# Role of Vertical Velocities in the Cooling of the Atlantic Cold Tongue

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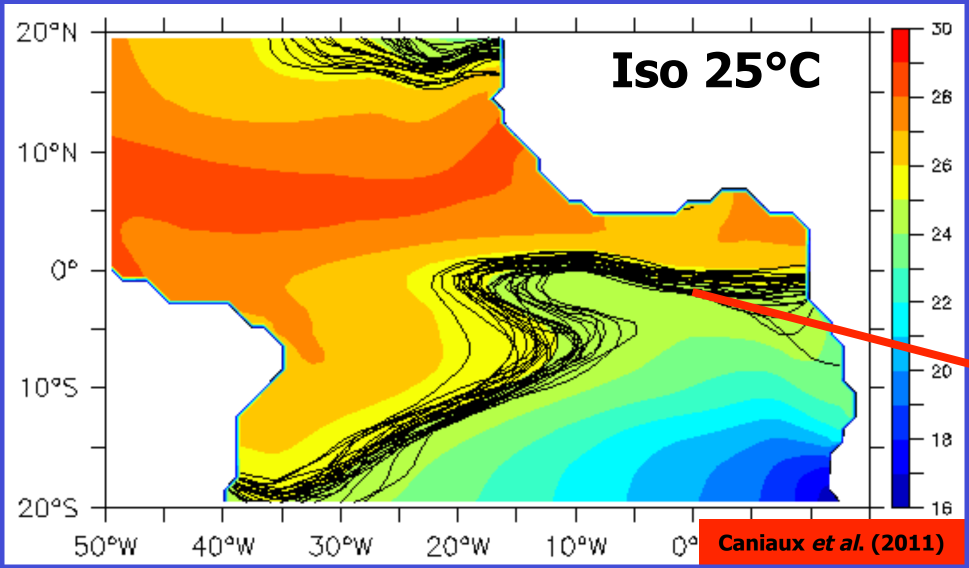
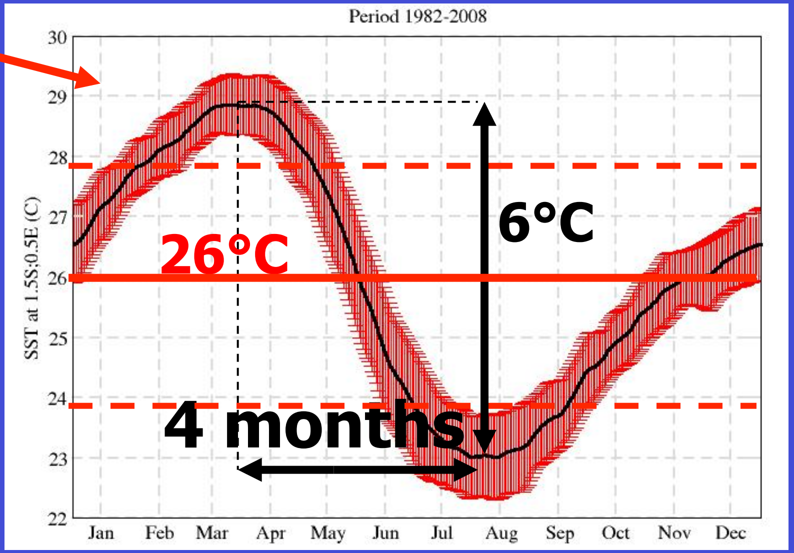
# The Atlantic Cold Tongue (ACT)




Reynolds' SSTs 1982-2008




Reynolds' SSTs at 0.5°W 1.5°S

- The most pronounced signal of the annual cycle in the equatorial Atlantic
- Seasonal cooling anomaly of SH surface waters
- Cooling begins in April and is the most intense in May and June

# The ACT and the equatorial upwelling

•**Hazeleger and Haarsma [*Clim. Dyn.*, 2005]:** "***One of the most important processes regulating the tropical SST is the upwelling in the tropics that is driven by the Ekman divergence on the equator.*** The Ekman pumping is balanced by vertical diapycnal mixing, which is large at the base of the well-mixed upper layer"

•**Richter and Xie [*Clim. Dyn.*, 2008]: "**In May, strong southerly surface winds in the Gulf of Guinea associated with the onset of the West African monsoon are instrumental in ***initiating the seasonal development of the equatorial cold tongue, by inducing upwelling*** along the southern African coast and ***in the open ocean just south of the equator*** [Mitchell and Wallace 1992; Okumura and Xie 2004]"

•**Hagos and Cook [*J. Clim.*, 2009]: "**Over the Gulf of Guinea the start of the monsoon season is accompanied by the acceleration of southerly winds across the equator. Because of variations of the Coriolis force with latitude, ***these winds drive upwelling (and cooling) to the immediate south of the equator*.** In addition, evaporation associated with these accelerated surface winds also significantly contributes to the seasonal cooling"

