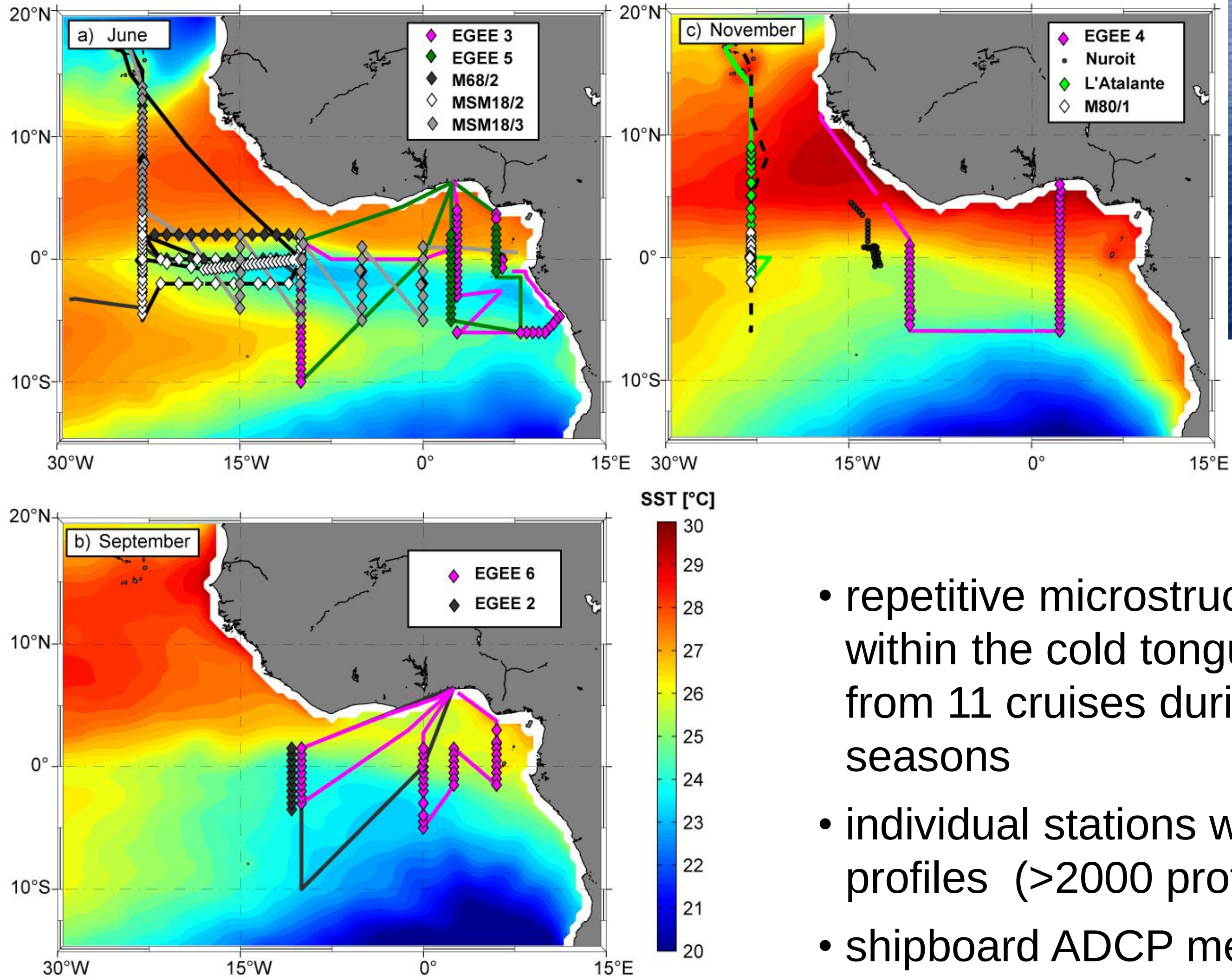
Mixing Observatories at GEOMAR

Ship-based microstructure systems



Autonomous microstructure platforms (MicroRider / Glider)

Ship-board Microstructure Measurements (2005-2011)

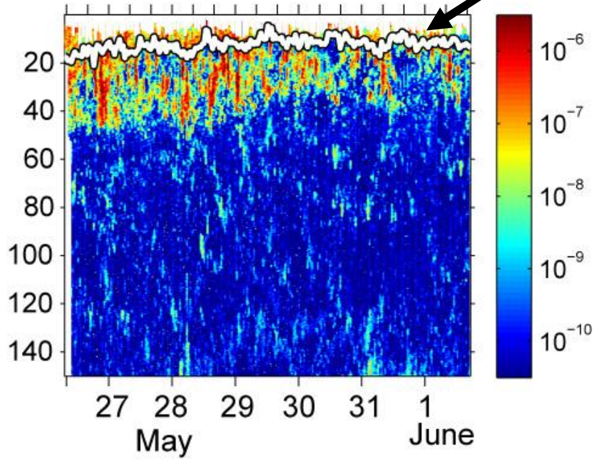


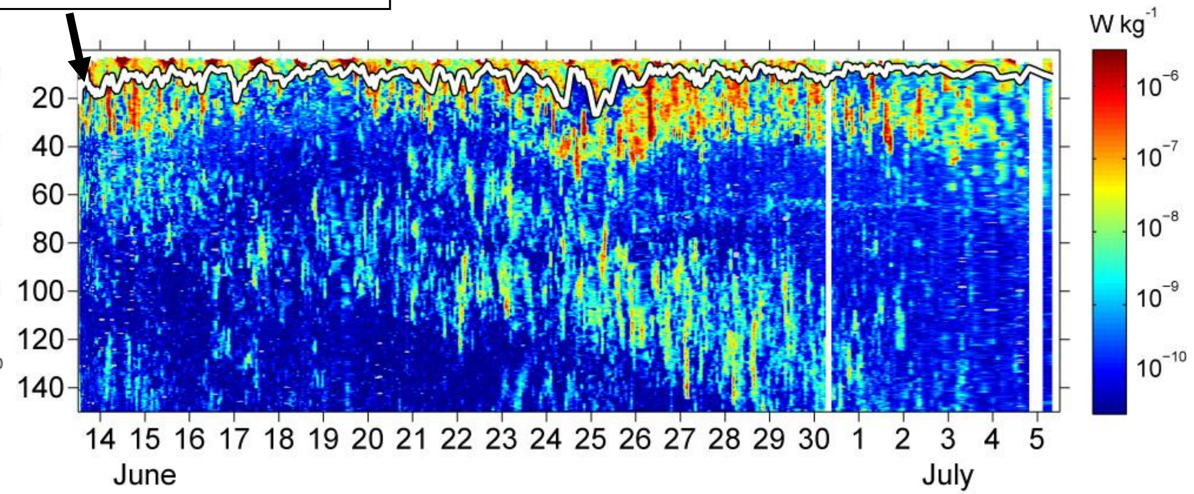
- repetitive microstructure sections within the cold tongue region from 11 cruises during different seasons
- individual stations with at least 3 profiles (>2000 profiles)
- shipboard ADCP measurements

Time Series of Turbulent Kinetic Energy from a MicroRider/Glider Package

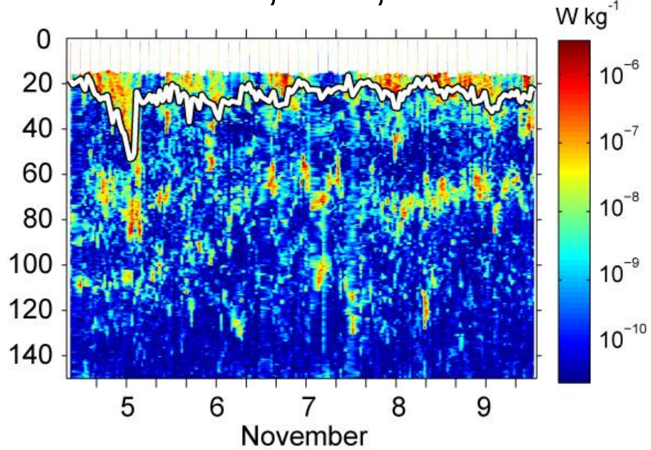
Mixed layer depth

May-July 2011, 0°N, 10°W





November 2009, 0°N, 23°W



- microstructure probe (Rockland Scientific) attached to a Glider
- measures autonomously for up to 4 weeks
- profiles the water column to 1000m in about 45 minutes

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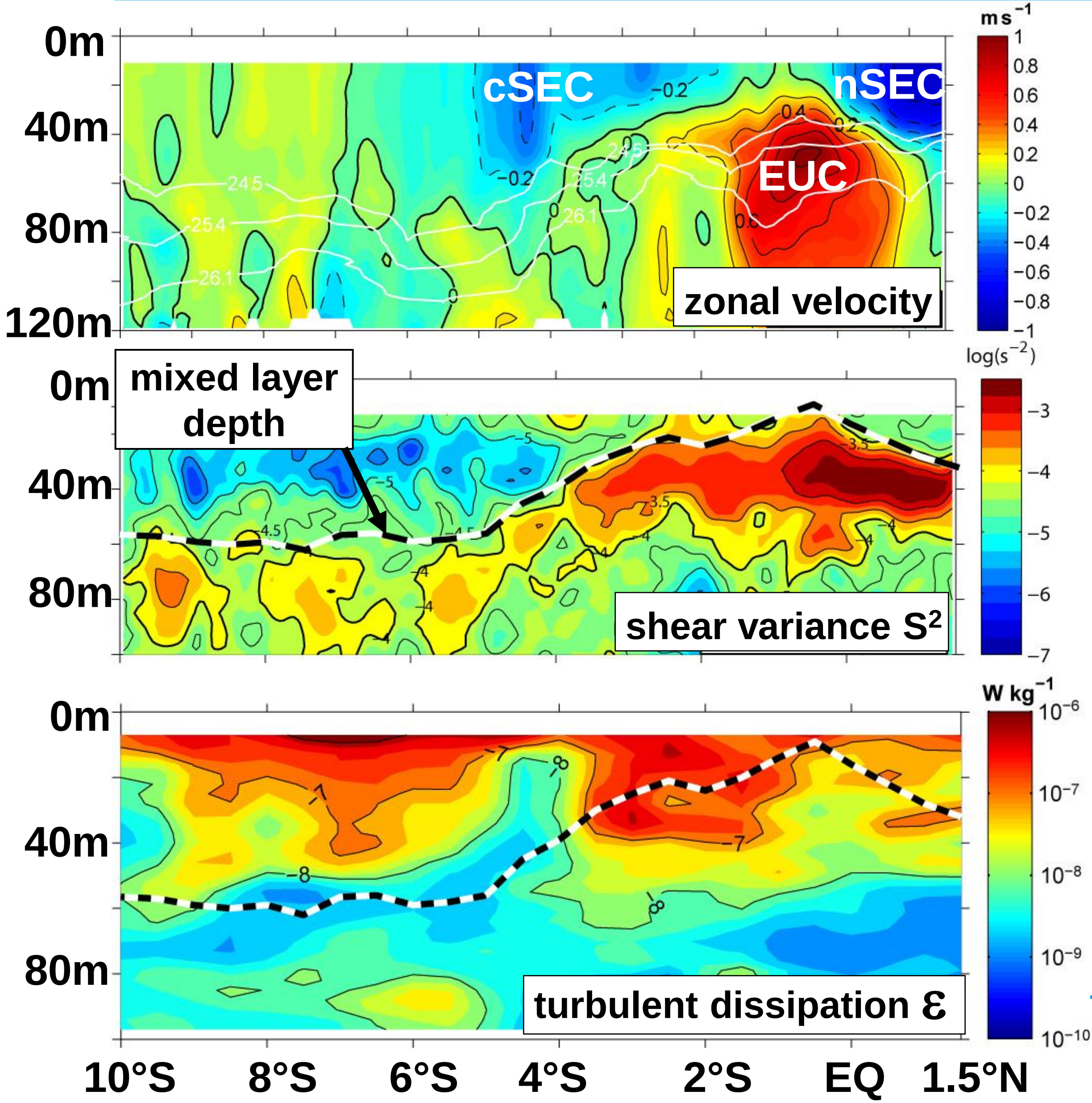
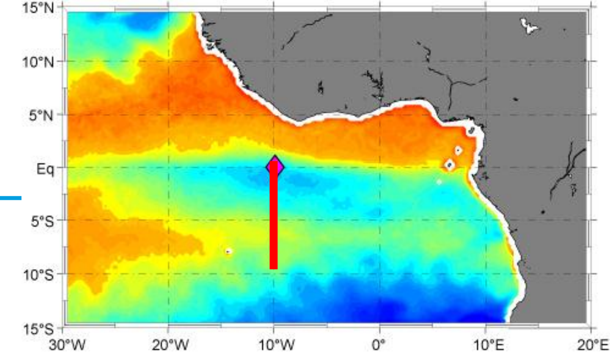
Latitudinal distribution of upper ocean turbulence: Section along 10°W

