Overview

Ocean Wave-Driven Upward-Mixing System by Atmocean, Inc.

Abstract

We describe the Atmocean wave-driven upward-mixing system, provide initial guidance on application-specific configurations and show concepts for geospatial control and volumetric optimization.

Cooling effects attributable to pumping 10 C. colder water during Hurricane Ike’s passage through the Central Gulf of Mexico suggest up to 40% additional cooling of the upper 75m ocean well before Ike’s eye reach NDBC data buoy 42001. Significant, but not yet modeled, reduction in intensity would be anticipated from this upper ocean cooling.

Ocean test data is provided, and available wave kinetic energy for the North Pacific, North Atlantic, Caribbean, and Gulf of Mexico is analyzed for nominal upward mixing volume per hour, both annually and for representative weeks in the Winter, Spring, Summer, and Fall.

Description of Atmocean Wave-Driven Upward-Mixing System.

Each Atmocean upward-mixing system consists of a wave-following buoy from which are suspended a series of double-sided valve “flappers” (photo adjacent), which rotate from horizontal to vertical as the buoy rises and falls on successive waves. On wave upslope, the horizontal flappers move water (above, beneath, & adjacent) upward while producing edge-turbulent mixing. On wave downslope, the flappers become vertical, allowing the entire system to sink, then fetching more water on the next wave upslope.

Figure 1. Picture of Valves.

Application Specific Configurations.

Here we describe conceptual configurations for the principle applications of wave-driven ocean upward-mixing pumps. A short application overview follows.

<u>Hurricane Mitigation</u>: Reduce hurricane intensity by pumping up colder deep water in the path of a hurricane to reduce upper ocean heat content and thereby reduce evaporation which is the primary convective energy source. Analysis of potential cooling for Hurricane Ike (2008) is provided below.

<u>Enhance Primary Production to Stimulate The Ocean Carbon Cycle:</u> Upward-mixing of nutrients should increase phytoplankton, absorbing dissolved CO_2 from the upper ocean.

<u>Mariculture</u>: Enhanced primary production supports higher trophic marine species.

Mitigate Coral Reef Bleaching: Cooling the upper ocean upstream of reefs may reduce thermal stress leading to bleaching, if ocean currents move the cooler water across the reef.

Mitigate Dead Zones: The system described here can be operated “upside down”, to produce downwelling. If the upper ocean contains higher concentration of oxygen, this water is mixed downward to low-oxygen regions.

For each application, the local ocean environment must be evaluated and tested to assess effects on the ecology, as well as practicality & effectiveness of the proposed mitigation efforts. Here we provide preliminary design criteria for each of these potential applications.

Application	Typical depth of operation	Valve units per string; Spacing	Valve Flappers Total Area	Estimated Minimum Wave Height	Est. Pump Spacing & approx. ocean area	Index of ocean area to valve area
Hurricane intensity reduction	From 125m To 15m	11 12 m	9 m^2	1.44 m	500 m. 250,000 m^2	27,778:1
Stimulate ocean carbon cycle	From 120m To 45m	16 5 m	7 m^2	1.20 m	1,000 m. 1 million m^2	142,857:1
Mariculture	From 125m To 5m	41 3 m	3.5 m^2	0.60 m	50 m 2,500 m^2	714:1
Mitigate coral reef bleaching	From 150m To 5m	59 2.5 m	3.5 m^2	0.60 m	200 m 40,000 m^2	11,428:1
Mitigate Dead Zones	From 2m To 30m	19 1.56 m	2.0 m^2	0.33 m	50 m 2,500 m^2	1,250:1

Table 1. Application Overview.

Geospatial Control is achieved by “weathervaning” (aligning) one or more valve units with prevailing currents, and adjusting connecting points off-center to produce a “skating” motion on wave upslope. Skating can be either upstream or downstream.