# Formation of the ACT

**Homogeneous frictional surface layer of constant depth H, on a ß plan, forced by a wind stress [Zebiak and Cane, 1987]**

$$\begin{cases} r u_s - \beta y v_s = \dfrac{\tau_x}{\rho_0 H} \\ \beta y u_s + r v_s = \dfrac{\tau_y}{\rho_0 H} \end{cases}$$

**Ekman pumping**

$$w(-H) = \frac{1}{\rho_0 (r^2 + \beta^2 y^2)} \left\{ \frac{\beta(\beta^2 y^2 - r^2)}{r^2 + \beta^2 y^2} \tau_x + \frac{-2\beta^2 y r}{r^2 + \beta^2 y^2} \tau_y + r \nabla . \tau + \beta y \nabla \wedge \tau \right\}$$

1 2 3 4

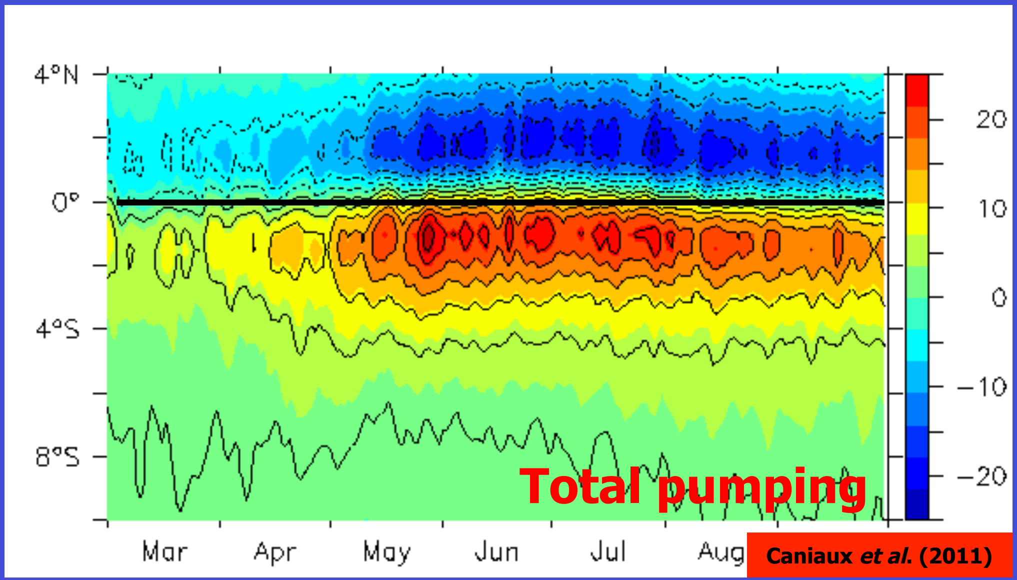
1: Zonal wind stress

