# Deposition of $^{7}$Be to Bermuda and the regional ocean: Environmental factors affecting estimates of atmospheric flux to the ocean

David Kadko[1] and Joseph Prospero[1]

Received 1 September 2010; revised 11 November 2010; accepted 7 December 2010; published 9 February 2011.

[1] The distribution of $^{7}$Be in ocean surface waters is used as tracer of upper ocean transport and atmospheric deposition processes. However, there is very little ocean deposition data available to characterize the temporal and spatial input of $^{7}$Be to the oceans and test model results. Here we measure the deposition of $^{7}$Be in bulk collectors at two sites at Bermuda over a span of nearly 2 years (April 2007 to January 2009) and compare these rates to the flux required to sustain the inventory of $^{7}$Be measured in the nearby Sargasso Sea. The Tudor Hill collector site undersampled (by ~40%) both the rainfall compared to other Bermuda sites and the $^{7}$Be flux required for the ocean inventory. On the other hand, the $^{7}$Be flux captured at the Bermuda Institute of Ocean Sciences station site (0.048 dpm cm$^{-2}$ d$^{-1}$) matched that expected from the ocean observations. Previously measured long-term atmospheric concentration of $^{7}$Be in surface air at Bermuda was used to estimate deposition velocities and scavenging ratios, and our estimates in this marine environment were found to be similar to those measured in continental regions. The deposition of $^{7}$Be to the oceans is overwhelmingly determined by wet processes; dry deposition to the ocean surface accounts for only a few percent, at most, of the total deposition to the ocean. We place these measurements in a longer-term and large-scale spatial context by using climatological rainfall data on Bermuda and ocean rainfall estimates from the Global Precipitation Climatology Program and Tropical Rainfall Measuring Mission.

**Citation:** Kadko, D., and J. Prospero (2011), Deposition of $^{7}$Be to Bermuda and the regional ocean: Environmental factors affecting estimates of atmospheric flux to the ocean, *J. Geophys. Res.*, *116*, C02013, doi:10.1029/2010JC006629.

## 1. Introduction

[2] The atmospheric input of numerous chemical species into the global ocean equals or exceeds that from river sources [*Duce et al.*, 1991]. Assessment of this input is difficult, however, because measurements of deposition rates to the ocean are rare. Furthermore, such measurements are susceptible to problems associated with temporal and spatial variability of precipitation and of the concentration of species within precipitation. Natural radionuclides delivered to the ocean from the atmosphere are useful tracers for characterizing global-scale transport and deposition. For example, the global distribution of $^{7}$Be in the atmosphere and its deposition to the ocean has been modeled [*Brost et al.*, 1991; *Koch et al.*, 1996, 2006], and parameters developed in such models can be extended to the modeling of other aerosol species including those from anthropogenic sources.

[3] The accumulation of $^{7}$Be in the upper ocean provides a means of assessing $^{7}$Be deposition on a global scale. The ocean inventory of $^{7}$Be is largely based on measurements of the vertical distribution of $^{7}$Be in the oceans, most notably in the work of *Young and Silker* [1980], who presented data from a large number of globally distributed ocean sites. These data have been widely used to constrain the estimates of $^{7}$Be deposition rates to the ocean. More recently, ocean profiles have also been measured in the northeastern Atlantic [*Kadko and Olson*, 1996] and the western Arctic [*Kadko*, 2000; *Kadko and Swart*, 2004]. There have been very few measurements made of the deposition rates of $^{7}$Be in rain at ocean sites [*Turekian et al.*, 1983; *Kim et al.*, 1999]; studies at coastal sites are more common [e.g., *Olsen et al.*, 1985, 1986; *Dibb*, 1989; *Todd et al.*, 1989; *Baskaran et al.*, 1993]. To our knowledge, no concurrent measurements of $^{7}$Be deposition with ocean profile measurements have been made prior to this study. It is well known that rainfall rates measured on islands are not necessarily representative of rainfall rates to the surrounding ocean, even at small Pacific atolls that are commonly used for satellite validation [*Huffman et al.*, 2007]. Consequently, the measured deposition rates of chemical species in island rain might not accurately reflect regional ocean deposition rates. To address this issue, we assess the atmospheric flux of $^{7}$Be measured at two sites at Bermuda over a nearly 2 year period. These data were compared to the

[1]Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA.


0148-0227/11/2010JC006629

standing crop of $^{7}$Be measured in the nearby Sargasso Sea. The objective was to determine how well the flux measured on the island matched that required to support the observed ocean inventory. This, by inference, provides a measure of how well the flux of other species measured in Bermuda rainfall reflects the actual oceanic deposition to the nearby ocean. We extend the analysis of this short-term data set by placing it in the context of long-term rainfall measurements on Bermuda and on the regional ocean using satellite rainfall data sets. Finally, to place our measurements in a global context, we compare the $^{7}$Be measurements and deposition parameters on Bermuda with those made in other (mostly continental) regions.

## 2. Background $^{7}$Be

[4] Be-7 is a cosmic ray-produced isotope (half-life of 53.3 days) that is deposited on the ocean surface primarily by rainfall and is subsequently homogenized within the surface mixed layer [e.g., *Silker*, 1972; *Aaboe et al.*, 1981; *Young and Silker*, 1980; *Kadko and Olson*, 1996; *Kadko*, 2000, 2009]. In the low-particle environment of the open ocean, particularly within the oligotrophic regime of the Sargasso Sea, $^{7}$Be is considered conservative with respect to particle scavenging removal [e.g., *Silker*, 1972; *Andrews et al.*, 2008].

[5] While most of the production of $^{7}$Be occurs in the stratosphere, the long residence time of aerosols in the stratosphere relative to the short half-life of $^{7}$Be dictates that the tropospheric production of $^{7}$Be determines the flux to the Earth's surface, although intrusions of stratospheric air into the troposphere are, at times, also important [*Feely et al.*, 1989]. Therefore, over broad oceanic regions, the $^{7}$Be flux and water column inventory vary as a function of rainfall, and, consequently, inventories in ocean surface waters are inversely related to salinity [*Young and Silker*, 1980; *Kadko and Olson*, 1996]. The water column inventory represents an integration of the flux over approximately the previous mean-life (77 days) of the isotope, assuming that advective processes represent a small component of the isotopic budget. While advective effects cannot be discounted from individual ocean profiles, long-term averages as compiled in this study likely mitigate the effect of these complications.

## 3. Methods

### 3.1. Atmospheric Deposition Measurements

[6] The $^{7}$Be flux was determined at two sites on the island of Bermuda. One was atop the 23 m sampling tower at Tudor Hill (TH), located on a steep slope at the extreme western end of Bermuda (32°15.95′N, 64°52.65′W) with the tower base 28 m above sea level. The second collection site was established at the Bermuda Institute of Ocean Sciences (BIOS) located 21 km northeast of TH, close to the eastern end of the island (32°22.28′N, 64°41.80′W). The collector was situated near ground level, clear of surrounding vegetation, at a meteorologic monitoring station in front of the BIOS laboratory, about 10 m above sea level. This is a Bermuda Air Quality Program site used for ambient air quality monitoring.

[7] To estimate the atmospheric deposition of $^{7}$Be, plastic buckets (660.5 cm$^{2}$) were deployed for collection of fallout over known time periods. Typically, collection times were about 3 weeks but varied as a function of rainfall, i.e., were longer when rainfall was less abundant. After collection, dilute HCl and stable Be yield tracer were added to the buckets. The $^{7}$Be was then coprecipitated with iron hydroxide, and the precipitate was dried in plastic petri dishes. The sample was subsequently counted by gamma spectrometry. The counting system was calibrated for all samples by preparing a commercial standard in a geometry identical to the samples. The stable Be in the precipitate was then measured by atomic absorption to calculate the $^{7}$Be recovery (generally ~70%) during precipitation.

