Tidal Characteristics Along the Western and Northern Coasts of Alaska

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Abstract

Historical and recent observations from tide stations established by the NOAA/NOS Center for Operational Oceanographic Products and Services (CO-OPS) show the complicated distributions of semi-diurnal and diurnal tides as well as non-tidal areas along the Western and Northern coasts of Alaska. The tide is mixed, mainly semidiurnal throughout the Bering Sea Shelf with exception of eastern Norton Sound, where diurnal tide dominates. The mixed, mainly semidiurnal tide coupled with strong meteorological effects dominates the Bering Strait, Southern Chukchi Sea and Beaufort Sea Shelves. The Northeastern Chukchi Sea appears to be non-tidal and is often masked by weekly weather patterns. The tide from Northern Pacific enters the Bering Sea through central and western Aleutian passages and propagates as a progressive wave to the shelf. Part of it then propagates on to the southeast Bering shelf and another part propagates northeastward through the Bering Strait and into Chukchi Sea. Amphidromic systems are formed in Bristol Bay, Norton Sound and off Chukchi Sea for semidiurnal tides. The largest amplitudes are found in upper Bristol Bay and in Kuskokwim Bay with a gradual decrease in amplitude approaching the Bering Strait. Co-tidal charts showing these tidal characteristics and the amphidromic systems are presented.

Introduction

The coastline of Western and Northern Alaska is surrounded by the Bering Sea, Chukchi Sea and Beaufort Sea with major embayment features of Bristol Bay, Norton Sound and Kotzebue Sound (Figure 1). The Beaufort Sea is considered part of the Arctic Ocean. Tides and weather in the Bering Sea, Chuckchi and Beaufort Sea play an important role in the distribution of ocean temperature, salinity and circulation and have been studied by observations or numerical models at various times over the past century (Harris 1911, Jeffreys 1921, Munk and MacDonald 1960, Hunkins 1965, Matthews 1971, Cartwright 1979, Pearson 1981, Kowalik and Matthews (1982), Kowalki and Proshutinsky (1993, 1994), Mofjeld (1984, 1986), Mofjeld et al. 1984, Liu and Leendertse (1979, 1981, 1982, 1990), Kowalik 1999, Foreman 2006 and Li et al. 2010). Although the tide in the Chukchi Sea and Beaufort is rather small (amplitude < 0.1m), a recent study indicates that it substantially impacts the ice motion and Arctic climate (Hibler III et al. 2006, Holloway and Proshutinsky 2007).

Tides along the Western and Northern Coasts of AK are not only critical to understanding regional physical oceanography, but also to supporting hydrographic surveying, commercial fishing, and coastal dredging, etc. Due to the increasing loss of summer sea ice extent in the Western and Northern Alaska, navigation will increase as vessels pursue shorter transit routes between the northern Pacific and Atlantic Oceans. The NOAA Office of Coast Survey (OCS) has developed an Arctic Charting Plan for modernizing nautical charts in the region. A more accurate and detail description of tides along the Western and Northern Coasts of AK becomes necessary to support the increasing navigation, shoreline mapping, and other commercial purposes.

Currently, there are only six NOAA National Water Level Observation Network (NWLON) tide stations along the Western and Northern Coasts of AK: Unalaska, Village Cove, Port Moller, Nome, Red Dog Dock, and Prudhoe Bay (Figure 1 & Table 1). The NWLON is a network of continuously operating stations managed by the Center for Operational Oceanographic Products and Services (CO-OPS). The NWLON stations provide long-term observations and tidal datum reference and tide predictions for NOAA's Nautical Charting Program and Navigation Services. Thirty-three (33) short-term stations have been installed in this region since 2003 for different purposes such as hydrographic surveys, Vertical datum transformation (VDatum) or U.S. Army Corp Engineers datum validation (Figure 1 & Table 1). Twenty-six (26) of these stations have at least 30 days of continuous 6 minute data. Thirty-four stations, including the six NWLON stations have accepted water level datum values. Twenty stations, including the six NWLON stations have accepted harmonic constants (HCs, Table 1). Before 2003, most historical stations were in the1900s, 1940s or 1950s and the time series were typically only a few days in length. The recent observations allow a more accurate and detailed knowledge of tides in this region possible. In this paper, we utilized the historical as well as recent observations to construct the spatial distribution of tide types and co-tidal charts, as well as to describe how tides propagate in this area.