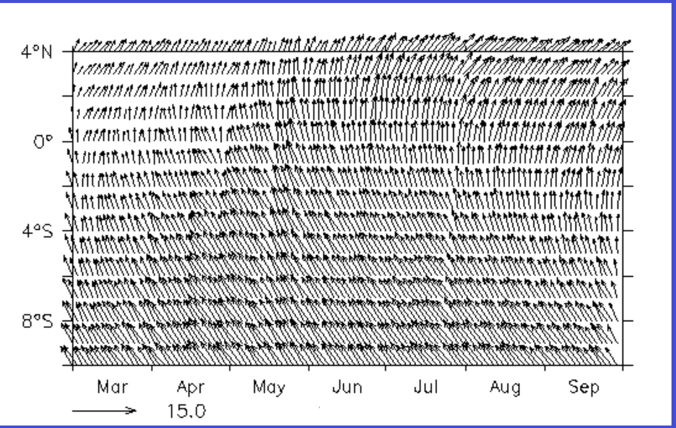
2: Meridional wind stress

3: Divergence of the wind stress

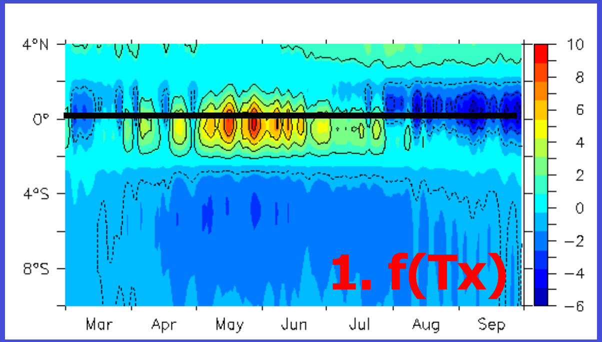
4: Wind stress-curl

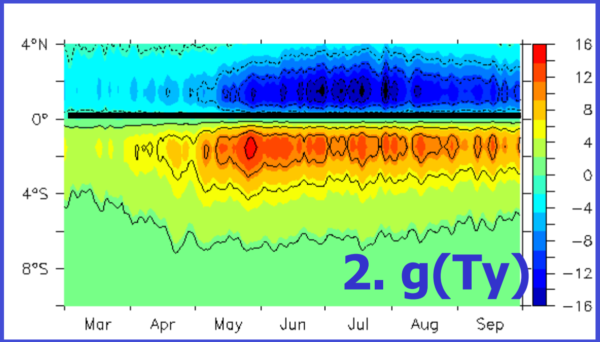
# The Ekman theory at the Equator

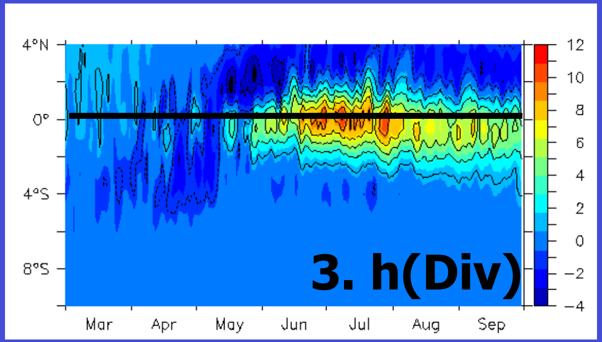


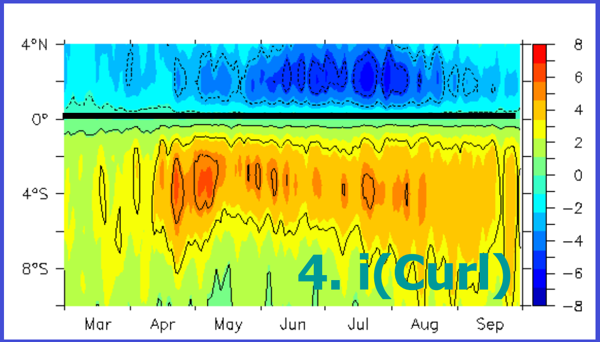




**Hovmøller 10°W-4°E**
**ECMWF 1998-2007**



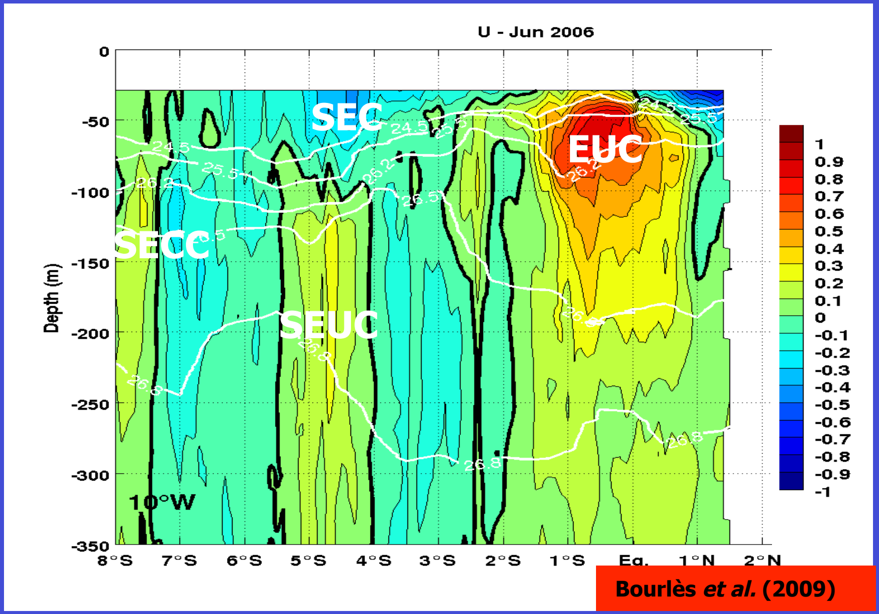



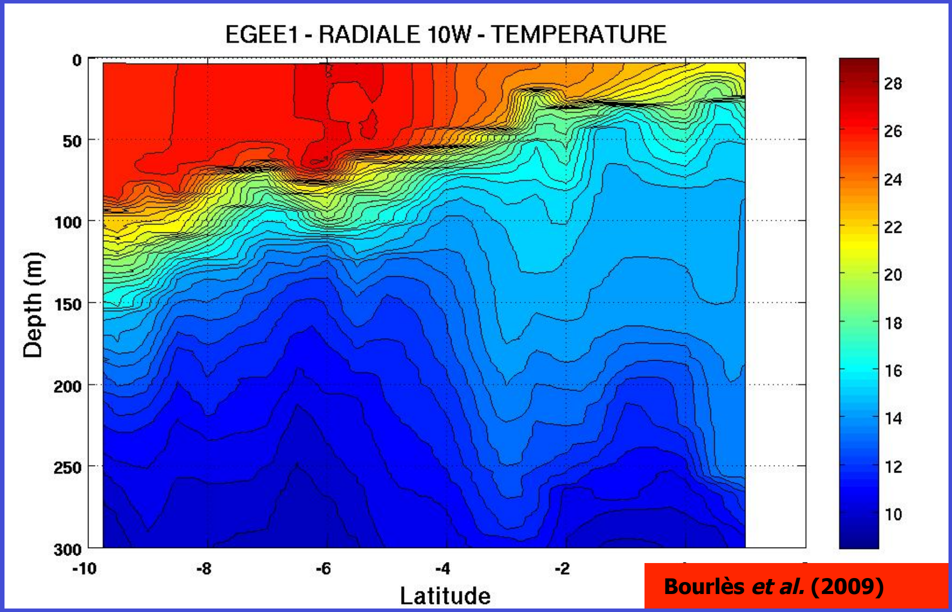

- **Pumping stronger in the belt 3°S-3°N**
- **Upwelling south of the equator**
- **All the terms strengthen the positive pumping from May to June**

