A basin-coherent mode of sub-monthly variability in Arctic Ocean bottom pressure

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[1] A sub-monthly mode of non-tidal variability of ocean bottom pressure (OBP) is observed in a 5-year record of deep-sea bottom pressure at the North Pole. OBP records from other regions in the Arctic show that the North Pole non-tidal mass fluctuation is part of a non-propagating basin-coherent variation that is well represented by the ice-ocean model PIOMAS, with a basin-averaged winter-only RMS of 3.3 cm. Wavelet analysis of the modeled OBP shows that the basin-averaged mass variations are non-stationary and only significant during the winter. The basin-averaged OBP is strongly related to the meridional wind component over the Nordic Seas. The ocean response is consistent with episodic wind forcing driving a northward geostrophic slope current. The mass transport anomaly associated with the mode is significant relative to the annual net mean flow. Citation: Peralta-Ferriz, C., J. H. Morison, J. M. Wallace, and J. Zhang (2011), A basin-coherent mode of sub-monthly variability in Arctic Ocean bottom pressure, Geophys. Res. Lett., 38, L14606, doi:10.1029/2011GL048142.

1. Introduction

[2] Mass fluxes into and out of the Arctic Ocean are fundamental to the distribution of heat and freshwater. Changes in these are of major concern due to their possible linkages with global climate, for example, by controlling stratification in the sub-Arctic seas and thereby modulating convection and the meridional overturning circulation. Direct measurements of the fluxes are challenged by spatial and temporal variability. In this paper we explore a heretofore-unknown sub-monthly mode of Arctic Ocean variability recorded by in situ ocean bottom pressure (OBP) measurements. We examine its effects on the circulation and the mass fluxes into and out of the Arctic basin using output from an ice-ocean model. The analysis of sub-monthly variations in Arctic Ocean mass and mass flux is feasible in part due to advances in ice-ocean modeling and also because we now have deep sea in situ observations of OBP that represent an integral measurement inherently less sensitive to high frequency noise than direct flux measurements.

[3] The first hints of the sub-monthly variations in Arctic OBP actually came from pairs of deep-sea pressure gauges monitoring the West Spitsbergen Current [Morison, 1991]. These showed OBP variations with a 19-day period, but the spatial extent and significance of the variations were unknown. Now we have sufficient observations and model results to show that sub-monthly variations in Arctic Ocean mass are significant compared to the mean fluxes into the basin, and to understand the associated circulation patterns.

2. Observations and Model Output

[4] Our observations come from pressure and tide gauges across the Arctic Ocean, shown in Figure 1. In conjunction with the North Pole Environmental Observatory program we deployed two Arctic bottom pressure recorders (ABPR) near the North Pole, ABPR1 at 89° 15.26′ N, 60° 21.58′ E, and ABPR3 at 89° 14.85′ N, 148° 7.54′ E [Morison et al., 2007]. ABPR1 recorded five full continuous years, from Spring 2005 to Spring 2010, and ABPR3 worked continuously for 3 years. Long-term drift errors in the later part of ABPR records were removed using monthly OBP observations from the Gravity Recovery and Climate Experiment, without compromising the high-frequency variations in OBP. The resulting de-trended records of the two ABPRs are highly correlated (R = 0.99). We averaged the first three years of data of both ABPR records (available at http://psc.apl.washington.edu/northpole/) to form a single record representative of the North Pole, and used ABPR1 data collected in April 2010 to complete the 5-year record.

[5] We also use time series from bottom pressure recorders (BPR) deployed by the Beaufort Gyre Exploration Project, BGEF, at a) 75° 0.449′ N, 149° 58.660′ W, b) 78° 1.49′ N, 149° 49.203′ W, and c) 76° 59.232′ N, 139° 54.563′ W (http://www.whoi.edu/beaufortgyre/data_mooring.html/), from August 2003 to August 2008. The BGEF BPR records are highly correlated with each other so we average them to obtain a single OBP record in the Beaufort Sea. OBP data from Pressure Inverted Echo Sounders deployed by the Alfred Wegener Institute at a) 78° 49.93′ N, 005° 00.87′ E, b) 78° 49.87′ N, 002° 47.59′ E and c) 78° 50.03′ N, 008° 19.91′ E (A. Beszczynska-Möller, personal communication, 2007), were averaged to give a time series of OBP representative of Fram Strait, from September 2003 to August 2006.

