

## Surface drifter pathways originating in the equatorial Atlantic cold tongue

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[1] Subtropical cells (STCs) connect subduction zones of the eastern subtropics of both hemispheres to the equatorial current systems via equatorward flow in the thermocline. Some of this thermocline water is converted back into warm near-surface water in the eastern equatorial cold tongue from whence it is exported poleward. Here we examine the export pathways from the cold tongue in the Atlantic based on recently available near-surface drifter data. We find that, similar to its Pacific counterpart, water upwelled in the Atlantic cold tongue follows multiple pathways back into the subtropics, but not directly to the subduction zones. Thus the subtropical cells are open to extensive influence from, and exchange with, the subtropical and midlatitude ocean. *INDEX TERMS*: 4231 Oceanography: General: Equatorial oceanography; 4279 Oceanography: General: Upwelling and convergences; 4512 Oceanography: Physical: Currents; 4532 Oceanography: Physical: General circulation. **Citation**: Grodsky, S. A., and J. A. Carton, Surface drifter pathways originating in the equatorial Atlantic cold tongue, *Geophys. Res. Lett.*, 29(23), 2147, doi:10.1029/2002GL015788, 2002.

### 1. Introduction

[2] A striking feature of both the eastern Pacific and Atlantic Oceans is the appearance of a tongue of cool ( $<24^{\circ}\text{C}$ ) water near the equator, which is a region of strong net surface heating [McCreary and Lu, 1994]. There is observational and modeling evidence [Lu *et al.*, 1998; Johnson and McPhaden, 1999; Malanotte-Rizzoli *et al.*, 2000; Johnson, 2001; Zhang *et al.*, 2002] that water upwelled into the cold tongue includes water subducted in the subtropics via the STCs. Changes in the STCs have been implicated in Pacific decadal climate variability [Kleeman *et al.*, 1999]. Less is yet known about the upper limbs of the STCs in the Atlantic. In this paper we use recently available drifter observations, together with historical ship drifts, and altimetry to describe the surface layer pathways originating in the Atlantic cold tongue.

[3] The temperature and circulation of the tropical Atlantic are both strongly seasonal. In boreal spring warm water spans the equator to  $15^{\circ}\text{N}$ . Within a few degrees of the equator extending to  $10^{\circ}\text{S}$  lie the northern and southern branches of the westward South Equatorial Current (SEC). The northern branch of the SEC provides source water for the near-coastal North Brazil Current (NBC) system and its associated rings. By summer in response to a northward

shift of the trade winds the eastward North Equatorial Countercurrent (NECC) forms. Along the equator mixed layer temperatures drop by several degrees in the region  $30^{\circ}\text{W}-0^{\circ}\text{W}$ ,  $4^{\circ}\text{S}-2^{\circ}\text{N}$  in response to a shallowing thermocline and strengthening easterlies, forming the center of the equatorial cold tongue.