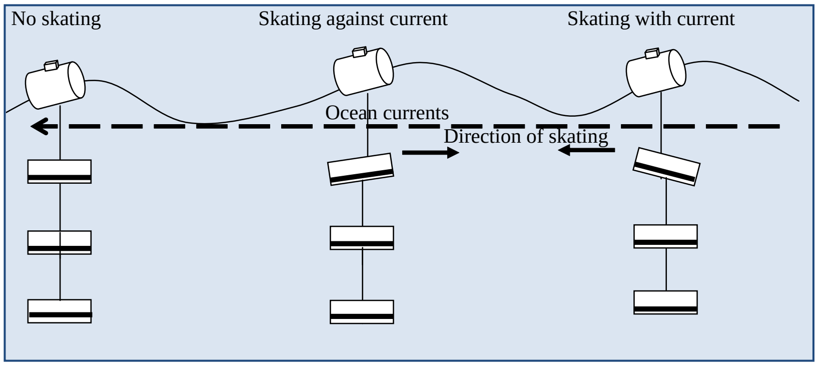


Figure 2. Geospatial Control Concept.

Hurricane Ike Predicted Ocean Cooling.

The large waves generated by hurricanes produce cooling of the upper ocean, as shown in the red bar graph of sea surface temperatures at NDBC Buoy 42001 as Hurricane Ike passed by in September, 2008 (Figure 3b). The distance of Ike from the buoy is shown on the top x-axis. Some natural cooling was seen when Ike was over 1,400 km away, and this natural cooling increased as Ike passed by NDBC 42001.

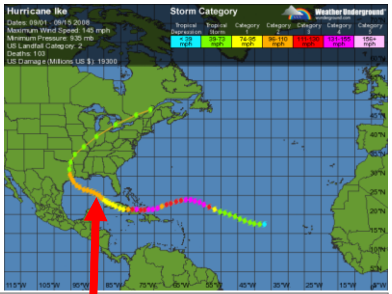


Figure 3a: Ike Track.