[8] At both sites, rainfall was monitored by rain gauges (model 03319; Cole Parmer Instrument Co.), a cylindrical tube with a 10 cm diameter knife-edge opening.

### 3.2. Measurement of $^{7}$Be Profiles at Ocean Stations

[9] The Bermuda deposition results were compared to the ocean inventory determined from $^{7}$Be profiles, collected monthly, from June–November 2007 and April–November 2008 in the vicinity of the U.S. Joint Global Ocean Flux Study Bermuda Atlantic Time-series Study (BATS) (31°50′N, 64°10′W) and hydrostation S (32°10′N, 64°30′W) in the Sargasso Sea. Samples were collected from the R/V *Atlantic Explorer* and subsequently processed by methods described in detail elsewhere [*Kadko*, 2009]. Briefly, $^{7}$Be was collected at various depths by pumping 400–700 L of seawater via a 1.5 inch hose through iron-impregnated acrylic fibers [*Lal et al.*, 1988; *Krishnaswami et al.*, 1972; *Lee et al.*, 1991]. The efficiency of the fiber for extraction of Be from seawater was determined by adding 500 mL of a 1000 ppm Be atomic absorption standard to a drum containing seawater. The seawater was pumped through an iron fiber cartridge and at every 100 L the Be content of the cartridge effluent was measured by atomic absorption. From these data, the integrated Be extraction efficiencies were calculated. On land, the fibers were dried and ashed. The ash was subsequently pressed into a pellet (5.8 cm diameter) and placed on a low-background germanium gamma detector. In some cases where low $^{7}$Be concentrations were expected (typically at depths greater than 190 m), two samples were taken from the same depth to assure adequate signal, and the ashed fibers were combined and placed in Marinelli beakers to accommodate the large ash volume. For such samples, up to ~1200 L were analyzed.

[10] The $^{7}$Be has a readily identifiable gamma peak at 478 keV. The detector was calibrated for the pellet and Marinelli beaker geometries by adding a commercially prepared mixed solution of known gamma activities to an ashed fiber, pressing the ash into a pellet or adding the ash to a beaker, and counting the activities to derive a calibration curve. The uncertainty of the extraction efficiency (4%) and the detector efficiency (2%) was, in all cases, smaller than the statistical counting error and the uncertainty in the blank.

## 4. Results

[11] The $^{7}$Be flux measurements taken on Bermuda are shown in Table 1. Sampling began at the TH site in April 2007 in anticipation of the collection of oceanic $^{7}$Be profiles initiated in June 2007. The measured ocean inventories, and the calculated steady state fluxes to support them, are shown in Table 2.

**Table 1.** $^{7}$Be Flux Measurements

| | | | Rain Volume (mm) | | Flux (dpm cm$^{-2}$ d$^{-1}$) | |
|---|---|---|---|---|---|---|
| Sample | Start Date | End Date | Tudor Hill | BIOS[a] | Tudor Hill | BIOS |
| F1 | 18 Apr 2007 | 8 May 2007 | 39.8 | 49 | 0.0207 ± 0.0006 | |
| F2 | 8 May 2007 | 14 May 2007 | 72.2 | 106.4 | 0.1417 ± 0.0067 | |
| F3 | 14 May 2007 | 21 May 2007 | 106.1 | 108.7 | 0.0705 ± 0.0019 | |
| F4 | 22 May 2007 | 30 May 2007 | 39.9 | 42.9 | 0.0127 ± 0.0011 | |
| F5 | 30 May 2007 | 18 Jun 2007 | 74.6 | 97.8 | 0.02845 ± 0.0013 | |
| F6 | 18 Jun 2007 | 25 Jun 2007 | 21.8 | 33.3 | 0.01235 ± 0.0011 | |
| F7 | 25 Jun 2007 | 3 Jul 2007 | 60.5 | 52.1 | 0.0487 ± 0.0030 | |
| F8 | 3 Jul 2007 | 23 Jul 2007 | 28.9 | 24.9 | 0.0210 ± 0.0007 | |
| F9 | 23 Jul 2007 | 7 Aug 2007 | 137.7 | 244.3 | 0.0593 ± 0.0018 | |
| F10 | 7 Aug 2007 | 16 Aug 2007 | 16.1 | 38.9 | 0.0157 ± 0.0011 | |
| F12 | 16 Aug 2007 | 28 Aug 2007 | 31.2 | 54.9 | 0.0297 ± 0.0019 | 0.0332 ± 0.0023 |
| F13 | 28 Aug 2007 | 3 Sep 2007 | 34.1 | 27.2 | 0.0580 ± 0.0057 | 0.1069 ± 0.0072 |
| F15 | 3 Sep 2007 | 18 Sep 2007 | 10 | 42.4 | 0.0088 ± 0.0008 | 0.0075 ± 0.0010 |
| F17 | 18 Sep 2007 | 2 Oct 2007 | 54.2 | 79.8 | 0.0701 ± 0.0020 | 0.1127 ± 0.0065 |
| F20 | 2 Oct 2007 | 15 Oct 2007 | 115.8 | 99.8 | 0.0228 ± 0.0022 | 0.0560 ± 0.0039 |
| F22 | 15 Oct 2007 | 30 Oct 2007 | 57.6 | 68.58 | 0.0176 ± 0.0015 | 0.0176 ± 0.0014 |
| F24 | 30 Oct 2007 | 12 Nov 2007 | 46.8 | 105.4 | 0.0434 ± 0.0038 | 0.0850 ± 0.0059 |
| F26 | 12 Nov 2007 | 3 Dec 2007 | 48.4 | 45.9 | 0.0300 ± 0.0020 | 0.0468 ± 0.0035 |
| F28 | 3 Dec 2007 | 18 Dec 2007 | 53.2 | 26.9 | 0.0365 ± 0.0013 | 0.0731 ± 0.0023 |
| F30 | 18 Dec 2007 | 7 Jan 2008 | 12.8 | 77.2 | 0.0370 ± 0.0005 | 0.0402 ± 0.0004 |
| F32 | 7 Jan 2008 | 28 Jan 2008 | 28.4 | 127.3 | 0.0132 ± 0.0003 | 0.0252 ± 0.0004 |
| F34 | 28 Jan 2008 | 18 Feb 2008 | 22.9 | 42.4 | 0.0056 ± 0.0002 | 0.0196 ± 0.0005 |
| F36 | 18 Feb 2008 | 19 Mar 2008 | 45.7 | 81.5 | 0.0217 ± 0.0006 | 0.0449 ± 0.0010 |
| F38 | 19 Mar 2008 | 27 Mar 2008 | 103.6 | 127 | 0.01745 ± 0.0012 | 0.0241 ± 0.0014 |
| F39 | 27 Mar 2008 | 18 Apr 2008 | 68.1 | 93.98 | | 0.0755 ± 0.0017 |
| F40 | 18 Apr 2008 | 7 May 2008 | 150.2 | 186.18 | | 0.1013 ± 0.0030 |
| F41 | 7 May 2008 | 3 Jun 2008 | 228.5 | 209.8 | | 0.0823 ± 0.0015 |
| F42 | 3 Jun 2008 | 2 Jul 2008 | 13.2 | 17.2 | | 0.0115 ± 0.0002 |
| F43 | 2 Jul 2008 | 24 Jul 2008 | 70.3 | 211.8 | | 0.0234 ± 0.0007 |
| F44 | 24 Jul 2008 | 19 Aug 2008 | 82.8 | 124.5 | | 0.0436 ± 0.0030 |
| F45 | 19 Aug 2008 | 18 Sep 2008 | 51.2 | 90.9 | | 0.0452 ± 0.0020 |
| F46 | 18 Sep 2008 | 13 Oct 2008 | 93.9 | 128.5 | | 0.04085 ± 0.0013 |
| F47 | 13 Oct 2008 | 7 Nov 2008 | 72.5 | 85.34 | | 0.0488 ± 0.0011 |
| F48 | 7 Nov 2008 | 21 Nov 2008 | 31.4 | 40.1 | | 0.0551 ± 0.0029 |
| F49 | 21 Nov 2008 | 11 Dec 2008 | 18 | 32 | | 0.0232 ± 0.0016 |
| F50 | 11 Dec 2008 | 19 Dec 2008 | 30.2 | 66.8 | | 0.0488 ± 0.0024 |
| F51 | 19 Dec 2008 | 9 Jan 2009 | 14.2 | 44.45 | | no sample |
| F52 | 9 Jan 2009 | 29 Jan 2009 | 56.1 | 86.36 | | 0.0572 ± 0.0031 |
| Average | | | | | 0.0302 ± 0.0223[b] | 0.0483 ± 0.0271[c] |