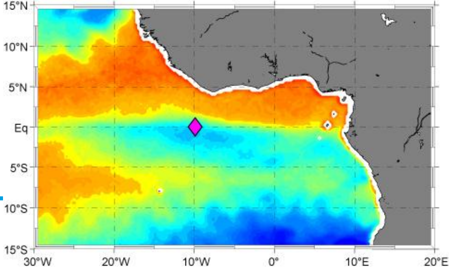


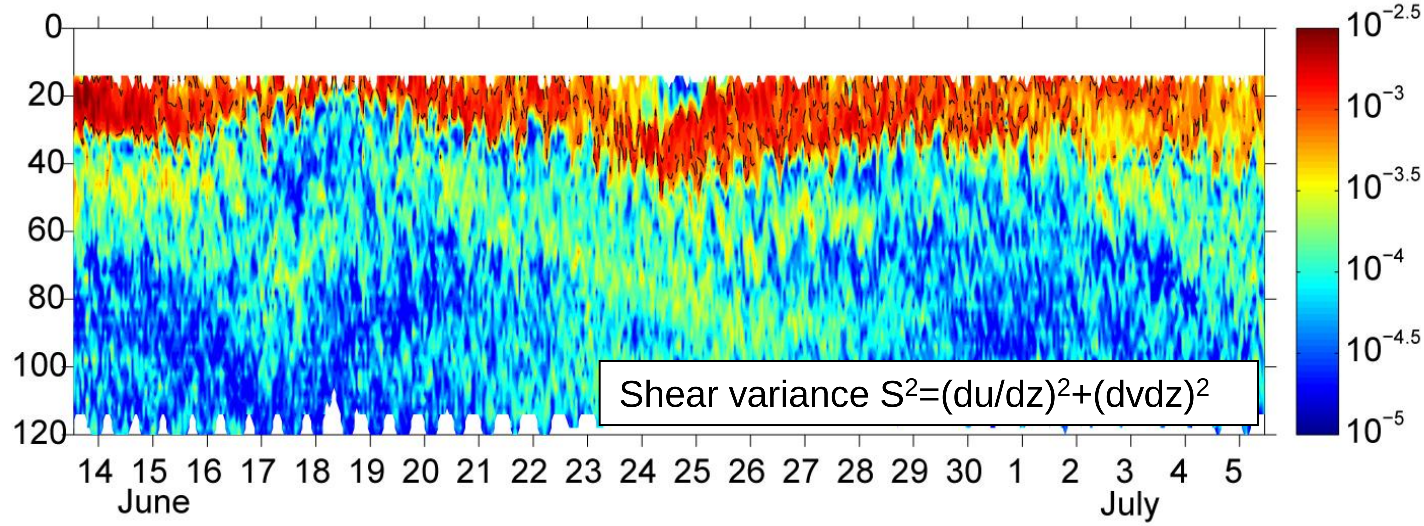


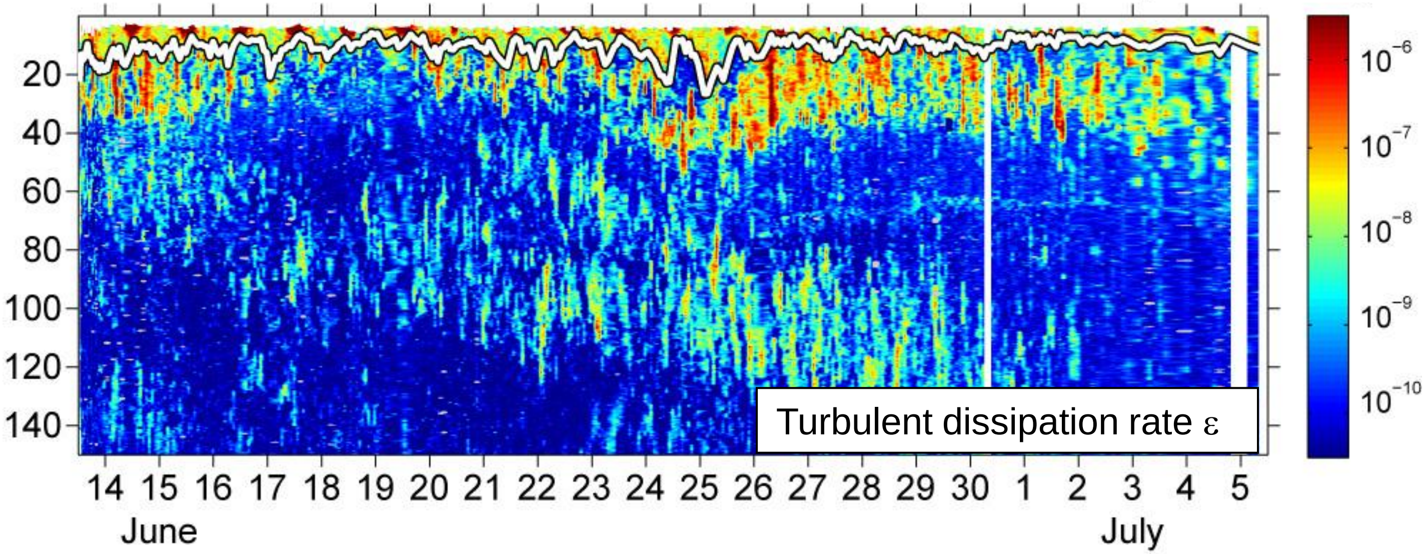
- elevated vertical shear of horizontal velocity at the base of the mixed layer extends from 3°S to 1.5°N
- elevated turbulence levels below mixed layer are found between 3°S and 1°N
- little mixing in stratified layer below MLD south of 4°N

(Hummels et al., 2013)

Vertical shear of horizontal current and turbulent kinetic energy dissipation rates

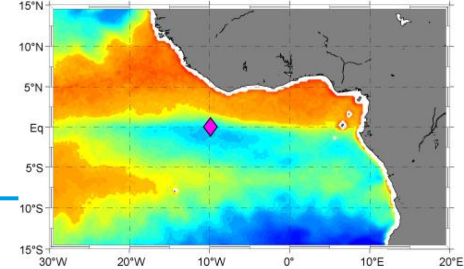


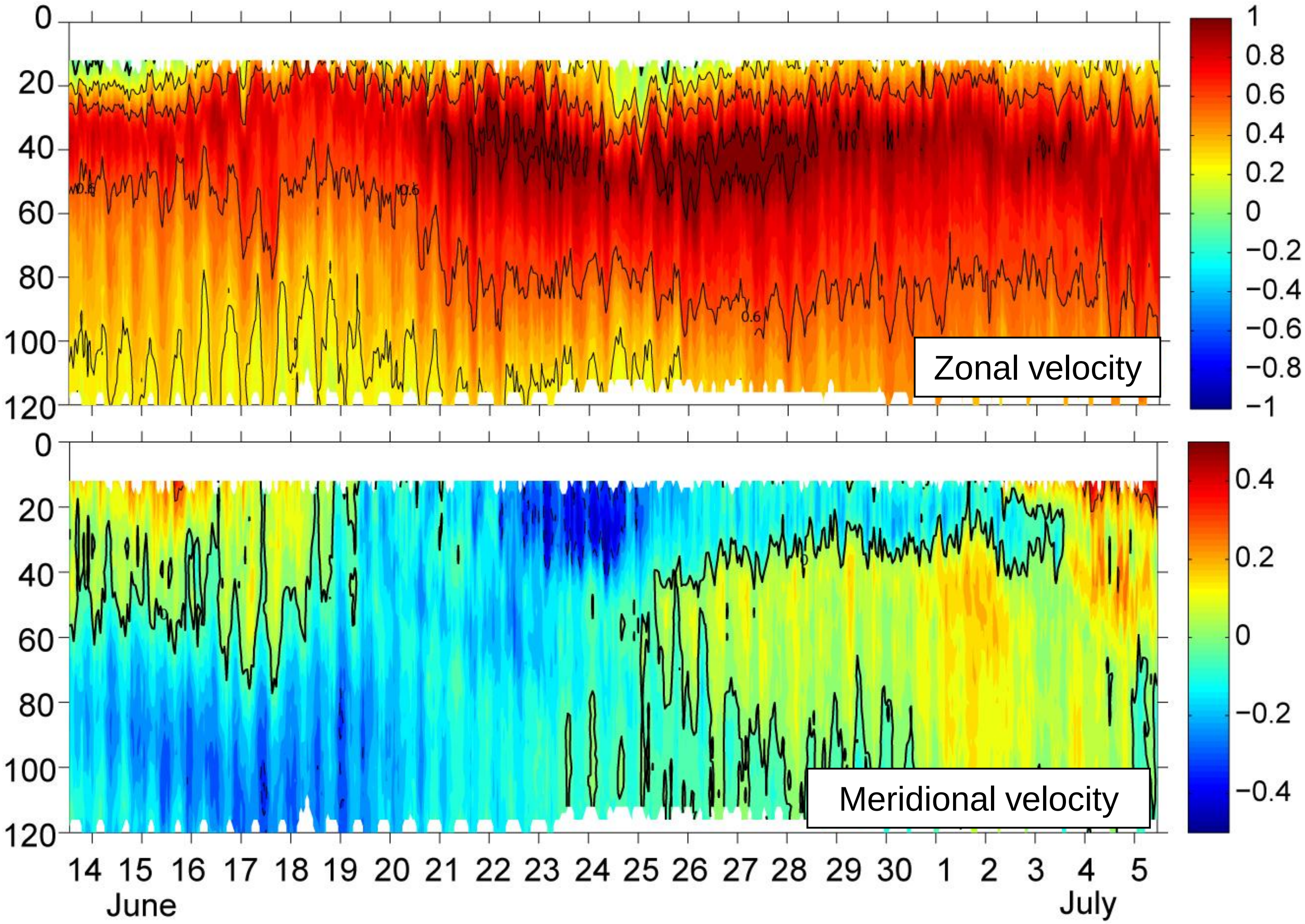




- elevated dissipation rates coincide with elevated shear variance
- bursts of elevated turbulence in the thermocline occur sporadically and last up to a few hours

Horizontal currents observed during the MircoRider/Glider mission





- Strong tidal currents in record with amplitude of ~8 cm s^{-1}
- core of the EUC located at 40m-60m depth

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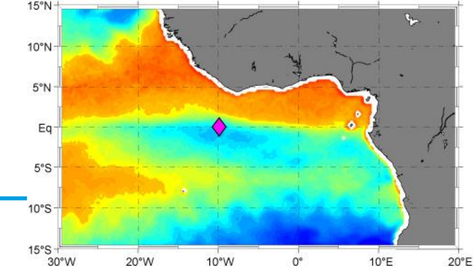
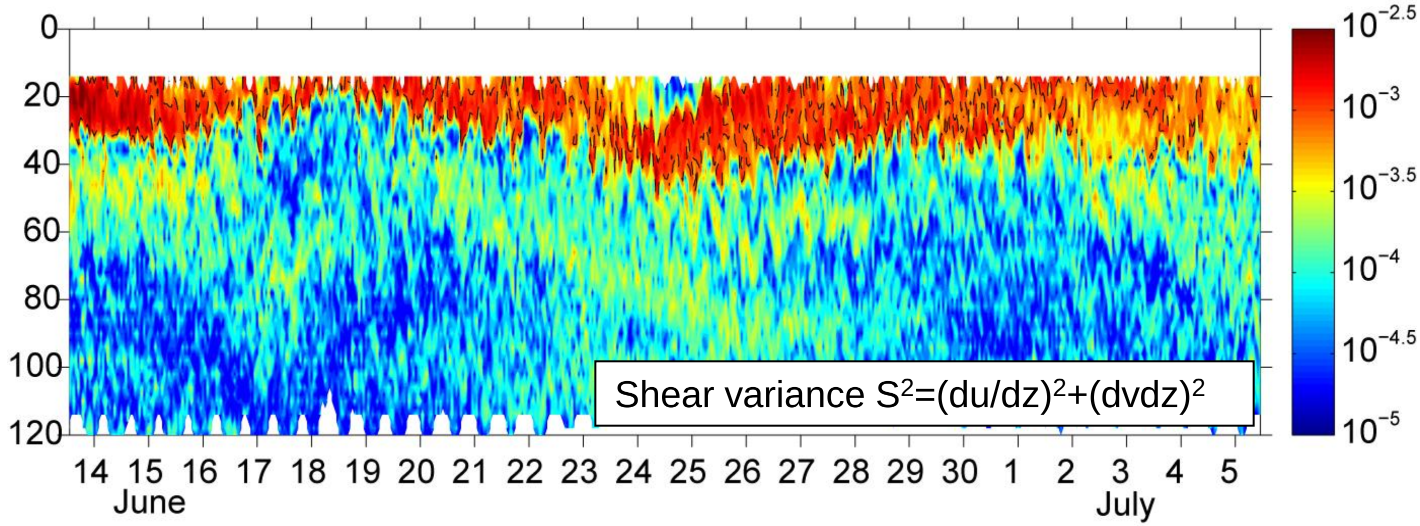
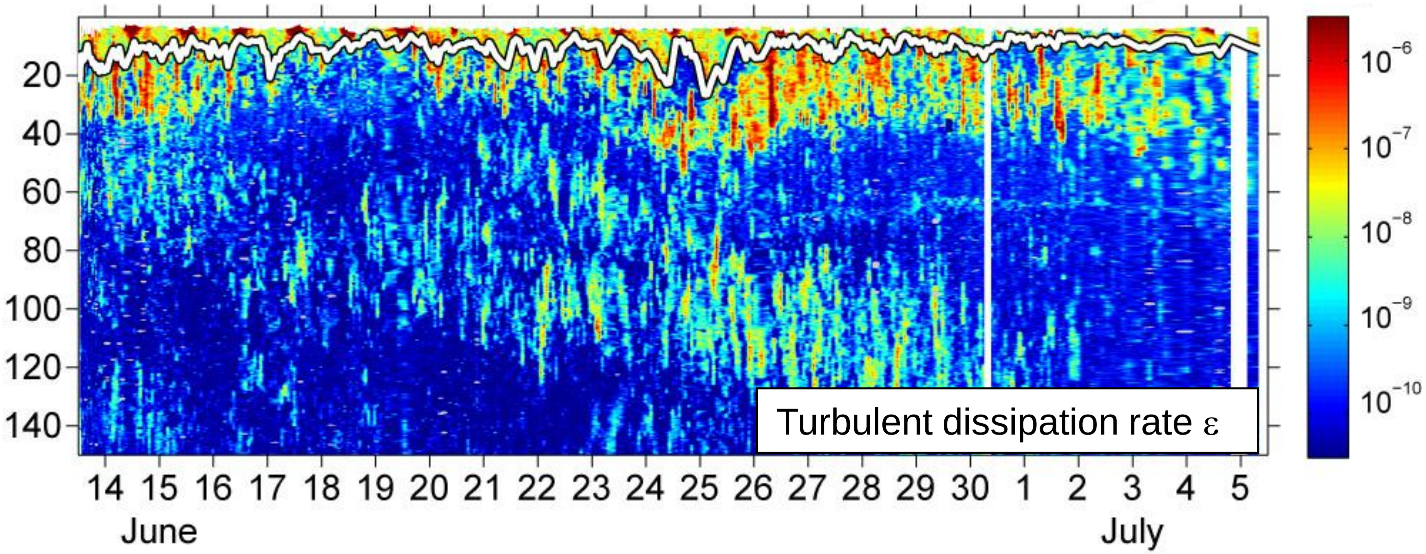
Vertical shear of horizontal current and turbulent kinetic energy dissipation rates

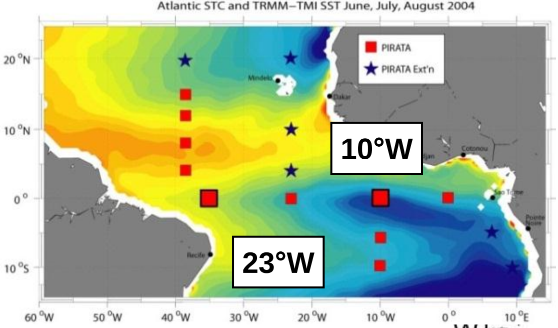






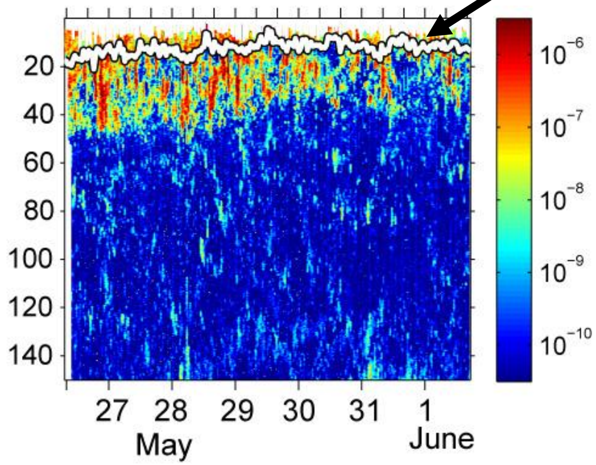
- elevated shear variance above the EUC core
- elevated dissipation rates coincide with elevated shear variance
- bursts of elevated turbulence in the thermocline occur sporadically and last up to a few hours