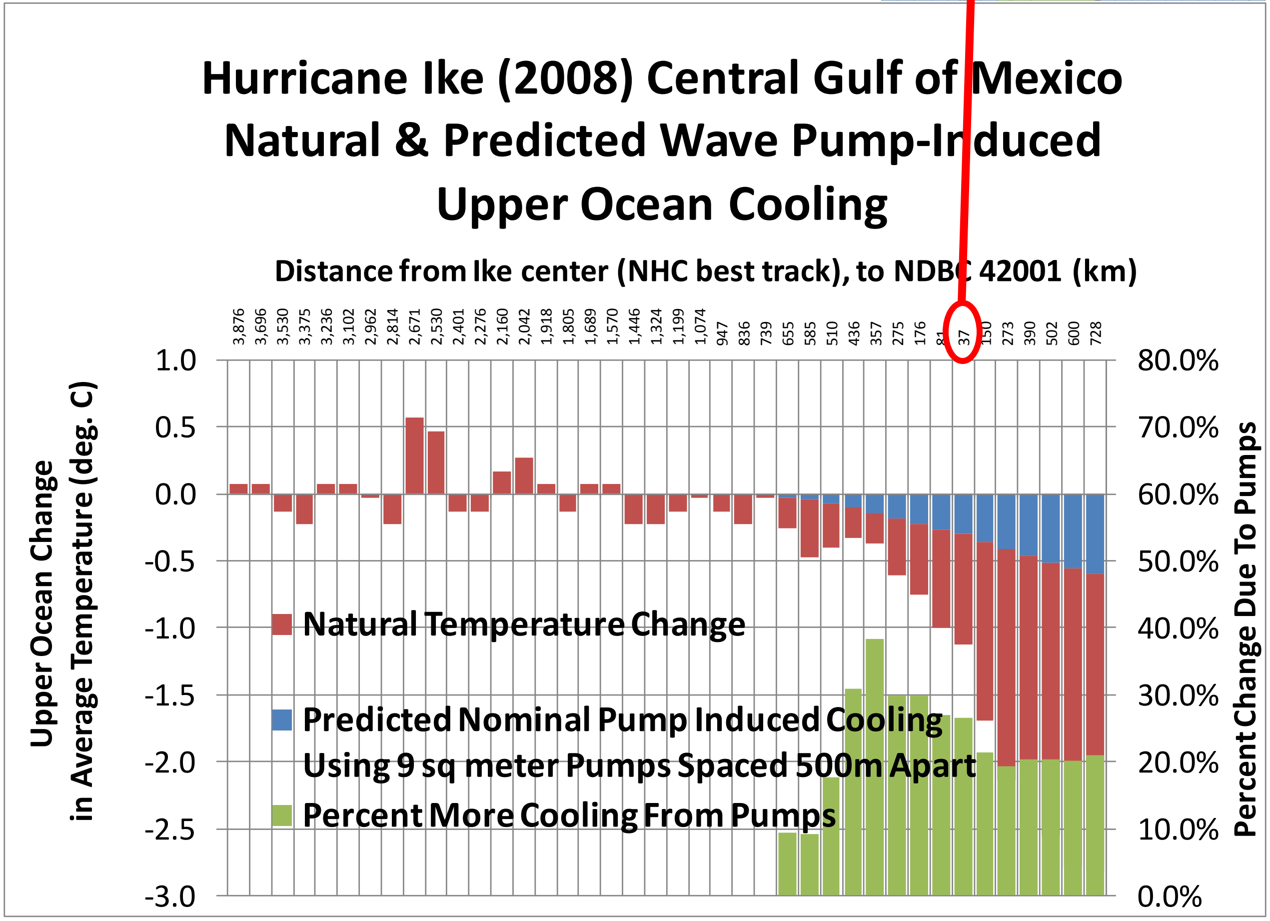


Figure 3b. Hurricane Ike Natural Cooling and Predicted Pump Cooling.

We superimposed a single 9 m^2 wave-driven pump on the buoy location and calculated the nominal upward mixing of deeper water based on the 42001 significant wave height and dominant period. The pumping region was defined as a volumetric region 500m on a side and 75m deep (the approximate 26°C. isotherm). Each vertical data point represents 6 hours of results using the National Hurricane Center best track for geographic coordinates.

Additional cooling from the pump became evident when Ike was almost 600km distant. The imposed cooling, as percentage of total cooling, peaked when Ike was 350km distant, after which natural cooling increasingly dominated.

The potential to significantly reduce upper ocean heat content when a hurricane is hundreds of kilometers out to sea, and thus reduce intensity before the hurricane reaches landfall, suggests a feasible avenue for more research and field trials to assess if this technology could provide mitigation benefits in hurricane-prone regions such as the Gulf of Mexico, Caribbean, Eastern North Pacific, Western North Pacific, and Indian Oceans.

Test Data.

Here we show GPS and temperature data from a test in April 2009 of a 1m diameter, 55m deep upward-mixing system with five valve pairs spaced at ~11m. Thermistors positioned on the cable 1m, 2m, 3m and 4m above the uppermost valve saw less morning solar gain than thermistors on the valve and at 5m above. We interpret this to mean the 1-2-3-4m water was cooled by upward mixing of deeper cold water. The steel valve heated from sunlight, offsetting the deep water cooling, and the 5m thermistor was above the upward-mixed plume of cold water.

