Measuring Ocean Bottom Pressure at the North Pole

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Abstract
High-precision deep Arctic Bottom Pressure Recorders (ABPRs) were developed to measure ocean bottom pressure variations in the perennial ice-covered Arctic Ocean. The ABPRs use the tsunami detection DART acoustic modem technology and have been programmed to store and transmit the data acoustically without the need to recover the instrument. ABPRs have been deployed near the North Pole, where the ice cover is a year-round challenge for access with a ship. Instead, the ABPRs have been built as light-weight mechanical systems that we can install using aircraft landing on the ice. ABPRs have provided the first records of uninterrupted pressure data over continuous years ever made in the central Arctic. The ABPR data have allowed us to identify and understand modes of Arctic Ocean bottom pressure variability that were unknown before the ABPR records and have offered new means of investigating and understanding the rapidly changing Arctic system. The ABPR records have also shown outstanding agreement with the satellite-sensed ocean bottom pressure anomalies from GRACE, providing ground truth data for validation of the satellite system. Due to the successful science findings as well as the ABPRs’ capability to fulfill the upcoming potential gaps of pressure measurements between GRACE and a GRACE follow-on mission, we highlight the urgent need to develop and maintain an Arctic observing network using ABPRs.

Keywords: ocean bottom pressure, pressure gauges, ABPR, Arctic Ocean circulation, ocean mass variability

Introduction
There is a fundamental need for sustained observations of the Arctic Ocean to understand and monitor ongoing environmental changes. Arctic Ocean change has been reflected in all of its climate components; e.g., the atmosphere and ocean have warmed (Overland et al., 2008; Polyakov et al., 2010); the sea ice volume and summer sea ice extent have dramatically decreased (Stroeve et al., 2007, 2008); sea ice has become thinner and therefore more mobile and susceptible to atmospheric and ocean stresses (Kwok, Spreen & Pang, 2013); the distribution of ocean mass, heat, and freshwater content in the Arctic have also changed, likely as a response to recent shifts on large-scale atmospheric and ocean circulation patterns (e.g., Morison et al., 2006). Furthermore, the Arctic atmosphere and ocean are projected to continue to warm faster than anywhere in the planet (polar amplification; IPCC, 2013).

Ocean bottom pressure (OBP) captures shifts in ocean mass that are part of sea level variability, tides, and circulation changes. The interpretation of ocean circulation from OBP data is dependent on the temporal and spatial coverage of the measurements, and in only a few regions of the Arctic Ocean have OBP data been collected. There are numerous tide gauges at the Arctic Ocean margin, and bottom pressure recorders have been deployed in the Beaufort Sea (Beaufort Gyre Exploration Project, http://www.whoi.edu/science/PO/pickart/RSP.htm). However, although the central Arctic has been found to be an important region for detecting shifts in the large-scale circulation of the Arctic Basin (Morison, Aagard, & Steele, 2000), until recently there had been no measurements of OBP in the central Arctic Ocean. The Gravity Recovery and Climate Experiment (GRACE) began measuring time-variable gravity in 2002, and this yields a remotely sensed measure of OBP all over the world ocean, but the temporal and
spatial resolution is limited. *In situ* pressure measurements are needed to provide GRACE ground truth and increased temporal resolution, and in the likely scenario of a gap in GRACE observations, *in situ* pressure data may provide continuity in central Arctic Ocean OBP measurements.

The Arctic Bottom Pressure Recorders (ABPRs) have been developed to overcome the special challenges of making *in situ* OBP measurements in the deep, perennially ice-covered central Arctic Ocean. The OBP gauges in the Beaufort Sea, Bering Strait, and Fram Strait can be serviced with ships in the summer when the ice cover is reduced or absent. Therefore, standard, off-the-shelf, deep ocean pressure recorders (e.g., Sea-Bird Electronics 53) can be included in standard moorings (e.g., BGEP moorings; http://www.whoi.edu/page.do?pid=66457). To access the stored ocean pressure data, these gauges can be recovered and redeployed annually. In contrast, reaching the North Pole by surface ship is challenging, and most science operations are performed with aircraft. This is exclusively true for the North Pole Environmental Observatory (NPEO) program (http://psc.apl.washington.edu/northpole/).

In such remote locations, without the power provided by a ship, there is little in the way of special equipment for handling heavy materials. Therefore, instrument weight is at a premium for central Arctic Ocean science operations. For example, as part of NPEO, from 2001 to 2011, we maintained a deep ocean mooring equipped with ocean current meters—point measurement and acoustic—conductivity (salinity), temperature sensors, upper looking sonar for measuring ice thickness, etc. However, the mooring deployment and recovery were always difficult and expensive because of the need to fly heavy gear to the exact mooring location, penetrate the ice, and retrieve the mooring through the recovery hole. To avoid such difficulties, we have sought a stand-alone ABPR design that would be relatively lightweight and easy to deploy and that could be interrogated for data without recovering the instrument (Figure 1). Here we describe the resulting development of two versions of ABPR, describe their performance, compare their observations to GRACE OBP, and review the resulting scientific highlights.

### ABPR Development

The ABPRs have been developed in two versions. The first version ABPRs (ABPRs 1–4) use only the electronics from bottom pressure recorders of the National Oceanic and Atmospheric Administration (NOAA) Detection and Assessment and Reporting of Tsunamis II (DART II) early detection and warning system (Meinig et al., 2005a, 2005b; Stalin et al., 2005). The second version (ABPR 5) uses the DART Easy to Deploy (ETD) bottom pressure recorder hull and electronics.