[a]Bermuda Institute of Ocean Sciences.
[b]For 18 April 2007 to 27 March 2008.
[c]For 16 August 2007 to 21 November 2008 (see section 4).

**Table 2.** Water Column Inventories

| | Site S | | BATS | |
|---|---|---|---|---|
| | Inventory (dpm m$^{-2}$) | Flux[a] (dpm cm$^{2}$ d$^{-1}$) | Inventory (dpm m$^{-2}$) | Flux[a] (dpm cm$^{2}$ d$^{-1}$) |
| 2007 | | | | |
| Jun | 46,538 | 0.0605 | 43,469 | 0.0565 |
| Jul | 24,809 | 0.0323 | 29,104 | 0.0378 |
| Aug | 31,468 | 0.0409 | 30,964 | 0.0403 |
| Sep | 39,388 | 0.0512 | 35,698 | 0.0464 |
| Oct | | | 28,567 | 0.0371 |
| Nov | 36,449 | 0.0474 | 37,053 | 0.0482 |
| 2007 Average | 35,730 | 0.0464 ± 0.0106 | 34,142 | 0.0444 ± 0.007 |
| 2008 | | | | |
| Apr | 33,961 | 0.0442 | 43,795 | 0.0569 |
| May | 43,860 | 0.0570 | 47,635 | 0.0619 |
| Jun | 39,315 | 0.0511 | 31,835 | 0.0414 |
| Aug | 31,888 | 0.0415 | 35,814 | 0.0466 |
| Sep | 35,231 | 0.0458 | 33,322 | 0.0433 |
| Oct | 30,115 | 0.0392 | 31,084 | 0.0404 |
| Nov | 50,468 | 0.0656 | 54,314 | 0.0706 |
| 2008 Average | 37,834 | 0.0492 ± 0.0094 | 39,686 | 0.0516 ± 0.012 |
| 2007–2008 Average | 36,957 | 0.0481 ± 0.0100 | 37,127 | 0.0483 ± 0.0103 |

[a]Steady state flux required to support observed inventory.

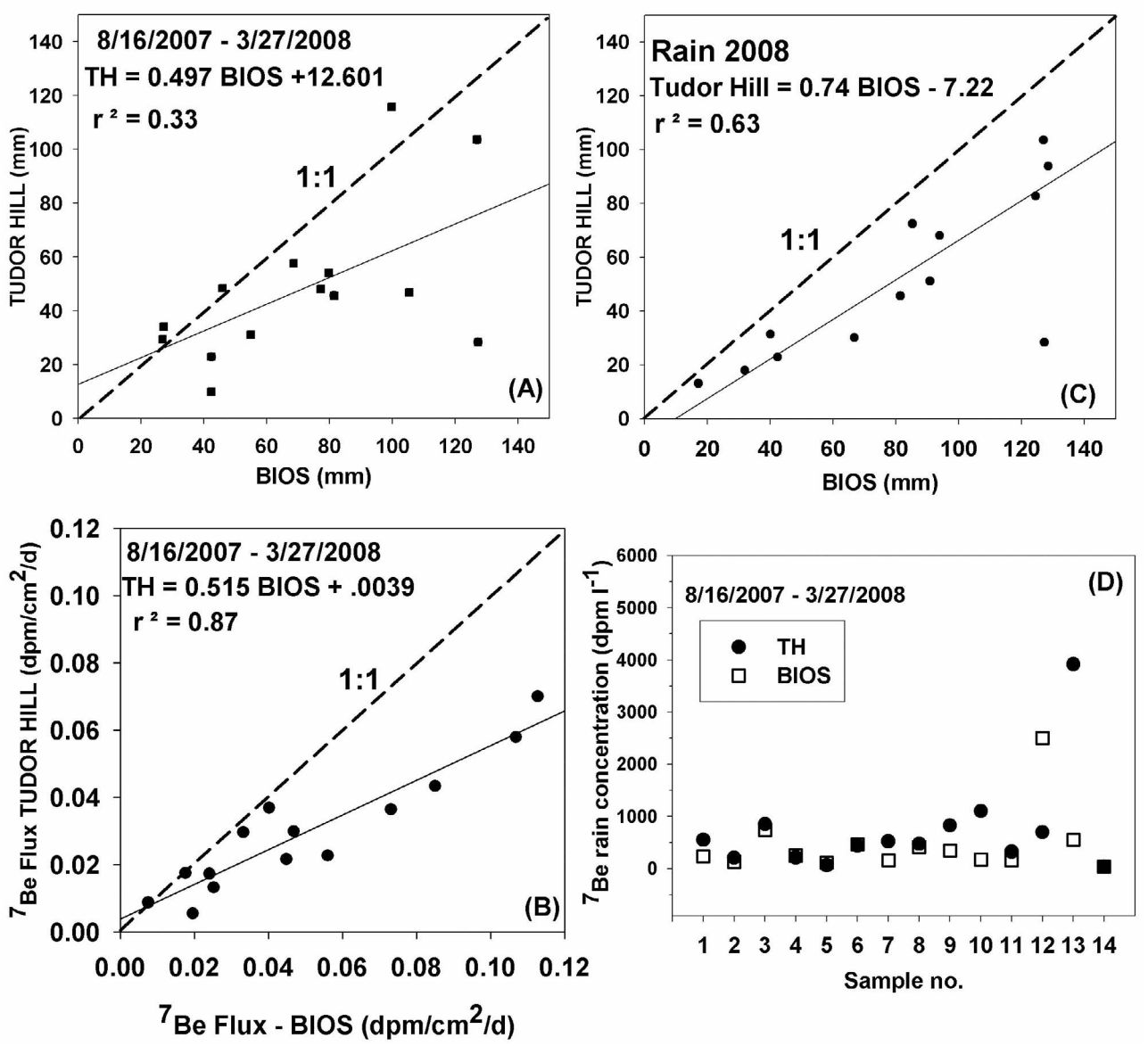


**Figure 1.** Rainfall and $^{7}$Be comparison between the two flux measurement sites at Bermuda. Over the $^{7}$Be flux intercomparison period (16 August 2007 to 27 March 2008), the Bermuda Institute of Ocean Sciences (BIOS) station site had higher (a) rainfall and (b) $^{7}$Be flux than the TH site. (c) Over the year 2008, ~35% more rain was recorded at the BIOS location than the Tudor Hill site. (d) $^{7}$Be concentrations for both sites plotted against sampling interval for the intercomparison period.