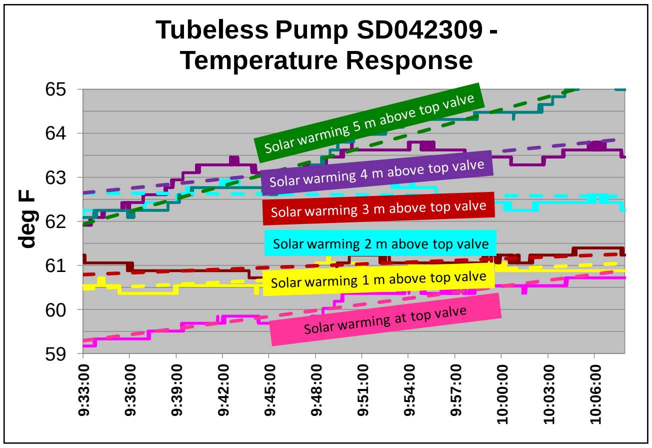
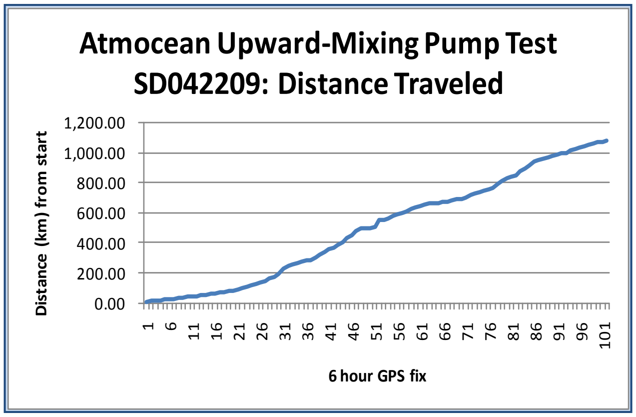


Figure 4. Thermistor Data From Ocean Test.



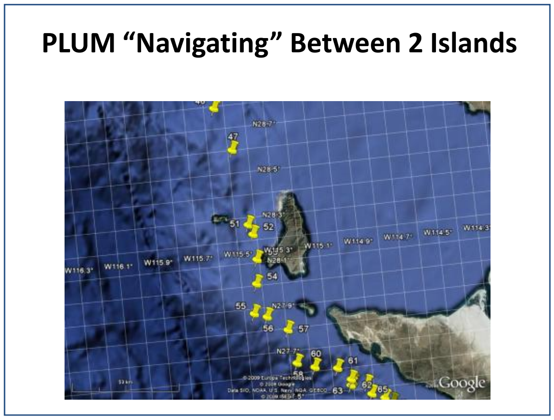


Figure 5a. Distance Traveled With Calif. Current.

Figure 5b. Passage Between Baja Islands

This system closely followed the California Current south from San Diego for 25 days until it was recovered near the tip of the Baja Peninsula. Interestingly, rather than washing up on shore, this system navigated a passage between two islands – demonstrating its tight coupling to the deeper currents.

Nominal Upward Mixing Volumes Based on Wave Kinetic Energy In North Atlantic, North Pacific & Caribbean Oceans, and Gulf of Mexico.

We define nominal upward-mixing as the potential volume of water moved upward per hour, which we derive by multiplying effective dominant wave height by 3,600/dominant wave period. Effective dominant wave height uses hourly data from National Data Buoy Center (NDBC) moored buoys, from which we subtract the amplitude required for a valve "flapper" to rotate 90°, plus an additional 20% to allow for cable stretch and buoy-wave compression (assumes 120m deep pump with 16 stages per Table 1 boldface). Thus, if the NDBC one-hour dominant wave height is 2.0m, our effective wave height for a one meter flapper will be (2.0-(1.0*120%)) = 0.8m. If the one-hour dominant period is 12 seconds, the nominal upward-mixing volume per hour is (0.8*(3,600/12)) = 240 vertical meters per square meter of valve area. In this example, if the design specifies 2m width and 3.5m length (7 m^2 area), the nominal upward-mixing is 240*7 = 1,680 m^3. Summing these hourly values for the calendar year gives us annual nominal upward mixing volume.

This nominal volume will be affected by many ambient ocean conditions including plume advection, eddies, upward-mixing of adjacent water, pump drift coinciding with average currents, etc. At this stage in development we do not have data which would allow us to predict the net upward-mixed volume. Given the dynamic ocean conditions, these data are best obtained *in situ*.

Below we provide full-year comparisons of nominal upward mixing for different ocean basins, based on full-year moored buoy historical data.