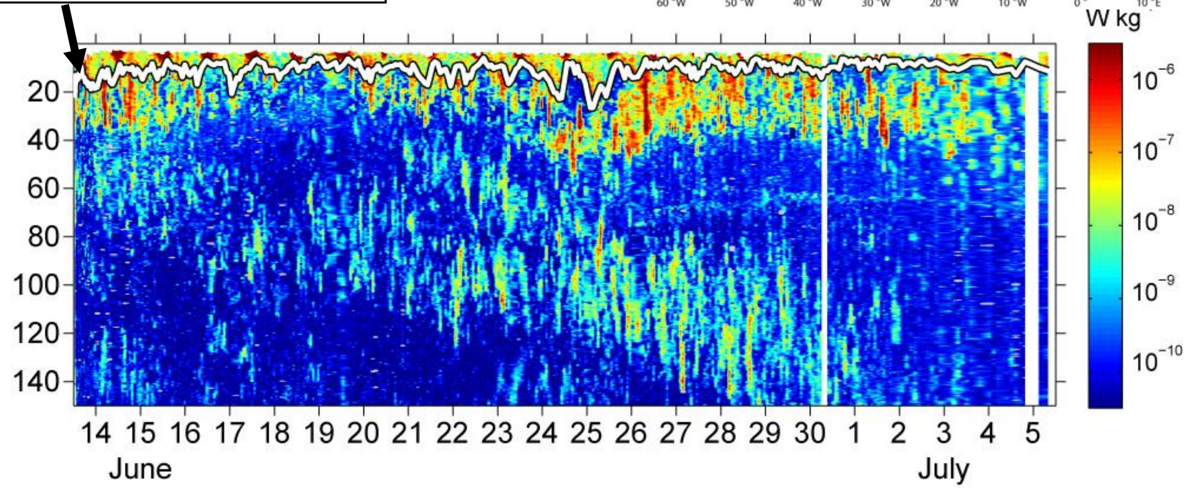
Time series of turbulent kinetic energy



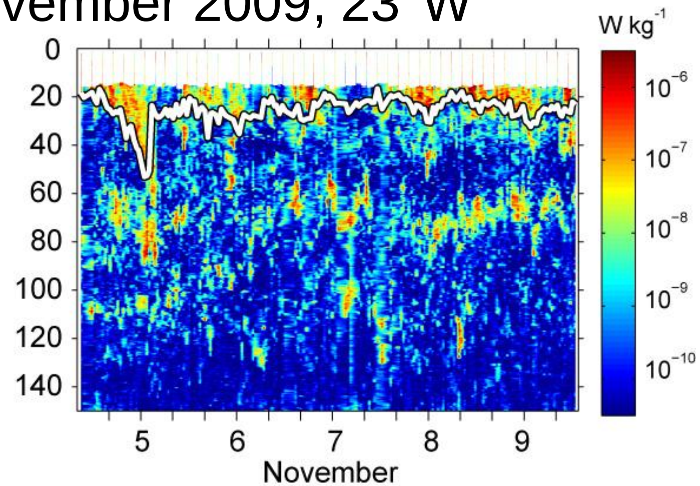
Mixed layer depth

May-July 2011, 10°W



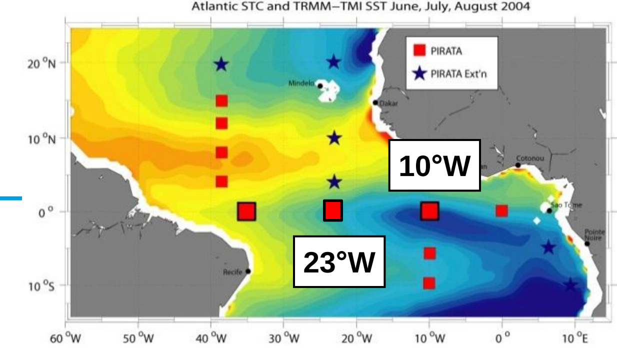


November 2009, 23°W



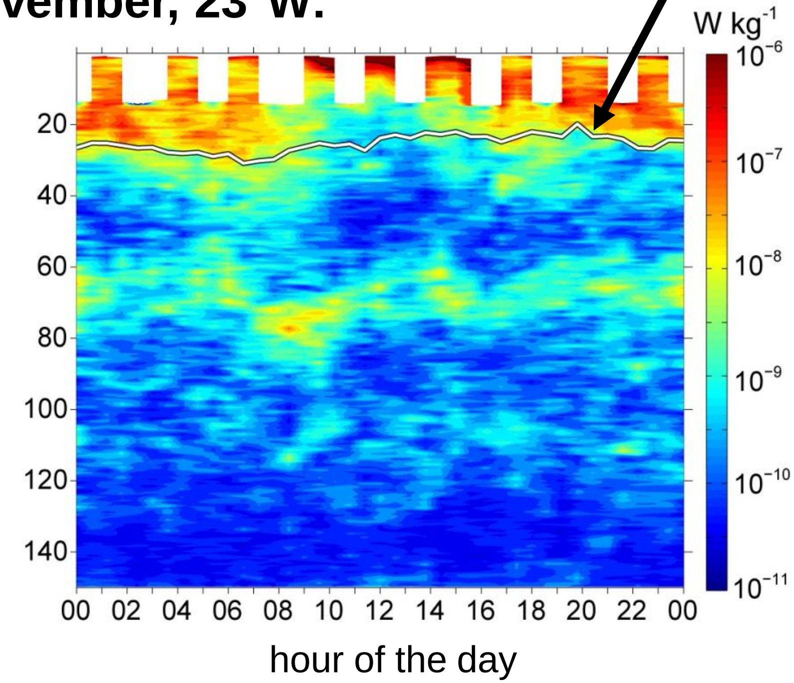
- strongly elevated dissipation rates (~1x10^{-4} Wkg^{-1}) in the mixed layer between 11am to 6pm
- at 10°W, elevated mixing levels (~1x10^{-6} Wkg^{-1}) below the mixed layer, particularly during night time
- at 23°W depth interval of low mixing disconnected from the mixed layer

Diurnal cycle of turbulent kinetic energy

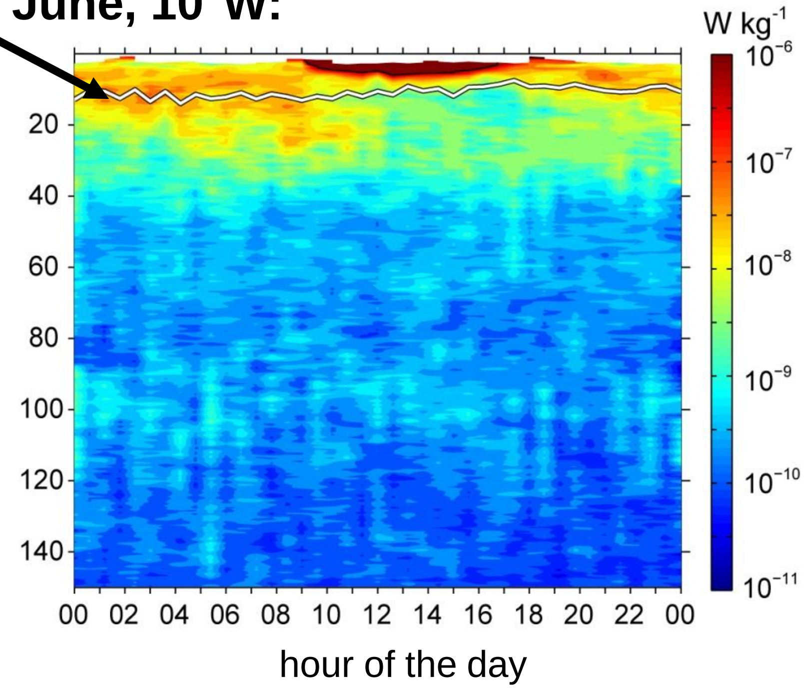


Mixed layer depth

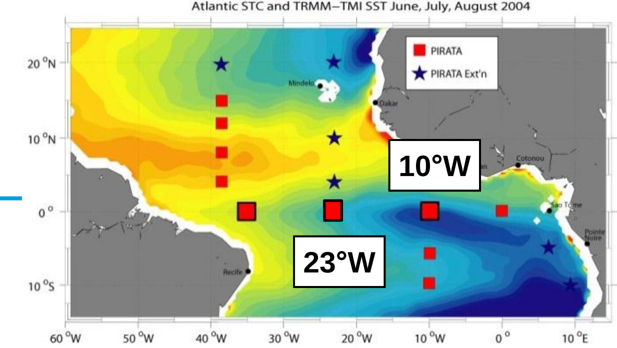
November, 23°W:



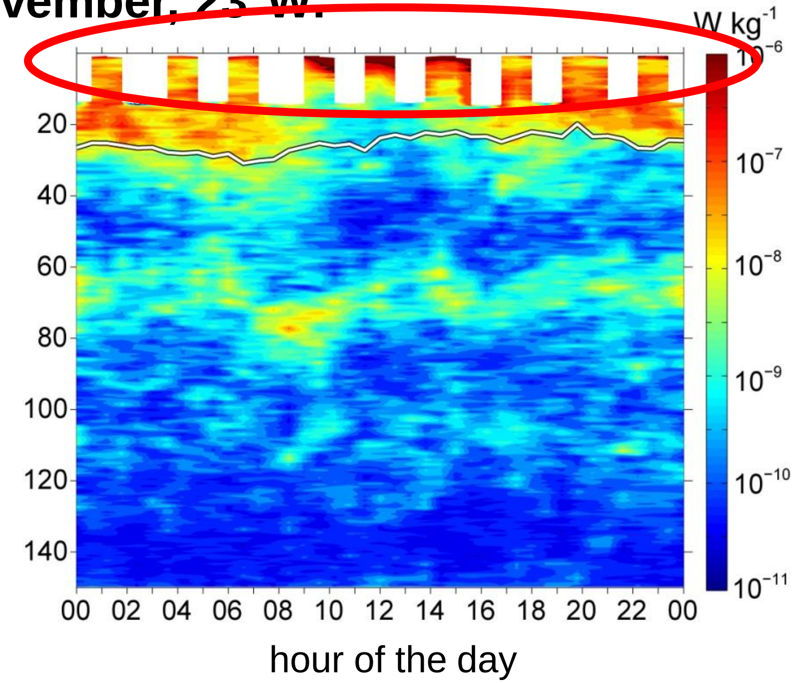
June, 10°W:



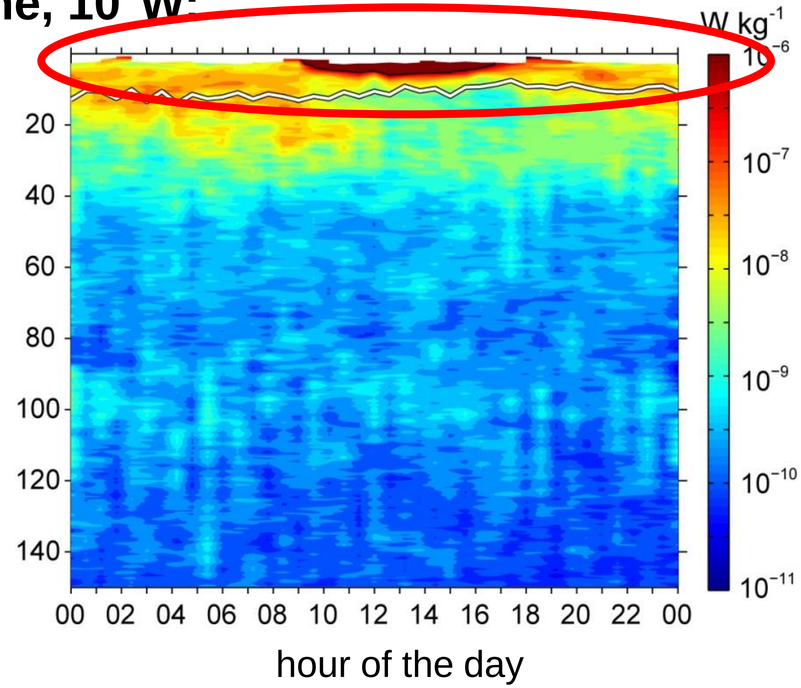
Diurnal cycle of turbulent kinetic energy



November, 23°W:

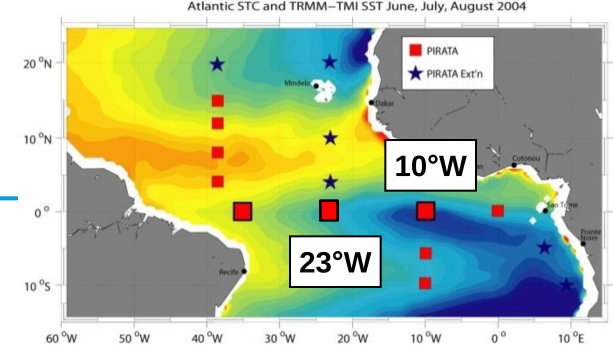


June, 10°W:

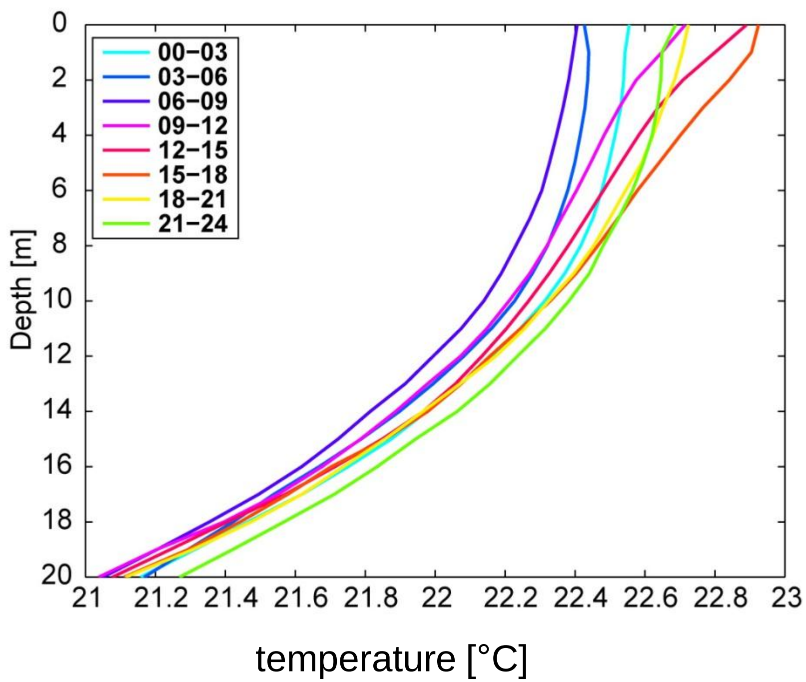


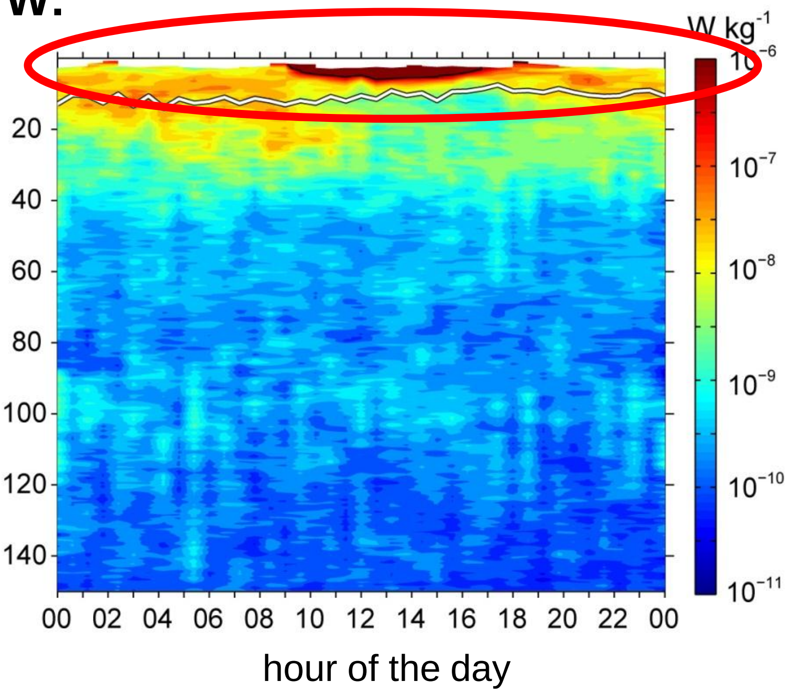
- At both location, strong mixed layer mixing occurs during day time from about 9am to 6pm.

