

A comparison of kinematic evidence for tropical cells in the Atlantic and Pacific oceans

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Kinematic evidence for the existence of Tropical Cells (TC) in the Atlantic Ocean is offered. Mean sections of meridional velocity, its horizontal divergence and vertical velocity are estimated from twelve available sections centered at about 35°W. Of the twelve sections, six were occupied in March and April, thus there is a boreal spring bias to the observations. Equatorial upwelling and off-equatorial downwelling, between 3°N and 6°N, represent the southern and northern boundaries of a northern hemisphere TC. Uncertainties for the estimates of average quantities are large. However, favorable comparisons with observational representations of Pacific TC's provide support for the existence of a northern hemisphere Atlantic TC.

1. INTRODUCTION

In the Pacific and Atlantic Oceans, meridional-vertical circulation is a superposition of larger Subtropical Cells (STCs) and more localized Tropical

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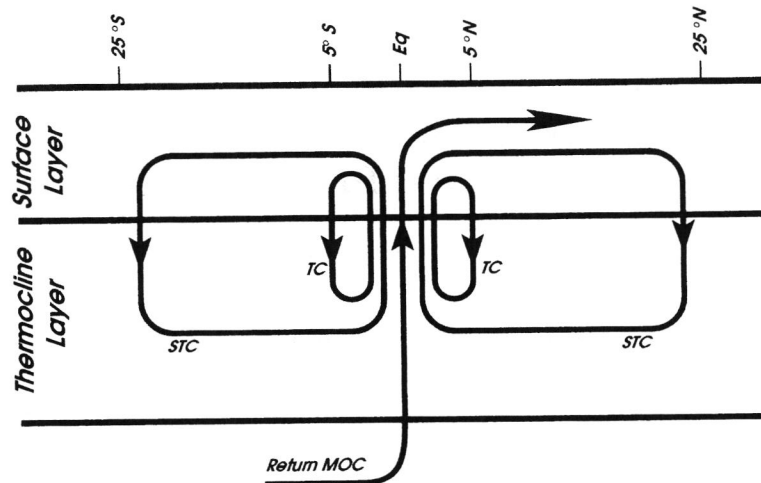


Figure 1. Schematic diagram representing the structure of Tropical Cells and Subtropical Cells as modeled by and modified from Lu *et al.* (1998).

Cells (TCs' Johnson *et al.*, 1998; Johnson *et al.*, 2001; Johns, 2001). These cells share equatorial upwelling, caused by Ekman divergences and poleward surface Ekman flow (Figure 1). The TC downwelling is located in surface convergence zones observed about 4 - 8 degrees from the equator. Completing the TC, this water is probably returned to the equator in the interior of the basin and at depths no deeper than the upper thermocline. The STCs extend to the subtropics where subduction causes a downwelling that reaches to greater densities than that of the TCs. STC transport to the equator occurs both along the western boundary and in the interior. Although the name TC is a recent addition to oceanographic terminology, in fact, these features have a long history. As described in Sverdrup *et al.* (1942), Defant (1936) characterized a TC in the North Atlantic located between the Equatorial Undercurrent (EUC) and the North Equatorial Countercurrent (NECC). Defant (1936) proposed that frictional forces acting between the equatorial currents caused the TC.

In the Pacific, Wyrтки and Kilonsky (1984) analyzed data from about 30 cross-equatorial hydrographic sections from ten cruises taken over 12 months during the Hawaii-to Tahiti Shuttle Program. They inferred upwelling at the equator and downwelling at 4°N from water-mass property distributions. They went on to argue that the downwelling is caused by convergence in the wind-driven surface Ekman transport. Johnson and Luther (1994) using a subset of the Hawaii-to-Tahiti Shuttle Acoustic Doppler Current Profiler (ADCP) data, estimated a similar, but statistically uncertain, pattern of near-equatorial upwelling and off-equatorial downwelling. Johnson *et al.* (2001), hereinafter JMF, used shipboard ADCP (SADCP) data to study equatorial Pacific circulation. They considered 85

cross-equatorial sections occupied over a ten-year period between 170°W and 95°W. They derived average vertical sections of the horizontal velocity components, horizontal divergence, and vertical velocity at a nominal longitude of 136°W, the approximate mid-longitude of their data. They find upwelling in the equatorial band as well as downwelling between 4°S and 6°S and 6°N and 9°N. Surface drifter data have also been used to diagnose near-surface divergence fields. They show upwelling near the equator and downwelling near 4°S and 4°N (Johnson, 2003). The downwelling regions represent the poleward boundaries of the Pacific TC's in both data sets.