[6] Tide gauge records are used from 2 locations on the Canadian Arctic Shelf, in Alert at 82° 29.51′ N, 62° 19′ W, from 2004 to 2007, and Holman at 70° 44.21′ N, 117° 45.5′ W, from 2003 to 2008 (http://www.meds-sdmn.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/inventory-inventaire/index-eng.htm). These were corrected for the inverted-barometer effect to yield bottom pressure, using local sea level pressure (SLP) from NCEP/NCAR reanalysis [Kalnay et al., 1996]. For the analysis of large-scale atmospheric patterns driving the ocean mass variations, we use daily SLP and winds at 925 hPa from the NCEP/NCAR reanalysis, from January 2000 to December 2009, north of 30°N.

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All OBP records are de-tided using the Matlab program t_tide [Pawlowicz et al., 2002], and averaged daily. To emphasize the sub-monthly variations, the de-tided OBP data are high-pass filtered with a 90-day cutoff period. We give OBP in cm of water equivalent.

In addition to in situ observations, we analyze the daily output of OBP, SSH and depth-dependant horizontal velocity from the Pan-Arctic Ice Ocean Modeling Assimilation System, PIOMAS [Zhang and Rothrock, 2003]. PIOMAS is a regional baroclinic ice-ocean model with 30 vertical levels and maximum spatial resolution of $\sim 20$ km. PIOMAS is one-way nested to a global ocean model at 49$^\circ$N, and is forced by the winds and surface atmospheric pressure from NCEP/NCAR reanalysis data. The model does not include tides, and assumes a perfect inverted barometer effect.

3. Ocean Bottom Pressure Variability

Our five-year hourly time series of OBP at the North Pole (Figure 1) represents the longest OBP record in the central Arctic. The high-pass filtered data reveals winter amplification of OBP variations (Figure 1). The RMS variance of the high-pass filtered, de-tided record is 4 cm, and the winter-only RMS is 4.6 cm. The power spectrum of the unfiltered OBP record at the North Pole shows a spectral peak around 0.05 cycles per day (cpd, $\sim 20$ days, Figure 1). Although its statistical significance is not far above the noise level, it resembles the OBP variations in the West Spitsbergen Current reported by Morison [1991].

All the OBP records used here overlap from April 2005 to August 2006. Similar to the records from the North Pole, we high-pass filter each time series and compare the OBP anomalies among regions. All records in the 5 regions are highly correlated with each other (at better than the 95% confidence level, $R = 0.58$ to 0.9, Table S1 in the auxiliary material) with no lag, except for the record from Fram Strait, which leads all the others by 1 day.

Large-scale coherent variations of OBP in the Arctic Ocean have been previously identified using modeling results [Hughes and Stepanov, 2004]. These agreed with tide gauge records from shallow regions of the Arctic, but most of the observations were from the Russian and Scandinavian continental shelves (Figure 1). Hence, the full spatial extent of the mass oscillation was not confirmed.

Figure 1. (a) De-trended, hourly ocean bottom pressure anomalies at the North Pole. (b) Tide signal extracted from Figure 1a. (c) North Pole daily non-tidal high-pass filtered OBP anomalies. (d) Power spectrum of the North Pole non-tidal OBP record (gray dots), smoothed spectrum (black) and the 95% confidence interval (thin gray). Shaded line highlights the 15–30 day period range. (e) Daily non-tidal high-pass filtered OBP records from Spring 2005 to Summer 2006 in five regions, color-coded in the map. Shaded lines highlight the coherence of OBP variations among regions. The map shows the regions of the OBP records, and the black dashed-lines delimit the area of the basin-averaged OBP from the model. Black dots in the map show the approximate location of the tide gauges of Hughes and Stepanov [2004], and gray lines show the 500 and 1000 m isobaths.