In the DART II application, pressure recorders or “tsunameters” are placed on the deep ocean bottom and sample pressure at 15-s intervals. The pressure perturbations due to wind waves and swell decay exponentially with depth and are not felt at the ocean bottom. Therefore, when the tsunameter detects a significant change in pressure, passage of a long wavelength and high-velocity tsunami is inferred. The tsunameter alerts a moored surface buoy of the tsunami’s appearance through an acoustic modem link. The surface buoy transmits the alert and a stream of high-frequency pressure data through the DART network.

Compared to tsunameters, the data requirements for ABPR are significantly different. They collect and store measurements at 15-min intervals instead of detecting pressure changes at 15-s intervals, and they have no requirement for real-time recognition of pressure events. However, the precise pressure measurements of the Paroscientific Digiquartz pressure sensors and the data telemetry capability using acoustic modems, negating the need for instrument recovery, satisfy two of the most critical requirements for the ABPRs. The challenges were to package the tsunameter electronics and modem system in a way suitable for remote deployment with central Arctic Ocean logistics and to modify the tsunami software to make them suitable for slow sampling over a long period with data recovery during brief annual modem sessions.

All the ABPRs use Paroscientific Digiquartz model 410K-101, 0–10,000 psi (0–68.94 MPa) pressure sensors with resolution of 0.25 mm and sensitivity better than 1 mm of water. The two versions differ with respect to modem, release equipment, and physical configuration.

The first version ABPRs (ABPRs 1–4) are equipped with external stand-alone ATM-421LF, 9–14 kHz acoustic transducers and transmit stored data to the surface with internal Benthos ATM-880 acoustic modems (Figure 2). In the first version ABPRs, the DART tsunameter electronics, Paroscientific 410 k pressure sensor, ATM 880 modem, and lithium battery pack are contained in a hard-anodized 21-cm-diameter, 1-m-long pressure case machined from a 21.6-cm-bar of 6061-T6 aluminum. The hull of the...
pressure case is bored to a 14.6-cm inside diameter, and the single end cap supports the electronics and batteries on the inside and pressure port, Subcon transducer, and communication connectors on the outside (Figure 2).

Because they were the first of their kind, ABPRs 1–4 were equipped with ORE 82-42XS acoustic releases. Each of these is the backbone of the instrument section; the ABPR pressure case and modem transducer are attached to it with a swiveling clamp arrangement. The anchor-table is a 117-cm diameter steel plate standing on short tubular legs (Figure 2). The acoustic release is held vertically to the steel table by the acoustic release jaw coupled to a pre-loaded yoke under the table. Flotation for the release-instrument section is provided by five 43-cm glass floats attached to the release with a 20-m Kevlar cable. In the deployed configuration, the pressure case lays horizontally on the ABPR anchor-table (Figures 2c and 2d). When actuated, the release drops the table and, with the attached instrument housing, rises to the surface under the glass floats. The total weight of the first version ABPR bottom unit is 261 kg in air. In water, it is designed to be stable in benthic conditions with current speeds of less than 0.05 m s\(^{-1}\) and, during a free-fall deployment, to descend at 1 m s\(^{-1}\).

The weight of the version 1 ABPR is light relative to the DART configuration but is heavy enough that, during deployment, the unit is assembled at the deployment site, and either slid over a pre-drilled hole in the ice and lowered into the water with an aluminum tripod (ABPR 1 and 3, Figure 2) for release and freefall to the sea floor, or picked up with a helicopter and lowered into an adjacent lead for release (ABPR 4, Figure 3). The Arctic BPR software includes a deployment mode under which the modem transmits instrument depth, temperature, and tilts every 2 min during the 4 h after the ABPR has been turned on. These transmissions during the instrument
descent are monitored using a Benthos ATM 891 modem deck unit and software modified from DART software for the measurement requirements of the ABPR. The data provide assurance that the descent proceeds at normal speed and the ABPR arrives at the bottom upright and functioning properly.

The second version ABPR (ABPR 5) uses the newest tsunami warning system design, DART ETD bottom pressure recorder or tsunameter (Lawson et al., 2011). The DART ETD system incorporates the DART surface buoy when used for tsunami applications, bottom anchor, and tsunameter in one palletized deployment package, which, when dropped off the stern of a ship, self-deploys the surface buoy, mooring line, and a bottom anchor containing the tsunameter (https://www.youtube.com/watch?v=4AoEUlcfdoY). The tsunameter module itself, including the modem transducer, is a single unit (Figure 4b). The electronics hardware for the ETD tsunameter is essentially identical to that of the earlier DART II units and ABPRS 1–4. However, it is mounted on a production ETD board set and a lithium battery pack. The board set consists of (1) high-resolution precision reciprocal counting circuit that continuously measures the pressure and temperature signals from the Parascientific sensor and integrates them over the sampling window; (2) a low-powered embedded computer that implements and regulates the primary functions of the ABPR: transmitting data, storing and retrieving water column heights, generating checksums, and conducting automatic mode switching; and (3) an acoustic modem that transmits digital data via MFSK (multiple frequency-shift keying) modulated sound signals.