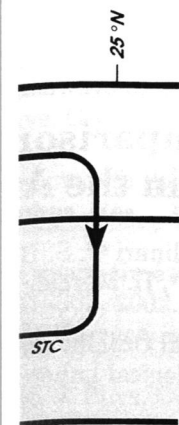
Herein, we search for kinematic evidence for TC's in the tropical Atlantic Ocean using similar data and analyses to that employed by JMF in the Pacific. We begin with a description of the data and analyses used, followed by estimates of the mean zonal velocity structure. Average meridional velocity, its horizontal divergence, and vertical velocity transects are then given. The vertical velocities are used to estimate upwelling transports. Throughout the discussion, we compare Atlantic characteristics with those of JMF both to support the Atlantic results and to consider the ubiquity of the TC feature. We conclude with a discussion of sampling and unresolved issues.

2. DATA AND ANALYSES

Twelve SADCPC sections occupied in the western equatorial Atlantic between 40°W and 30°W are used in this study (Figure 2). The characteristics of these sections are summarized in Table 1. Spatially, they vary in (1) latitudinal extent within the band 7°S to 7°N; (2) shallowest depth resolved, 20m to 40m; and (3) deepest depth available, 200m to 400m. Figure 3 shows the availability of data by depth and latitude. Maximum coverage is between 30m and 200m and 4°S and 6°N, which are limits used for most of our analyses. Temporally, more than half of the cruises are in early boreal spring, with the rest spread over the remainder of the year (Table 1).

The SADCPC data were acquired from the World Ocean Circulation Experiment (WOCE) SADCPC Data Assembly Center in Honolulu, Hawaii, except for the THALASSA, 1999 and OCEANUS 2000 cruises, provided by the principal investigators. Analyses procedures for each cruise varied (e.g., Wilson *et al.*, 1994 and Bourles *et al.*, 1999). However, qualitatively, SADCPC uncertainties are largest in the cross-stream direction (zonal in the case of these sections) and are of the order 0.05-0.10 m/s (JMF).

The average zonal current structure of the western tropical Atlantic is computed from the SADCPC data and compared with similar structure in the Pacific. The comparison serves two purposes: (1) it provides qualitative support for the results derived from the limited number of Atlantic sections (12 versus 85 in the Pacific, JMF); and (2) provides validation information for global modelers who simulate the tropics. Volume transports were estimated for the EUC and



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2001). These cells share poleward surface Ekman convergence zones; the TC, this water is basin and at depths no the subtropics where densities than that of the western boundary and in tion to oceanographic described in Sverdrup North Atlantic located the North Equatorial frictional forces acting

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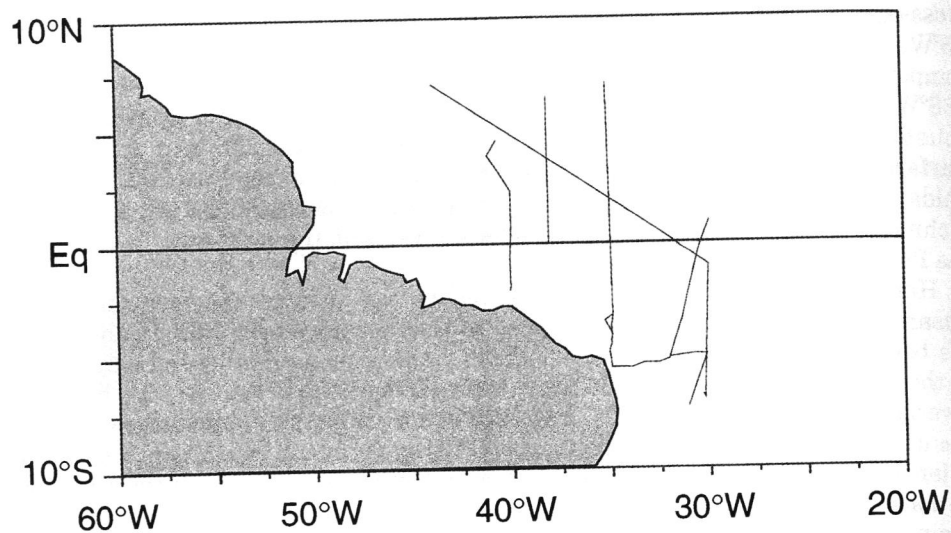


Figure 2. Locations of the sections used in this study.

