Mass Transport and Internal Flow Patterns at Windward Passage

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Introduction and Motivation

The Gulf Stream system is fed via Atlantic inflow through the passages of the Bahamas and the Caribbean. Its role both as a return pathway for the Sverdrup flow from the North Atlantic subtropical gyre and as the upper western boundary component of the Meridional Overturning Cell (MOC) is well-documented (Schmitz and Richardson, 1991; and others).

Historically, a disparity has existed between the amount of research focused on the downstream components of this system (Florida Current, Gulf Stream, Gulf Stream extension) and the upstream study of Atlantic inflow into the Caribbean Sea through the Caribbean passages. Windward Passage, one of the largest of these passages, separates the islands of Cuba and Hispaniola in the northern Caribbean Sea. Despite being recognized as an important inflow channel to the Caribbean for over 70 years (Seiwell, 1938; Wüst, 1963; Worthington, 1966; and others), direct oceanographic observations in the region utilizing modern techniques are limited. As a result, scientists studying Caribbean transport pathways or attempting to compute water mass budgets for the region have been forced to rely on indirect measurements of volume transport and variability at Windward Passage (Johns *et al.*, 2002). Typically, direct transport measurements of the other Caribbean passages (including Old Bahama Channel and Northwest Providence Channel in the Bahamas) have been subtracted from the well established mean transport of ~32 Sv at 27°N in the Florida Straits (1 Sv = $10^6 m^3 s^{-1}$) (Baringer and Larsen, 2001), with the remainder being attributed to inflow at Windward Passage. This remainder has been estimated to be 7 Sv (Johns *et al.*, 2002).

In 2003, the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS) and NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) began a focused research study of Windward Passage and the surrounding region in efforts to resolve the mean current flow through the passage and to gain a better understanding of the variability and structure associated with the flow. As part of this project, titled the Windward Passage Experiment, a moored array was deployed across the passage, and four regional hydrographic surveys were conducted.

Methodology

The study's moored array consisted of five current meter moorings, two inverted echo sounders (IES), and two shallow pressure gauges, deployed between Cuba and Haiti along the sill of Windward Passage. The array was operational for 16 months, between October 2003 and February 2005.

Over this same period, four oceanographic research cruises were conducted in the region. Repeat hydrographic stations were occupied during each survey, and full water column measurements of conductivity, temperature, depth, dissolved oxygen, and velocity were collected using an instrumentation package equipped with a Sea-Bird 9*plus* CTD+O_2 and 24 bottle rosette water sampler, a lowered downward-looking 150 kHz RD Instruments (RDI) broadband acoustic Doppler current profiler (LADCP), and an upward-looking 300 kHz RDI Workhorse LADCP (cruises 2-4 only). Stations were located along sections at Windward Passage and passages *upstream*, including passages between Cuba and Great Inagua, Haiti and Great Inagua, and selected passages through the southern Bahamas and Turks and Caicos. Sections were also established *downstream* of Windward Passage across the axis of the Cayman Basin at two locations.

Continuous current velocity measurements of the near-surface flow were made with hull-mounted ADCP instrumentation (cruises 1 and 4: RDI 150 kHz broadband ADCP and RDI 38 kHz Ocean Surveyor ADCP; cruises 2 and 3: RDI 150 kHz narrowband ADCP), and continuous measurements of surface temperature and salinity were recorded via the ship's thermosalinograph flow-through system. Satellite-tracked, Lagrangian drifting buoys were deployed during the last three surveys (cruises 2-4).

Results

Volume transport calculations for Windward Passage and the surrounding regional passages were derived from LADCP data collected during the project's four research cruises. LADCP data collected in Windward Passage were detided using current meter data from the moored array. The total transport through Windward Passage and the internal flow patterns found there are highly variable. In general, the velocity structure in the passage can be characterized by inflow of surface and thermocline waters, outflow of intermediate waters, and deep inflow of upper North Atlantic Deep Water (uNADW) just above the deepest part of the passage sill. The four detided Windward Passage section transports yield a mean inflow of 3.5 Sv. With only four occupations and such a high degree of variability the standard error (SE) of this calculation is large (2.1 Sv). However, the value agrees closely with a mean transport of 3.6 Sv calculated from the project's current meter array (SE = 1.7 Sv). Both volume transport calculations (shipboard and moored array) are approximately half of the previously estimated inflow contribution for Windward Passage. With recent results from Badan et al. (2005) suggesting a lower volume transport for the Yucatan Channel (23 Sv versus 28 Sv), it is unclear as to where the remaining flow, still present at 27°N in the Florida Straits, is coming from. With these additional data, and recent transport measurements now available for other Caribbean passages, the water mass budget for the Caribbean (previously assessed by Johns *et al.* in 2002) should be revisited.

Water mass transports, calculated for each occupation of the three sections of the "triangle" formed by the islands of Cuba, Haiti, and Great Inagua, are also highly variable. Recirculations found in the triangle passages while the surveys were being conducted contributed to this variability, and to the resulting high standard error.

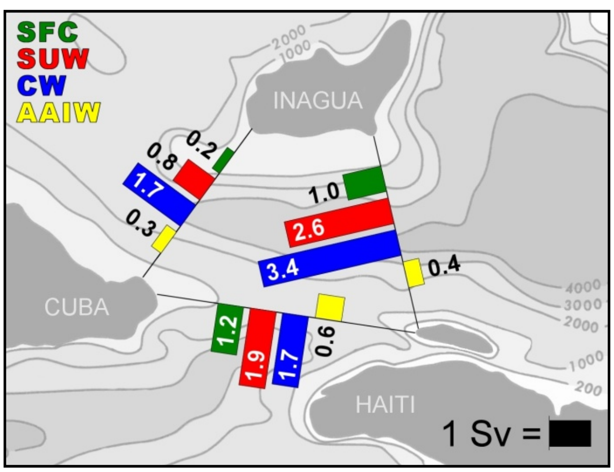

Figure 1. Mean water mass transports at the "triangle" formed by Cuba, Haiti, and Great Inagua, calculated from LADCP and CTD data collected during four shipboard occupations. Means are shown for Surface Water (SFC), Subtropical Underwater (SUW), Central Water (CW), and Antarctic Intermediate Water (AAIW) density classes.

The mean water mass transport calculations for the triangle show that Surface Water (SFC) and Subtropical Underwater (SUW) enter the domain from the east and predominantly flow into the Caribbean through Windward Passage. Central Water (CW) enters from the same direction and bifurcates, with approximately equal portions flowing south (into the Caribbean), and west (north of Cuba). The net transport of Antarctic Intermediate Water (AAIW) is out of the Caribbean with similar amounts flowing west and east to either side of Great Inagua. These water mass transport means are shown in Figure 1.

The accuracy of the project's LADCP velocity profiles will be improved by the inclusion of available hull-mounted ADCP and CTD data in the data processing routines. Section transport estimates will be recalculated incorporating processed hull-mounted ADCP profiles with the finalized LADCP data set.

References

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