The second version ABPR is designed to operate for 5 years and not be recovered. The pressure sensor is like that in the DART II and ABPR recorders. Also like the earlier DART instruments and ABPRs, the ETD tsunameters and second version ABPR use Benthos ATM-880 acoustic modems, but they use ATM-421MF transducers for medium-frequency (16–21 kHz) data telemetry. The smaller size of these transducers allows them to be mounted directly on the single pressure case, obviating the need for cabling and underwater connectors. The ETD tsunameter is licensed to and produced by Science Applications Incorporated (SAIC).

The compactness, light weight, and endurance of the ETD tsunameter make it ideal for bottom pressure measurement in remote locations of ice-covered seas. In the version 2 ABPR application the ETD tsunameter is attached to a 90-cm diameter steel disk anchor plate (and vertical drag element) with a tubular vertical mast. It has a rubber-cushioned cup that is designed to capture a plunger-shaped strut projecting from the bottom of the tsunameter pressure case (Figure 4). The cup and plunger arrangement is an ETD design required to cushion the tsunameter impact when the ETD anchor hits the bottom at up to 2 m s$^{-1}$ without damage to the quartz element in the pressure sensor. In the ABPR application, without the inertia of the heavy ETD anchor, we wanted to limit free-fall descent speed to 1 m s$^{-1}$, a rate that was satisfactory for ABPRs 1–4 landing in the Arctic Ocean bottom. To achieve the 1 m s$^{-1}$ descent rate, the deployment hardware includes a 1-m diameter drogue parachute surrounding a Dacron line at 20 m above...
the mounting mast. The Dacron line projects through the drogue for attachment to the release hook of the deployment helicopter. After the ABPR free falls to the sea floor, the Dacron line and drogue chute are meant to sink to the bottom where the chute will not exert drag on the top of the ABPR and tip it over.

Data recovery from the ABPRs is achieved using a Benthos ATM-891 deck modem with custom ABPR software on a laptop computer and an ATM-421 (LF for ABPRs 1-4, MF for ABPR 5) transducer lowered through a hole in the sea ice. This requires flying to and landing on the sea ice within a radius of the instrument site determined largely by the modem transducer characteristics and depth. The ATM-421 transducers for the instrument and surface modems have a beam width of about 45°, so in principle, for a 4,000-m ocean depth, the landing site has to be within about 3,000 m of the instrument location. By landing with a ski-equipped Twin Otter airplane and using the low-frequency system, we have successfully recovered data, but with increasing error rates when near and beyond 3,000 m. Performance in terms of error rate, especially with the medium-frequency system, is much better if data recovery is done from within 1,000 to 1,500 m. Therefore, recent data recoveries have been done using helicopters landing on the ice within a few hundred meters of the instrument site (Figure 3f).

The data recovery is facilitated by the user-friendly character of the ABPR software, which automatically sets up the file structure for the uploaded data, tracks the modem error checking and recovery as uploads progress, and provides for specification of upload parameters. After initial range measurement and modem and instrument checks, we usually upload data at 2,400 baud and block sizes of 2,000 bytes, because this combination yields an acceptable signal to noise ratio of the data transmission. However, other baud rates and block sizes may also be used (e.g., baud = 600 bytes/s, block size = 700 bytes). To ensure we get a year’s data before drifting out of range, pressure measured on the hour is uploaded first, then on-the-half-hour data, quarter-after data, and finally quarter-to-the-hour data. If transmission errors and recoveries are not too numerous, 1-year pressure data can be uploaded in about 90 min. The pressure records are converted and provided in units of equivalent water thickness by the
Satellite Observations of OBP by GRACE

Since 2002, GRACE has provided nearly full Arctic Ocean coverage of OBP measurements. The GRACE system consists of two satellites, one following the other in an orbit inclined at 89°. The range between the satellites (~220 km) is measured by a microwave link, and the rate of range change is used to derive the time-varying gravity field. This is related to mass change or bottom pressure in the ocean (Wahr et al., 1998). The footprint of the measurements is several hundred kilometers, and gravity solutions are done in spherical harmonics so that GRACE OBP is given for the whole Arctic Ocean without a data hole at the Pole. GRACE-derived monthly data have contributed to our understanding of the diverse processes controlling mass changes in the Earth system, in both ocean and on land. GRACE-derived OBP measurements have served to identify large-scale patterns of the mass distribution and ocean circulation in the Arctic Ocean (e.g., Peralta-Ferriz et al., 2014; Morison et al., 2012, 2007) and in many other regions (e.g., Rietbroek et al., 2006; Park et al., 2008; Kanzow et al., 2005).

In situ pressure measurements have been critical to the interpretation of the satellite measurements and in our case, vice versa. Pressure gauges provide ground truth validation for GRACE, and their greater temporal resolution allows us to explore higher-frequency variations not resolved by GRACE (e.g., Peralta-Ferriz et al., 2011). Furthermore, pressure gauge data can be used to reduce errors due to tidal aliasing in the satellite observations. Conversely, GRACE provides a check on longer-term drift in in situ gauges. In the context of spatial resolution, in situ pressure gauges within a few 100 km of coastlines can conceivably be used to separate true OBP signals from the leakage of satellite-sensed gravity signals due to the mass changes on land.