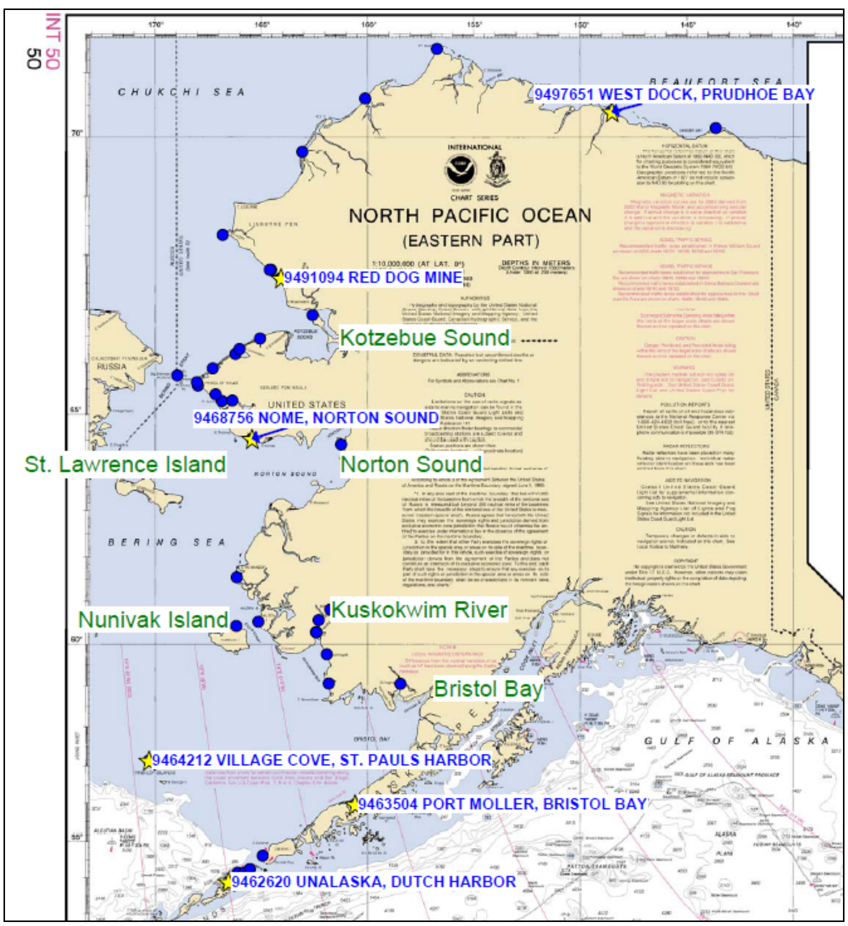


Figure 1. NWLON and recent subordinate stations (installed after 2003)

Table 1. NWLON stations and subordinate stations installed since 2003. Stations with currently accepted (published) tidal datums (1983-2001 National Tidal Datum Epoch) or Harmonic Constants are marked as "Y" in Datums or HCs column.

#	Station Id	Station Name	Data Time Series	Datums	HCs	Latitude	Longitude
1	9462620	Unalaska, Dutch Harbor *	01/01/96-current	Y	Y	53.88000	-166.53700
2	9462662	Reef Bight	05/29/09-08/09/09	Y	Y	54.13000	-166.09833
3	9462694	Akutan	03/07/09-05/01/09	Y	Y	54.13328	-165.77731
4	9462719	Akun Cove	04/10/09-09/06/09	Y	Y	54.23330	-165.53300
5	9462787	Cape Sarichef	06/02/07-08/09/07	Y	Y	54.60000	-164.92800
6	9463502	Port Moller *	09/15/06-current	Y	Y	55.99000	-160.56200
7	9464212	Village Cove *	04/12/02-current	Y	Y	57.12531	-170.28517
8	9465374	Snag Point	05/30/07-11/01/07	Y	Y	59.04000	-158.44700
9	9465396	Platinum	06/02/07-10/02/07	Y	Y	59.04670	-161.81800
10	9465831	Kwinak	06/01/10-09/30/10	Y	Y	59.75055	-161.91544
11	9466057	Popokamute	06/24/10-09/08/10	Y	IP	60.27028	-162.41017
12	9466153	Helmick Point	06/06/10-09/14/10	IP	IP	60.27000	-162.41000
13	9466217	Mekoryuk	07/01/10-09/30/10	Y	Y	60.41670	-166.16700
14	9466298	Nelson	07/01/10-09/3010	Y	IP	60.51670	-165.13300
15	9466328	Lomavik	06/02/10-09/12/10	Y	IP	60.55428	-162.29714
16	9466477	Bethel	06/01/10-09/30/10	Y	Y	60.80000	-161.75000
17	9466931	Dall Point	06/08/07-09/07/07	Y	IP	61.53170	-166.14800
18	9468691	Shaktoolik	07/14/10-08/23/10	Y	IP	64.38022	-161.23514
19	9468756	Nome*	10/01/92-current	Y	Y	64.50000	-165.43000
20	9469237	Point Spencer	07/24/05-09/02/10	Y	IP	65.25670	-166.84700
21	9469239	Teller	07/18/05-09/02/05	Y	IP	65.26670	-166.35300
22	9469338	Lost River	07/25/05-08/31/05	Y	IP	65.39000	-167.14500
23	9469439	Tin City	06/24/07-08/16/10	Y	Y	65.55830	-167.97500
24	9469460	Lopp Lagoon West	09/09/03-09/19/03	Y	N/A	65.62500	-168.02500
25	9469541	Little Diomede Island	07/28/10-08/09/10	Y	N/A	65.75706	-168.94954
26	9469626	Ikpek Lagoon	09/16/03-10/03/03	Y	N/A	65.89330	-167.27300
27	9469804	Shishmaref Inlet Inside	09/12/03-09/20/03	Y	N/A	66.17000	-166.20700
28	9469854	Shishmaref Inlet 2	08/30/03-10/04/03	Y	Y	66.26330	-166.02000
29	9469982	Lagoon at 165 West	09/14/03-09/21/03	Y	N/A	66.46170	-165.05500
30	9490424	Kotzebue	09/01/03-09/30/03	Y	Y	66.90170	-162.58200
31	9491094	Red Dog Dock*	08/30/03-current	Y	Y	67.57670	-164.06500
32	9491247	Kivalina Lagoon	09/06/03-09/27/03	IP	N/A	67.72670	-164.53200
33	9491253	Kivalina	08/26/03-10/06/03	Y	Y	67.72670	-164.59200
34	9491873	Point Hope	09/26/03-09/29/03	Y	N/A	68.34170	-166.80800
35	9493300	Point Lay	07/24/08-10/03/08	NT	NT	69.74472	-163.06417
36	9494168	Wainwright Inlet	07/28/08-10/05/08	NT	NT	70.59830	-160.10800
37	9494935	Barrow Offshore	08/09/08-12/31/09	IP	IP	71.36011	-156.72986
38	9497645	Prudhoe Bay*	07/30/94-current	Y	Y	70.40000	-148.52700
39	9499176	Barter Island, Arctic	08/15/08-10/26/08	Y	Y	70.12856	-143.61103

*Current NWLON stations

IP: In Progress

NT: Non-tidal

Methodology and Results

Tides are the periodic rise and fall of the water surface of the Earth resulting from gravitational interactions between the Sun, Moon and Earth and include both vertical (tide) and horizontal (tidal current) components. The tide-producing forces resulting from the gravitational interaction vary approximately as the mass of the attracting body and inversely as the cube of its distance. The tide-producing force exerted by the Moon is slightly more than twice as great as that of the Sun. The astronomical forces make the tide predictable. The size of tide range, the timing of high and low waters, the type of tide, as well as the speed and timing of the tidal current is determined by basin-scale and local-scale hydrodynamics. The variation in tide range over a waterway is usually depicted on corange charts and the variation in the phase lag of high and low waters is likewise depicted on co-tidal charts.