[12] The initial ocean sampling suggested a mismatch between the flux measured at TH and that required to sustain the observed ocean inventory. The average flux to the Sargasso Sea based on the $^{7}$Be inventories at sites S and BATS for 18–20 June was 0.0585 dpm cm$^{-2}$ d$^{-1}$, while the average measured flux at TH from 18 April to 25 June was only 0.037 dpm cm$^{-2}$ d$^{-1}$. If the TH deposition rates were representative of the true oceanic deposition rate, this would have suggested a large advective input of $^{7}$Be into the Sargasso Sea, with important implications for transport of nutrients and carbon into the region [e.g., *Michaels et al.*, 1994; *Toggweiler*, 1994]. To test the possibility that the TH flux measurements were undersampling the $^{7}$Be flux, it was decided to perform parallel $^{7}$Be measurements at an alternate site on a nonelevated position on the BIOS campus. The two sites were sampled concurrently between 16 August 2007 and 27 March 27 2008. Figures 1a and 1b show that over this period, the flux and rainfall determined at BIOS were systematically greater that at the TH location. The deficit of $^{7}$Be flux at TH relative to the BIOS site was nearly identical to the relative deficit in rainfall. For this period, the weighted mean flux at TH was 0.027 dpm cm$^{-2}$ d$^{-1}$, while at BIOS it was 0.0455 dpm cm$^{-2}$ d$^{-1}$, a factor of 1.69 greater than at TH. The rain at TH was 532 mm compared to 824 mm at BIOS, 1.55 greater than at TH. In 2008, BIOS recorded 1.35 times higher rain accumulation than TH for the entire year (Figure 1c). The similarity between the deficit of rain and flux over the intercomparison period suggests that the

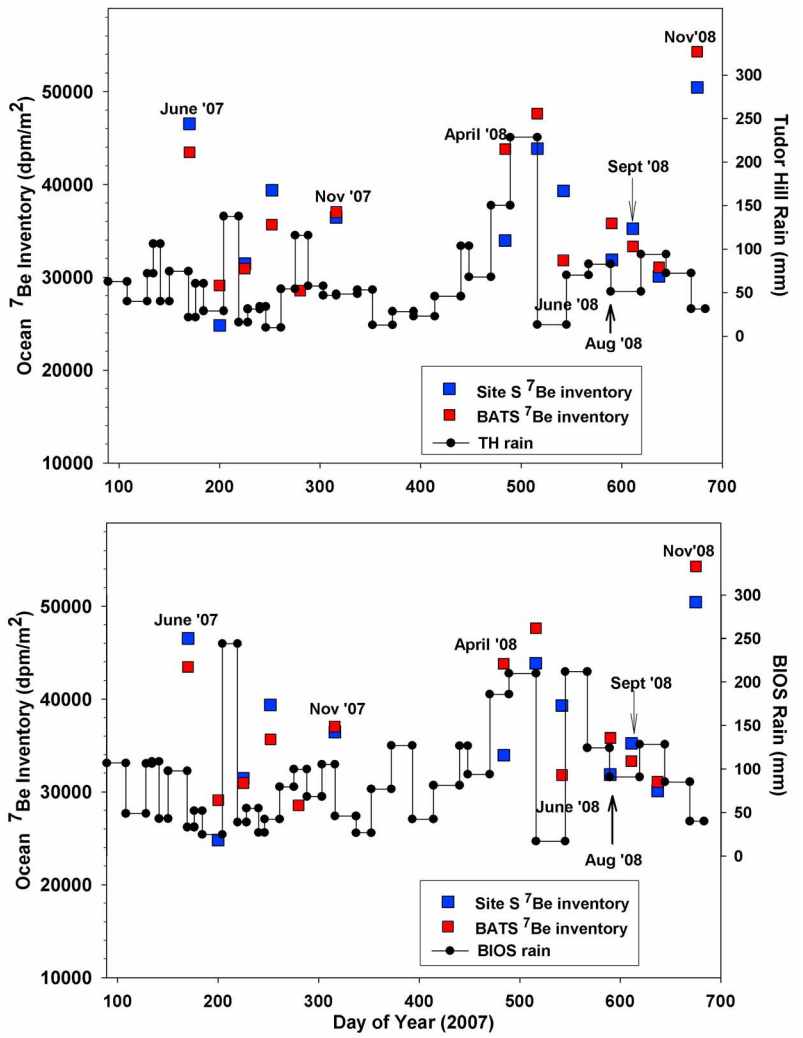


**Figure 2.** A comparison of the rainfall accumulation over each rainfall collection period (segments bracketed by black dots) and ocean inventory (red squares, Bermuda Atlantic Time-series Study (BATS); blue squares, site S). (top) Tudor Hill rain. (bottom) BIOS rain.

$^{7}$Be concentration in the rain for the two sites was similar (Figure 1d). The average oceanic $^{7}$Be flux determined from the ocean inventory for the sampling period between June 2007 and November 2008 was 0.048 ± 0.010 dpm cm$^{-2}$ d$^{-1}$, nearly identical for the two oceanic locations (Table 2). This matched the weighted (by collection time) average flux determined in precipitation at the BIOS site (16 August 2007 to 21 November 2008) of 0.048 ± 0.027 dpm cm$^{-2}$ d$^{-1}$ (standard deviation of the mean). *Turekian et al.* [1983] previously reported a similar value for precipitation collected at the same site in Bermuda (0.047 dpm cm$^{-2}$ d$^{-1}$). The weighted mean flux between the period 18 April 2007 and 21 November 2008, which brackets the ocean sampling period, was constructed as (1.7 × TH flux (for the period 18 April 2007 to 16 August 2008) + BIOS flux (for the period 16 August 2008 to 21 November 2008)) and equals 0.051 dpm cm$^{-2}$ d$^{-1}$, which again, within the uncertainty of the measurements, would support the ocean inventory. The factor 1.7 applied to the TH result is derived from the entire intercomparison period between TH and BIOS. Figure 1c shows that the difference in rainfall persisted over the entire year (2008); the rainfall accumulation for TH and BIOS was 996 and 1549 mm, respectively, yielding a relative deficit of 0.64 at TH. These results suggest the TH location was undersampling the rain and associated $^{7}$Be flux and, by inference, would underestimate the delivery by rain of other atmospheric aerosol species to the ocean. In section 5.1 we discuss more fully the issues of rainfall amounts and their representativeness.