# The Ekman theory is too simplified

- The equatorial ocean is not at rest
- The equatorial ocean is not spatially homogeneous
- The equatorial ocean is strongly stratified



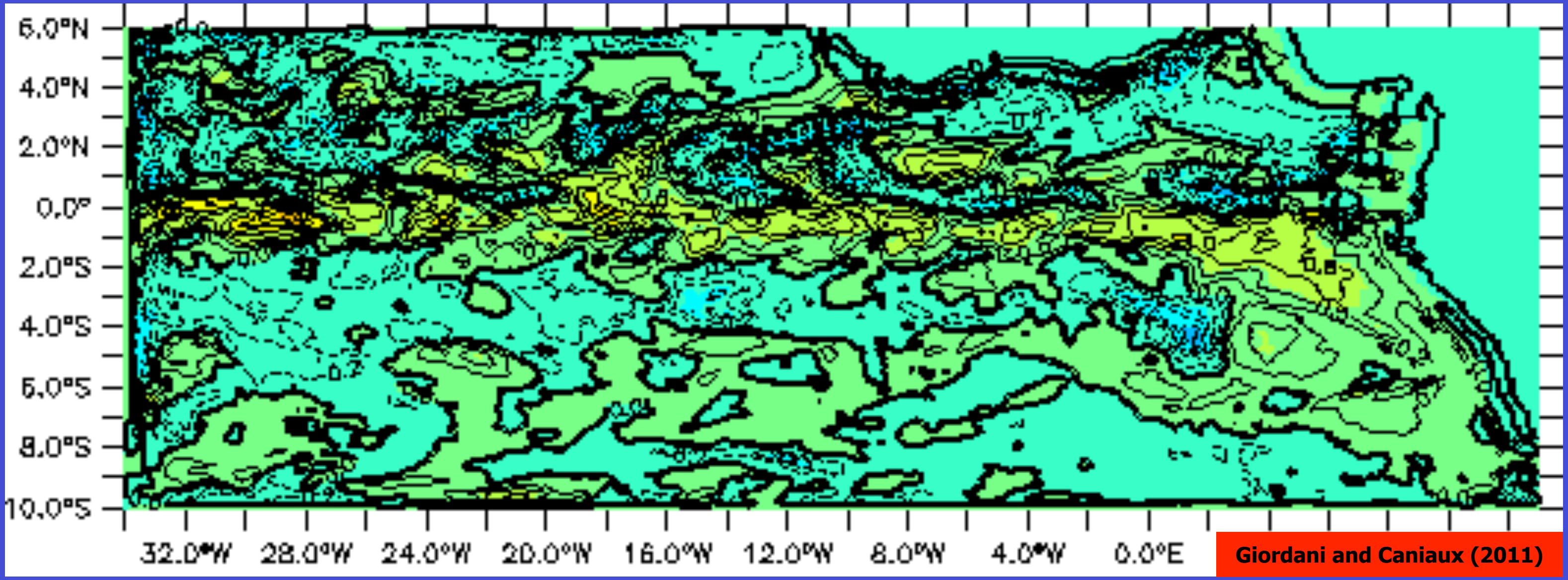

Zonal current
EGEE-1 cross-section at 10°W
June 2005




Temperature
EGEE-3 cross-section at 10°W
June 2006

# Vertical velocities in the ACT

**Regional PE model, $\Delta x$=17 km, $\Delta y$=9 km, $\Delta z$=1 to 150m**
**Initialization, surface and boundary forcings: MERCATOR MNATL12**
**[Giordani *et al.*, 2005a, 2005b; Giordani and Caniaux, 2011]**