Diurnal cycle of temperature and turbulent kinetic energy



June, 10°W:

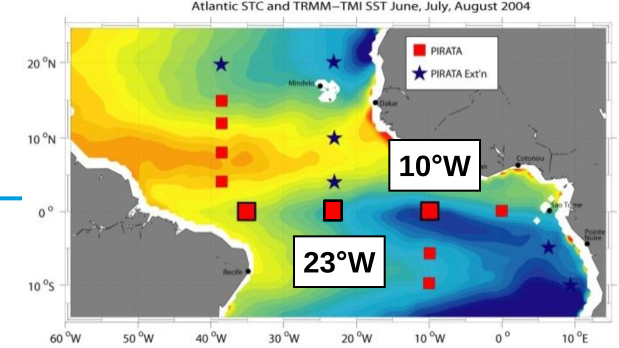




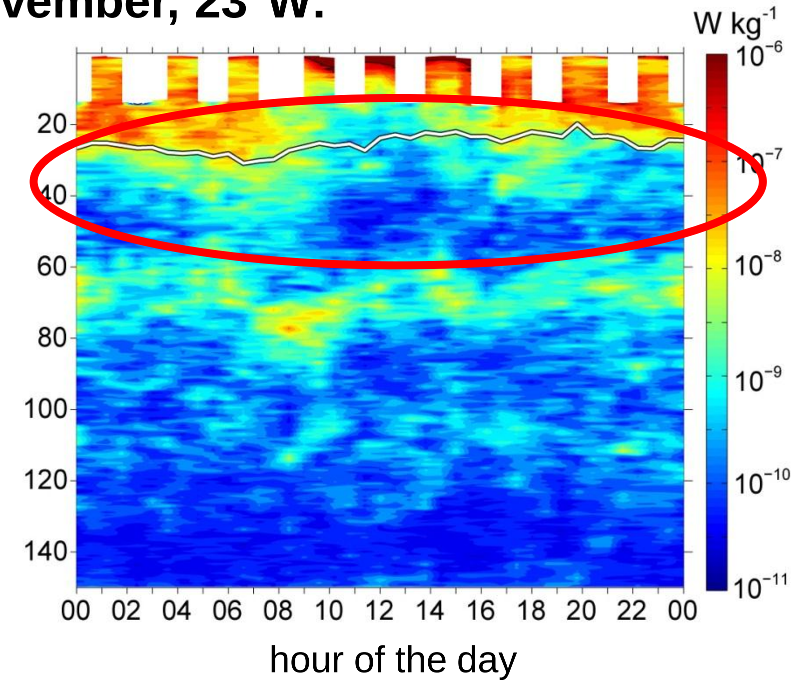
- concurrently, temperature in the upper 5 meters of the water column shows a diurnal cycle of 0.5°C. Strong stratification develops during day time.

➢ due to the stratified mixed layer, wind-induced vertical turbulent momentum transport is thus greatly inhibited leading to large shear.

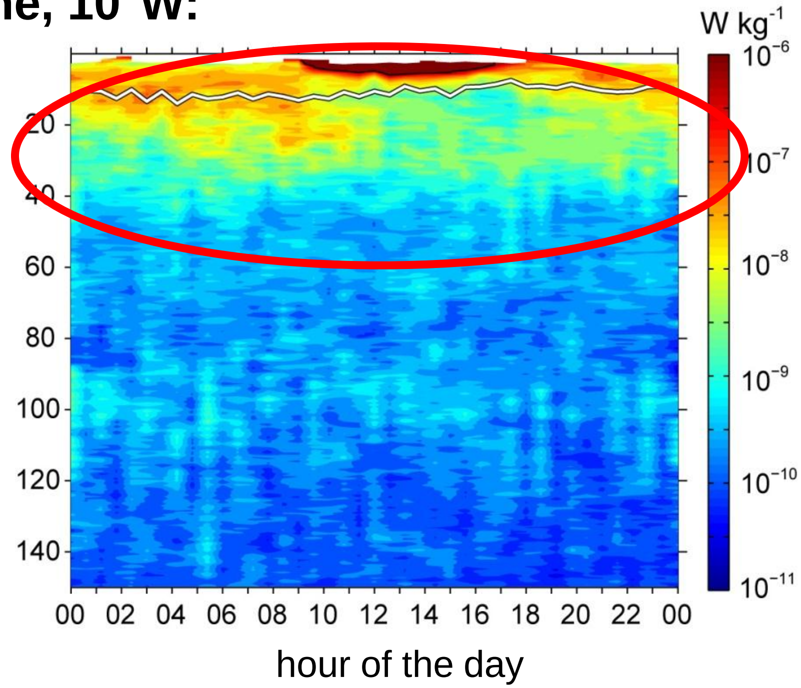
Diurnal cycle of turbulent kinetic energy



November, 23°W:



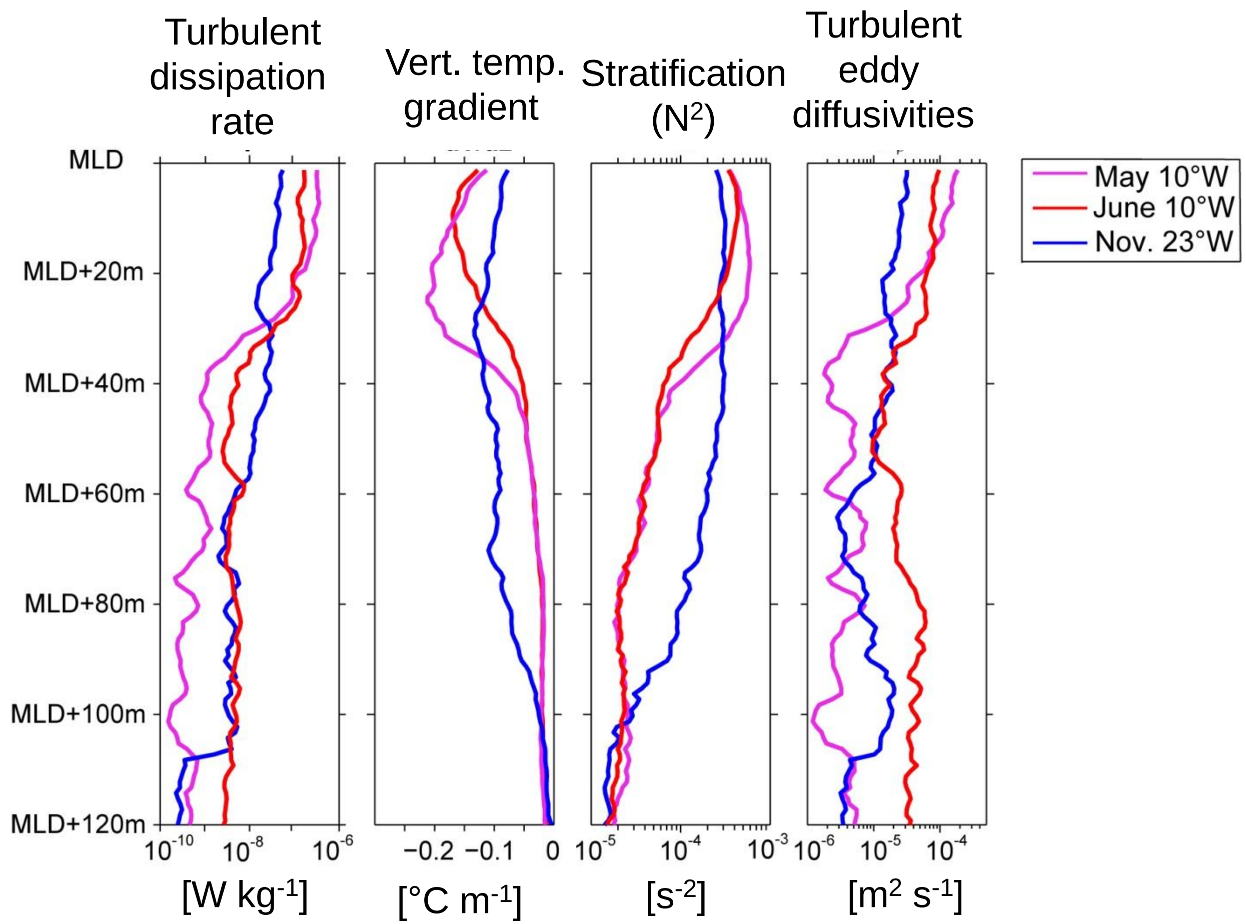
June, 10°W:



- first clear evidence of nighttime enhancement of mixing in the upper thermocline at both location.
- “Deep cycle turbulence” is stronger in the 10°W data from summer
- day and night differences about an order of magnitude

Average Mixing Quantities

- Summer upper ocean average turbulent dissipation rate an order of magnitude higher than at 23°W in Autumn.

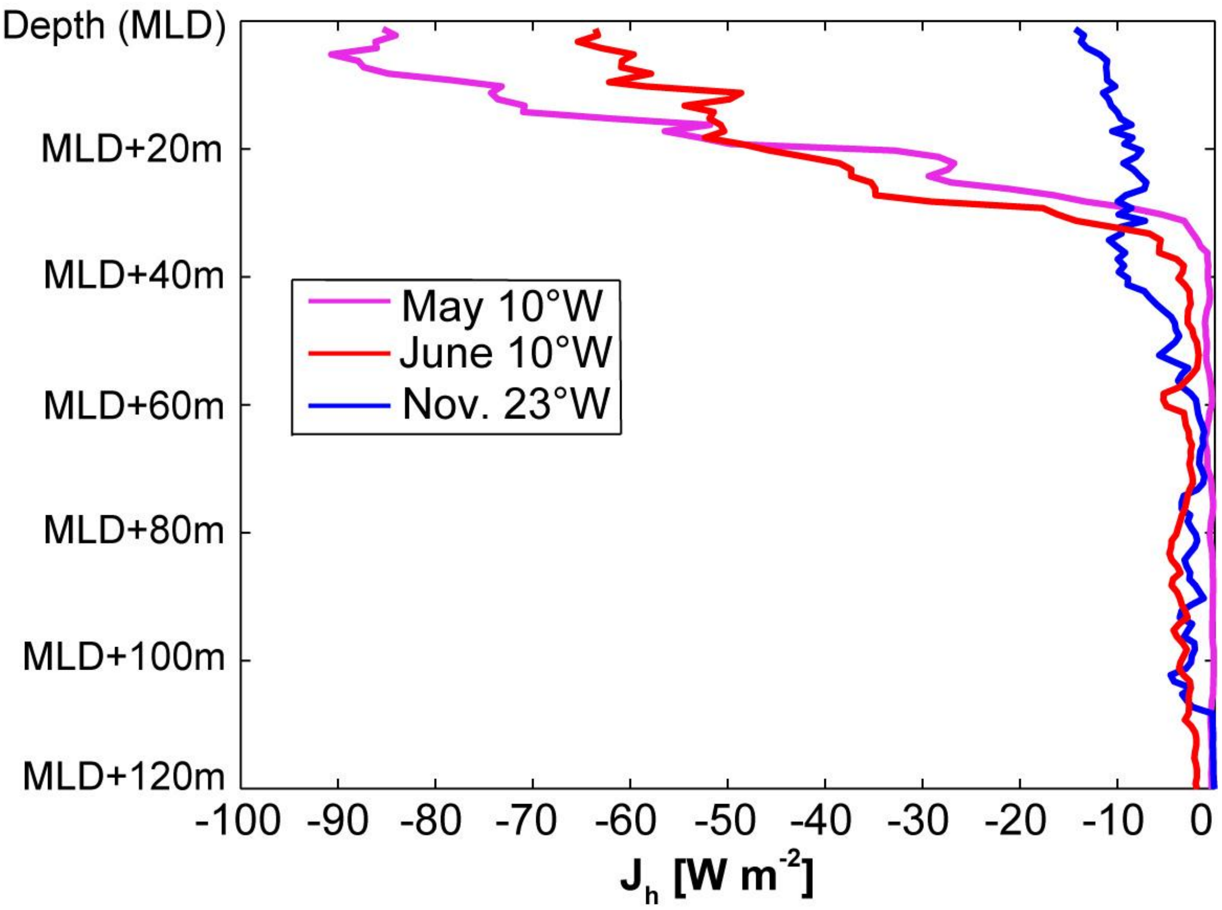


Turbulent heat flux divergence

- Average heat loss of the mixed layer due to turbulence:

  May (6 days) ~ 80W/m^2
  June (21 day) ~ 60W/m^2
  Nov.(6 days) ~ 15 W/m^2

- Mixed layer heat is redistributed to the upper 40m of the thermocline



Seasonal Variabilty of Mixing Parameters

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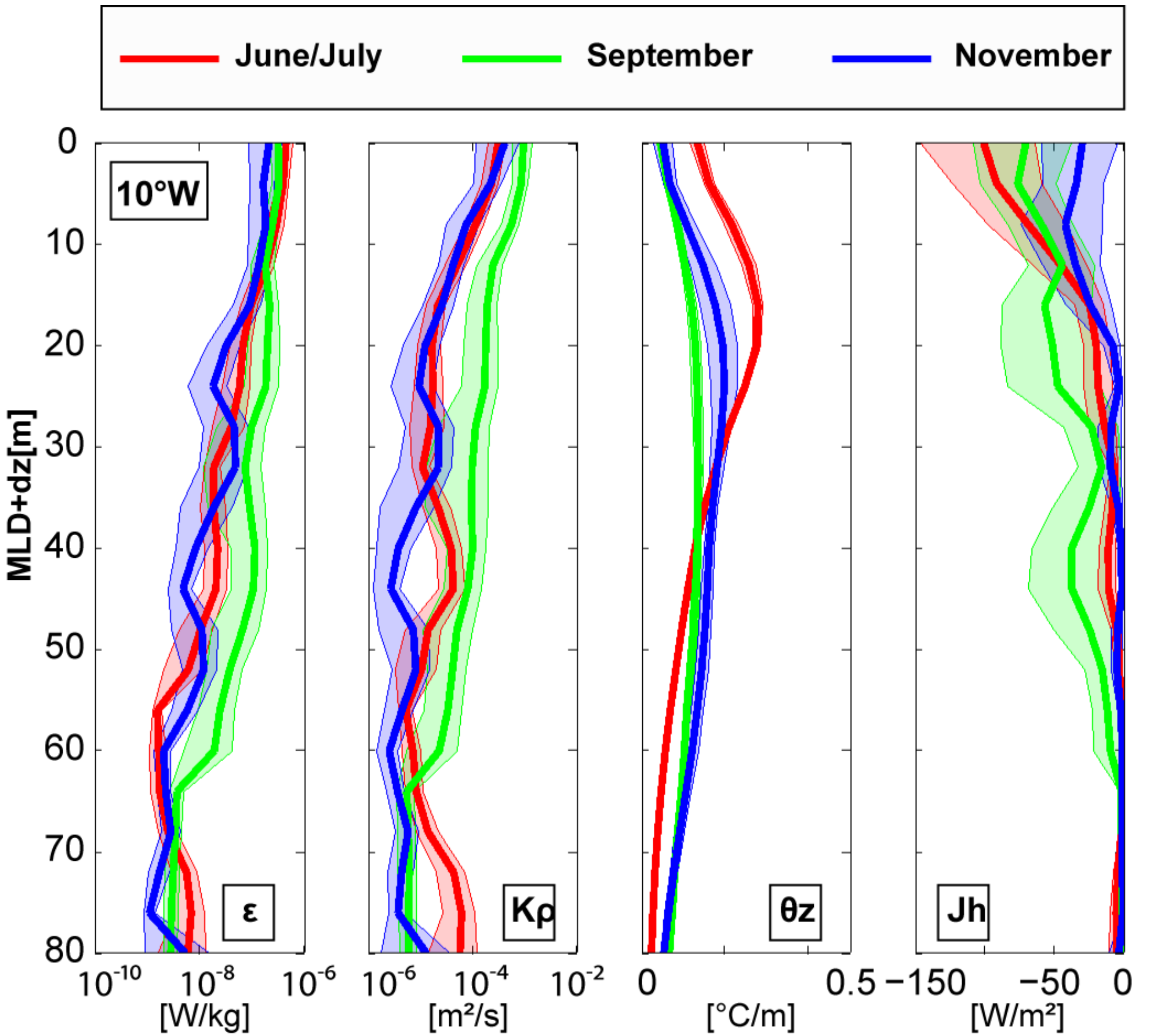
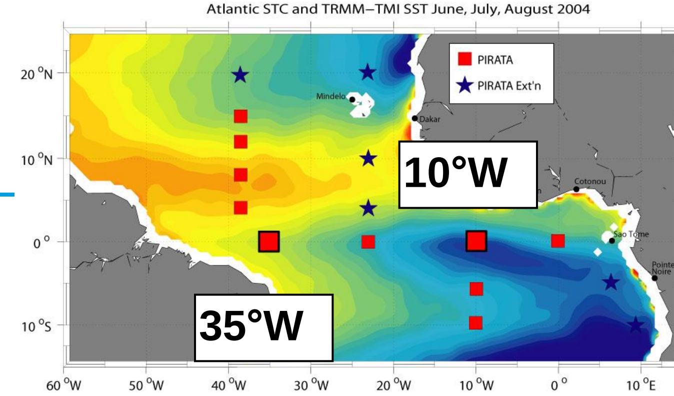


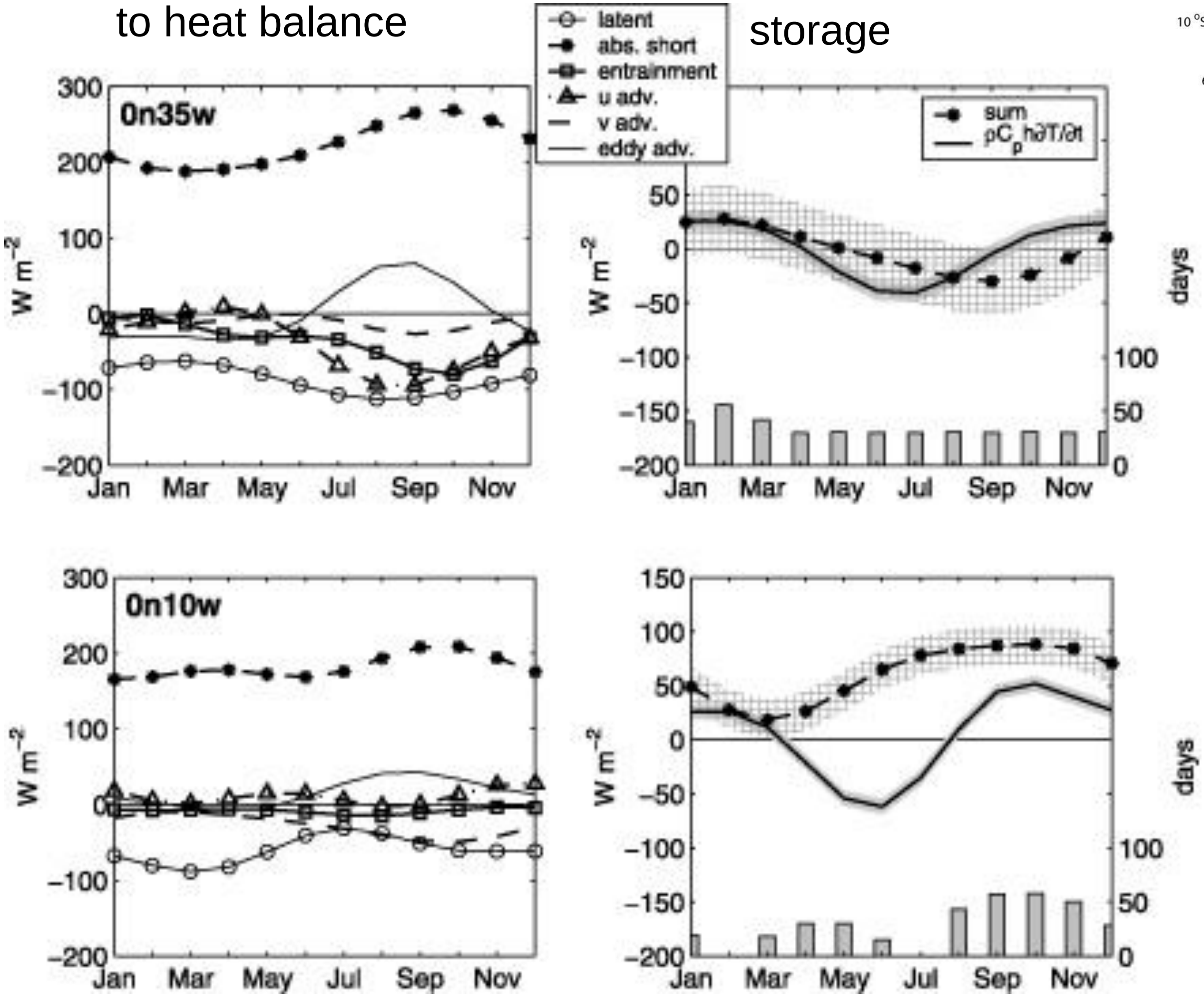
MSS data from 8 cruises from 10°W elevated dissipation rates from June to November resulting in a significant heat flux below the MLD

Recall:
Mixed Layer Heat Balance from Observations



individual contributions to heat balance

sum and local storage



Heat balance within the region of the equatorial cold tongue could not be closed

Study did not include estimates of turbulent heat flux at the base of the mixed layer

(Foltz et al., 2003)

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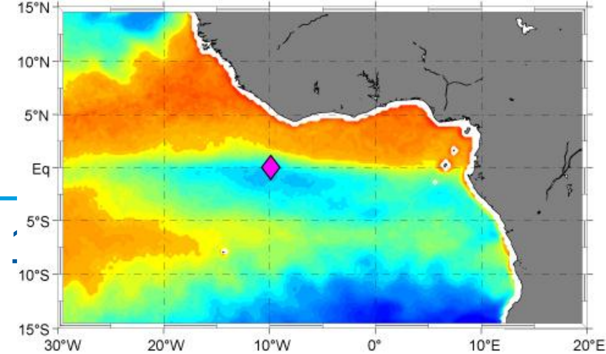
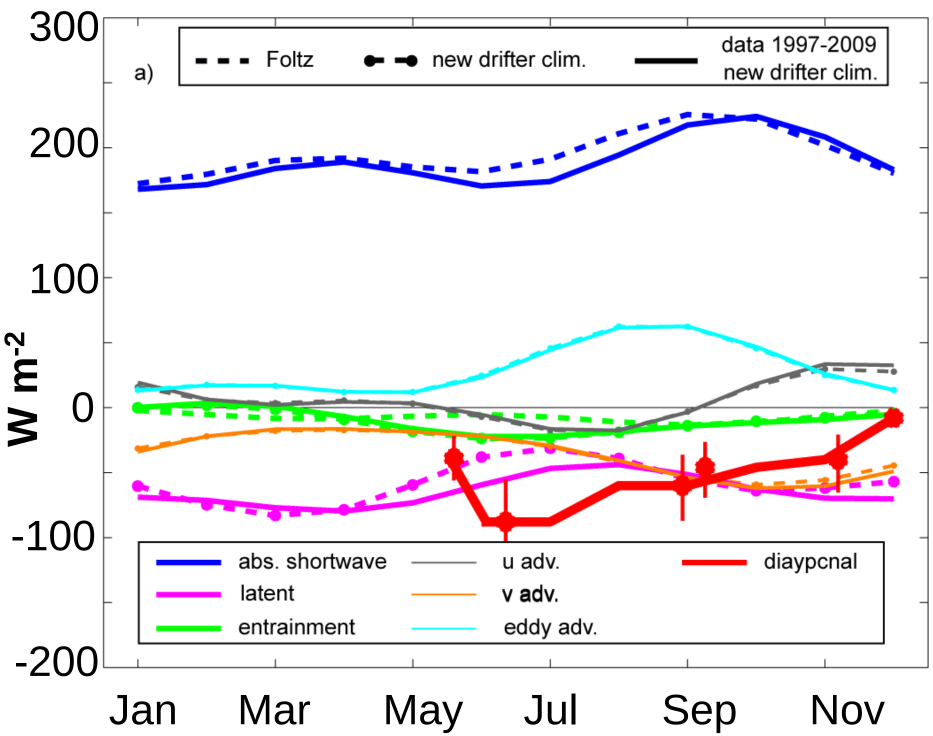
Conclusions Part I

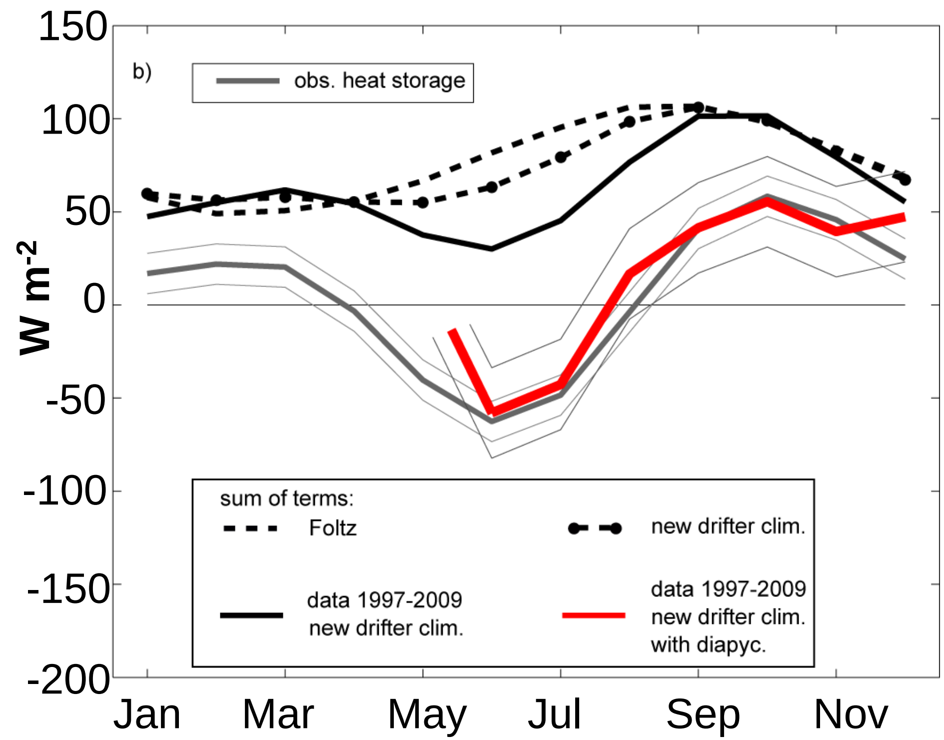
Seasonal cycle of mixed layer heat budget at 0°N,



Individual terms of mixed layer heat balance



Sum of terms and heat storage



(Hummels et al., 2013)

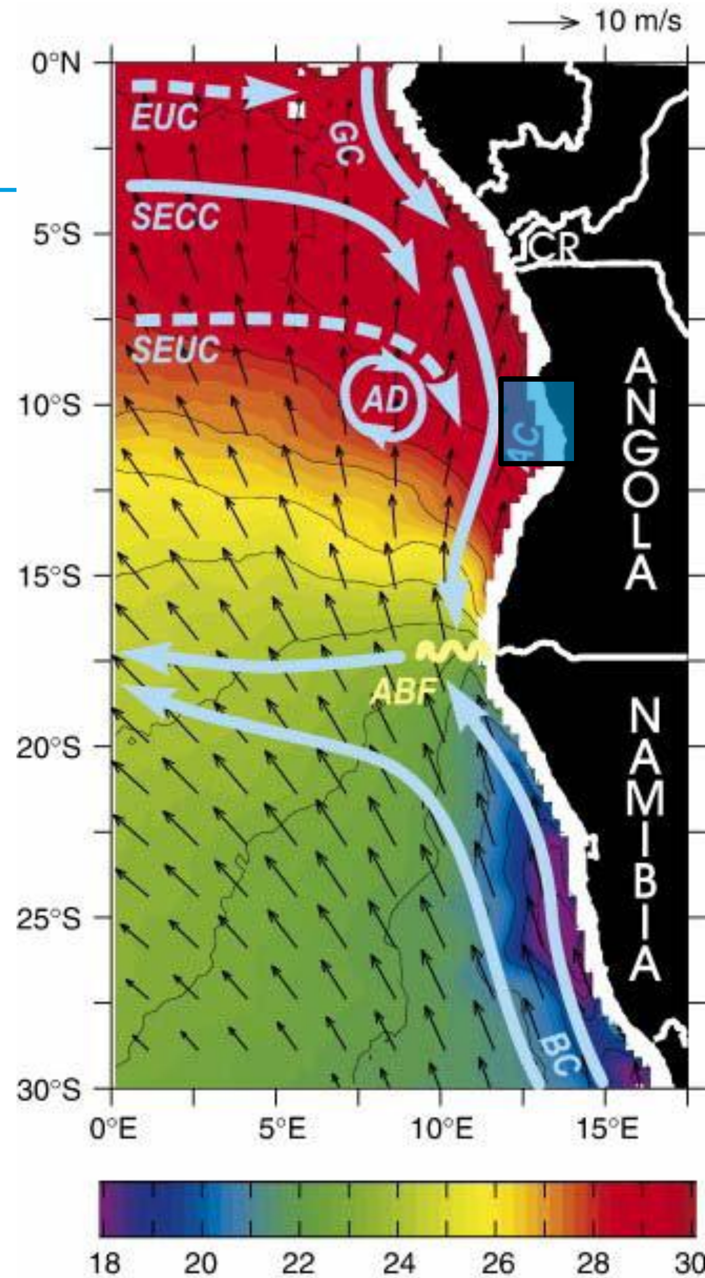
Roadmap

- Motivation: Tropical Atlantic Climate and mixed layer heat balance
- Mixing and diapycnal heat flux in the equatorial Atlantic
- Mixing and diapycnal heat flux on the shelf off Angola
- Conclusions