[13] Figure 2 shows a plot of the rainfall accumulation at BIOS and TH compared to the ocean inventories at sites S and BATS. There is a qualitative similarity between the rainfall at the two sites, and the inventories generally reflect the trends in rainfall. In Figure 3a, the running average of the flux measurements is seen to track the changes in ocean inventories over time. Note that for the TH data plotted here, a factor of only 1.4 is applied as was observed for this partial segment of the comparison period (16 August 2007 to 12 November 2007). In Figure 3b, the cumulative $^{7}$Be ocean inventory expected from progressive input and decay of the measured

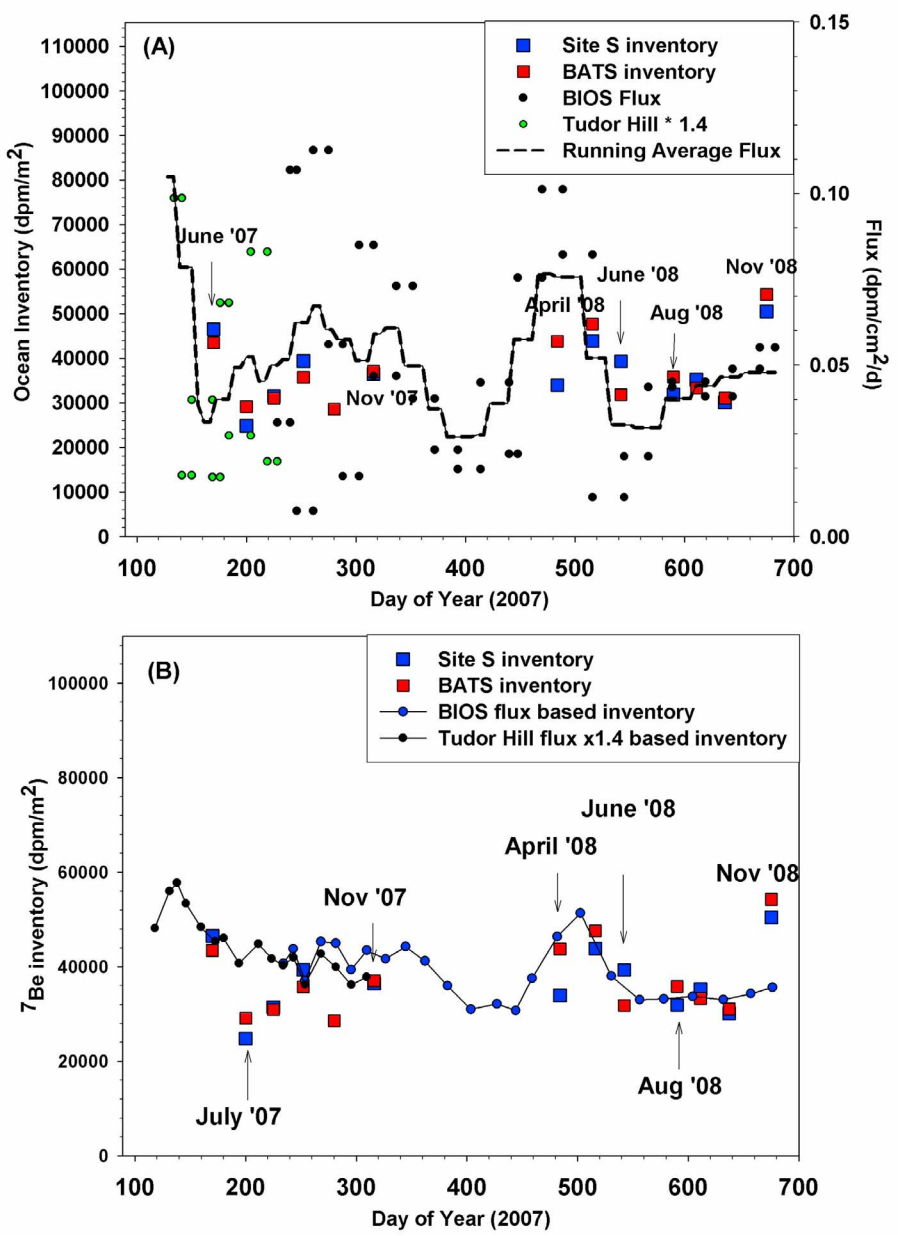


**Figure 3.** (a) Individual flux measurements (black dots, BIOS; green dots, Tudor Hill × 1.4), ocean inventories (red squares, BATS; blue squares, site S), and the running average of the flux measurements. (b) Cumulative $^{7}$Be ocean inventory expected from progressive input and decay of the measured flux.

flux is plotted [e.g., *Dibb*, 1989]. The calculated flux generally predicts the observed ocean inventory.

## 5. Discussion

[14] Our study shows that there is a substantial difference in the rainfall amounts and $^{7}$Be deposition rates measured at the two deposition sampling sites, and that the rate at BIOS closely matches that necessary to sustain the water column inventory of $^{7}$Be at the two ocean profile sites. To assess the significance of our measured rates relative to the ocean standing inventory, we must address several issues. The first is to establish how well our measured rain rates compare with long-term rainfall measured at Bermuda. The second is to assess the representativeness of rainfall rates measured on Bermuda relative to that on the surrounding ocean. It is well known that islands generate their own climate and that, consequently, the measured rainfall may be biased. We consider these issues below. We also make use of earlier measurements of $^{7}$Be air concentration on Bermuda to constrain various deposition parameters often used in estimating the deposition of aerosols to the oceans.

### 5.1. Historical Rainfall Measurement on Bermuda

[15] Rainfall rates are highly variable both spatially and temporally. To relate our measurements of $^{7}$Be deposition as

**Table 3.** Bermuda Rainfall Estimates

| Source | Location | Start Date | End Date | Amount (cm/yr) |
|---|---|---|---|---|
| Bermuda Meteorological Service[a] | airport | 1949 | 2008 | 146 |
| Playle | Somerset | 1974 | 1999 | 152 |
| Galloway, University of Virginia | Harbour Radio Tower | Apr 1980 | Jun 1988 | 150 |
| Galloway, University of Virginia | Tudor Hill | Aug 1989 | Feb 1997 | 94 |
| University of Miami | BIOS | Jan 2007 | Jan 2009 | 146 |
| University of Miami | Tudor Hill | Jan 2007 | Jan 2009 | 108 |
| Global Precipitation Climatology Project (GPCP) (V2.1)[b] | 2.5° × 2.5° box | 1998 | 2004 | 124 |
| Tropical Rainfall Measuring Mission (TRMM) (3B-43)[b,c] | 2.5° × 2.5° box | 1998 | 2004 | 123 |

[a]This includes the data collected by the U.S. Navy (1949–1994).
[b]The GPCP and TRMM data are the average for a 2.5 × 2.5 grid box that contains Bermuda.
[c]TRMM data multiplied by 1.16.

representative of Bermuda and the adjacent ocean, we need to place our measurements in a larger time-space context. To this end, we use rainfall data from various sources, summarized in Table 3. The annual averages are shown in Figure 4. The longest record of rainfall on Bermuda is that obtained by the U.S. Navy (USN) (1949–1994) at the airfield located immediately to the south of BIOS on St. David's Island (32.36°N, 64.70°W). When the Navy departed, measurements were continued by the Bermuda Meteorological Service (BMS) at the same location, now the Bermuda International Airport. The average annual long-term (1949–2008) rainfall rate on Bermuda is 146 cm. In most months, the rates fall into a relatively narrow range, 11–13 cm/month, with a dry spell in April–May (~8 cm) and a sharp peak in October (16 cm/month).