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Auxiliary materials are available in the HTML. doi:10.1029/2011GL048142.
Also, the OBP records of Hughes and Stepanov [2004] were analyzed in monthly averages, for which a sub-monthly oscillation could have not been detected and may have been aliased into the monthly values. Our pressure record compilation suggests that the sub-monthly oscillation is indeed a basin-wide mode of OBP variability, with coherent anomalies in both the shallow Western and deep Central Arctic Ocean, at zero lag.

The non-tidal high-pass filtered observations of OBP variations are well represented by the filtered OBP from PIOMAS at all five regions. Although the model tends to underestimate the observed amplitudes, all model-in situ correlation coefficients are above $R = 0.53$ and are significant at better than the 95% confidence level (Table S1 in the auxiliary material). Therefore, we average the daily PIOMAS OBP output from 2000 to 2009 over the Arctic basin, delimited by Fram Strait, the Barents Sea entrance path, the Bering Strait and the northern passages into the Canadian Archipelago (CA). The ocean mass within the CA is not included in the average (see map in Figure 1).

The high-pass filtered basin-averaged OBP from the model captures the observed winter amplification of OBP (Figure 2a). The RMS variance of the high-pass filtered basin-averaged OBP is 2.6 cm, and the winter-only RMS variance is 3.3 cm.

Year to year variations in the observed OBP suggests that the signal is non-stationary. To test this, we perform a wavelet analysis on the unfiltered basin-averaged OBP. We use a Morlet mother wavelet, and a Monte Carlo simulation to extract the significance of the wavelet power, tested against red noise [Grinsted et al., 2004; Torrence and Compo, 1998]. The wavelet power spectrum of the basin-averaged OBP is shown in Figure 2b. The sub-monthly peaks are only significant during the winters and typical periods for individual years range from 15 to 30 days.

4. Atmospheric Forcing

A regression map of the SLP and wind field at 925 hPa, projected on the modeled standardized basin-averaged OBP of Figure 2a (Figure 3) shows that the basin-averaged OBP is highly correlated with the sea level atmospheric pressure gradient between Scandinavia and Greenland and southerly winds in the Nordic Seas. To
characterize the SLP gradient, we select the locations with the largest positive and negative correlation coefficients between SLP and basin-averaged OBP (Figure 3). We refer to the difference in SLP between these two locations as the SLP gradient time series (Figure 2c). The maximum correlation with the daily basin-averaged OBP is with SLP gradient leading OBP by 2 days (Figure 3). The atmospheric pattern associated with the basin OBP variation is consistent with a wind-driven slope current through the Nordic Seas, as illustrated in Figure 3.

The time series and the wavelet power of the SLP gradient are shown in Figures 2c and 2d. The SLP gradient, consistent with the basin-averaged OBP, shows the winter increase in energy (Figure S1 in the auxiliary material), and the strongest energy of the SLP gradient is concentrated within the 5–30 day period range. The cross-wavelet power between SLP gradient and basin-averaged OBP (Figure 2e) indicates that both time series share the high-energy episodes, and their common power is largest at the sub-monthly scale (\(\sim 15–30\) day periods), with lags ranging from near 0° to \(\sim 30°\). The regression map (Figure 3) and the wavelet results suggest that the wintertime variations in basin OBP are forced by the atmospheric circulation. The sea level pressure regression pattern shown in Figure 3 strongly resembles the leading empirical orthogonal function of 6–30 day bandpass filtered 500-hPa height over the Atlantic sector [Rennert and Wallace, 2009, Figure 2]. The prevalence of this pattern is attributable to the episodic occurrence of blocking events.

Additional atmospheric forcing enhances the mass entering the basin through the Bering Strait, as suggested by the regression maps of SLP projected onto modeled OBP at individual locations in the basin closer to the Bering Strait pathway (Figure S1 in the auxiliary material). However, there is no correlation between basin-averaged OBP and SLP near the Bering Strait (Figure 3).