SST and Circulation off Angola

Southern eastern boundary current system at latitudes <15°S

- Winds are weak;
- Maximum "upwelling" i.e. coldest SSTs occur during July;
- Maximum alongshore wind stress occurs in April/May



(modified from Rouault et al. 2007)

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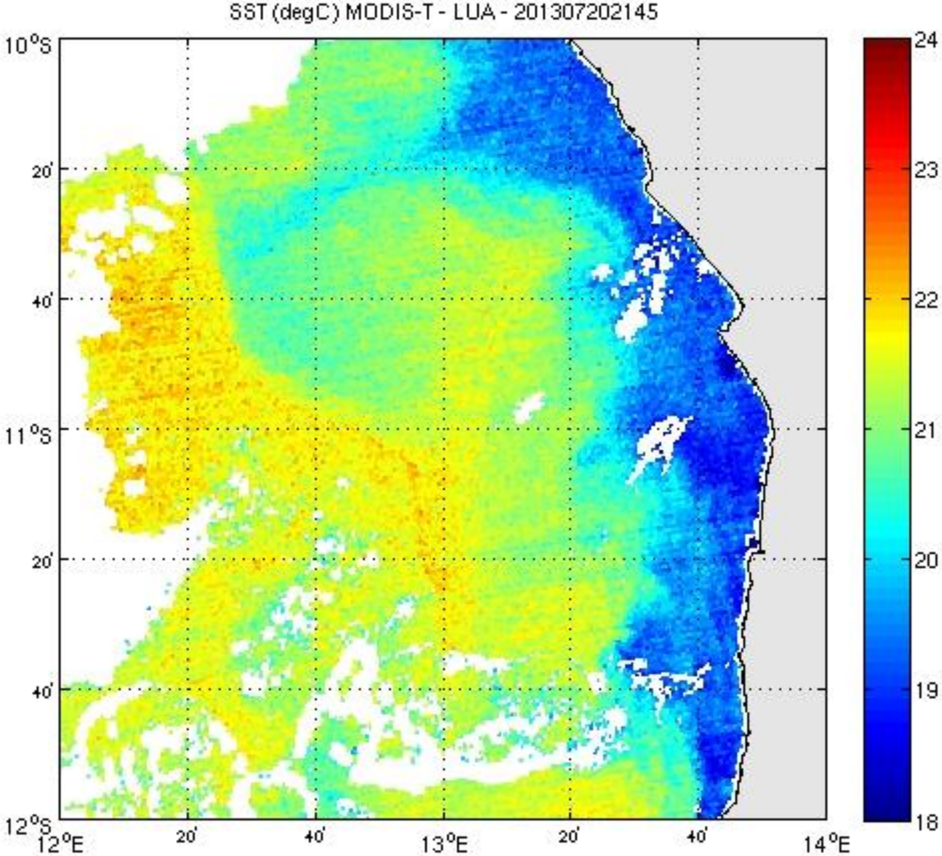
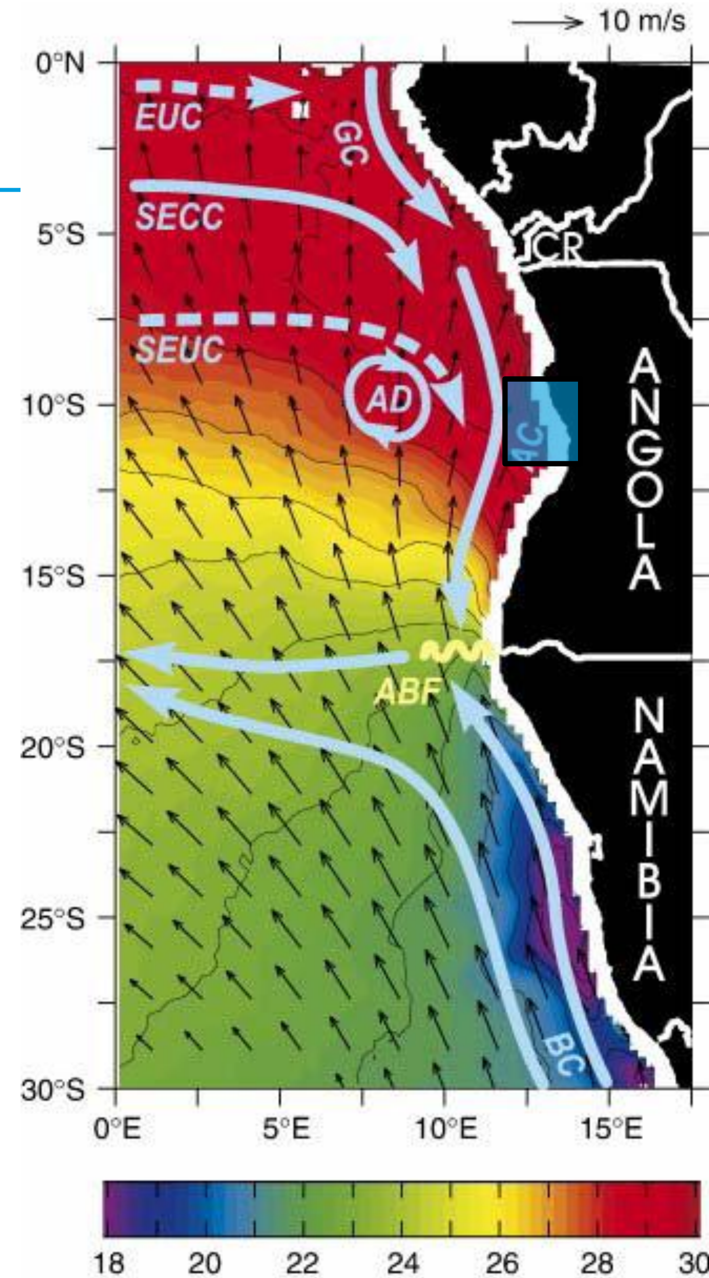
SST (10°S-12°S) and Circulation off Angola

SST during 20 July 2013



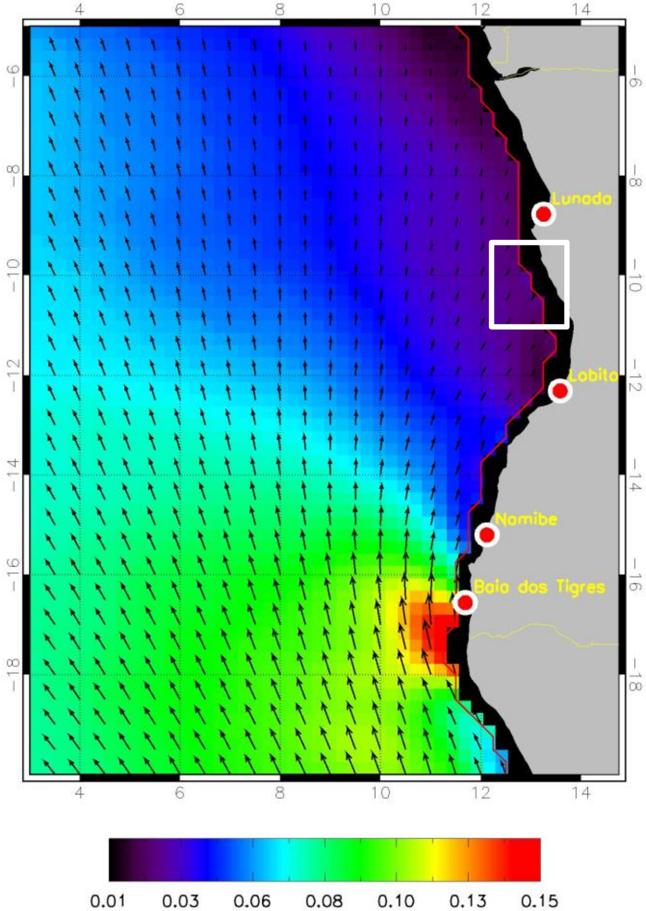


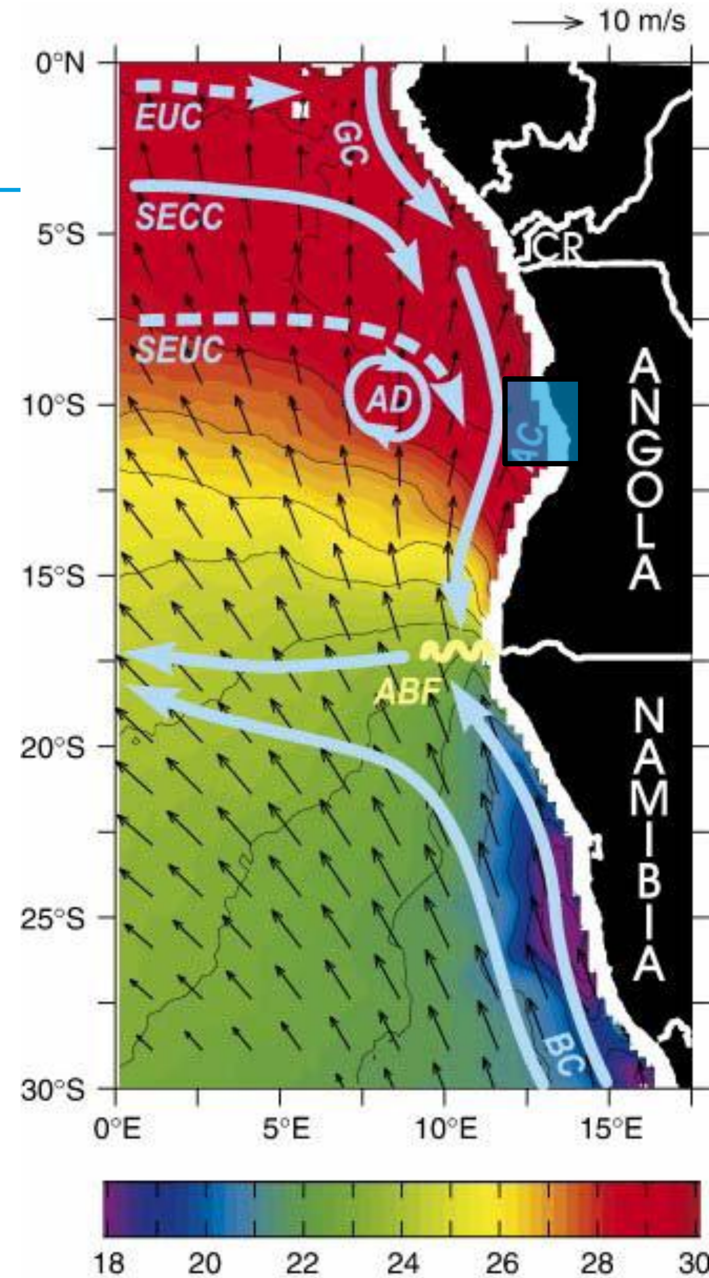
Cold SST are limited to shelf regions having Water depth <100m.

(modified from Rouault et al. 2007)

Wind stress and Circulation off Angola

Wind stress from SCOW climatology,
Rinsen and Chelton (2000)





(modified from Rouault et al. 2007)

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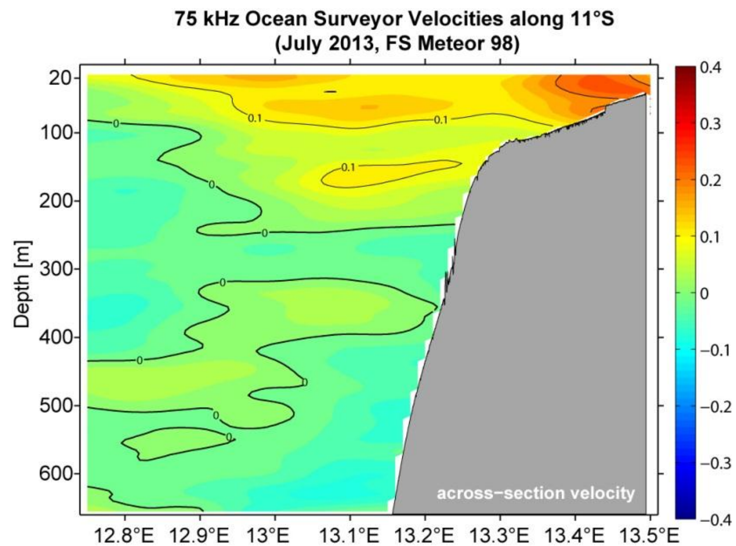
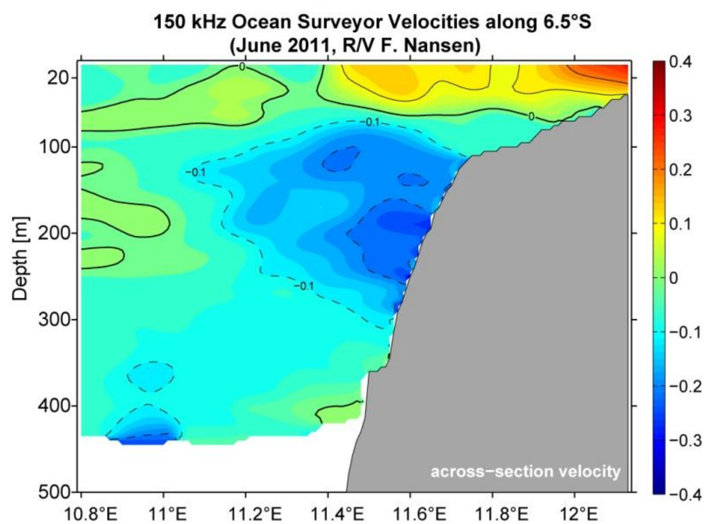
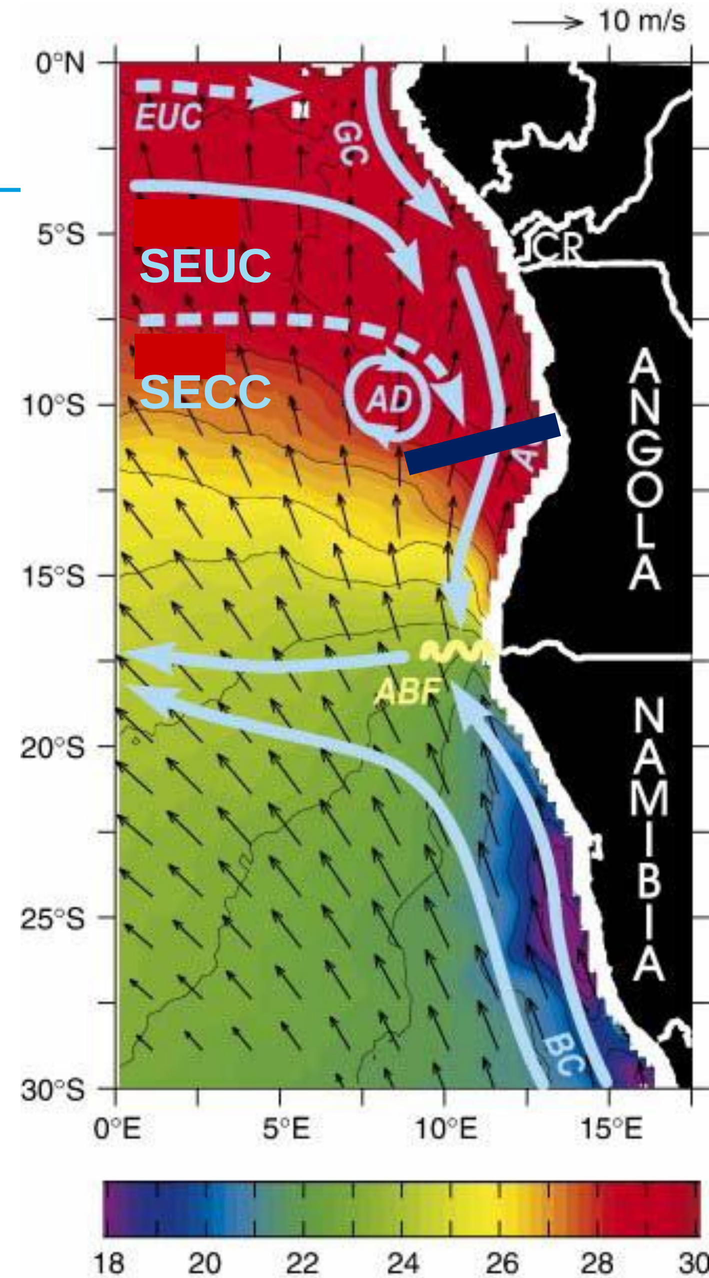
Circulation and SST of Angola