1. Tide type distribution

Classification of the type of tide is based on characteristic forms of a tide curve determined by the local relationship of the semidiurnal and diurnal tidal components. When the two high waters and two low waters of each tidal day (24.84 hours) are approximately equal in height, the tide is semidiurnal; when there is a relatively large diurnal inequality in the high or low waters or both, the tide is mixed; and when there is only one high water and one low water in each tidal day, the tide is diurnal. Tide types may be quantitatively classified (e.g., Defant 1961) by the amplitude ratio (F ratio) of:

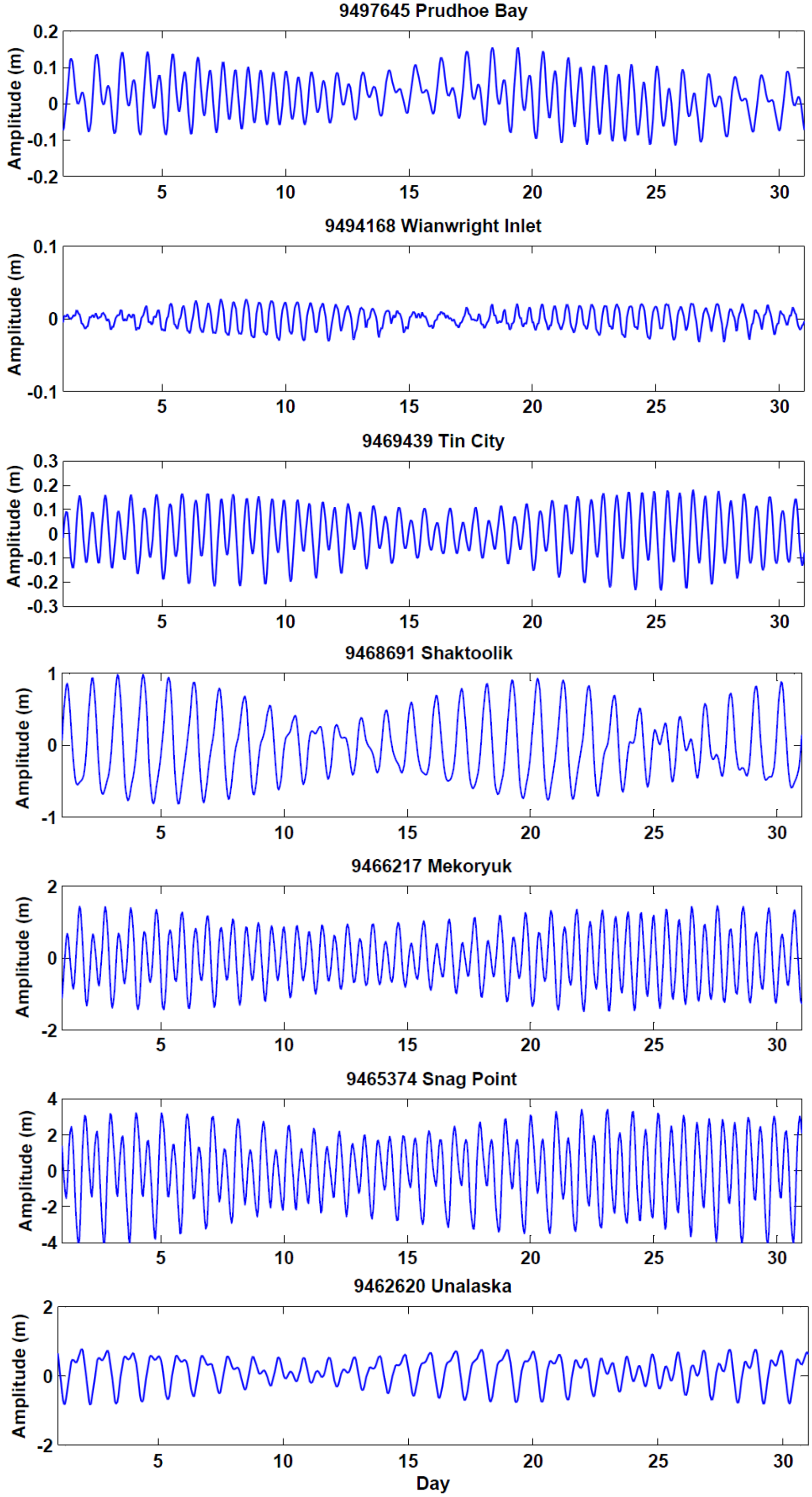
$$F = (K_1 + O_1) / (M_2 + S_2) \qquad (1)$$

K_1 is the principal lunar diurnal constituent, O_1 is the principal solar diurnal constituent, M_2 the principal lunar semidiurnal constituent and S_2 is the principal solar semidiurnal constituent. If the ratio is less than 0.25, the tide is classified as semidiurnal; if the ratio is from 0.25 to 1.5, the tide is classified as mixed, mainly semidiurnal; if the ratio is from 1.5 to 3.0, the tide is classified as mixed, mainly diurnal; if the ratio is greater than 3.0, the tide is classified as diurnal. Since S2 is so small throughout the Bering Sea, it is substituted by N2 in the equation.

Thirty-one HCs including accepted and working HCs in Table 1, as well as HCs from stations installed prior to 2003 in the study area were used to do analysis (Figure 2). HCs were generated by Fourier transformation if data is shorter than 180 days (6 months) or least-square analysis if data is longer than 180 days (Parker, 2007). Accepted HCs are published on CO-OPS website (www.tidesandcurrents.noaa.gov). The F ratio was calculated at each station according to equation (1) and loaded into ArcGIS for interpolation.