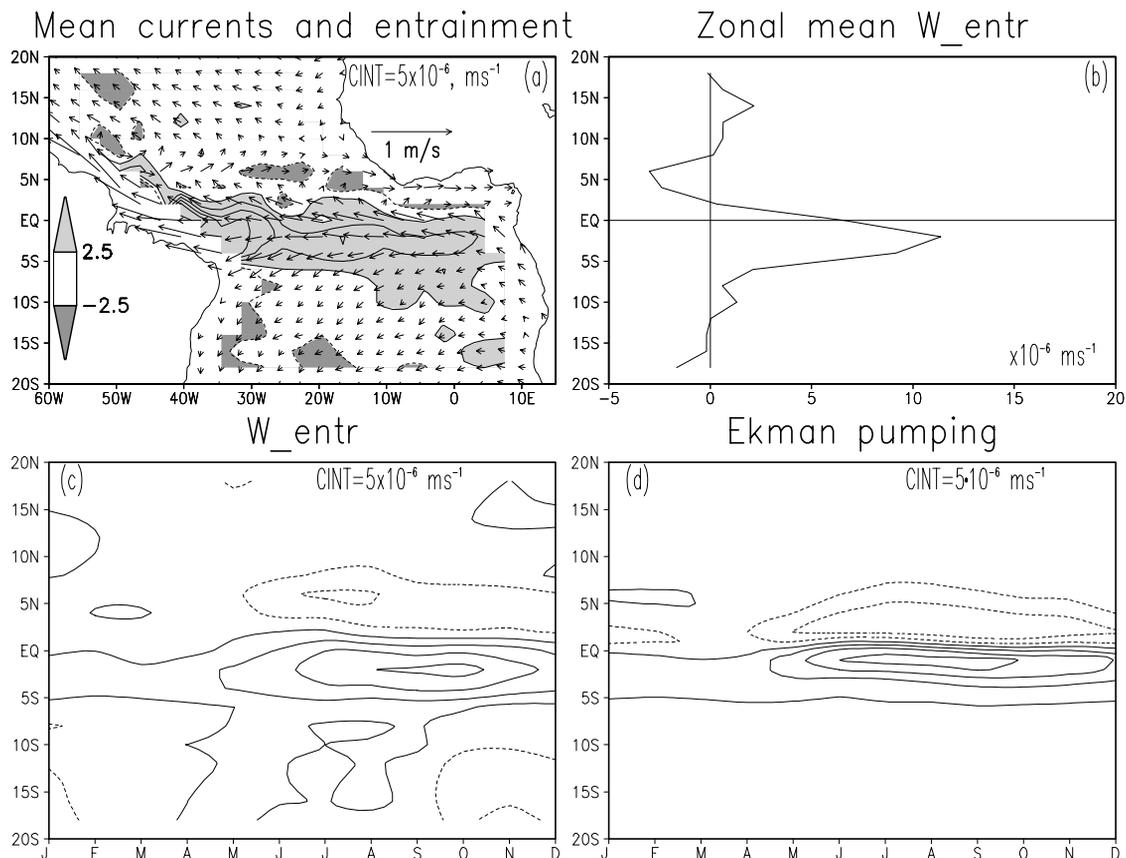
[4] In zonal and time average the meridional-vertical circulation of the upper ocean is dominated by the STCs, in which high salinity water is subducted in the subtropics, flows equatorward along the thermocline, then upwells into the mixed layer of the equatorial zone, where it is exported poleward. If this water is then returned to the subduction regions it forms a closed loop with a cycle time of a few years. However, examination of the pathways in the upper limb of the STCs in the Pacific [Johnson, 2001] shows northwestward transport supported mostly by the Ekman drift. Hence this water reenters the subtropics in the west, away from the subduction zones that feed the lower limb of the STCs. This result suggests the STCs are open circulations, rapidly exchanging water with the subtropical ocean. Motivated by this result, here we examine the pathways of mixed layer water as observed in the drifter record of the tropical Atlantic during 1997–2001 and in related data sets.

### 2. Data and Analysis

[5] This study is based on five data sets: 15 m-drogued drifter velocity and position, as well as a gridded velocity analysis, itself resulting from drifter data, climatological surface velocity from historical ship drifts, altimeter sea level, ERS 1/2 scatterometer winds, and ocean mixed layer depth.

[6] Our analysis uses 55 drifter trajectories within the  $15^{\circ}\text{S}-30^{\circ}\text{N}$  band, obtained from the WOCE/TOGA archive at the NOAA/AOML, that pass within the rectangular domain  $4^{\circ}\text{S}-2^{\circ}\text{N}$  and  $30^{\circ}\text{W}-0^{\circ}\text{E}$  during the cold tongue seasons of boreal summer and fall (June–November) when SSTs are low and entrainment is strong.

[7] Because of limitations on the number and coverage of surface drifters, we supplement our velocity discussion using a multivariate optimal interpolation analysis of climatological seasonal near-surface currents on a  $3^{\circ} \times 2^{\circ}$  grid following Grodsky and Carton [2001] (see Figure 1). The analysis combines Eulerian velocities obtained from the drifter tracks with near-surface pressure variations based on TOPEX/POSEIDON altimetry and ERS 1/2 monthly scatterometer winds of Bentamy *et al.* [2001], which together provide information on the geostrophic and ageostrophic components of the near-surface currents. A first guess of the seasonal currents is provided by historical ship drifts [Richardson and Walsh, 1986]. The ocean mixed



**Figure 1.** Climatological near-surface currents. (a) Annual mean currents and entrainment/detrainment velocity,  $w_e$ . (b) Zonally averaged (35°W–10°E)  $w_e$  with latitude. (c) Seasonal cycle of  $w_e$  with latitude. (d) Seasonal cycle of Ekman pumping with latitude. Ekman pumping close to the equator is calculated using the linear friction. All contours are drawn at the intervals  $[-7.5 -2.5 2.5 7.5 12.5 17.5] \times 10^{-6} \text{ ms}^{-1}$ . Positive/negative values are shown with solid/dashed lines.

layer depth,  $h$ , is the seasonal climatology of *Kara et al.* [2000].