VM-ADCP measurements from July 2013 along the 11°S Section off Angola



VM-ADCP measurements from June 2011 (courtesy M. Ostrowski)





(modified from Rouault et al. 2007)

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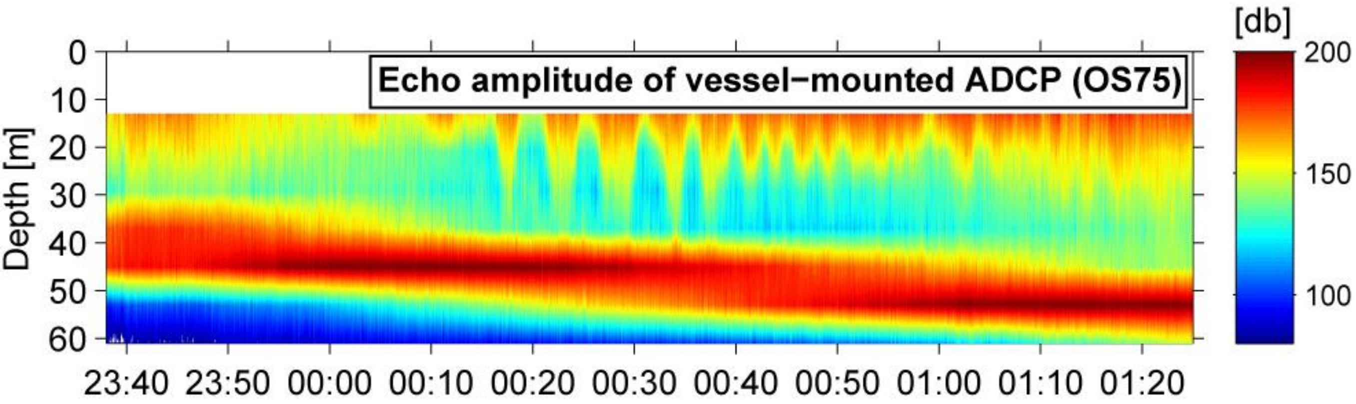
Convergence zones from tidal bores on the Angolan Shelf

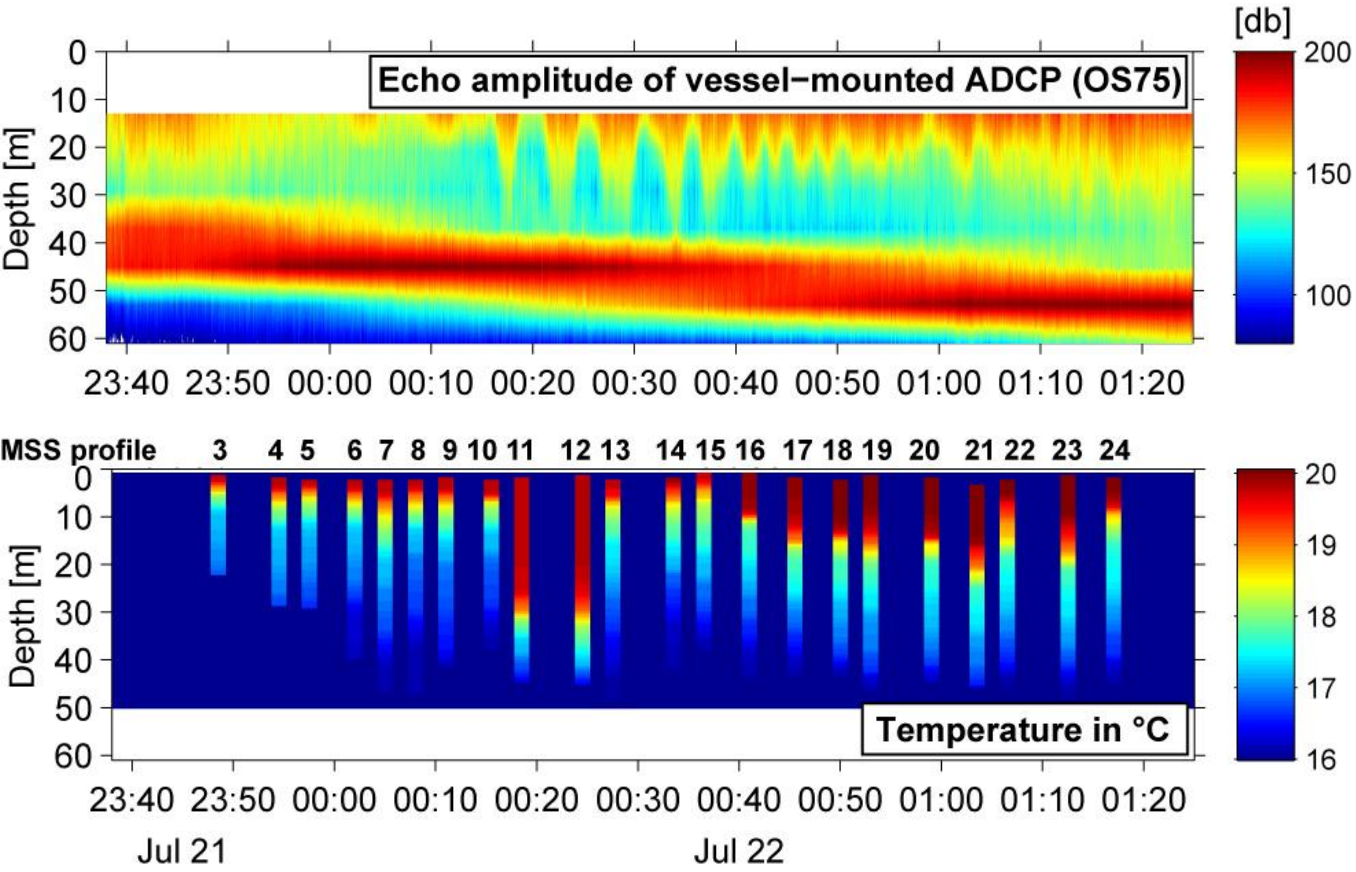
Photo: Marek Ostrowski

Tidal bores as observed by VM-ADCP



Echo amplitude of VM-ADCP measurements (OS 75) during a microstructure station on the shelf at 11°S.

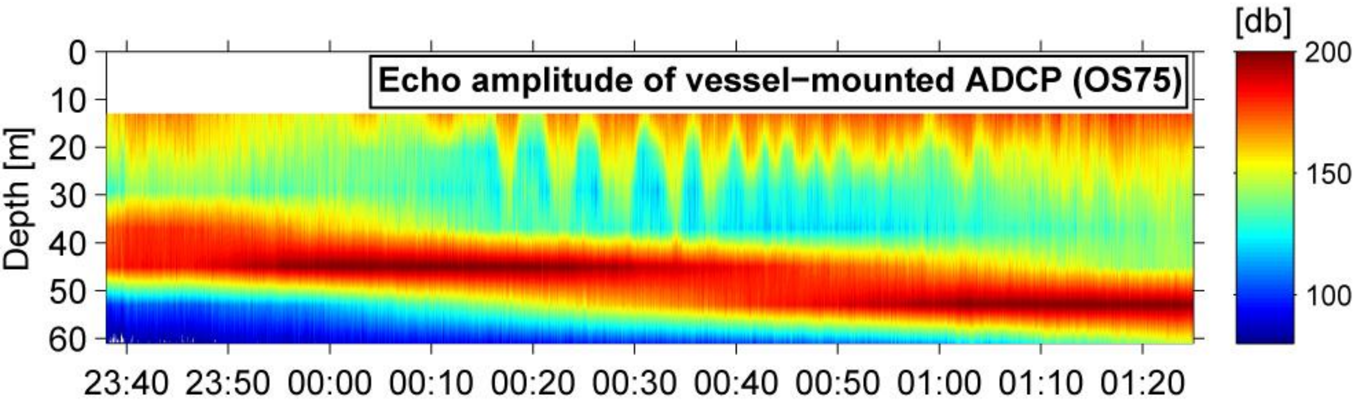
Tidal bores as observed by VM-ADCP and temperature profiles from MSS measurements



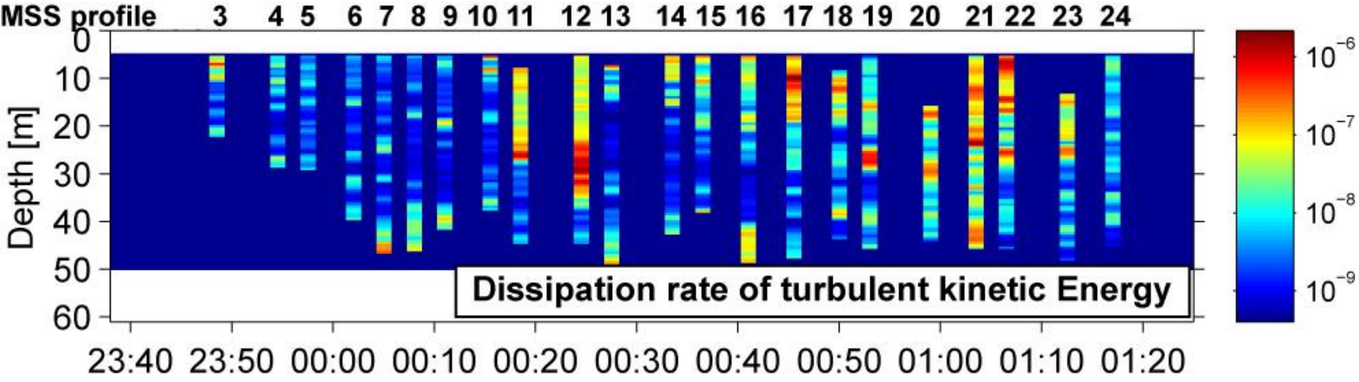
Echo amplitude of VM-ADCP measurements (OS 75) during a microstructure station on the shelf at 11°S

Temperature profiles as measured by the MSS probe. The warm surface waters nearly fill the whole water column during the presence of the bores.

VM-ADCP Echo Amplitude and Dissipation Rates of Turbulent Kinetic Energy

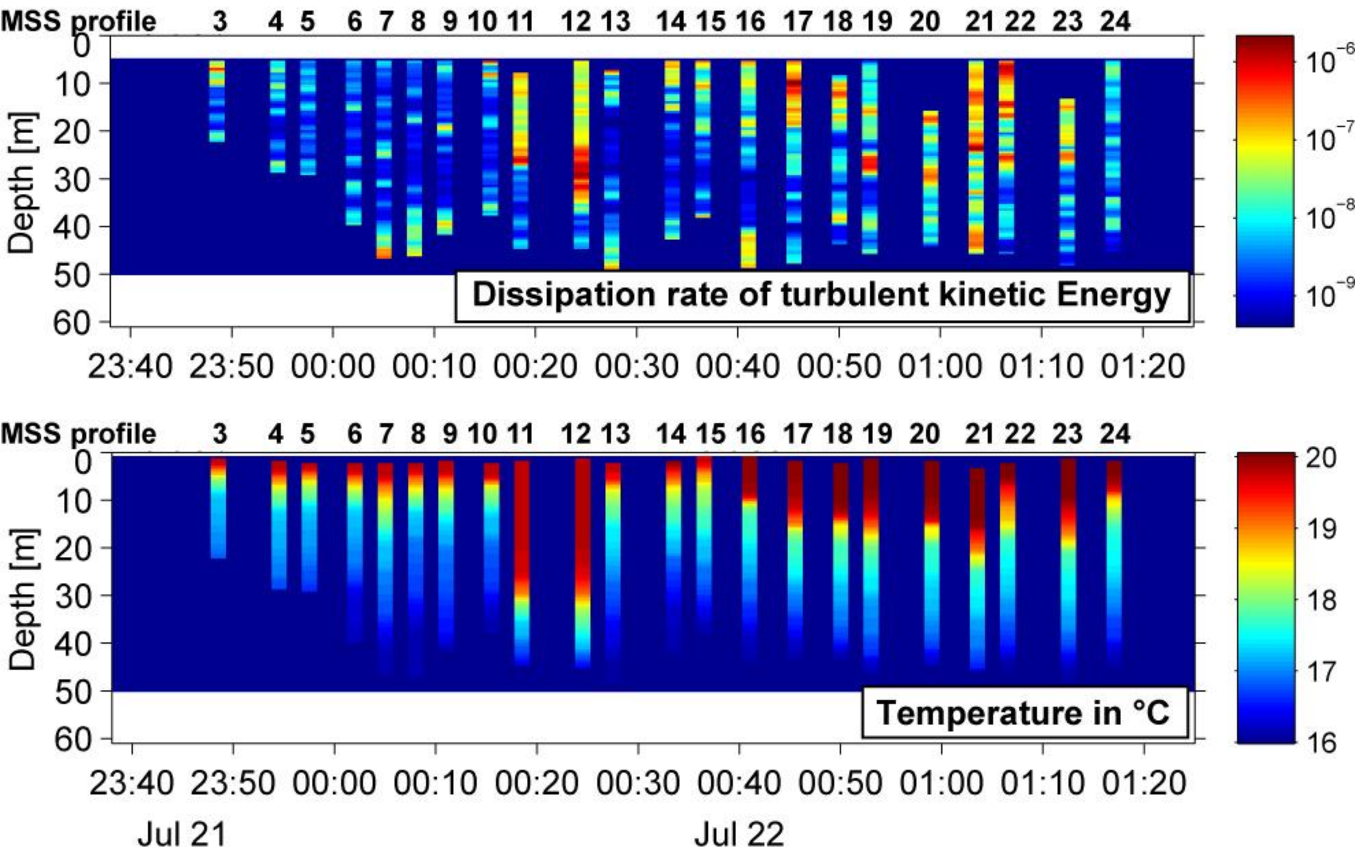


Echo amplitude of VM-ADCP measurements (OS 75) on the shelf at 11°S



Dissipation rates of turbulent kinetic energy . Enhanced mixing is indicated during the presence of the bores