5. Ocean Circulation and Mass Exchange Associated With the Sub-monthly Mode

Ocean circulation changes at sub-monthly timescales are barotropic [Vinogradova et al., 2007; Bingham and Hughes, 2008], and for which we use depth-integrated only velocity fields from PIOMAS. Composite maps of the PIOMAS model anomalies of SSH and depth-integrated velocity field (mSv per unit length = 10^{3} m^{2} s^{-1}), reveal the ocean circulation at times of maximum and minimum basin-averaged OBP and the state 3 and 6 days before and after the maximum basin-averaged OBP (Figure 4). The composites for maximum and minimum average OBP are based on the dates when OBP anomaly exceeds 1.5 standard deviations, which occurs only during winter (n = 42 dates over the 10 years analyzed, Figure 2a). We then generate the composites of the flow through Bering Strait, Fram Strait, Barents Sea path and the CA, to the Arctic Ocean, and the total net volume flow into the basin (Table S2 in the auxiliary material).

The SLP pattern observed in association with enhanced southwesterly winds (i.e., high over Scandinavia and low over Greenland) is first discernible six days prior to maximum average OBP. The resultant SSH gradient yields the aforementioned slope current into the Arctic Ocean (Figure 3). This sets up gyre circulation patterns, cyclonic at maximum average OBP and anticyclonic at minimum OBP in the Eurasian Basin, with counter-rotating patterns in the Nordic Seas (Figure 4).

During the maximum and minimum basin-averaged OBP, there is minimum mass exchange between Arctic and...
The largest net volume inflow towards the Arctic basin through Bering and Fram Straits, CA and Barents Sea paths is between 1.51 and 1.37 Sv (6 to 3 days before maximum, respectively). Most of the mass transport is through Fram Strait, followed by the Barents Sea path. The composite daily progression of net flow into the basin, integrated over time relative to the maximum OBP (not shown), divided by the area of the Arctic Ocean, represents an increase of a basin-averaged OBP of ∼3.5 cm. This mass increase is consistent with the wintertime RMS value of OBP from PIOMAS to within 10% error. The largest net volume transport exiting the basin is between 1.25 and 1.11 Sv (3 to 6 days after maximum OBP, respectively).

The circulation associated with the sub-monthly mode largely follows the topography (Figure 4). Topographic steering of the flow in the Nordic Seas and Arctic Ocean has long been recognized [e.g., Isachsen et al., 2003; Nøst and Isachsen, 2003], but sub-monthly variations have been unknown. The temporal mean of the vertically integrated velocity from PIOMAS (not shown) consists of cyclonic circulation in the Nordic Seas and the Eurasian Basin, northward flow into the basin through the east side of Fram Strait, and flow southward from the basin through the west side of Fram Strait, in agreement with previous modeling results and observations [e.g., Nøst and Isachsen, 2003]. Isachsen et al. [2003] showed that the flow variability in the Nordic Seas and Arctic Ocean is well represented by a barotropic model, and the flow follows the bathymetry. The opposing vortices revealed by PIOMAS (Figure 4) at maximum and minimum basin OBP show the vertically-integrated flow anomaly, and represent a measure of the strengthening and weakening of the climatological-mean field at the sub-monthly timescales, owing to the atmospheric forcing in the Fram Strait region.