The amplitude ratio shows the complicated distributions of semi-diurnal and diurnal tides as well as non-tidal areas along the Western and Northern coasts of Alaska (Figure 2). Figure 3 demonstrates the wide-array tide curves in this region using simultaneous plots of predicted tides. The tide is mixed, mainly semidiurnal ($0.25< F< 1.5$) throughout the Bering Sea Shelf with exception of Norton Sound ($F> 3.0$), where the diurnal tide dominates. The tides in the southwestern Bering (Unalaska and Village cove) are mixed, mainly diurnal ($1.5 < F<3.0$). The mixed, mainly semidiurnal, low range tide coupled with strong meteorological effects dominates water level variations in the Bering Strait, Southern Chukchi Sea and Beaufort Sea Shelves. The Northeastern Chukchi Sea appears to be non-tidal (Mean Range of tide < 0.06m) and tides are often masked by weekly weather patterns. However, stations in the Northern Chukchi Sea had to be located inside estuary entrances and may not represent tides along the outer coast.

Figure 2. The amplitude ratios used to depict type of tide along the Western and Northern coasts of AK



Mixed, Mainly Semidiurnal Tides along the Beaufort Sea

Mixed, Mainly Semidiurnal Tides with extremely low amplitude (< 0.06 m) in the Southern Chukchi Sea. This amplitude doesn't meet the threshold for official tidal predictions.

Mixed, Mainly Semidiurnal Tides near the Bering Strait

Diurnal Tides in Norton Sound

Mixed, Mainly Semidiurnal near Kuskokwim Bay

Mixed, Mainly Semidiurnal Tides with Extremely High Amplitude (>6 m) in Bristol Bay

Mixed, Mainly Diurnal Tides in the Western Bering Sea (Unalaska, Village Cove)

Figure 3. Predicted tides at Unalaska, Snag Point, Mekyuk, Shaktoolik, Tin City, Waiwright inlet and Prudhoe Bay.

2. Co-tidal charts

Thirty-four (34) stations (including NWLON stations) have accepted tidal datums. Cotidal and corange lines are constructed based on Greenwich High Water Intervals (HWI), Low Water Intervals (LWI), Great Diurnal Tidal Range (GT) and Mean Range (MN) datums at those stations. The cotidal lines in Figure 4 & 5 represent HWI and are the average time interval between the Moon's transit over the Greenwich meridian and the time of high water at any location. The estimated cotidal lines shown pass through locations having the same co-tidal hour. A slow tide progression is showed by the increasing closeness of the cotidal lines, as seen in Bristol Bay, Kuskokwim River, Northern Bering Sea, etc. Tides propagate rapidly across the deep western Bering Sea basin and part of it then propagates on to the southeast Bering shelf. A semi-amphidronic system in the total tide is formed in northern Bristol Bay as a result of the presence of an amphidromic point for the semidiurnal tides. Another part propagates northeastward through St. Lawrence Island and into Norton Sound. Co-tidal lines cannot be constructed in Norton Sound due to the lack of data and the change of tide type. Tides are mixed, mainly semidiurnal at the entrance of sound and diurnal in the Sound. Tides propagate further northward through the Bering Strait into Chukchi Sea and Kotzebue Sound. The interference of tides from Bering Sea and tides propagating southward from the Arctic Ocean results in an amphidromic point off Point Lay (Kowalik and Matthews, 1982). Co-tidal lines also cannot be constructed in Kotzebue Sound due to the lack of data and the change of tide type. Hotham Inlet, an arm of Kotzebue Sound, is non-tidal. The northeastern Chukchi Sea appears to be non-tidal according to observations and thus no cotidal lines are shown. However, as mentioned above, stations in the Northern Chukchi Sea are located inside estuaries and may not represent tides along the outer coast. Additional observations along the Beaufort Sea shelf are needed to complete a comprehensive set of co-tidal lines.