Buoy ID	Lat.	Long.	Geographic ID	Ocean Basin	Data Full Year	Annual Nominal Upward Mixing for a 7 m^2 pump (000 m^3)
42001	25.9N	89.7W	Mid Gulf	Gulf of Mexico	2008	7,672
42002	25.8N	93.7W	Western Gulf	Gulf of Mexico	2009	7,708
42059	15.0N	67.5W	Eastern Carib.	Caribbean	2008	14,060
42057	16.8N	81.5W	Western Carib.	Caribbean	2009	4,425
41041	14.4N	46.0W	Mid Atlantic	Atlantic	2009	21,079
41046	23.9N	70.9W	East of Bahamas	Atlantic	2009	14,971
51028	0.0N	153.9W	Xmas Island	Pacific	2005	10,843
51002	17.1N	157.8W	SSW of Hawaii	Pacific	2008	24,427
51003	19.0N	160.7W	SW of Hawaii	Pacific	2009	21,792

51101	24.3N	162.1W	N of Hawaii	Pacific	2007	22,918
46047	32.5N	118.0W	San Diego	Pacific	2009	7,711

Table 2. Predicted Upward-Mixing Produced By 7m^2 Wave-Driven Atmocean Pump

As the nominal upward-mixing volumes shown here are all based on a 7m^2 pump, the variability is directly attributable to wave kinetic energy available in different ocean regions. In addition, considerable seasonal, weekly, and even daily variability of wave kinetic energy is seen. Delivery of colder and higher-nutrient water will be directly proportional to the nominal upward mixing volumes shown above.

In Appendix 1 we provide a comparison of nominal upward mixing volumes per hour for the full year and for four one-week periods selected to coincide with Winter, Spring, Summer, and Fall for Gulf of Mexico, Caribbean, North Pacific, and North Atlantic. These 1-week periods encompass the week beginning on calendar day 55, and on each 90-day subsequent week during the year. Again we use the 120m deep, 7 m^2, 16 stage pump to derive these data.

<u>Discussion.</u> For the 7 m^2 design, upward-mixing system used in this analysis, nominal volumes generally are greater in Winter and Fall than Spring and Summer. Larger ocean basins generally produce more wave-driven upward mixing than smaller basins. Variability within a day was as much as 9,000 m^3 per hour (see 42001 Gulf of Mexico, February 28th).

<u>Interannual Variability.</u> Next we explored interannual variability in nominal annual upward-mixing volumes in the North Pacific at Buoys 51028 (Christmas Island), 51002 (SSW of Hawaii), and 46047 (San Diego). No pattern emerges from this simple analysis.

Buoy ID	Year 1 & Volume	Year 2 & Volume	Year 1 / Year 2
51028	2005: 10.8 million m^3	2006: 15.9 million m^3	67.9%
51002	2007: 30.2 million m^3	2008: 24.6 million m^3	122.8%
46047	2007: 8.0 million m^3	2009: 7.7 million m^3	103.9%

Table 3. Interannual Upward-Mixing Variability Within Ocean Basins

Conclusions. To provide initial guidance to the scientific community, we have provided some engineering, design, application, and potential performance characteristics of Atmocean's wave-driven upward mixing pump system. Initial testing suggests the device functions as expected. Analysis suggests a wide variation of nominal upward mixing across all spatial and temporal domains – ocean basin, annual and interannual, as well as seasonal, weekly, and even daily time periods. Further ocean testing will no doubt inform us and the readers of issues not presently contemplated. We welcome comments and suggestions, as well as future independent or collaborative testing and modeling efforts.