[16] A long-term data set was also obtained by a weather enthusiast, B. Playle, who made systematic measurements from 1974 to 1999 and provided the data to the USN-BMS. The readings were taken in Somerset on the extreme western end of Bermuda at a site 3.2 km north of TH. As seen in Figure 4, the Somerset data closely track those at the USN-BMS site and suggest that rainfall is relatively uniform across the island. In another study, *Galloway et al.* [1993] presented a data set from an automatic collector started in April 1980 and ending in February 1997. Over the period April 1980 to June 1988, the collector was located at Harbour Radio Tower, Bermuda (HRT), 32°22′N/64°41′W, in St. George's on the eastern end of the island a short distance from BIOS and the USN-BMS airport site. In August 1989, the collection site was moved to the atmo-

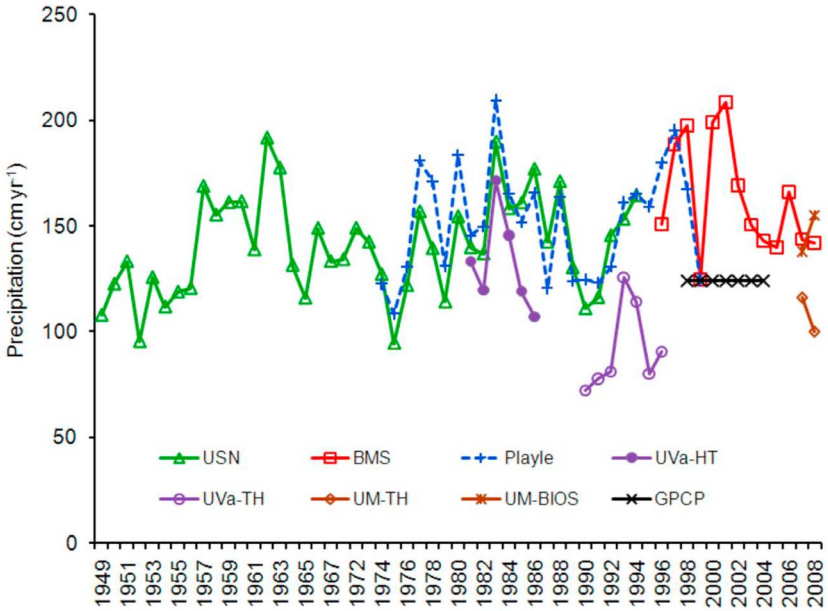


**Figure 4.** Precipitation measurements on Bermuda. Annual rainfall measurements made on Bermuda over the period 1949 to 2008 are summarized. USN, U.S. Navy at the air field; BMS, Bermuda Meteorological Service at the air field, now serving as the airport; Playle, a private individual residing in Somerset; UVa-HT, University of Virginia using a collector located at Harbour Tower; UVa-TH, University of Virginia using a collector located at Tudor Hill; UM-BIOS, University of Miami sampler at BIOS; UM-TH, University of Miami sampler at Tudor Hill; GPCP, Global Precipitation Climatology Project estimate of precipitation to Bermuda Region.

spheric chemistry station located at TH, the same location used for the University of Miami (UM) measurements made for this work, where it operated until February 1997. The data from these two sites are shown in Figure 4. There is a clear difference between the two sites. For the most part, the data at HRT closely track the USN data and the Playle data from Somerset; in contrast, the TH data fall well below these data. The mean annual rainfall at HRT was 150 cm/yr, and that at TH was 94 cm/yr. Thus the HRT rate is 1.6 times that at TH. Also shown in Figure 4 are the measurements made for this work (UM) at TH and BIOS for the years 2007 and 2008. The BIOS station yielded 146 cm/yr, very similar to that measured by BMS (~142 cm yr$^{-1}$) over the same period. For TH, the annual rate calculated in this manner is 108 cm, with the resulting ratio of BIOS to TH for the UM data at 1.35, comparable to the University of Virginia (UVa) ratio of HRT to TH data, which was 1.6.

[17] These diverse data sets lead to a wide range of estimates. One clear conclusion is that there is a substantial and consistent difference between measurements made at samplers located at TH by both UM and UVa and all other samplers on the island. Especially notable is the difference between measurements made at TH and those made at Somerset, 3.2 km to the north, and at sites in the eastern end of Bermuda (BIOS, Harbour Radio Tower, and airport) being about 40%–60% higher than the TH measurements. The UVa and UM measurements are quite consistent in this respect. This difference could be attributed to a number of causes. One could be related to a real difference in rainfall across the island. The other could be due to the location of the precipitation collector at TH, on the top of a 20 m tall tower placed on the side of a steep bluff. This site is often exposed to strong winds both because of its location on the coast and because of the effects of the hill on the wind at the site. Rain collector efficiency is very sensitive to wind velocity; to obtain accurate rainfall data, wind screens must be used [*Sieck et al.*, 2007; *Strangeways*, 2010].

[18] To place the Bermuda deposition data in a larger context, we compare our data with large-area data sets of ocean precipitation. The first is from the Global Precipitation Climatology Project (GPCP), a monthly 2.5° × 2.5° latitude-longitude gridded data set [*Adler et al.*, 2003]. The product is based on a merged analysis that incorporates precipitation estimates from low-orbit satellite microwave data, geosynchronous-orbit satellite infrared data, and surface rain gauge observations. These show that Bermuda is located in a region where there is a relatively large synoptic scale gradient in rainfall rates with higher rates to the north and lower rates to the south. The GPCP (version 2.1) mean rainfall estimate for the years 1998–2004 obtained for the 2.5 × 2.5 box centered on Bermuda is 124 cm yr$^{-1}$ (D. Bolvin, Science Systems and Applications, Inc., NASA Goddard Space Flight Center, personal communication, 2010). The second large-scale precipitation data set is obtained from the Tropical Rainfall Measuring Mission (TRMM) [*Huffman et al.*, 2007]. The TRMM (3B-43) average across the same 2.5° box used in the GPCP estimate is 106 cm yr$^{-1}$. TRMM estimates are believed be low by about 16% [*Adler et al.*, 2003]. If this correction is applied, the deposition estimate would be 123 cm yr$^{-1}$.

[19] The longer-term measurements made by the BMS, UVa at HRT, and the large-area estimates from GPCP and TRMM yield rates that fall into a rather narrow range, from 123 to 146 cm yr$^{-1}$, which exceeds that measured in all cases at TH. However, it should be noted that the GPCP value is the average for the years 1998–2004 when the measured rainfall rates on Bermuda were above average (Figure 4). Another problem with this comparison is that the GPCP data are averaged over a large area; as Bermuda is located in a region with a large rainfall gradient, the large averaging box could encompass a large range of rainfall rates that do not necessarily reflect rainfall on Bermuda. Nonetheless, the relatively close agreement between the GPCP and TRMM values and those measured on Bermuda provide some assurance that the measurements on Bermuda (excluding TH) are reflective in a broad way of deposition to the surrounding ocean.

### 5.2. Deposition Parameters

[20] The accurate assessment of atmospheric inputs to the oceans is difficult because of the dearth of measurements and the large temporal and spatial variability of deposition. Consequently, the ocean community must rely on atmospheric transport and deposition models [e.g., *Gao et al.*, 2003; *Hand et al.*, 2004; *Jickells et al.*, 2005; *Mahowald et al.*, 2005, 2009], but these models themselves are unconstrained as to the amounts of rainfall delivered to the ocean and the parameterization of aerosol removal processes. Alternatively, natural radionuclides such as $^{7}$Be, which are delivered to the ocean from the atmosphere, provide useful tracers for the input of atmospherically derived chemical species into the ocean. For such species, the source terms are definable, and measurements are not readily contaminated within normal environmental conditions [*Turekian et al.*, 1983].

[21] The flux ($F_i$) of an element into the ocean is described by the sum of wet and dry deposition processes, respectively [e.g., *Duce et al.*, 1991]:

$$F_i = R \times S \times Cp_i \times \rho_r/\rho + Cp_i \times Vd, \quad (1)$$

where $R$ is the precipitation rate, $S$ is the scavenging ratio (the ratio of the concentration of a substance in rain, $Cr$, to that on particles, $Cp_i$), $\rho_r$ is the density of water, $\rho$ is the density of air (1200 g m$^{-3}$), and $Vd$ is the dry deposition velocity (cm s$^{-1}$).