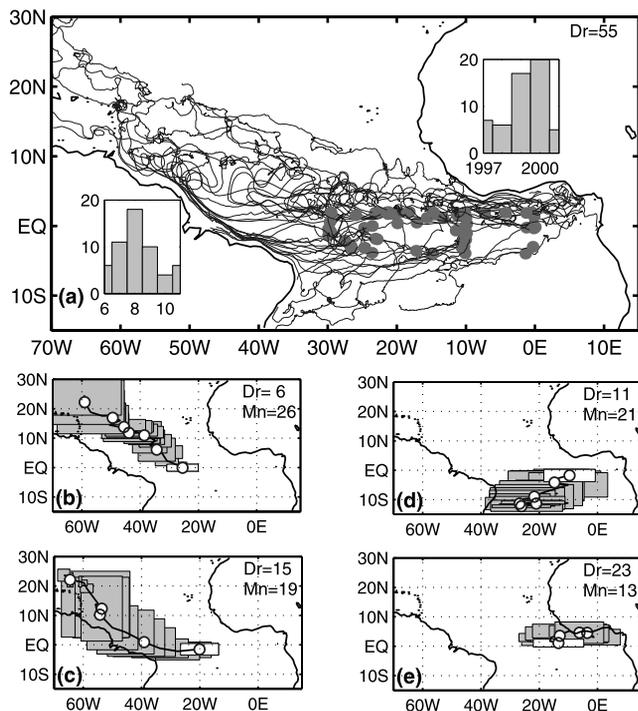
### 3. Results

[8] This section is organized in the following way. First we identify the spatial structure and timing of the entrainment of cool subthermocline water in the tropical Atlantic mixed layer. Then we consider the trajectories crossing through the cold tongue. It will turn out that the pathways taken by the drifters are determined by where they originate within the cold tongue. Finally we explore the sensitivity of pathways to point of origin using our gridded velocity analysis.

[9] We estimate the rate of entrainment of water into the mixed layer,  $w_e$ , following *Swenson and Hansen* [1999] as the sum of the rate of deepening of the mixed layer,  $dh/dt$ , and upwelling at its base, which can be calculated from the divergence of mixed layer velocity,  $h\nabla \cdot \mathbf{u}$ . While entrainment heat flux is only defined while  $w_e$  is upward, actually  $w_e$  can be either upward/downward (entrainment/detrainment). Figure 1b shows that on annual average entrainment zonally averaged between 35°W and 10°E is mainly confined to a band of latitudes between 7°S–2°N, with a maximum of  $\sim 12 \times 10^{-6} \text{ m/s}$  at 2°S and a band average of  $\sim (5.9 \pm 1.5) \times 10^{-6} \text{ ms}^{-1}$ , values similar to those found by *Weisberg and Qiao* [2000] and by *Meinen et al.* [2001] in

the Pacific cold tongue. Entrainment also occurs near the eastern boundary but our estimates become unreliable in this region because of lack of data. The maximum entrainment is displaced slightly south of the equator in the east as a result of the southerly component of wind that produces upwelling to the south and downwelling to the north of the equator. The uncertainties here and below derive from estimates of velocity accuracy [*Grodsky and Carton*, 2001] and data distribution.

[10] Integrating within the meridional band 7°S–2°N in the ocean in the longitude band 35°W–10°E gives a total upwelling of  $(26 \pm 8) \times 10^6 \text{ m}^3 \text{ s}^{-1}$  (26 Sv) about half of the value found by *Johnson* [2001] in the Pacific. Our estimate is in line with the *Roemmich* [1983] estimate of 25 Sv obtained based on Ekman divergence between 8°S and 8°N. Weak off equatorial detrainment with peak velocity of  $-3.5 \times 10^{-6} \text{ ms}^{-1}$  at  $\sim 5^\circ\text{N}$  occurs mostly between 3°N and 8°N (Figure 1b) and could be evidence of the downwelling limb of the shallow tropical cell [*Lu et al.*, 1998]. In contrast to the Pacific [*Johnson*, 2001], the shallow tropical cell in the Atlantic develops only north of the equator. Integration over the zonal band between 35°W and 10°E gives a total downwelling rate of  $4 \pm 2 \text{ Sv}$  suggesting that roughly 15% of the water that upwells on the equator downwells before it reaches 8°N. Note that *Richardson and Reverdin* [1987] found a stronger downwelling rate of 8 Sv based on ship drifts. Finally, we consider seasonal variations of  $w_e$ .