**May-August mean W (m $d^{-1}$)**

- **Upwelling between 2°S-1°N**
- **1 m $d^{-1}$ in the equatorial upwelling**
- **0.2 m $d^{-1}$ offshore the Gabonese coast**

# Sources of vertical velocity in the PE system

- In the Ekman model, w is a linear function of $\tau_x$, $\tau_y$, Div( $\tau$ ) and Curl( $\tau$ ). What occurs in a more complex model?
- In a PE model, w is *diagnosed* from the continuity equation and cannot be related to its physical sources
- In the PE system, Giordani and Caniaux [2011] identified (by using the divergence equation) not 4, but *18 terms* source of w : wind stress (3 terms), pressure field (4), horizontal current (5) and 6 terms considered as the response of the ocean to the forcings

# Sources of vertical velocity in the PE system

$$\frac{\partial w}{\partial t} = \sum_i F_i$$

**Wind stress**

$$F_{\tau_x} = -\int_0^t \int_{-z}^0 \left(\beta \frac{\partial \tau_x}{\partial z}\right) dz dt$$

$$F_{rot\tau} = \int_0^t \int_{-z}^0 f \vec{k} \vec{\nabla} \times \left(\frac{\partial \vec{\tau}}{\partial z}\right) dz dt$$

$$F_{div\tau} = \int_{-z}^0 \left(\frac{\partial \vec{\nabla} \vec{\tau}}{\partial z}\right) dz$$

**Current**

$$F_v = -\int_0^t \int_{-z}^0 (2\beta f v)\, dz dt$$

$$F_{Def_D} = -\int_{-z}^0 Def_1(D) dz$$

**W**

$$F_{stretch\zeta} = \int_0^t \int_{-z}^0 \left(f(\zeta + f)\frac{\partial w}{\partial z}\right) dz dt$$

$$F_{NL} = \int_0^t \int_{-z}^0 \left(-fw\frac{\partial \zeta}{\partial z} + \beta w \frac{\partial u}{\partial z} + fTilt(\zeta)\right) dz dt + \int_{-z}^0 (Adv(D) + Def_2(D))\, dz$$

**Pressure and Current**

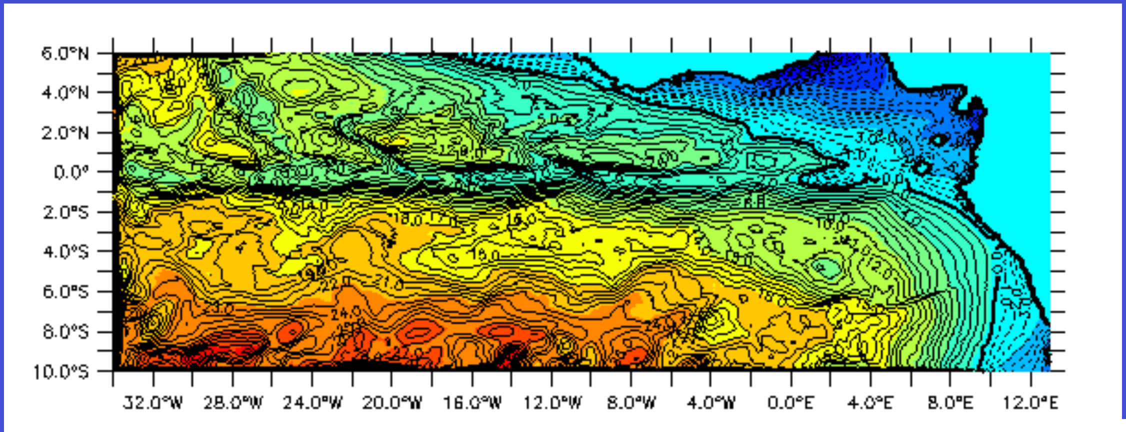
$$F_{p1} = \int_0^t \int_{-z}^0 \left(\frac{\beta}{\rho}\frac{\partial P}{\partial x}\right) dz dt$$

$$F_{p2} = \int_{-z}^0 \left((f\zeta - \beta u)_{t=0} + \int_0^t (fAdvh(\zeta) - \beta Advh(u))\, dt - \frac{1}{\rho}\nabla^2 P\right) dz$$