[22] The ocean community has largely resorted to the use of canonical values of $Vd$ [*Duce et al.*, 1991] that are related to particle size distribution. The size distribution of $^{7}$Be radioactivity is predominantly submicrometer with an activity mean diameter of about 0.5 $\mu$m [*Winkler et al.*, 1998]. For such aerosol particles, $Vd$ is 0.1 cm s$^{-1}$ plus or minus a factor of 3. Calculating from concentrations in air using $F_i = Cp_i \times Vd$, with this canonical value (0.1 cm/s) and the measured $^{7}$Be air concentration on Bermuda [*Arimoto et al.*, 1999], 4.4 mBq m$^{-3}$ (2.64 × 10$^{-7}$ dpm cm$^{-3}$), the dry deposition rate would be 2.3 × 10$^{-3}$ dpm cm$^{-2}$ d$^{-1}$, only 5% of the measured flux of 0.048 dpm cm$^{-2}$ d$^{-1}$ derived from the ocean inventory and rain collection. Thus wet deposition dominates. The $^{7}$Be concentration used here falls within the range of concentrations of $^{7}$Be measured in a broad range of (mostly continental) environments 3.98 to 5.9 mBq m$^{-3}$ [*Akata et al.*, 2008].

[23] Neglecting dry deposition, we can calculate the scavenging ratio using our $^{7}$Be flux measurements. The required deposition rate to maintain the water column inventory of

$^{7}$Be is 0.048 dpm cm$^{-2}$ d$^{-1}$. Using the annual rainfall rate for Bermuda of 146 cm (0.40 cm d$^{-1}$) based on long-term measurements (1949–2008) from the Bermuda Meteorological Service (http://www.weather.bm/climate.asp), and the air concentration ($Cp_i$) from *Arimoto et al.* [1999],

$$\begin{aligned} F_i &= R \times S \times Cp_i \times \rho^{-1}, \\ F_{7Be} &= Cp_{7Be}\left(R \times S \times \rho^{-1}\right) = 0.048 \text{ dpm cm}^{-2} \text{ d}^{-1} \\ &= 2.64 \times 10^{-7} \times 0.40 \times S \times 833. \end{aligned} \quad (2)$$

This yields $S$ = 546. A lower limit of this term is derived ($S \sim 328$) if the Tudor Hill flux is used.

[24] These scavenging ratios are comparable to those reported in the literature, which mostly report on continental measurements. Scavenging ratios of various chemical species in rain were measured over a 2.5 year period from 1989 to 1991 based on measurements at TH [*Galloway et al.*, 1993]. The scavenging ratios measured for nss-$SO_4$, $NO_3^-$, and MSA were 210, 342, and 240, respectively. The scavenging ratio for Na was considerably higher, 640, because Na is concentrated primarily in the marine boundary layer. *Akata et al.* [2008] summarized a wide range of reports (mostly at continental sites) and obtained scavenging ratios of $^{7}$Be that ranged from 130 to 2100 with a mean value of 640. An extended study by *Todd et al.* [1989] along the coast of Virginia at ~37°N (that is, in a marine-influenced environment in roughly the same latitude of Bermuda) obtained annual values of 370 and 375 in 1983 and 1984.

[25] Finally, the $^{7}$Be deposition rates we observe on Bermuda and the nearby BATS site are consistent with average rates determined by runs of the ECHAM5 model for the period 1986–1990 (U. Heikkilä, personal communication, 2010). This model run has been validated against a large number of $^{7}$Be surface air and deposition observations from different continents and was found to reproduce the observations within a factor of 2 [*Heikkilä et al.*, 2008, Figure 2].

## 6. Conclusions

[26] We have presented concurrent estimates of $^{7}$Be deposition from island-based bulk collectors and ocean profile measurements to constrain estimates of ocean deposition rates by wet and dry deposition. Excluding measurements at Tudor Hill, rainfall amounts and $^{7}$Be flux measurements on Bermuda are generally consistent with those to the surrounding ocean. Wet deposition accounts for over 95% of the total deposition to the adjacent ocean. Dry deposition to the ocean surface, calculated using the deposition velocity of 0.1 cm s$^{-1}$, commonly used for submicrometer aerosols, accounts for only a few percent at most of the total $^{7}$Be deposition. In oceanic regions where routine rain collection is not possible, our results suggest that $^{7}$Be flux estimates based on the ocean $^{7}$Be inventory allows an independent assessment of the rain (and scavenging) rates over the ocean, a very difficult parameter to constrain, and one that will be invaluable in assessing the atmospheric input of trace elements.

[27] **Acknowledgments.** We thank the captain and crew of R/V *Atlantic Explorer* for their able field support. Mark Stephens provided important at-sea and laboratory technical assistance, and Chris Marsay and Mark de Jong were responsible for collection of the Bermuda rain samples. We thank J. Galloway and W. Keene, of the University of Virginia, for use of their Bermuda rainfall data and U. Heikkilä for helpful discussions. The comments of two anonymous reviewers were appreciated. This work was supported by the Chemical Oceanography Program of the NSF (grants OCE-0549522 (D.K.) and OCE-0623189 (J.P.)).

## References

Aaboe, E., E. P. Dion, and K. K. Turekian (1981), $^{7}$Be in Sargasso Sea and Long Island Sound waters, *J. Geophys. Res.*, *86*, 3255–3257, doi:10.1029/JC086iC04p03255.

Adler, R. F., et al. (2003), The Version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-present), *J. Hydrometeorol.*, *4*, 1147–1167, doi:10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2.

Akata, N., H. Kawabata, H. Hasegawa, T. Sato, Y. Chikuchi, K. Kondo, S. Hisamatsu, and J. Inaba (2008), Total deposition velocities and scavenging ratios of $^{7}$Be and $^{210}$Pb at Rokkasho, Japan, *J. Radioanal. Nucl. Chem.*, *277*(2), 347–355.

Andrews, J. E., C. Hartin, and K. O. Buesseler (2008), $^{7}$Be analyses in seawater by low background gamma-spectroscopy, *J. Radioanal. Nucl. Chem.*, *277*(1), 253–259, doi:10.1007/s10967-008-0739-y.

Arimoto, R., J. A. Snow, W. C. Graustein, J. L. Moody, B. J. Ray, R. A. Duce, K. K. Turekian, and H. B. Maring (1999), Influences of atmospheric transport pathways on radionuclide activities in aerosol particles from over the North Atlantic, *J. Geophys. Res.*, *104*(D17), 21,301–21,316, doi:10.1029/1999JD900356.

Baskaran, M., C. H. Coleman, and P. H. Santschi (1993), Atmospheric depositional fluxes of $^{7}$Be and $^{210}$Pb at Galveston and College Station, Texas, *J. Geophys. Res.*, *98*(D11), 20,555–20,571, doi:10.1029/93JD02182.

Brost, R. A., J. Feichter, and M. Heimann (1991), Three-dimensional simulation of $^{7}$Be in a global climate model, *J. Geophys. Res.*, *96*, 22,423–22,445, doi:10.1029/91JD02283.

Dibb, J. E. (1989), Atmospheric deposition of beryllium 7 in the Chesapeake Bay region, *J. Geophys. Res.*, *94*(D2), 2261–2265, doi:10.1029/JD094iD02p02261.