**Figure 2.** Fate of drifters crossing the cold tongue ( $4^{\circ}\text{S}$ – $2^{\circ}\text{N}$ ,  $30^{\circ}\text{W}$ – $0^{\circ}\text{E}$ ) during June–November. (a) Combined drifter trajectories. Inlays in (a) present distribution of points of origin by months and by years. (b) Trajectories entering the NEC. (c) Trajectories entering the SEC and the NBC. (d) Trajectories entering the SEC and continuing in the Southern Hemisphere. (e) Drifters entering the NECC and thus being carried eastward. Mean trajectory of each group is shown by solid line with open circles indicating four-month intervals. Shaded rectangles show standard deviation of drifter coordinates during a month. White rectangles show the initial spread of drifter locations belonging to each group. Digits *Dr* indicate number of drifters in each group while *Mn* indicates number of months when at least 2 drifters are alive.

Entrainment/detrainment increases in vicinity of the equator during boreal summer and fall (Figure 1c). These increases correspond to the seasons of peak Ekman pumping (Figure 1d). This correspondence reflects the principal role of winds in driving  $w_e$ .

[11] Next we consider the fate of the upwelled water by examining 55 drifter trajectories that pass through the cold tongue ( $30^{\circ}\text{W}$ – $0^{\circ}\text{E}$ ,  $4^{\circ}\text{S}$ – $2^{\circ}\text{N}$ ) during the cold tongue seasons (Figure 2a). The time of origin of the trajectories is distributed inhomogeneously between different months and years (see insets in Figure 2a). Most frequently the trajectories originate during late summer–early autumn and during 1999–2000. We partition the drifter trajectories based on whether a drifter finally crosses the meridian  $40^{\circ}\text{W}$  and if it does, whether it crosses this meridian north or south of latitude  $5^{\circ}\text{N}$ . Drifters that remain east of  $40^{\circ}\text{W}$  are separated into two groups by checking if a drifter eventually goes south of the equator. This partitioning allows us to discriminate between trajectories entering the NEC, the near-coastal NBC system, remaining in the southern branch of the SEC, or entering the eastward NECC. The

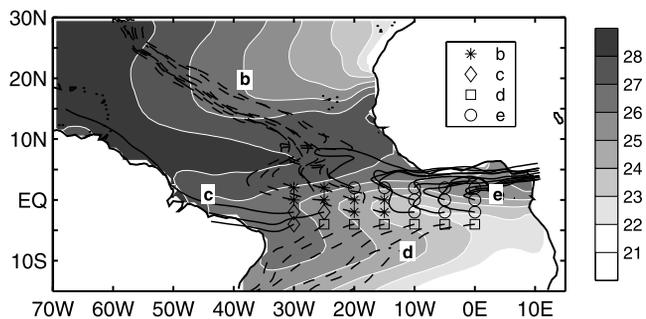
trajectory points of origin are defined as the location of deployment or the location where a drifter trajectory crosses into the cold tongue for the first time.

[12] Six trajectories cross  $40^{\circ}\text{W}$  north of  $5^{\circ}\text{N}$  (Figure 2b). Their points of origin are all located in the western section of the cold tongue west of  $20^{\circ}\text{W}$ . The mean trajectory heads northwestward through the northern branch of the SEC, passing the latitude of the NECC in boreal spring when it is weak, finally crossing into the NEC and reaching  $20^{\circ}\text{N}$  in approximately two years after exiting the cold tongue region. We call the drifters with these trajectories the NEC group.

[13] Drifter trajectories that cross  $40^{\circ}\text{W}$  south of  $5^{\circ}\text{N}$  originate in the western part of the cold tongue on or south of the equator (Figure 2c). They drift westward in the southern branch of the SEC, entering the region near the western boundary after 4 months and then traveling rapidly to the northwest in the NBC system so that they reach the western subtropics after about a year and a half (the SEC + NBC group). A third group of 11 buoys shown in Figure 2d that is transported into the southern hemisphere originates south of the equator and east of  $20^{\circ}\text{W}$ . These trajectories are swept southwestward by the southern branch of the SEC (the SEC group) and reach  $10^{\circ}\text{S}$  after approximately two years.