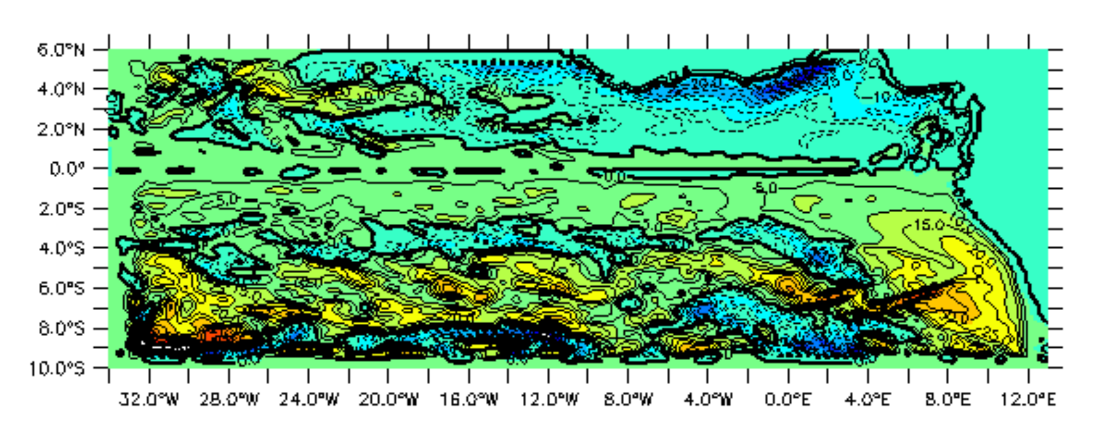
$$F_{Baro\zeta} = \int_0^t \int_{-z}^0 f Baro(\zeta) dz dt$$

$$F_{BaroD} = \int_{-z}^0 Baro(D) dz$$

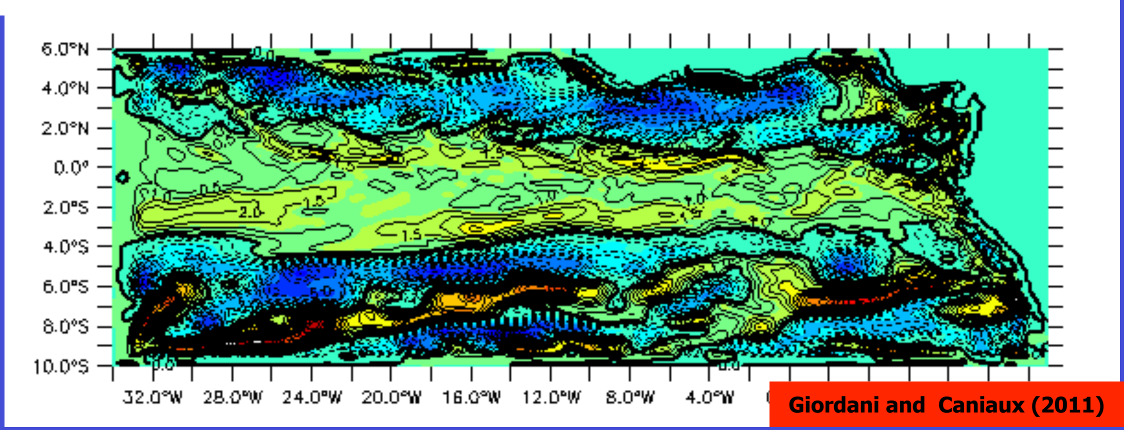
# Sources of vertical velocity in the ACT