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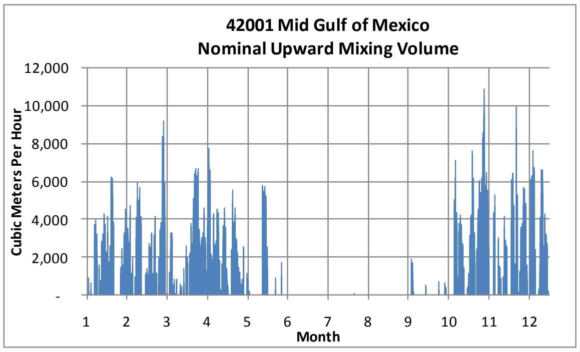
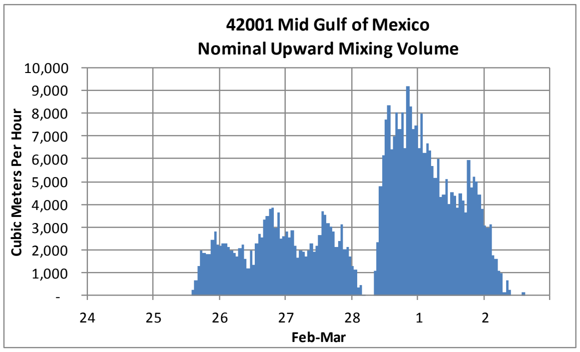
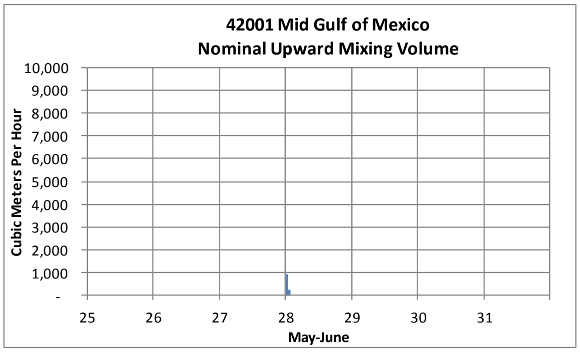
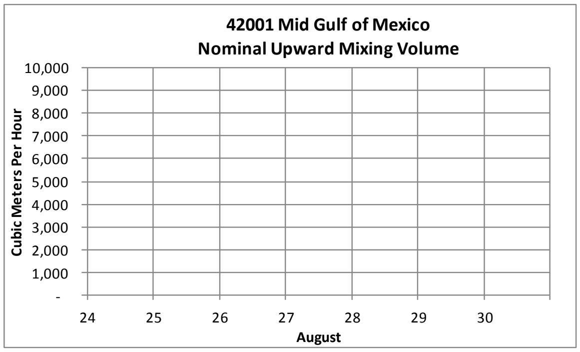
Appendix 1. Potential Upward Mixing.

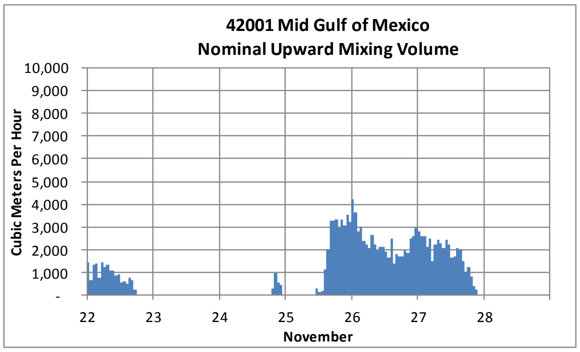
42001 Mid Gulf of Mexico (2008)