The GRACE satellite mission has exceeded its original 5 years of life expectancy. After 12 years of measuring, to save the instrument batteries, the satellites are now put in a dormant mode during those months when the solar panels do not see the sun for extended periods. A follow-on mission is expected starting in 2017.

ABPR Deployment and Data Recovery

ABPR 1, ABPR 3, ABPR 4, and ABPR 5 were deployed as part of the NPEO (http://psc.apl.washington.edu/northpole) operations in spring 2005. ABPR 2 will be discussed below.
Table 1 shows the locations of all five ABPRs deployed in the Arctic Ocean. ABPR1 was deployed at 89°15.26′ N, 60°21.58′ E, in 4,300 m of water, the site of a NPEO mooring recovery and deployment (Figures 1 and 2). ABPR 3 was deployed near the base of the Lomonosov Ridge at 89°14.85′ N, 148°7.54′ E, in approximately 4,200 m of water, the site of the Russian-operated base ice camp Barneo. Both deployments used a hole made with 122-cm-diameter hole melter and a tripod to lower the ABPRs into the water for free fall to the sea floor.

ABPR 1 provided a total of 5 years of continuous pressure data, 2 years more than its designed battery life, and stopped working in spring 2010. ABPR 3 provided the expected 3 years of measurements and stopped working in spring 2008. Neither ABPR 1 nor ABPR 3 were recovered. We attempted to recover ABPR 1 in 2010 during NPEO operations. Although the acoustic release functioned properly, the ABPR 1 system failed to surface (pressure measurements indicated sensor remained at the bottom). We concluded the hardware that allows the floats to bring the released ABPR to the surface was heavily corroded after 5 years underwater, as suggested by the NPEO mooring hardware (of the same manufacturing batch as the hardware in our ABPR 1 system), which became heavily corroded within only 2 years after its deployment.

In spring 2006, ABPR 4 was deployed very close to the North Pole at 89°58.593′ N, 178°14.84′ E, using a Barneo-based helicopter that lowered the ABPR into the water through a refrozen lead (Figure 3). ABPR 4 was deployed in approximately 4,200 m of water and provided 1 year of measurements. Unlike ABPRs 1 and 3 (both of which provided data every 15 min), ABPR 4 had a modem malfunction at the end of the first hourly data upload, for which only hourly data were recovered. The ABPR modem continued uncontrolled transmissions that drained the batteries during the following year. ABPR 4 was not recovered.

Version 2 of the ABPR, ABPR 5, was deployed in spring 2010 very near the North Pole, at 89°58.708′ N, and 32°55.433′ W, in approximately 4,200 m of water (Figure 4). The deployment was part of the NPEO operations and used a Mi-9 helicopter from the ice-camp Barneo. ABPR 5 was initialized while on the ice, and the helicopter lowered it through an opening in the thin ice of an adjacent lead. Upon release, it free fell at the design rate, 1 m s \(^{-1}\), to land upright on the sea floor, while pressure (depth), temperature, and tilts were monitored through the acoustic modem system in deployment mode. Four years of continuous measurements of OBP have been recovered from ABPR 5. To date, this is the only ABPR currently operating at the North Pole.

The 5-year raw record from ABPR 1 and the 3-year raw record from ABPR 3 are shown in Figure 5. The first year of data in both ABPRs presented a negative trend in pressure lasting up to 2 months. This behavior is broadly consistent with Wearn and Larson (1982), who found that Digi-quartz sensors show declining drift for the 2 months after pressurization with slight steady drift thereafter and who concluded that initial drift was due to elastic creep of the sensor bellows material. Watts and Kontoviannis (1990) found similar results and concluded that preconditioning Digi-quartz sensors by pressurizing them for several months prior to deployment could reduce drift. Other rapid changes in bottom pressure records may occur in events of “slippage” (e.g., Meredith et al., 2011), in which the pressure gauge may slide on the continental slope, producing a sudden increase in pressure that, if it is relatively small, may be misinterpreted as a real geophysical signal.

### Table 1

<table>
<thead>
<tr>
<th>ABPR</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Period</th>
<th>Sampling</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABPR 1</td>
<td>89°15.26′ N</td>
<td>60°21.58′ E</td>
<td>Apr. 2005 to Apr. 2010</td>
<td>15 min</td>
<td>At North Pole, version 1</td>
</tr>
<tr>
<td>ABPR 2</td>
<td>78°55.15′ N</td>
<td>5°37.76′ E</td>
<td>Sept. 2012 to ongoing</td>
<td>15 min</td>
<td>Fram Strait, version 1</td>
</tr>
<tr>
<td>ABPR 3</td>
<td>89°14.85′ N</td>
<td>148°7.54′ E</td>
<td>Apr. 2005 to Apr. 2008</td>
<td>15 min</td>
<td>North Pole, version 1</td>
</tr>
<tr>
<td>ABPR 4</td>
<td>89°58.59′ N</td>
<td>178°14.84′ E</td>
<td>Apr. 2006 to Apr. 2007</td>
<td>15 min</td>
<td>North Pole, version 1</td>
</tr>
<tr>
<td>ABPR 5</td>
<td>89°58.71′ N</td>
<td>32°55.43′ W</td>
<td>Apr. 2010 to ongoing</td>
<td>15 min</td>
<td>North Pole, version 2, no release</td>
</tr>
</tbody>
</table>
GRACE OBP, at least for the following ~1.5 years. The first year of OBP data from ABPR1 and ABPR 3 were described and reported in Morison et al. (2007).