w due to the zonal wind stress




w due to the wind stress curl



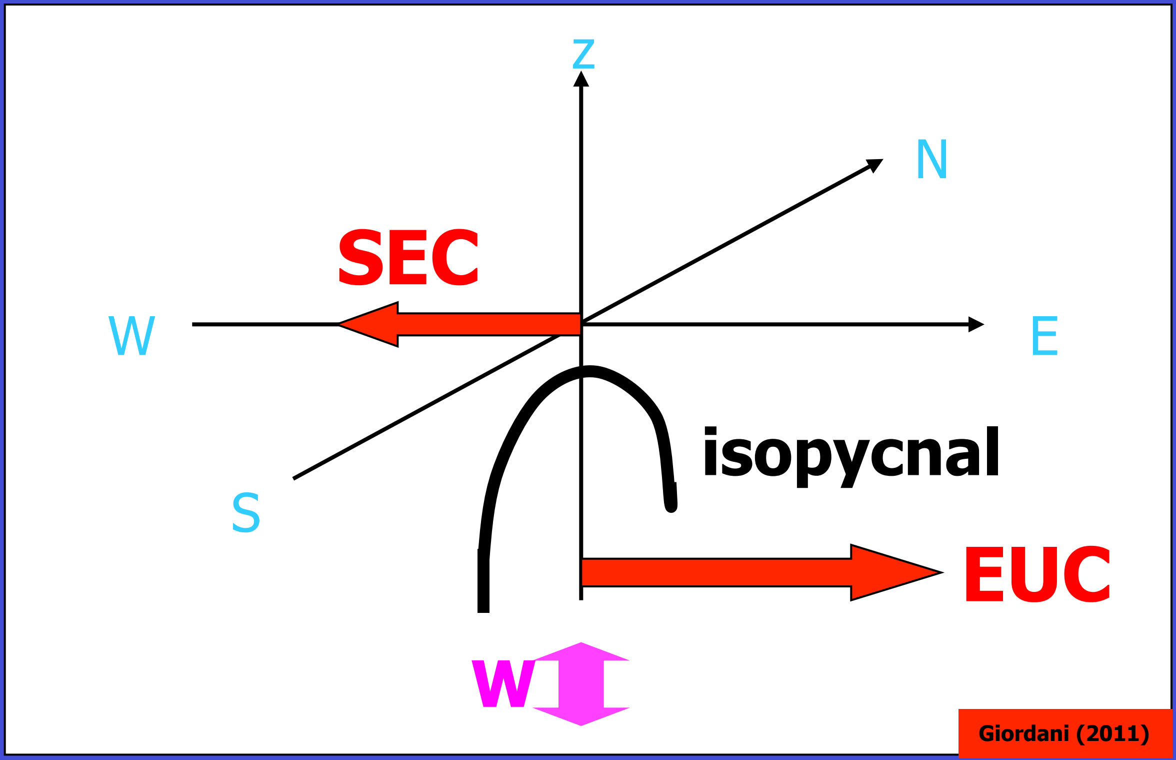

w due to imbalance between the circulation and the pressure

Giordani and Caniaux (2011)

# Existence of an equatorial balance

$$\frac{g}{\rho}\nabla^2\rho = \beta\frac{\partial u}{\partial z} - f\frac{\partial \zeta}{\partial z}$$

Vertical derivative of the linearized, stationarized form of the divergence equation




- Curvature of the density = sum of an equatorial term and a geostrophic term
- Easterly winds break the equatorial balance, which is restored by w
- W adjusts the density to the momentum field

# Existence of an equatorial balance

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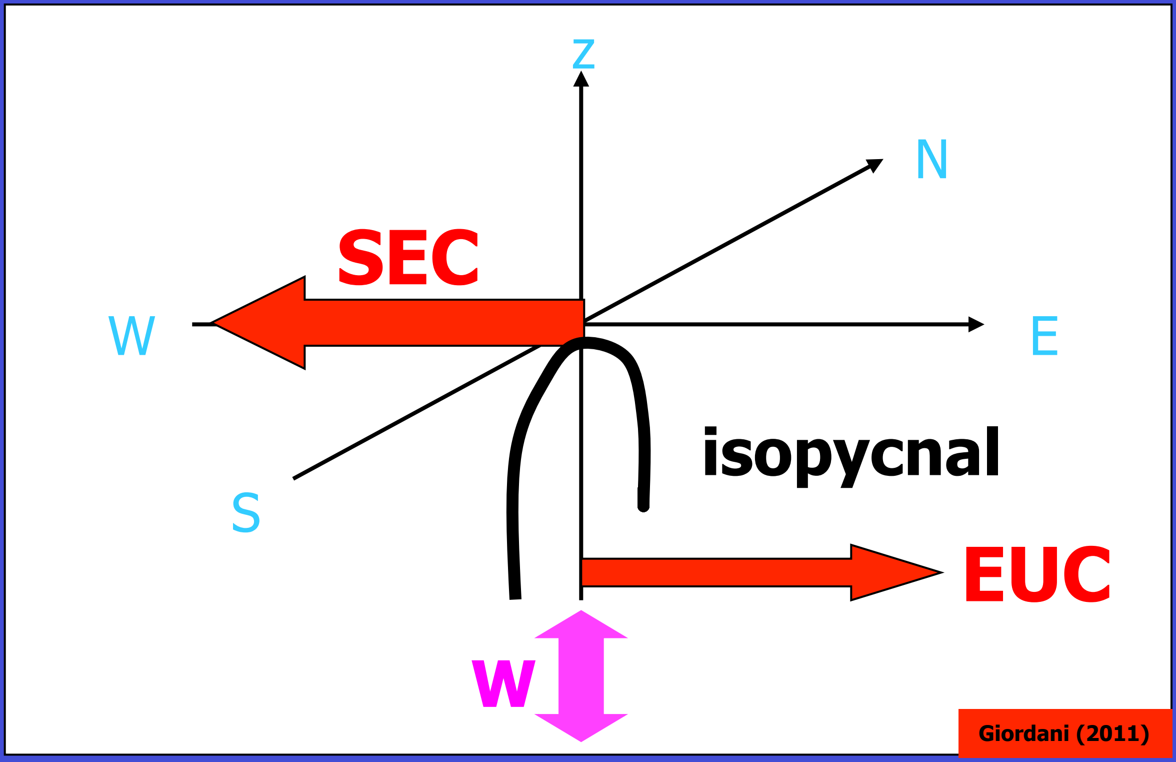


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# Where does the ACT cooling come from?