Table 1.
Description of hull mounted ADCP sections

VESSEL	DATE DEEPEST	LONGITUDE	LATITUDE		SHALLOWEST	DEPTH
			RANGE	DEPTH		
L'ATALANTE	Jan. 31 - Feb.5 '93	35°W	5.58°S - 7.00°N		28m	700m
METEOR	May 29 - Jun.3 '91	35°W	5.61°S - 2.45°N		28m	330m
METEOR	Nov. 1 - 5 '92	35°W	4.97°S - 3.97°N		29m	400m
METEOR	Mar.12 - 16 '92	35°W	4.81°S - 4.50°N		32m	400m
EDWIN A. LINK	Apr.26 - May 1'96	35°W	4.78°S - 7.00°N		16m	340m
METEOR	Jun.7 - 9 '91	30°W	5.25°S - 0.87°N		28m	330m
MAURICE EWING	Mar. 1 - 8 '94	30°W	6.98°S - 0.99°S		26m	390m
		30°W	0.99°S			
		43.8°W	7.00°N			
METEOR	Mar. 6 - 10 '94	40°W	2.00°S - 4.47°N		26m	400m
OCEANUS	Mar. 7 - 15 '01	35°W	0.60°S - 6.80°N		23m	400m
		38°W	.0°S - 6.40°N		23m	400m
THALASSA	Jul. 19 - 29 '99	35°W	5.59°S - 6.99°N		30m	700m

North and South Equatorial Undercurrents (NEUC and SEUC), these are often called the North and South Subsurface Countercurrents in the Pacific. For each cruise, the transports for each current were computed within the areas bounded by either 300m, the surface in the case of the EUC and/or the 0 m/s speed contour.

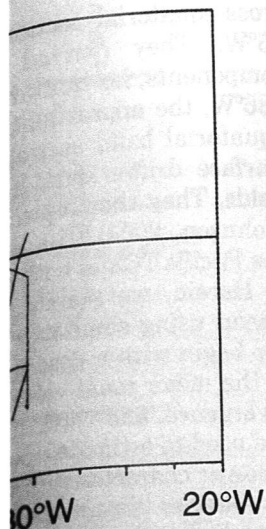
Meridional velocity, its horizontal divergence and vertical velocity sections were estimated for each cruise (using a one-degree of latitude by 10 m grid). To obtain near-surface values of meridional velocity in their Pacific work, JMF used objective mapping to extrapolate vertical shear from the top few SADCPC bins to the surface. For the Atlantic, we use the more conservative estimate of no vertical shear above 30m (or 40m when required) and thus simply extrapolate this meridional velocity to the surface. Differences between the two approaches of extrapolation can lead to different estimates of volume transport as shown by Marin and Gouriou (2000). They computed a 1.4 Sv (1 Sv = 10^6 m³/s), 20% difference in directly observed Ekman volume transport through the upper 100m of a trans-Atlantic section at 7.5°N. However, because of the many complicating factors that contribute to the vertical structure of near-surface velocity in the tropics (e.g., thermocline depth, mixed layer depth, etc.), it is difficult to select quantitatively the best approach for extrapolation to the surface. In the Pacific, JMF have the necessary spatial fields of zonal and meridional velocity components to compute both terms in the expression for horizontal divergence. In the Atlantic, there are insufficient SADCPC data zonally to compute representative estimates of $\partial u/\partial x$. Thus the divergence sections are estimated from only the meridional velocity. The adequacy of this assumption is discussed in the next section. To estimate vertical velocity sections, we then integrate the divergences with respect to depth assuming a rigid lid at the sea surface.

The individual sections were averaged to estimate mean transects for each variable. In addition, a section of the standard error of the mean for the meridional velocity was computed from the individual transects to provide a measure of the uncertainty in the results. Implicit in this uncertainty method is the assumption that instrument errors are much less than geophysical noise as in JMF. This minimum measure of uncertainty was used because of the few sections available for analysis.

The small signal-to-noise ratio in the meridional velocity field, to be described, results in extended areas of larger uncertainty in the divergence and vertical velocity fields. Thus, uncertainty estimates are not provided for these sections. However, as will be described, confidence in these sections is obtained through favorable comparisons with similar average sections from the Pacific (JMF).

A compilation of tropical Atlantic satellite drifting buoy trajectories are used to provide another estimate of near surface horizontal divergence. Data are available from 1989 to the present, with the majority of the information collected after 1992.

The buoys were deployed as contributions to both WOCE and the Tropical Ocean Global Atmosphere (TOGA) programs. The standard WOCE/TOGA buoy is drogued at 15m. Drift characteristics of the buoys have been determined and under typical tropical Atlantic wind/wave conditions the drifters exhibit a slippage



SHALLOWEST

DEPTH	DEPTH
28m	700m
28m	330m
29m	400m
32m	400m
16m	340m
28m	330m
16m	390m
28m	400m
28m	400m
28m	400m
30m	700m