After October 2006, however, 1.5 years into the record, the ABPR 1 OBP data began to display a drift characterized by rapidly declining bottom pressure. The drift initially had an exponential behavior (i.e., early 2007 through spring 2008), and after the third year of the record, the drift became more linear (i.e., since spring 2008). The drift (declining pressure at a rate of about 2 m year$^{-1}$) was described in Peralta-Ferriz (2012) and removed by first fitting an exponential function from the first part of the record and then a linear function to the latter part of the pressure record (Figures 5a and 5b).

The ABPR 3 observed a similar drastic negative-pressure drift as ABPR 1, but it appeared earlier than it did in ABPR 1 (compare Figure 5c to Figure 5a). The declining pressure drift in the ABPR 3 was removed by comparing to ABPR 1 (Figure 5d), which did not show a similar anomalous drift until June 2007.

The OBP anomalies from de-drifted ABPR 1 and ABPR 3 are highly correlated (15-min sampling, $R = 0.96$, significant above the 95% confidence level; the daily averages yield $R = 0.98$, significant above 95% confidence level) through the overlapping 3 years of observations. The absolute RMS values of the de-tided ABPR 1 and ABPR 3 records (during the overlapping 3 years) are 5.56 and 5.67 cm, respectively. The RMS difference between the records is 1.63 cm water equivalent based on the first 1.5 years of the records (e.g., Morison et al., 2007) and 1.68 cm based on the three years of total overlapping record.

The ABPR 4 recorded pressure from spring 2006 to spring 2007. The ABPR 4 record did not show an initial drift due to settling of the instrument, but it showed a smooth negative trend for the full record, amounting to ~20 cm year$^{-1}$ (see Figure 5e for raw record and Figure 5f for de-drift record). This behavior is typical of Digiquartz sensors (Wearn & Larson, 1982; Watts & Kontoviannis, 1990; Spencer & Vassie, 1997). However, part of this negative trend coincides with the period of seasonal drop in OBP, which is typically in the spring. Despite the drift/trend, the hourly record of ABPR 4 shows a high correlation ($R = 0.97$, significant above the 95% confidence level) with ABPR 1 during the overlapping period (Figure 5e).

The large drift in ABPR 1 and ABPR 3 overlapped in time with the year that ABPR 4 operated. ABPR 4 was deployed only ~80 km from both ABPR 1 and ABPR 3 (Figure 1) and did not experience the unusual long-term negative drift recorded by

![FIGURE 5](http://www.ingentaconnect.com/content/mts/mtsj/2014/00000048/00000005)
both ABPR 1 and ABPR 3. This is just one indication that the extreme drifts in the ABPR 1 and ABPR 3 records are not due to a natural signal, but are instead instrumental.

ABPR 2, of the same manufacturing batch as ABPRs 1, 3, and 4, was originally planned to be deployed in spring 2008 as part of the yearly NPEO operations. However, we chose not to deploy it, and instead we brought it home to examine it and perform additional tests at Paroscientific. Results of the tests did not reveal any indication that ABPR 2 would display the same anomalous drift as shown by ABPR 1 and ABPR 3. Though speculations on behavior after deployment cannot be fully forecasted (e.g., Polster, Fabian & Villinger, 2009), we decided to deploy ABPR 2 just off the coast of Svalbard in Fram Strait (in generally ice-free conditions), in approximately 2,300 m of water, at 78°N, 5°E. Our reasoning was to deploy ABPR 2 in an environment of (logistically) easier access (at least during part of the year) than near the ice-covered region of the North Pole and be able to recover and examine it in the case it presented the same behavior as ABPR 1 and ABPR 3. ABPR 2 was deployed in September 2012 aboard the R/V Lance, as part of a student cruise operated by the University Centre in Svalbard. The first year of data from ABPR 2 was collected in September 2013 as part of the yearly mooring operations of the western Fram Strait (Greenland Sea), led by the Norwegian Polar Institute (NPI).

Every year since 2011, we have recovered the pressure data from the version 2 ABPR, ABPR 5, including an April 2014 upload. In this most recent data recovery, the ice remained close to the ABPR 5 position resulting in excellent modem communica-tions with a minimum of errors and error recovery.

ABPR 5 OBP data displayed an initial drift similar to those discussed above for ABPRs 1–4, lasting ~10 months. The drift decreased for the rest of the record (Figure 6). The total drift from 2010 through 2014 was corrected using GRACE-derived OBP at the North Pole through January 2014 (Figure 7). Here we use the GRACE Release 5 monthly solutions from the University of Texas, Center for Space Research (unless use of Release 4 is specified). These solutions were processed by Don P. Chambers (Chambers, 2006; Chambers & Bonin, 2012) and available at http://grace.jpl.nasa.gov. Monthly averages of the de-tided ABPR 5 pressure record were subtracted from the overlapping GRACE data (Figure 7a). A fourth-degree polynomial fit was applied to the residual, and the resulting function was then subtracted from the ABPR record (Figure 7b). This function generated the lowest RMS difference between GRACE and ABPR 5 (RMS = 1.87 cm) compared with other fits. The comparison between GRACE and the corrected monthly averaged ABPR 5 pressure data is shown in Figure 7c. The correlation coefficient

![FIGURE 6](image)

Four years of OBP anomalies from ABPR 5. (a) Raw record, (b) tides, (c) daily (black), and monthly (gray) averages of de-tided ABPR 5 OBP record.
between the GRACE-derived OBP data and corrected-ABPR 5 data is $R = 0.84$, significant above the 99% confidence level. The correction applied to ABPR 5 also yielded the lowest RMS error value between GRACE and the ABPR 5, compared to the RMS error we would get if correcting only the first 11 months of the ABPR 5 pressure where the largest drift in pressure occurred (by either linear, exponential, or higher-degree polynomial functions).