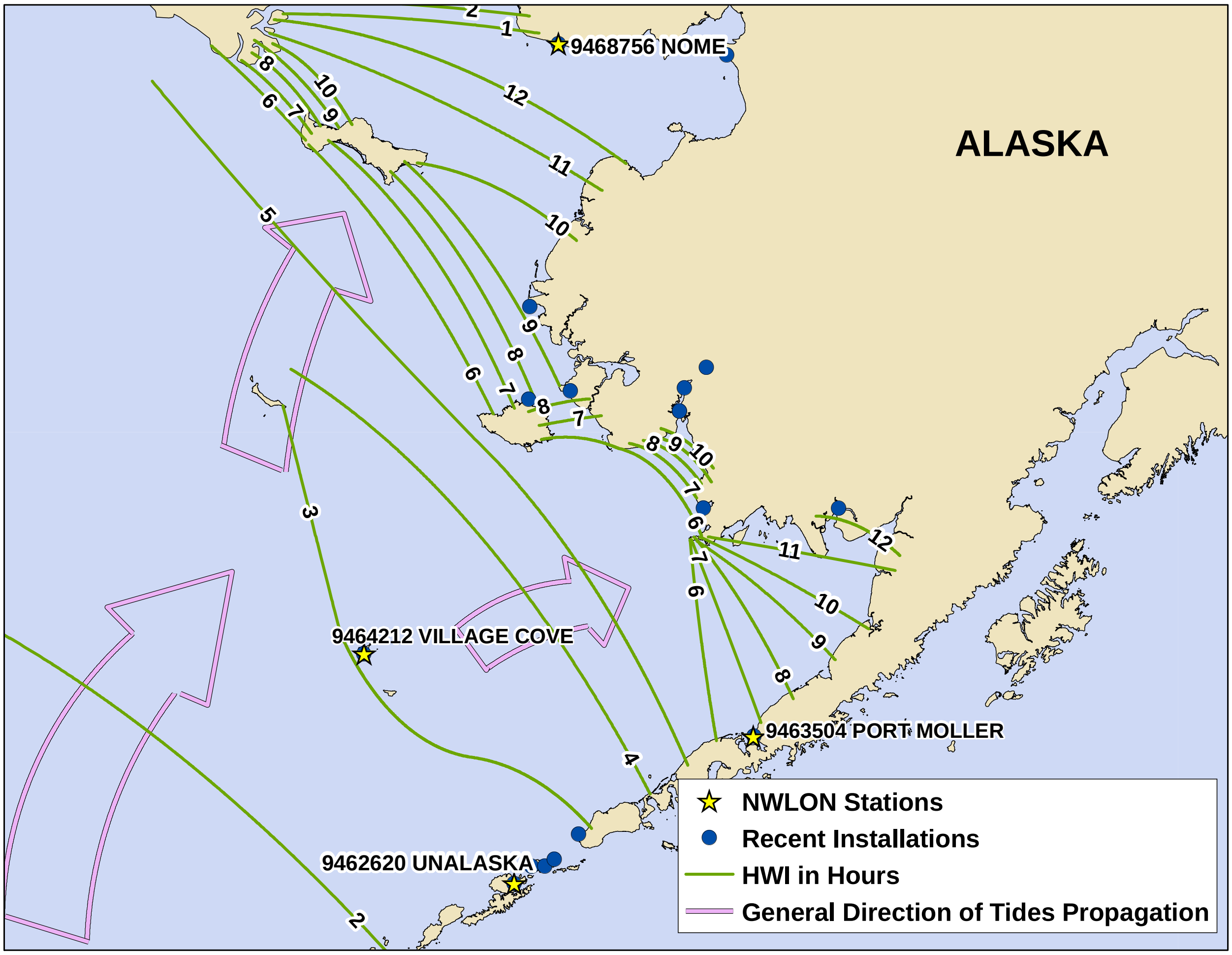


Figure 4. Cotidal lines along the Eastern Bering Sea Shelf.

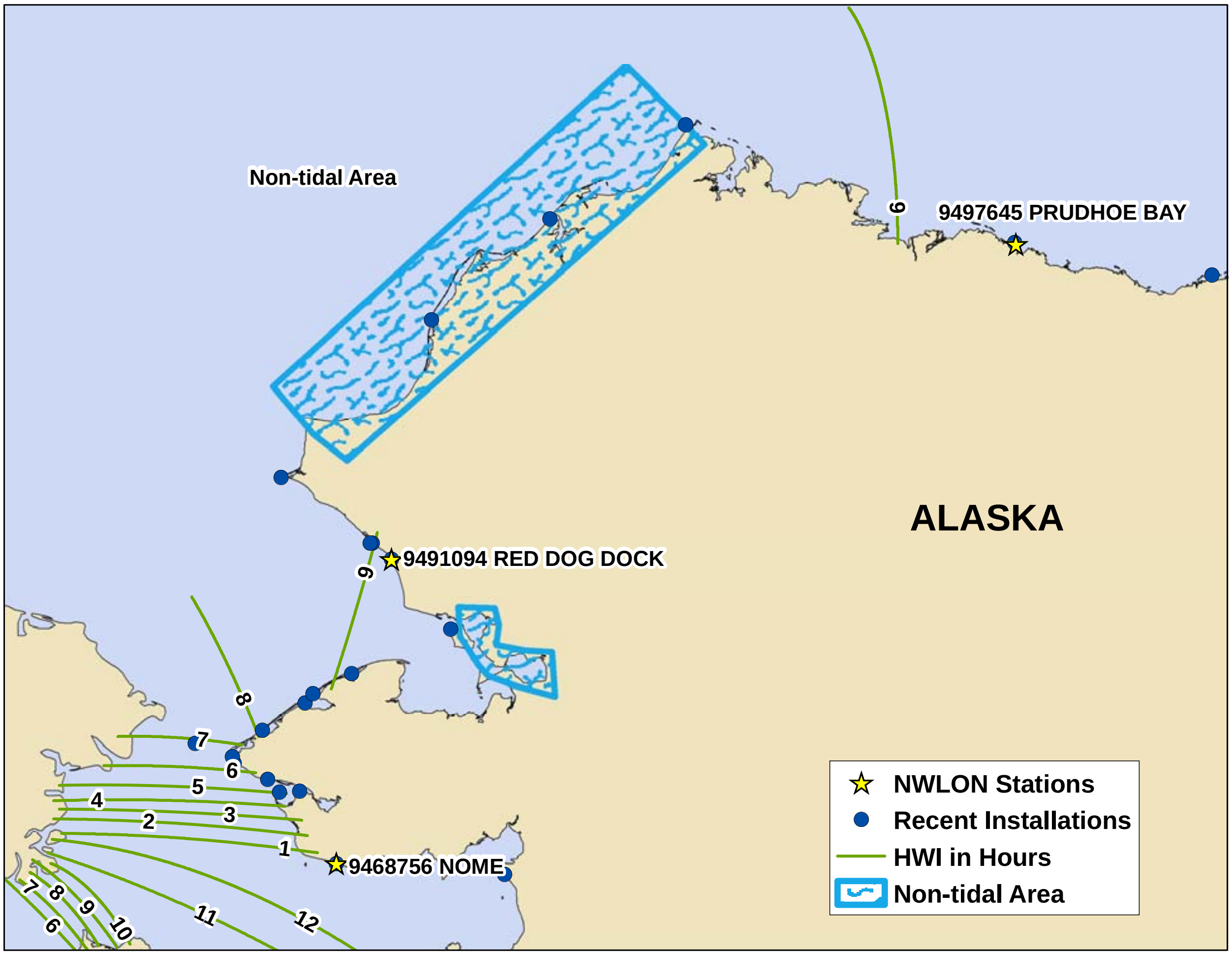


Figure 5. Cotidal lines along the Chukchi Sea and Beaufort Sea Shelves

3. Co-range Charts

The estimated co-range lines shown pass through locations having equal Great Diurnal Range (GT) of tide (Figure 6 & 7). The diurnal range is the difference in height between mean higher high water (MHHW) and mean lower low water (MLLW). A rapid change of tidal range is showed by the increasing closeness of the corange lines. The range of tide generally increases moving from the open ocean onto the shelf and into the shallow water bays or estuaries. The GT increases from 1.0m (3.0ft) from the Western Bering Sea to more than 6.0m (20.0ft) in the upper Bristol Bay and to 3.6m in Kuskokwim Bay. The GT decreases further up Kuskowim River due to the shallow bathymetry and river effects (Wolcott et al, 2011). When tides propagate northeastward through the Bering Strait into the Chukchi Sea, tidal range (GT) decreases from 1.0m (3.0ft) to 0.3m (1.0ft). The GT is about 0.6m (2.0ft) near St. Lawrence Island and the entrance of Norton Sound. GT increases to 1.0 m (3.0ft) in eastern Norton Sound.