[14] The remaining 23 trajectories originate close to or north of the equator, mostly east of  $20^{\circ}\text{W}$ . They remain in the eastern basin as a result of rapidly entering the eastward NECC in the second half of the year (Figure 2f). Tropical Instability Waves, which perturb the meridional position of the NECC, produce some divergence in longitudinal position of this group (the NECC group). However, on average they require one year of travel to approach the Greenwich meridian implying an average eastward speed of less than  $10\text{ cm/s}$ .

[15] The results presented above suggest that the point of origin within the cold tongue has a significant influence on the near-surface trajectories because of the direction and seasonality of the prevailing currents. We explore this possibility by calculating simulated trajectories using the gridded analysis of seasonal near-surface currents described in Section 2 (see Figure 3). All 28 simulated



**Figure 3.** Trajectories with points of origin in the cold tongue ( $4^{\circ}\text{S}$ – $2^{\circ}\text{N}$ , and  $30^{\circ}\text{W}$ – $0^{\circ}\text{E}$ ) during August accounting for the seasonally varying currents. Trajectories shown have points of origin on a  $5^{\circ}$  and  $2^{\circ}$  longitude-latitude grid. Four symbols mark trajectories corresponding to Figures 2b, 2c, 2d, and 2e. The trajectories are overlaid on climatological August SST.

trajectories begin in August, which is a peak month of the cold tongue. 30% of the simulated trajectories originating in the northwestern quadrant of the cold tongue ( $30^{\circ}\text{W}$ – $20^{\circ}\text{W}$ ,  $0^{\circ}\text{N}$ – $2^{\circ}\text{N}$ ) and even south of the equator between  $20^{\circ}\text{W}$  and  $15^{\circ}\text{W}$  go northwestward (like the NEC group). 10% of the trajectories beginning on or south of the equator on the western periphery of the cold tongue are transported by the northern branch of the SEC westward into the NBC, and thence into the northern subtropical gyre (SEC + NBC group) northwestward. 20% of the simulated trajectories with a point of origin along the southern edge of the cold tongue region between  $25^{\circ}\text{W}$  and  $0^{\circ}\text{E}$ , in contrast, follow the southern branch of the SEC into the southern subtropics (SEC group). 40% of the simulated trajectories that originate in the northwest part of the cold tongue region rapidly enter the NECC and thus are transported eastward into the Gulf of Guinea (like the NECC group). Calculations of trajectories beginning earlier or later during the upwelling season reveal the same four groups of trajectories but with different partitioning percentages.

#### 4. Discussion

[16] Recent studies point to the eastern northern and particularly southern subtropics as major subduction regions for water entering the tropical Atlantic thermocline [Zhang *et al.*, 2002] and providing a source for the 26 Sv we find being entrained into the mixed layer in the cold tongue region of the eastern equatorial Atlantic. However, despite its potentially important role in Atlantic climate the surface limb of the Atlantic STCs have received limited attention. In this paper we examine the trajectories of 55 near-surface drifters deployed over the past five years and find four major pathways for water exiting the cold tongue region, none of which lead directly back to the subduction regions.

[17] The drifters originating on the western periphery of the cold tongue (west of  $\sim 15^{\circ}\text{W}$ ) are transported into the northern subtropical gyre by the westward moving northern branch of the SEC either directly across the NECC in boreal spring, or through the near-coastal NBC system. The second pathway is the faster route to the subtropics and requires roughly one and a half years, while the first requires approximately two years.

[18] The drifters with a point of origin on or south of the equator, east of  $20^{\circ}\text{W}$  follow a third pathway southwestward in the southern branch of the SEC reaching the southern subtropical gyre after about two years. The drifters originating east of  $20^{\circ}\text{W}$  mostly north of the equator are diverted eastward by the NECC and are carried into the Gulf of Guinea, reaching the Greenwich meridian after a year.

[19] Further narrowing of the uncertainty of the observational estimates will require additional drifter deployments in the tropical Atlantic cold tongue, perhaps as part of a larger effort to define the climate variability in the region.

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