The de-drifted monthly averaged ABPR 5 pressure record captures well the month-to-month variability of OBP as measured by GRACE (Figure 7c). The correction above may be applied to the high-frequency data by subtracting the same polynomial from the raw (i.e., higher frequency) ABPR data.

**Data Processing and Comparison With GRACE**

For all ABPR records, hourly averages were taken, and the tidal constituents were extracted and removed from the signal using the Matlab program t_tide (Pawlowicz et al., 2002). The tidal amplitudes and phases of the diverse constituents from ABPRs at the North Pole (1, 3, 4, and 5) are highly consistent with each other. This is not surprising given that the sensors were deployed relatively close to each other (~115 km apart or less, see Figure 1 and Table 1). Here we only show the largest constituents of the tides in the central Arctic near the North Pole (Table 2). A complete list of tidal constituents for ABPRs 1, 3, 4, and 5 OBP records are included in Peralta-Ferriz (2012, Appendix C). The complete tidal time series at the North Pole from ABPR 1 is illustrated in Figure 8, and that from ABPR 5 is illustrated in Figure 6. The constituent with the largest amplitude at the North Pole as revealed by ABPR 1 is the semi-diurnal $M_2$ tide (frequency = 0.0805 cph) with an amplitude of ~6.4 cm, followed by the fortnightly tide $M_f$ (0.00305 cph) with ~3.02 cm and the $S_2$ tide (0.0833 cph) with ~2.8 cm. These ABPR results represent the first and only in situ measurements of tides in the Central Arctic.

The monthly averages of OBP anomalies from the 5-year ABPR 1 record (de-meaned, de-tided, and de-drifted) are compared with the monthly OBP data from GRACE at the North Pole in Figure 8d. These two records are well correlated ($R = 0.84$, significant above the 95% confidence level). The RMS difference between the 5-year records of GRACE and ABPR 1 (2005–2010) is 1.9 cm, which is consistent with the RMS difference between ABPR 5 and GRACE from 2010 to 2014 (RMS error = 1.87 cm) but is also significantly lower than the GRACE RL04-ABPR RMS difference for the first year and a half of averaged ABPRs 1 and 3-GRACE Release 4 (RL04) comparison (3.1 cm, see Morison et al., 2007).
TABLE 2
Largest tidal constituents of ABPRs 1, 3, 4, and 5 (North Pole) and ABPR 2 (Fram Strait). Uncertainties in the amplitude and phase lag (degrees relative to center time) are denoted with the ± symbol.

<table>
<thead>
<tr>
<th>ABPR</th>
<th>Tide</th>
<th>Constituent Frequency (cpH)</th>
<th>Amplitude (cm)</th>
<th>Greenwich Phase LAG (Degrees)</th>
<th>Signal-to-Noise Ratio (SNR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABPR 1</td>
<td>M2</td>
<td>0.0805114</td>
<td>6.47 ± 0.02</td>
<td>060.40 ± 0.22</td>
<td>6.3e+4</td>
</tr>
<tr>
<td></td>
<td>K1</td>
<td>0.0417807</td>
<td>2.72 ± 0.02</td>
<td>339.61 ± 0.45</td>
<td>1.2e+4</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>0.0833333</td>
<td>2.81 ± 0.02</td>
<td>111.62 ± 0.44</td>
<td>1.5e+4</td>
</tr>
<tr>
<td></td>
<td>MF</td>
<td>0.0030501</td>
<td>3.02 ± 0.93</td>
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For a more direct comparison between the GRACE RL04 and GRACE RL05, we have looked at their records for the same 5-year period than the longest in situ record of OBP, i.e., ABPR 1 (2005–2010). We find that the GRACE RL04 (RMS = 3.88 cm) variability is larger than the GRACE RL05 (RMS = 2.8 cm). The RMS difference between GRACE RL04 and RL05 is 1.95 cm. The RMS difference between ABPR 1 (RMS ABPR 1 = 3.4 cm) and GRACE RL04 during the 5-year period (RMS diff = 2.58 cm) is ~40% larger than the RMS difference between ABPR 1 and GRACE RL05 (RMS diff = 1.71 cm). This significant improvement in the records from the earlier to the later GRACE releases (relative to the in situ observations) is also reflected in their correlation coefficients with the ABPR 1, increasing from $R = 0.75$ to $R=0.87$ (with GRACE RL04 and GRACE RL05, respectively).