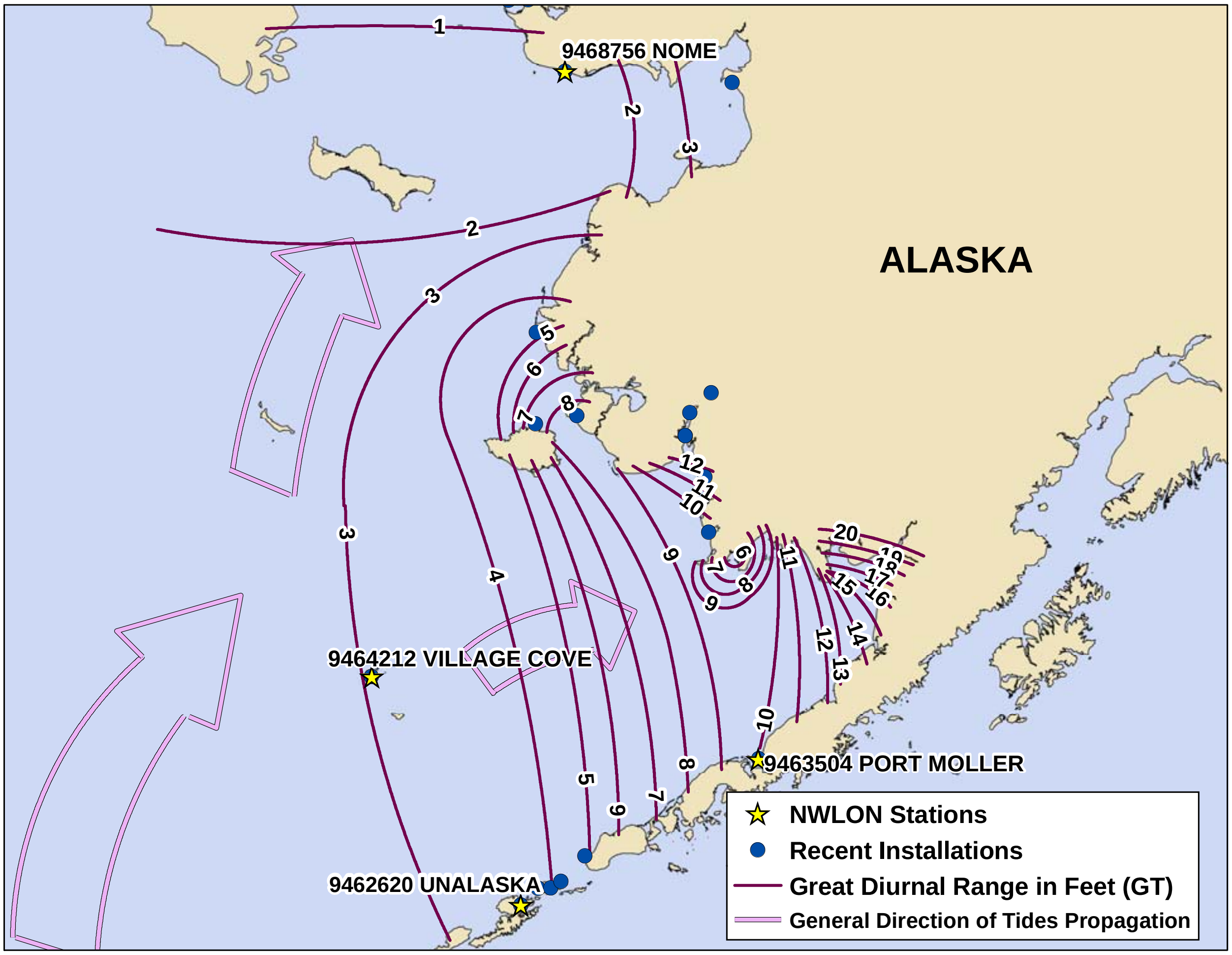


Figure 6. Corange lines along the Eastern Bering Sea Shelf.

Meteorological influences can have a significant effect on the rise and fall of the tide, especially in shallow water areas and areas of low range of tide. The GT in the Bering Strait, Chukchi Sea and Beaufort Sea Shelves is extremely low (less than 0.06m) and coupled with the relatively shallow water, the tide is often masked by the wind stress and barometric pressure changes from the weekly weather patterns.