- **Hizard [1973]** suggested that surface water enrichment is caused by both ***equatorial divergence*** and ***vertical mixing***

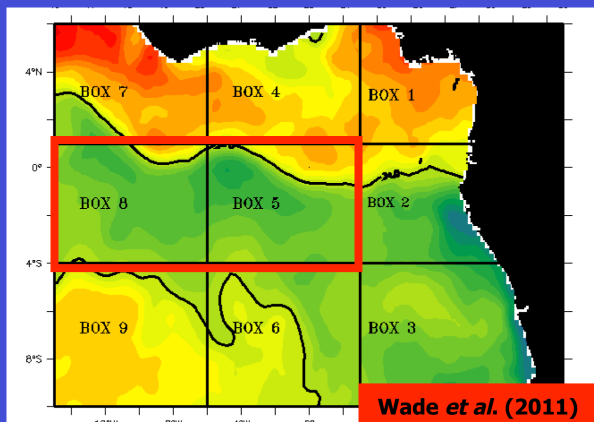
- **Weingartner and Weisberg [1991]** found that ***vertical advection* is** the main source of cooling in the ACT

- **Foltz *et al*. [2003]** estimates that vertical advection is negligible and that ***vertical mixing*** could be responsible for the discrepancy of nearly 100 W $m^{-2}$ in the heat budget of the ACT

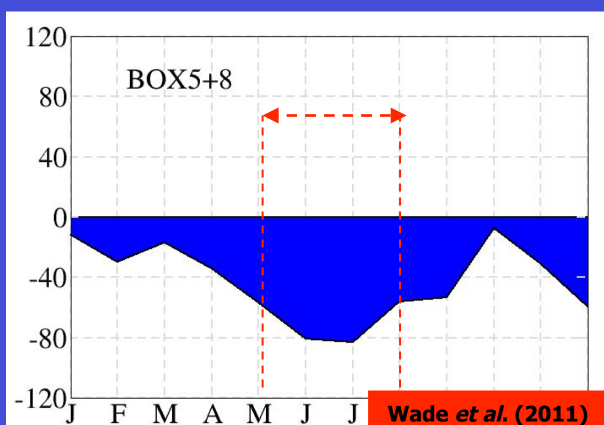
- **Yu *et al*. [2006]** and **Peter *et al*. [2006]** found that the equatorial cooling comes from the sub-surface **(*vertical mixing, vertical advection*** and ***entrainment*)**

# Role of vertical mixing in the cooling of the Atlantic cold tongue

| MJJA 2006 (W m$^{-2}$) | Wade *et al.* [2011] | Giordani *et al.* [2012] |
|---|---|---|
| Surface flux | 43 | 31 |
| Horizontal advection | -1 | 14 |
| Entrainment | 3 | 3 |
| Vertical mixing | -69 | -72 |
| Heat storage | -24 | -24 |

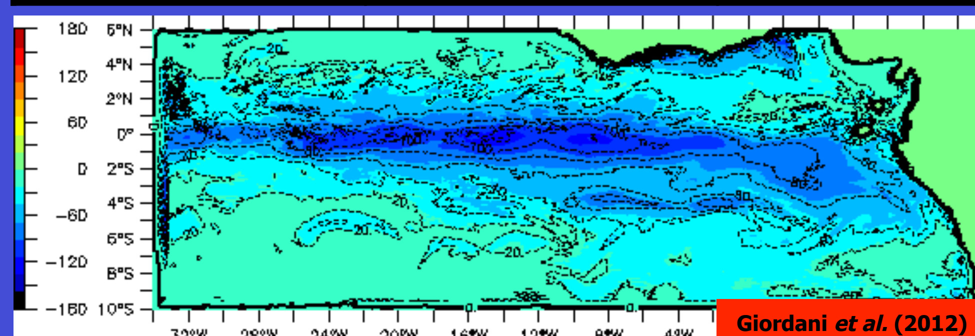


Wade *et al.* (2011)



Wade *et al.* (2011)

ARGO float ML heat budget



Giordani *et al.* (2012)

Model ML heat budget

# Conclusions

1. **The equatorial upwelling is an *indirect* response of the ocean to the wind forcing**

2. **The intensification of the southeasterly trades increases the vertical shear and brings the thermocline closer to the surface**

3. **W are instrumental for *preconditioning* the mixed layers**

4. **ARGO float mixed layer heat budget [Wade *et al*., 2011], in-situ measurements [Hummels *et al*., 2012] and numerical simulations [Jouanno *et al*., 2011; Giordani *et al*., 2012] suggest that *turbulent mixing* is a significant cooling source in the cold tongue**