Based on the first year and a half of the in situ OBP records (2005–2006),
Morison et al. (2007) estimated the uncertainty of GRACE RL04 (~2.8 cm) and the uncertainty of the ABPR 1 (~1.3 cm, which is only slightly smaller than the RMS difference between the 30-day smoothed ABPR 1 and ABPR 3, ~1.56 cm). While the ABPR uncertainty may not differ in the 5-year record relative to the first 1.5-year, the 5-year ABPR-GRACE RL05 RMS difference does show an improvement from the earlier GRACE RL04 to ABPR comparison. Removing the RMS uncertainty of the ABPR (1.3 cm, Morison et al., 2007) from the GRACE RL04 to ABPR 1 RMS difference (1.7 cm) yields a GRACE RL05 uncertainty of ~1.4 cm. This amounts half of the uncertainty estimated for GRACE RL04 (i.e., 2.8 cm, see Morison et al., 2007), which indicates the new GRACE solutions have improved comparison with in situ OBP data and decreased the uncertainty in their record with time.

Using GRACE RL05 (hereinafter GRACE), we have matched the 5-year ABPR 1 OBP data with the 4-year ABPR 5 OBP data to obtain a 9-year time series of OBP record representative of the North Pole (Figure 9). ABPR 1 and ABPR 5 represent the longest records of OBP variations ever measured in the Central Arctic. The monthly record of OBP from GRACE is well correlated with the monthly averages of the 9-year merged ABPR OBP record ($R = 0.87$, significant above 95% confidence level).

Lastly, we discuss the OBP data from ABPR 2 in Fram Strait. In September 2013, we successfully recovered the first year of pressure anomalies from this version 1 ABPR, ABPR 2 (Figure 10a). The raw data did not show indication of the drift as recorded by the previously discussed version 1 ABPRs. The similar basic processing has been applied to the first year of pressure data from ABPR 2 as to the previous ABPRs. Similar to the other ABPRs, the largest signal of the record corresponds to the tidal oscillations. We used the same techniques to extract and remove the tides, as in the ABPRs near the North Pole. The semidiurnal M2 tide is the largest constituent from ABPR 2 (amplitude = 38.5 cm), followed by the S2 tide (amp = 14.3 cm). Note that these amplitudes are much larger than the observed amplitudes at the North Pole. The major tidal components extracted from ABPR 2 are shown in Table 2. After the tidal signal was calculated (Figure 10b) and removed from the raw OBP record, daily and monthly averages of the record were computed (Figures 10c and 10d). The daily OBP record from ABPR 2 is significantly correlated with the daily record from ABPR 5 for the overlapping period ($R = 0.54$, significant above 95% CI). The agreement between the records is particularly good for the short timescale oscillation (Figure 10d). This result is consistent with the previous finding of basin-wide
coherent variability of Arctic OBP at submonthly timescales (Peralta-Ferriz et al., 2011).

GRACE Release 5 OBP anomalies in Fram Strait and the in situ OBP record from ABPR 2 are compared in Figure 10d. The disagreement between the monthly binned OBP records suggests that GRACE solutions might be contaminated by the mass changes over land (e.g., Greenland ice-sheets). The correction and assessment of these errors in the GRACE solutions in Fram Strait are beyond the scope of this paper and will be investigated in the future, especially when we recover the subsequent pressure data of ABPR 2.

Submonthly Variability

The in situ OBP changes from the ABPRs revealed the persistence of wintertime, non-tidal submonthly oscillations in OBP (Peralta-Ferriz et al., 2011). The energy of these variations is concentrated between 18- and 25-day periods. The ABPRs and other in situ records from available pressure sensors and tide gauges in the Arctic Ocean suggest that these oscillations in OBP are coherent throughout the basin. This mode of variability in OBP is associated with the zonal surface atmospheric pressure gradient (i.e., high over Scandinavia and low over Greenland), which resembles winter atmospheric blocking events (e.g., Rennert & Wallace, 2009). The SLP gradient produces a sea level gradient driven by Ekman transport that, in turn, enhances a northward slope current in the Nordic Seas. This northward ocean flow increases the mass flux into the Arctic Ocean through Fram Strait and, to a lesser extent, through the opening of the Barents Sea. These changes in OBP are dominated by the sea surface height variability, which suggests a predominantly barotropic character of the ocean at these timescales, everywhere in the basin. Details on the circulation due to these OBP oscillations are explained in Peralta-Ferriz et al. (2011). To date, GRACE solutions at higher temporal resolution than monthly are a work in progress by the GRACE processing centers and are not yet available for the Arctic Ocean. Thus, variations in OBP at submonthly and shorter timescales may only be observed with in situ data.

Seasonal Variability

At seasonal timescales, the variability of the Arctic OBP has been studied using ABPR-validated GRACE OBP (Peralta-Ferriz & Morison, 2010). GRACE reveals two major spatial patterns of seasonal variability in OBP; The first one is a basin-scale variation analyzed in terms of the basin-averaged annual cycle of OBP, with a maximum amplitude of nearly 2.5 cm during late summer to early fall. The second pattern exhibits a see-saw oscillation of mass between the East Siberian Sea and the Kara/Barents seas region. Both modeling results (Dobslaw & Thomas, 2007) and observations (Peralta-Ferriz & Morison, 2010) have shown that the annual oscillation of the
basin-averaged OBP change may be mainly attributed to runoff. Peralta-Ferriz and Morison (2010) complemented this work by developing a simple analytical model and found that, in addition to the effects of runoff, the net precipitation minus evaporation ($P-E$) and the SLP variation play a minor but significant role on the annual cycle of Arctic OBP.