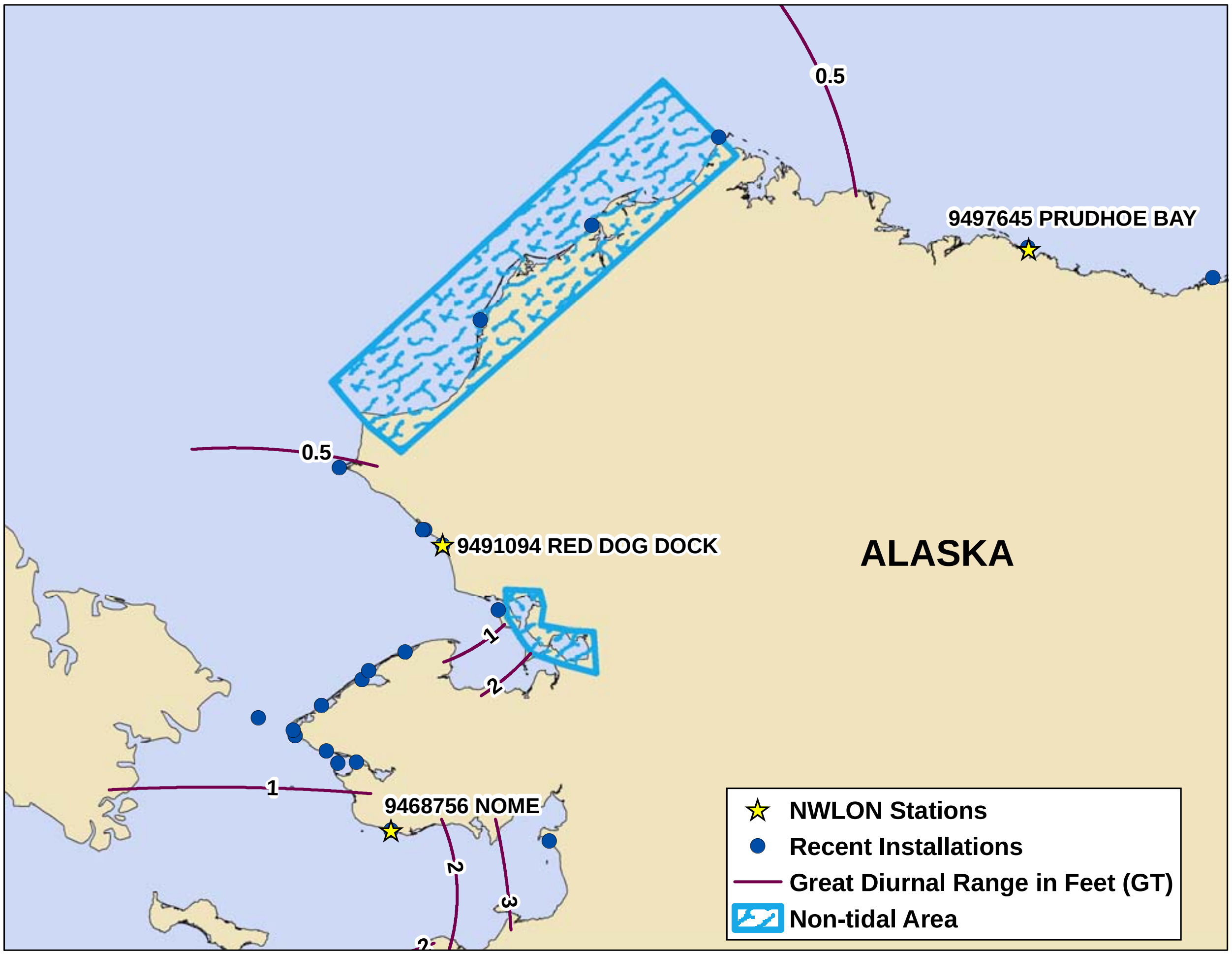


Figure 7. Corange lines along the Chukchi Sea and Beaufort Sea Shelves

Discussion

1. Tide Characteristics amphidromic points, tide propagation

The complicated distribution of tide types is due to the interaction of semidiurnal and diurnal constituents with the unique bathymetry and topography along the Western and Northern Coasts of Alaska topography. The tides enter the Bering Sea as progressive waves from the Northern Pacific Ocean, mainly through the central and western passages of the Aleutian-Commander Islands. The Arctic Ocean is a secondary source of tides from the north. Tides in the Bering Sea are dominated by four tidal constituents M2, N2, K1, and O1. Tides in the Chukchi Sea and Beaufort Sea are dominated by M2, S2, K1 and O1. The difference in frequency between diurnal and semidiurnal tidal waves results in the different dynamics of the tide propagation. Gravity, Coriolis force, and bathymetry play the major role in tidal hydrodynamics. Semidiurnal constituents M2 and N2, comparing with diurnal constituents K1 and O1, tend to have a stronger interaction with the bathymetry due to the shorter wavelength. Observations and numerical models indicate that semidiurnal amphidromic systems are formed in northern Bristol Bay, in Norton Sound and Off Chukchi Sea (Pearson et al., 1981; Kowalik, 1999). The amplitude of semidiurnal constituents diminishes and the amplitude of diurnal constituents increases or remains constant near the semidiurnal amphidromic points.   This results in semi-amphidromic systems for the total tide.

Distribution of cotidal HWI lines and corange GT lines shows the locations having the same cotidal hours and ranges. However, the same cotidal hours and ranges can have totally different tide characteristics. The diurnal inequality and tide type can be different. For example, HWI and GT at Port Moller, AK (9463502) are similar to HWI and GT at Platinum; however, tide curves are completely different from each other due to the different amplitude and phase relationships of the semidiurnal and diurnal harmonic constants.

2. Data limitation

Severe environmental conditions and remoteness have limited the collection of the required location and length of observations required to provide datum control and harmonic analyses to describe the tide sufficiently. There are 19 NWLON gaps along the Western and Northern Alaska Coasts (Figure 8 & 9). NWLON geospatial gaps means that there is a lack of control for determination of tidal datums in that area. Nineteen (19) years is the time period necessary to incorporate all of the major astronomical tide producing cycles (e.g. the 18.6 year nodal cycle (Parker 2007). All tidal datums are referenced to specific 19-year National Tidal Datum Epochs (NTDE) and the present NTDE is 1983-2001. NTDE datums for short-term stations are computed and adjusted to the NTDE using simultaneous comparison with an appropriate nearby control station (NOAA, 2003). First Reduction is used to calculate tidal datums for short-term stations where NWLON stations with the same tidal characteristics are not available. Because these time periods are typically much less than 19-years, the datum error at those stations is significantly greater than those with a full NTDE determination. Prudhoe Bay Red Dog and Nome now have datums determined form several years of data but are still short of 19-years.