TKE-Dissipation Rates and temperature profiles from MSS measurements

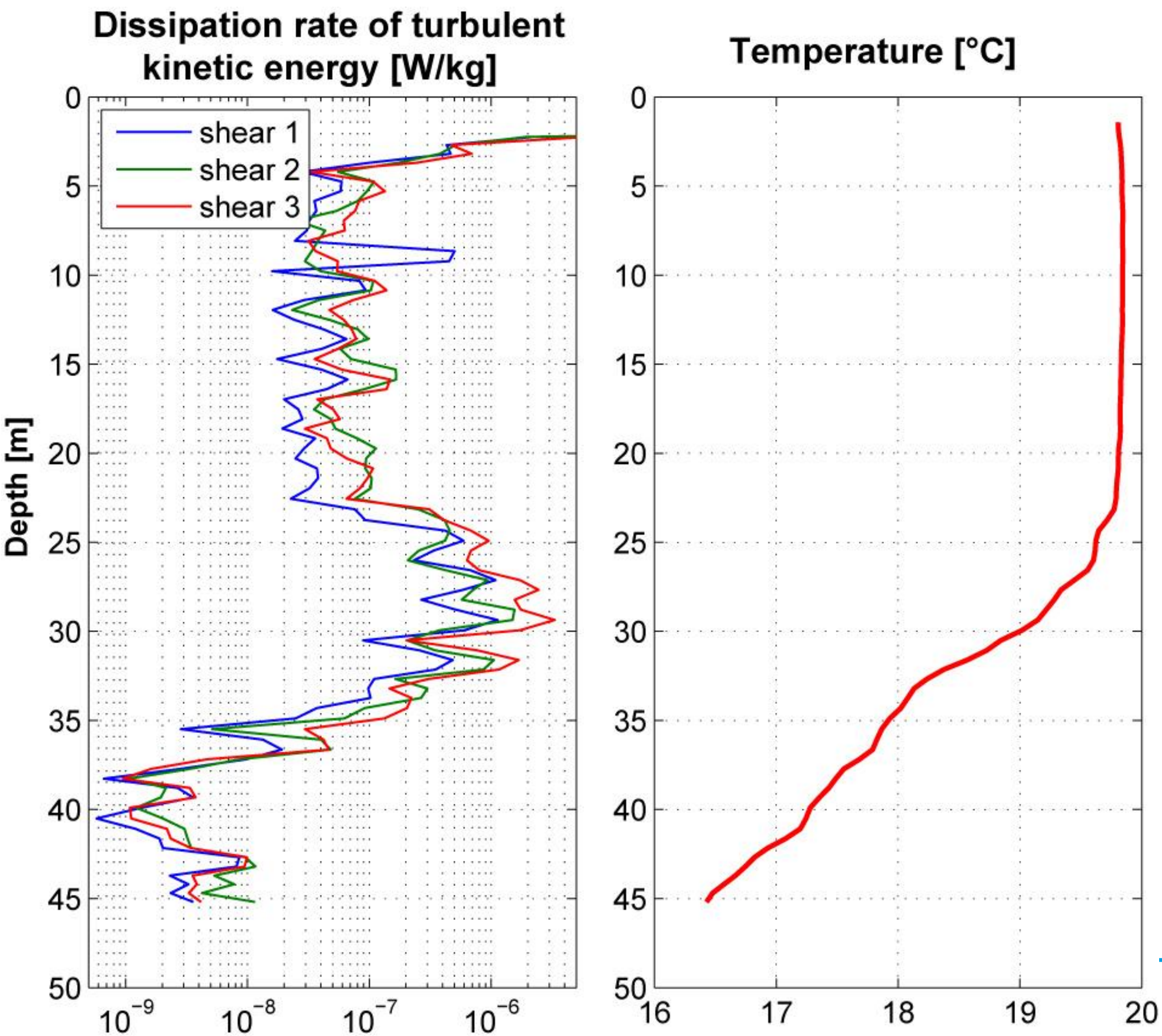


Enhanced mixing is observed during the periods of strong displacements of the thermocline.

Thermocline displacements are only of short duration.

MSS Measurements within a Solitary Wave

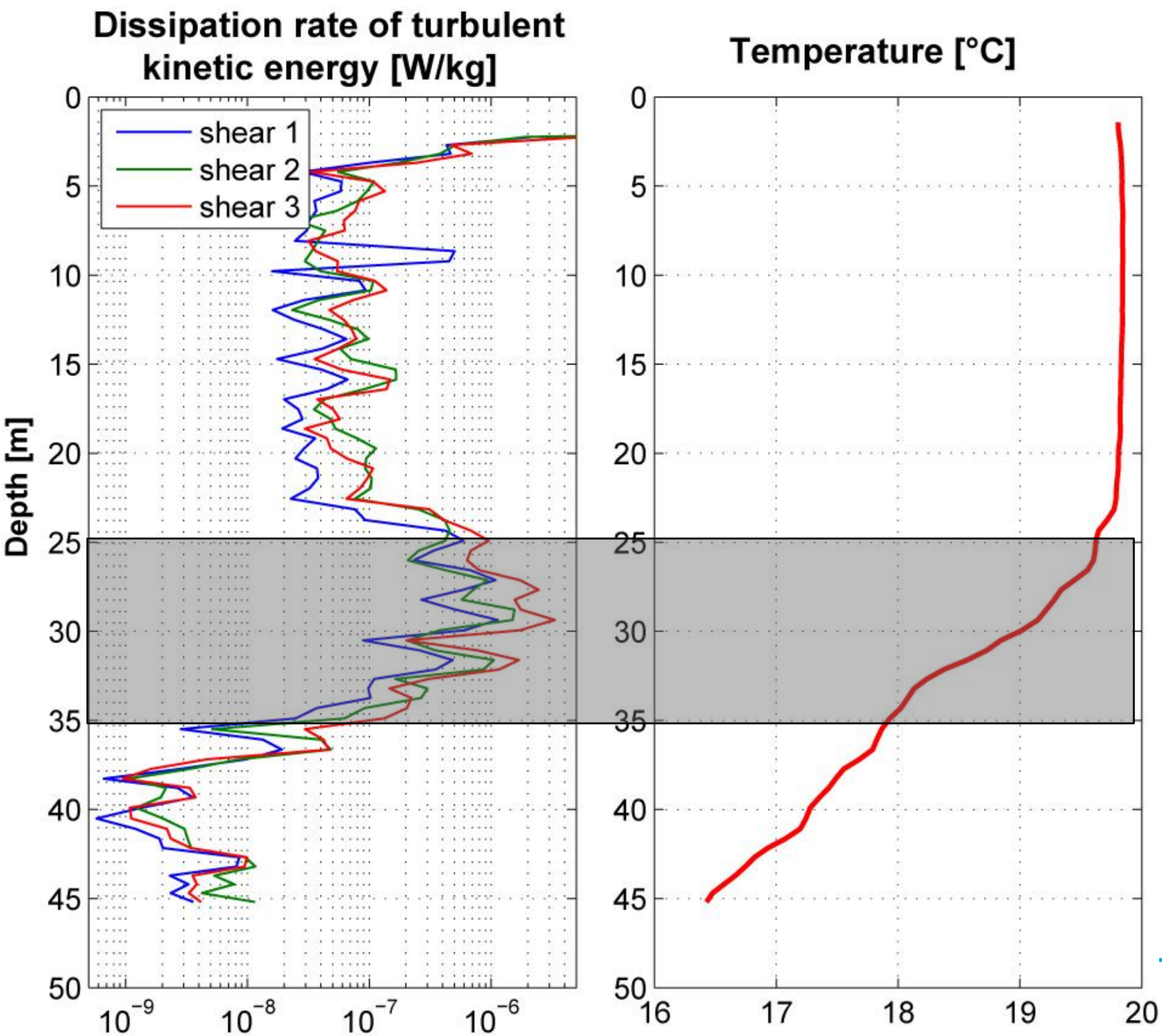
MSS Profile 12



During the presence of the bores, elevated mixing occurs in the region of high temperature gradients.

MSS Measurements within a Solitary Wave

MSS Profile 11



Diapycnal heat flux:

$J_h = \rho\ c_p\ K_\rho\ dT/dz$

$dT/dz = -0.1859\ Km^{-1}$

$K_\rho = 3.64 \times 10^{-4}\ m^2 s^{-1}$

$c_p = 3.99 \times 10^3 J\ kg^{-1} K^{-1}$

$\rho = 1025\ kg/m^3$

➢ $\mathbf{J_h = -\ 280\ W\ m^{-2}}$

Solibore mixing contributes significantly to mixed layer heat balance!!!

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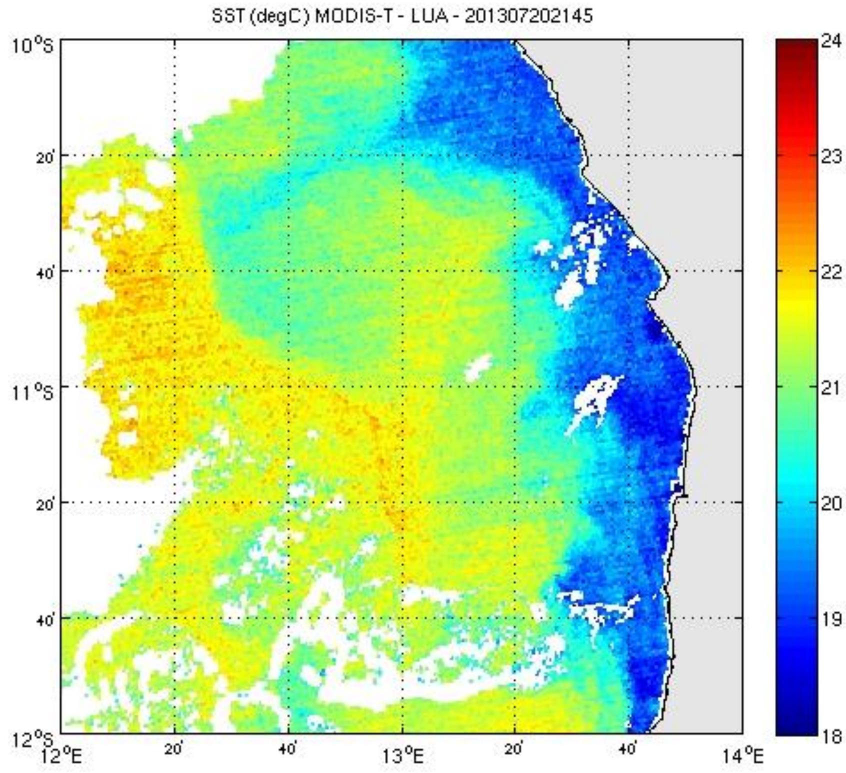
Conclusions

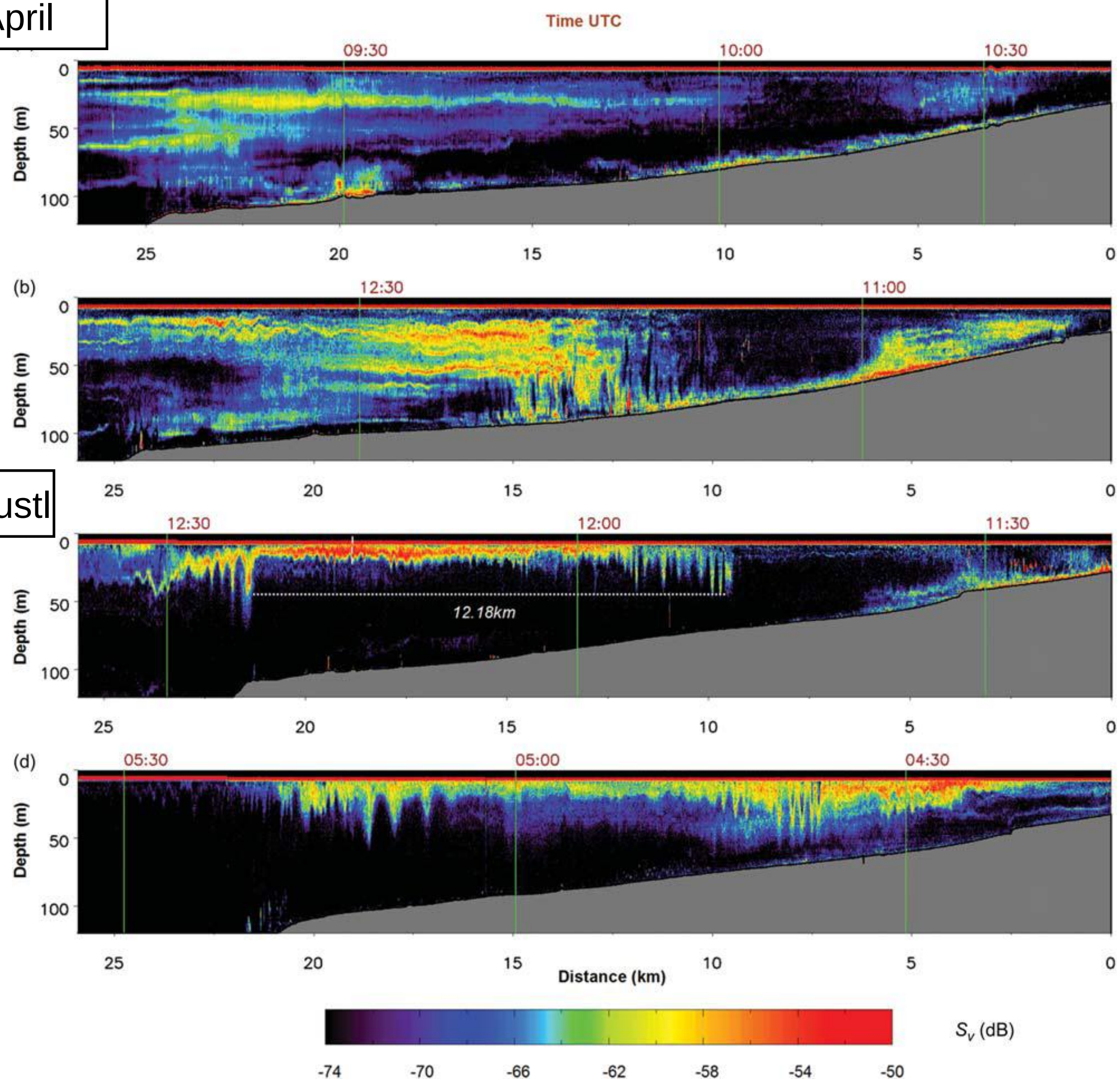


- ➢ Trains of solitary waves likely dominate the cooling of the mixed layer and thus are responsible for the cold surface water near the Angolan Coast

Conclusions II

April

August|



- Seasonality of the SST may originated from strong seasonal changes in upper ocean stratification. During periods of strong stratification, tides are reflected differently and non-linear waves can not develop. A strong seasonal cycle of stratification of Angola and Peru

(Ostrowski et al., 2008)