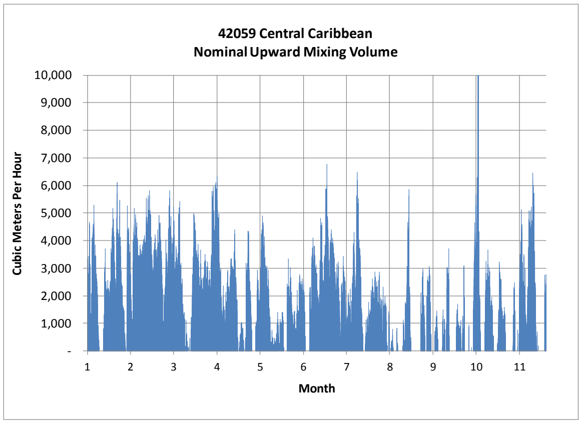


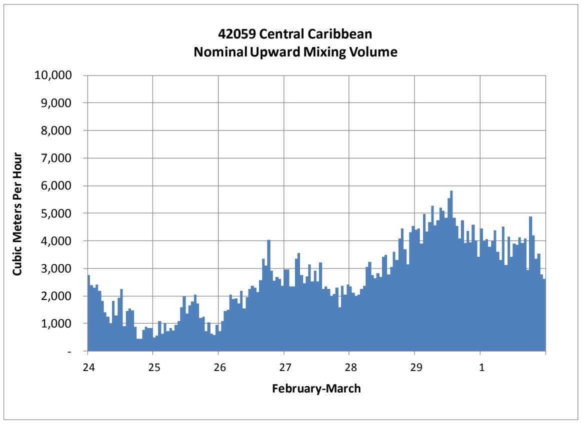


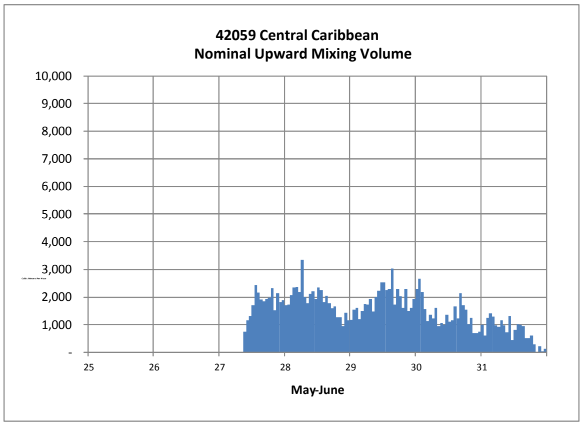


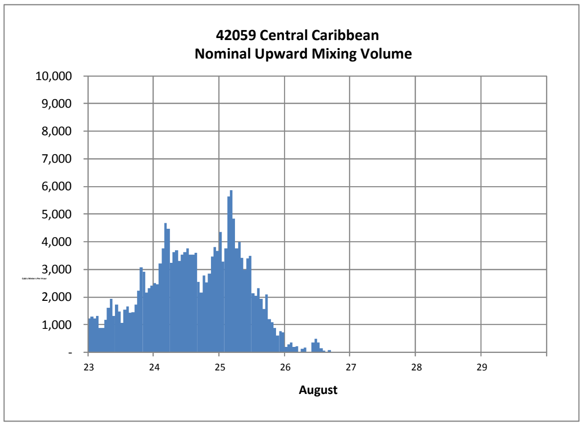


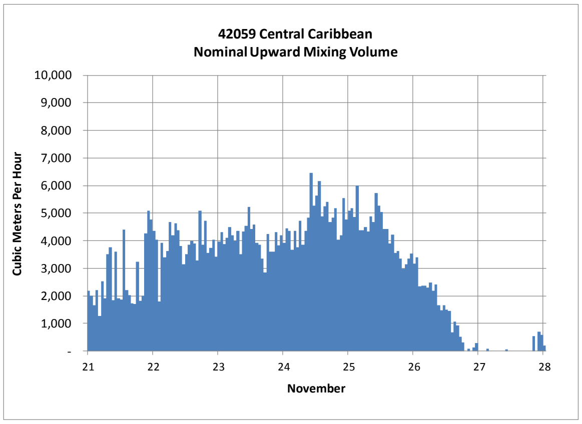
42059 Central Caribbean (2008)