There is also a lack of observations at the geospatial density needed to fully understand the tidal characteristics. Observations are especially needed at Cape Newenham, the southern side of Nunivak Island, Norton Sound, St. Lawrence Island, Kotzebue Sound, the Northern Coast of Chukchi Sea and Prudhoe Bay area. The observations at Cape Newenham and the southern side of Nunivak Island are needed to further understand the semidiurnal amphidromic point in Bristol Bay. The observations in Norton Sound are needed to better understand tides propagation and the change of tide type. No recent observations are available at St. Lawrence Island since 1950s. Two stations will be installed in FY11 for the NOAA VDatum Program, which will reduce the gap. The observations at Kotzebue Sound are need to better understand the rapid phase changes and the amplitude diminishment of semidiurnal constants when tides propagating into the Sound. The observations on the Northern side of Chukchi Sea are needed to make sure it is non-tidal along the outer coast. Tides along the Northern Coast of AK (Prudhoe Bay area) are critical for the hydrodynamic models in the Arctic Ocean and understanding the global climate. A two-year deployment of a bottom mounted tide gauge at Barrow Alaska as increased our knowledge of tide along the North Slope west of Prudhoe Bay. The bottom mounted tide gauge may be a good alternative to collect water level data under severe environmental conditions along the Western and Northern Coasts of Alaska.

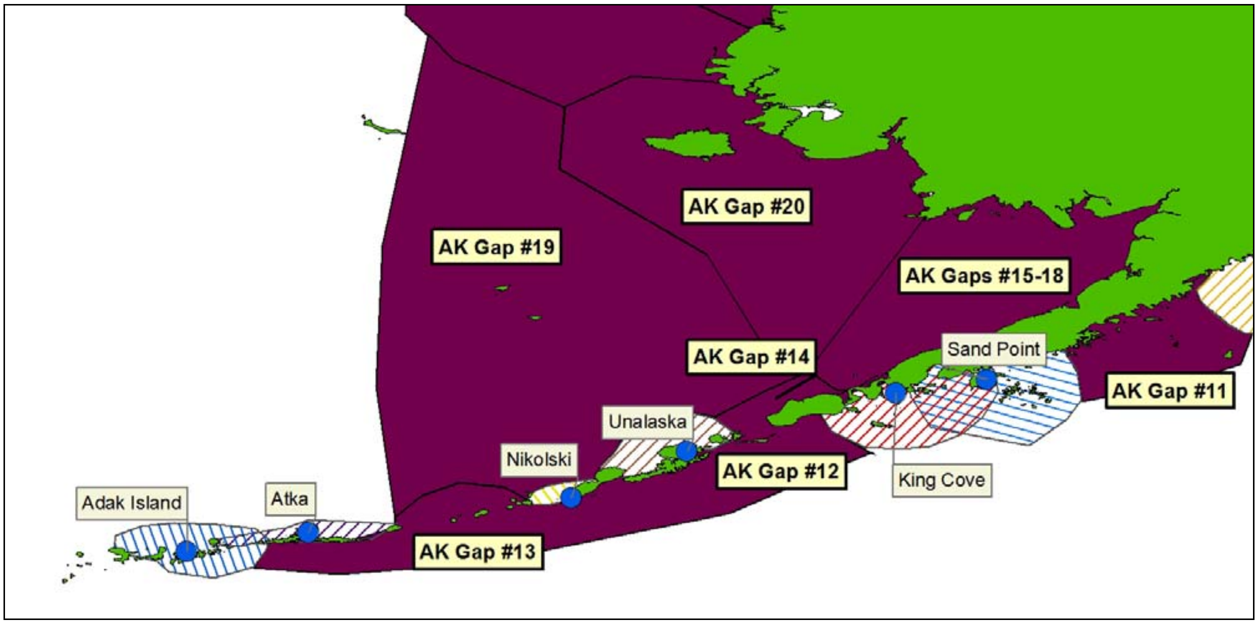


Figure 8. NWLON gaps analysis for the eastern Aleutian Islands, Bristol Bay and Alaskan Peninsula (Gill and Fisher, 2008)

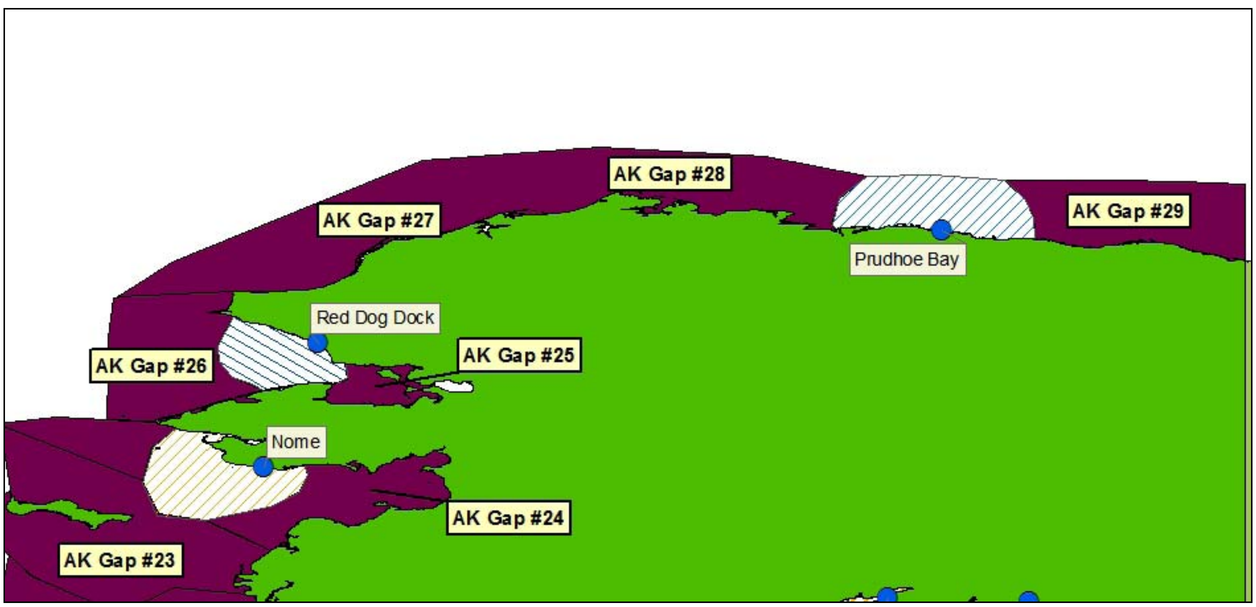


Figure 9. NWLON gaps analysis for the Chukchi Sea and North Slope, Alaska (Gill and Fisher, 2008)

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