Duce, R. A., et al. (1991), The atmospheric input of trace species to the world ocean, *Global Biogeochem. Cycles*, *5*(3), 193–259, doi:10.1029/91GB01778.

Feely, H. W., R. J. Larsen, and C. G. Sanderson (1989), Factors that cause seasonal variations in beryllium-7 concentrations in surface air, *J. Environ. Radioact.*, *9*(3), 223–249, doi:10.1016/0265-931X(89)90046-5.

Galloway, J. N., D. L. Savoie, W. C. Keene, and J. M. Prospero (1993), The temporal and spatial variability of scavenging ratios for NSS sulfate, nitrate, methanesulfonate and sodium in the atmosphere over the North Atlantic Ocean, *Atmos. Environ.*, *27A*(2), 235–250.

Gao, Y., S.-M. Fan, and J. L. Sarmiento (2003), Aeolian iron input to the ocean through precipitation scavenging: A modeling perspective and its implication for natural iron fertilization in the ocean, *J. Geophys. Res.*, *108*(D7), 4221, doi:10.1029/2002JD002420.

Hand, J. L., N. M. Mahowald, Y. Chen, R. L. Siefert, C. Luo, A. Subramaniam, and I. Fung (2004), Estimates of atmospheric-processed soluble iron from observations and a global mineral aerosol model: Biogeochemical implications, *J. Geophys. Res.*, *109*, D17205, doi:10.1029/2004JD004574.

Heikkilä, U., J. Beer, and J. Feichter (2008), Modeling cosmogenic radionuclides $^{10}$Be and $^{7}$Be during the Maunder Minimum using the ECHAM5-HAM general circulation model, *Atmos. Chem. Phys.*, *8*, 2797–2809, doi:10.5194/acp-8-2797-2008.

Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, E. J. Nelkin, K. P. Bowman, Y. Hong, E. F. Stocker, and D. B. Wolff (2007), The TRMM Multi-satellite Precipitation Analysis (TMPA): Quasiglobal, multi-year, combined-sensor precipitation estimates at fine scales, *J. Hydrometeorol.*, *8*(1), 38–55, doi:10.1175/JHM560.1.

Jickells, T. D., et al. (2005), Global iron connections between desert dust, ocean biogeochemistry, and climate, *Science*, *308*, 67–71, doi:10.1126/science.1105959.

Kadko, D. (2000), Modeling the evolution of the Arctic mixed layer during the fall 1997 SHEBA Project using measurements of $^{7}$Be, *J. Geophys. Res.*, *105*, 3369–3378, doi:10.1029/1999JC900311.

Kadko, D. (2009), Rapid oxygen utilization in the ocean twilight zone assessed with the cosmogenic isotope $^{7}$Be, *Global Biogeochem. Cycles*, *23*, GB4010, doi:10.1029/2009GB003510.

Kadko, D., and D. Olson (1996), Be-7 as a tracer of surface water subduction and mixed layer history, *Deep Sea Res.*, *43*, 89–116, doi:10.1016/0967-0637(96)00011-8.

Kadko, D., and P. Swart (2004), The source of the high heat and freshwater content of the upper ocean at the SHEBA site in the Beaufort Sea in 1997, *J. Geophys. Res.*, *109*, C01022, doi:10.1029/2002JC001734.

Kim, G., L. Y. Allemana, and T. M. Church (1999), Atmospheric depositional fluxes of trace elements, $^{210}$Pb, and $^{7}$Be to the Sargasso Sea, *Global Biogeochem. Cycles*, *13*(4), 1183–1192, doi:10.1029/1999GB900071.

Koch, D. M., D. J. Jacob, and W. C. Graustein (1996), Vertical transport of tropospheric aerosols as indicated by $^{7}$Be and $^{210}$Pb in a chemical tracer model, *J. Geophys. Res.*, *101*(D13), 18,651–18,666, doi:10.1029/96JD01176.

Koch, D., G. A. Schmidt, and C. V. Field (2006), Sulfur, sea salt, and radionuclide aerosols in GISS ModelE, *J. Geophys. Res.*, *111*, D06206, doi:10.1029/2004JD005550.

Mahowald, N. M., A. R. Baker, G. Bergametti, N. Brooks, R. A. Duce, T. D. Jickells, N. Kubilay, J. M. Prospero, and I. Tegen (2005), Atmospheric global dust cycle and iron inputs to the ocean, *Global Biogeochem. Cycles*, *19*, GB4025, doi:10.1029/2004GB002402.

Mahowald, N. M., et al. (2009), Atmospheric iron deposition: Global distribution, variability, and human perturbations, *Annu. Rev. Mar. Sci.*, *1*(1), 245–278, doi:10.1146/annurev.marine.010908.163727.

Michaels, A. F., N. R. Bates, K. O. Buesseler, C. A. Carlson, and A. H. Knap (1994), Carbon-cycle imbalances in the Sargasso Sea, *Nature*, *372*, 537–540, doi:10.1038/372537a0.

Olsen, C. R., I. L. Larsen, P. D. Lowry, N. H. Cutshall, J. F. Todd, G. T. F. Wong, and W. H. Casey (1985), Atmospheric fluxes and marsh-soil inventories of $^{7}$Be and $^{210}$Pb, *J. Geophys. Res.*, *90*, 10,487–10,495, doi:10.1029/JD090iD06p10487.

Olsen, C. R., I. L. Larsen, P. D. Lowry, and N. H. Cutshall (1986), Geochemistry and deposition of $^{7}$Be in river-estuarine and coastal waters, *J. Geophys. Res.*, *91*, 896–908, doi:10.1029/JC091iC01p00896.

Sieck, L. C., S. J. Burges, and M. Steiner (2007), Challenges in obtaining reliable measurements of point rainfall, *Water Resour. Res.*, *43*, W01420, doi:10.1029/2005WR004519.

Silker, W. B. (1972), Beryllium-7 and fission products in the GEOSECS II water column and applications of their oceanic distributions, *Earth Planet. Sci. Lett.*, *16*, 131–137, doi:10.1016/0012-821X(72)90247-6.

Strangeways, I. (2010), A history of rain gauges, *Weather*, *65*(5), 133–138, doi:10.1002/wea.548.

Todd, J. F., G. T. F. Wong, C. R. Olsen, and I. L. Larsen (1989), Atmospheric depositional characteristics of beryllium 7 and lead 210 along southeastern Virginia coast, *J. Geophys. Res.*, *94*(D8), 11,106–11,116, doi:10.1029/JD094iD08p11106.

Toggweiler, J. R. (1994), Vanishing in Bermuda, *Nature*, *372*, 505–506, doi:10.1038/372505a0.

Turekian, K. K., L. K. Benninger, and E. P. Dion (1983), $^{7}$Be and $^{210}$Pb total depositional fluxes at New Haven, Connecticut, and Bermuda, *J. Geophys. Res.*, *88*, 5411–5415, doi:10.1029/JC088iC09p05411.

Winkler, R., F. Dietl, G. Frank, and J. Tschiersch (1998), Temporal variation of $^{7}$Be and $^{210}$Pb size distributions in ambient aerosol, *Atmos. Environ.*, *32*(6), 983–991, doi:10.1016/S1352-2310(97)00333-6.

Young, J. A., and W. B. Silker (1980), Aerosol deposition velocities on the Pacific and Atlantic Oceans calculated from $^{7}$Be measurements, *Earth Planet. Sci. Lett.*, *50*, 92–104, doi:10.1016/0012-821X(80)90121-1.

D. Kadko and J. Prospero, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA. (dkadko@rsmas.miami.edu)