Figure 4. Composite maps of the anomalies of high-pass filtered sea surface height (color contours) and depth-integrated velocity (vectors) from 10 years of daily model output (2000–2009), for when the basin-averaged OBP is (top left) 6 days before maximum, (middle left) 3 days before maximum, (bottom left) at maximum, (top right) 3 days after maximum, (middle right) 6 days after maximum, and (bottom right) at minimum. Composite maps of SLP anomaly are shown inside the panels for each corresponding phase of basin-averaged OBP. Bathymetry is shown in magenta, with 1000 m interval contours. Faint green and white arrows emphasize the general patterns of the circulation associated with the winter sub-monthly mode of variability.
Although the spectral peak in OBP at around 20 days (Figure 1) is at the uncertainty level, the variance-preserving spectrum (Figure S2 in the auxiliary material) depicts a strong concentration of energy between 15 and 30 days. Modeling results and the comparison with SLP gradient spectra suggest that this is due to a broader peak in the spectra of atmospheric forcing and a frequency limitation in the ocean response. Isachsen et al.’s [2003] model assumes that mass divergence in the surface Ekman layer is balanced by convergence in the bottom Ekman layer, and based on observed wind stress in the Nordic Seas ($\tau = 0.1 \text{ N m}^{-1}$) and typical values of depth $H = 3000 \text{ m}$, density $\rho = 1000 \text{ kg m}^{-3}$, and ocean currents $u \sim 10 \text{ cm s}^{-1}$, the associated spin-down timescale of the response to surface forcing $(T_{\text{H butterfly}})^{-1}$ is about 30 days (see Isachsen et al. [2003] for model details). Following their analysis, the depth-integrated currents from PIOMAS, which are of order 1 cm s$^{-1}$, yield a decay timescale of $\sim 3$ days, which corresponds to a period of $2\pi * 3$ days $\sim 18$ to 22 days. This suggests that the ocean response will be limited at shorter periods.

The variance-preserving spectra of SLP gradient and basin-averaged OBP (Figure S2 in the auxiliary material) show similar peaks around 1/18 cpd, but at higher frequencies the spectra of SLP gradient show less roll-off with frequency, and the frequency response function (ratio of OBP and SLP gradient Fourier transforms, Figure S3 in the auxiliary material) rolls off at greater than the inverse of frequency squared above $\sim 1/15$ cpd. The circulation decay timescale from Isachsen et al. [2003] and the low-pass filter characteristic of the OBP/SLP frequency response function, all suggest that the ocean is unable to respond to the SLP gradient above a cutoff frequency around 1/18 to 1/15 cpd. Combined with the increase with frequency in variance preserving spectral density of the forcing (SLP gradient) below $\sim 1/15$ cpd, the ocean response cutoff produces a more peaked response in ocean mass than is shown by the forcing (Figure S2 in the auxiliary material).

The 2-day lag between the SLP gradient and the basin OBP (Figure 3) is also consistent with the ocean spin-down time taken from Isachsen et al. [2003] and by itself suggests the importance of inertial effects. If the variation in ocean mass represented the filling of a vessel balanced by basin pressure forced leakage paths, we would expect OBP in the basin to rise and fall in phase with the forcing (wind-driven slope current should follow SLP gradient within 1/f) so as to balance leakage against inflow. Alternatively if leakage were negligible, the ocean mass would represent only the integral of the periodic forced inflow and OBP would lag the forcing by $90^\circ$ (e.g., 4 to 7-day lag for a 15 to 30 day period). The 2-day lag suggests a situation between these two extremes with impedance of the leakage paths by friction and inertial effects. Similar wind-driven effects on basin-scale mass variations through a narrow strait have been documented in the Mediterranean Sea (e.g., through the Strait of Gibraltar) [Fukumori et al., 2007].

6. Summary and Speculation

Wavelet analysis indicates that the wind forcing and ocean response are episodic, significant during wintertime, and vary from year to year in strength and predominant period. The sub-monthly Arctic mass variations are due to wind-driven slope currents forced by zonal SLP gradient and southwesterly winds. The PIOMAS wind-forced mass fluxes into and out of the Arctic Ocean are large enough to produce the observed sub-monthly mass variations and associated barotropic topographically controlled circulation patterns, and the timescales and frequency response is consistent with the theory of Isachsen et al. [2003].

The sub-monthly mass variations are large and their associated longer-term effects may be important. The wind events that cause them conceivably have associated net effects on the mass transport into the Arctic Ocean, and sub-monthly variations must clearly impact the attempts to observe Fram Strait mass transport. We also speculate that if temperature fluctuations prove to be correlated with the changes in mass flux at sub-monthly timescales, the mass transport variations could result in a long-term change in Arctic Ocean heat content [e.g., Schauer et al., 2004].


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