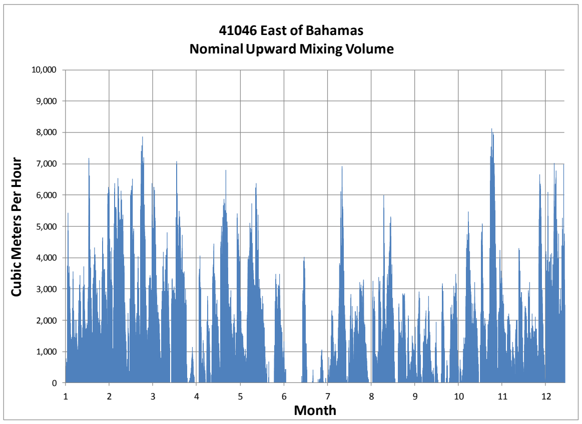


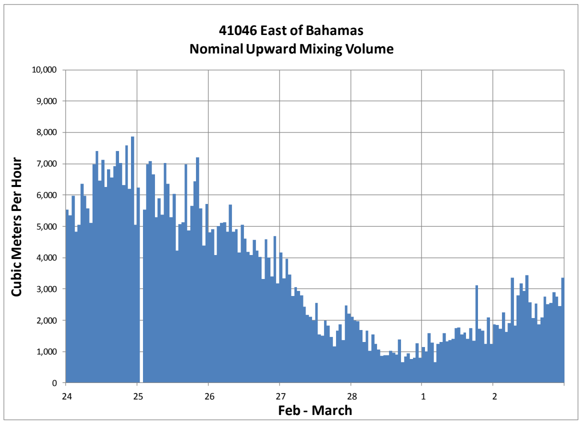


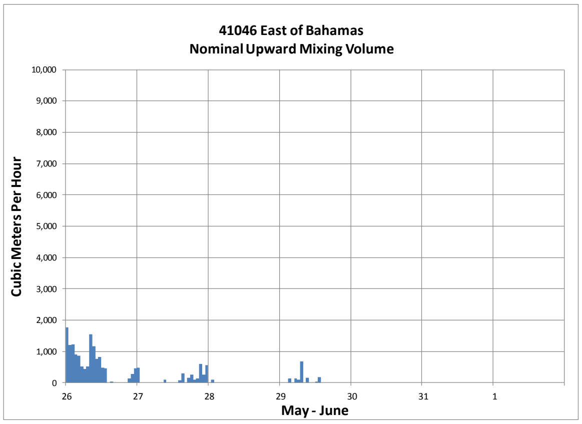


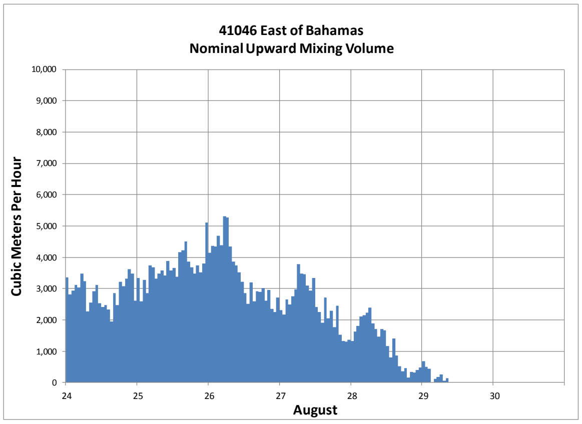


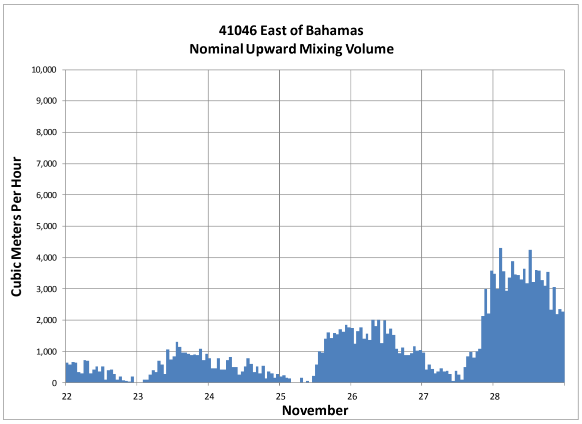
41046 East of Bahamas (2009)











51003 SW of Hawaii (2009)