Peralta-Ferriz (2012) suggests that the observed spatial variability of Arctic OBP at seasonal timescales (high OBP anomaly in the Kara and Barents seas during late winter to early spring and low OBP anomaly in the East Siberian Sea) may be attributed to the seasonal character of the regional wind forcing: the winter westerlies enhance northward flow into the Barents Sea that increases the mass in the Barents and Kara seas through surface Ekman transport. During the fall, strong winds tend to flow eastward along the East Siberian Sea, increasing the mass on the shelf. These dynamics were identified using maximum covariance analysis between GRACE OBP and NCEP/NCAR (Kalnay et al., 1996) surface winds.

**Monthly to Interannual, Nonseasonal Variability**

The nonseasonal, month-to-month variations in OBP were identified using empirical orthogonal function (EOF) analysis on 9 years of monthly GRACE data, from 2002 to 2011 (Peralta-Ferriz et al., 2014). Together, the three leading modes of variability explain nearly 80% of the GRACE-OBP total variance, with the first two explaining ~70% of the variance in Arctic OBP. The first mode (50% of the variance) corresponds to a basin-coherent change in OBP that is confirmed by and highly coherent with the monthly averages of ABPR records at the North Pole. The spatial coverage of GRACE plays a fundamental role in this investigation. Forced by northward winds over the Nordic Seas and to a lesser extent over Bering Strait, the first mode of OBP is energetic during the winter and weak during the summer. The basin-coherent mass increase appears to respond to increased flow mainly through Fram Strait by a northward slope current: the northward component of the wind would set up a surface slope to the east, which would in turn enhance a northward geostrophic flow into the Arctic Ocean.

The second mode (20% of the variance) shows an OBP increase in the Siberian shelves and an OBP decrease in the Central Arctic. This mode is attributed to the phases of the Arctic Oscillation (AO, Thompson and Wallace, 1998). While in several other studies, many changes in the Arctic system have been related or attributed to different strengths of the AO, Peralta-Ferriz et al., (2014) identified for the first time the effects of AO strength on mass redistribution in the Arctic Ocean.

**Interannual Timescales and Trends**

The study by Morison et al. (2007) was the first one to compare ABPR pressure observations with GRACE-derived OBP data in the Arctic Ocean.
The excellent agreement between the two time series provided an \textit{in situ} validation for the GRACE records in the central Arctic, which were then used to identify trends in Arctic OBP from 2005 to 2007. The authors attributed the OBP variations to the changes in the vertically averaged density of the water column. The density changes may reveal shifts of the ocean circulation in the central Arctic, characterized by the shifts in the frontal line between Pacific- and Atlantic-derived water masses. Subsequently, Morison et al. (2012) showed that, by combining ABPR-validated GRACE OBP with altimetry-derived dynamic ocean topography, a measure of the multiyear trends in the freshwater content of the Arctic may be obtained, and the associated changes in the ocean circulation revealed.

**Discussion**

The capability of the ABPRs to measure bottom pressure perturbations in the perennially ice-covered central Arctic has contributed significantly to our understanding of Arctic Ocean circulation variability. The OBP measurements have served as a basis and validation for remote sensing systems with coverage in the Arctic Ocean, e.g., the satellites GRACE, CryoSat, and others with polar orbit. The scientific findings described and the ground true validation of satellite data from GRACE and CryoSat would not be possible in the Central Arctic without the ability to measure bottom pressure under the sea ice un-interrupted over a year and longer and without the possibility to collect the data with acoustic modems.

Furthermore, although the state of the art coupled atmosphere-ice-ocean models generally capture Arctic Ocean OBP and circulation patterns (e.g., Peralta-Ferriz et al., 2011, 2014), the models tend to underestimate the observed amplitude of the variability, particularly at inter-annual or longer timescales. Thus, ABPR data serve as validation for ocean models.

The comparisons between the North Pole ABPR and GRACE observations of OBP discussed here reveal a significant improvement relative to the earlier comparisons between the two records (e.g., Morison et al., 2007). These improvements are very encouraging because they show how fast we are capable of improving methods and minimizing uncertainties down to the centimeter level, both in the performance of the ABPRs (uncertainty $< 1.3$ cm) and GRACE (e.g., uncertainties from $-2.8$ cm for GRACE release 4, down to $-1.4$ cm for GRACE release 5).

Overall, the next few years are critical to developing a satellite and pressure gauge system to go with satellite altimetry in determining ocean circulation changes. The GRACE system has already reached its initial design life. It is expected to last through 2016, but the follow on gravity mission is not expected to be launched until 2017. We believe that an enhanced world ocean array of bottom pressure measurements should be established soon enough to allow worldwide inter-calibration with GRACE observations and to cover a possible gap in space-borne OBP observations through the period between GRACE and the GRACE follow on.

**Conclusions**

ABPRs were designed and developed to overcome the logistic difficulties and high cost of oceanographic operations in the perennial sea ice covered Arctic Ocean. Both versions 1 and 2 of ABPRs have demonstrated the ability to record pressure data continuously for over 3 and up to approximately 5 years. The performance of the ABPRs is highlighted by the reduced uncertainties in the pressure records and the excellent agreement with ABPRs deployed nearby as well as with remote sensing observations of OBP from GRACE. The success of these operations is reflected in a broad amount of science results, ranging from the fundamental validation of satellite and modeling efforts to providing empirical observations of tides in Central Arctic, and to the discovery of various modes of variability in Arctic Ocean circulation at different timescales.

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