Position of Aleutian Low drives dramatic inter-annual variability in atmospheric transport of glacial iron to the Gulf of Alaska

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Key Points:

Large scale inter-annual variability in the aeolian transport of glacial iron to offshore regions of the Gulf of Alaska are detected

Aleutian low position drives magnitude of glacial Fe dust transport to northern Gulf of Alaska in fall

Rapid changes in weather can produce dust storms and significant offshore Fe deposition even during very wet seasons

Index Terms and Key Words: glaciers, iron limitation, aerosol iron, regional climate variability

Abstract

Our understanding of glacial flour dust storm delivery of iron to the Gulf of Alaska (GoA) is limited. Here we interpret concurrent time-series satellite, meteorological, and aerosol geochemical data from the GoA to examine how inter-annual variability in regional weather patterns impacts offshore aerosol glacial Fe deposition. In 2011, when a northerly Aleutian Low (AL) was persistent during fall, dust emission was suppressed and highly intermittent due to prevalent wet conditions, low winds and a deep early season snowpack. Conversely, in 2012, frequent and prolonged fall dust storms and high offshore glacial Fe transport were driven by dry conditions and strong offshore winds generated by persistent strong high pressure over the Alaskan interior and Bering Sea and a southerly AL. Twenty five-fold inter-annual variability in regional offshore glacial aerosol Fe deposition indicates that glacial dust's impact on GoA nutrient budgets is highly dynamic and particularly sensitive to regional climate forcing.

Introduction:

Iron is an essential micronutrient that limits phytoplankton growth in much of the offshore subarctic north Pacific. In oceans adjacent to glacierized watersheds, particulates derived from glacial weathering (glacial flour) are considered a relatively soluble source of iron [*Schroth et al.*, 2009]. Indeed, transport of glacial iron offshore has been suggested to impact the spatial and temporal distribution of phytoplankton biomass [*Ana M. Aguilar-Islas et al.*, 2016; *Lippiatt et al.*, 2011; *Strom et al.*, 2016]. Recent investigations in the Gulf of Alaska (GoA) confirm that glacial Fe may be transported offshore via a number of mechanisms including: transport of nearshore, glacial flour rich waters offshore via eddies [*Brown et al.*, 2012; *Lippiatt et al.*, 2011], continental shelf sediment resuspension [*Lam et al.*, 2006; *Lippiatt et al.*, 2010], and via dust storms sourced in exposed riverbed sediments of the heavily glacierized GoA watershed and coastline [*Crusius et al.*, 2011]. Whilst many aspects of the former two mechanisms of offshore transport of glacial Fe have been directly measured over both time and space via water sampling programs, dust storm deposition of glacial Fe offshore has only been inferred based on remotely sensed MODIS satellite imagery. Direct measurements of offshore dust are required to validate satellite observation and, more importantly, to better constrain the potential role of these events in the offshore Fe cycle in relation to changing environmental conditions spanning seasonal, inter annual, decadal, and glacial-interglacial timescales [*Ana M. Aguilar-Islas et al.*, 2016; *Hamme et al.*, 2010; *Martin*, 1990; *Martin et al.*, 1991; *Melancon et al.*, 2014; *Muhs et al.*, 2016; *Siswanto et al.*, 2016].

Along the GoA's coastline, dust storms sourced in glacierized river valleys and deltas occur when a particular suite of hydro-meteorological conditions occur in concert, including: the autumn recession of peak summer discharge in glacial rivers; dry weather; minimal low elevation snowpack; and a strong north to south atmospheric pressure gradient near the GoA coast driven by high pressure positioned over the Bering Sea and interior of Alaska and low pressure to the south off the British Columbia coast [*Crusius et al.*, 2011]. These hydro-meteorological conditions expose freshly weathered glacial flour, recently deposited in the flood plains of glacierized river valleys, to dry katabatic-enhanced offshore winds, producing the dramatic low-elevation dust storms that have been frequently captured by the MODIS satellites from late September through December [*Crusius et al.*, 2011; *Schroth et al.*, 2009]. Furthermore, our examination of historical MODIS data suggests that the frequency, severity and spatial distribution of these events varies dramatically in both time and space. Yet it is not possible to quantify accurately the inter-annual variability in dust activity and related offshore aeolian loading of glacial Fe using the MODIS image record, as cloud cover in the region may prevent viewing dust events, and at best, the variability of Fe transport can only be inferred. Here, we analyze a unique continuous time series of offshore transport of glacially derived aerosol Fe near the continental shelf break at the northern end of the GoA adjacent to the Fe-limited waters [*Lippiatt et al.*, 2011]. Fe aerosol time series are coupled with concurrent analysis of dust-source area meteorology and regional climatology to quantify variability in meteorological conditions in the source area and discus impacts on the loading of reactive glacial aerosol Fe offshore over time.

Northern Gulf of Alaska Aerosol Observatory: In August of 2011, we deployed an automated sequential aerosol sampler on Middleton Island (Figure 1). Time-integrated aerosol samples were collected continuously through the spring of 2013. Middleton Island is an ideal site to sample glacially derived aerosols because: 1) It often lies in the trajectory of glacial flour dust plumes emanating from their most consistent source detected by MODIS, the Copper River Valley (e.g. Figure 1); 2) It sits approximately 100 km offshore of the southern Alaska coastline, near the continental shelf break (Figure 1), beyond which Fe limitation is more prevalent [*Boyd et al.*, 2007] and aerosol deposition could be a particularly important source of Fe; 3) there is minimal risk of potential contamination from local sources, as the island is covered by peatlands, 4) USGS sea bird research and Federal Aviation Administration facilities provide useful infrastructure in this remote offshore site. In September 2010, a meteorological station was also deployed in the Copper River Valley (CRV) to monitor the ambient meteorological conditions in the major dust source area for plumes that have been visually detected over Middleton Island, the Copper River floodplain and delta (Figure 1). Concomitant changes in temperature, atmospheric pressure, wind speed, and relative humidity capture the timing and duration of a dust event within the CRV. Additional precipitation data, event monitoring via MODIS, regional climatological reanalysis and geochemical analytical methods are discussed in the Methods section of the Supplemental Information.

Results and Discussion:

Dust Season Fall 2011: The fall of 2011 was characterized by extremely wet conditions and early development of a deep snowpack (Figure 2C). Snow depths at the 1405 ft. Mt Eyak SNOTEL site remained above 30 inches after the first week of November and 50 inches of water equivalent precipitation fell on that site from 10/1 through 12/31, the period that is typically peak dust season (Figure 2C). Regionally, there was a strong and well-defined sea surface and 500mb low pressure anomaly positioned across the region for most of the fall dust season (Figure 2A), indicating a more northern Aleutian Low. This produced ambient conditions in the glacierized valleys of the Chugach and Wrangell-St Elias Ranges (the dust source area), that suppressed glacial flour dust storms, including frequent precipitation, a deep early snowpack and a steady stream of moist low pressure systems traversing the Aleutian Islands and northern GoA (Figure 2A,C).

Yet despite these generally unfavorable seasonal conditions for dust generation and offshore transport, three dust events were detected with MODIS. All were relatively minor (visually) in spatial coverage and severity relative to events detected in previous years, (e.g. Figure 1). The satellite-detected events occurred on October 10th, November 2nd through the 3rd and November 11th of 2011, well within the typical time frame for dust storm generation in this region [*Crusius et al.*, 2011; *Schroth et al.*, 2009]. During these events, there were dramatic systematic changes in the autumn meteorological conditions at our monitoring site (Figure 3A). Indicative of the arrival of dry air associated with the high pressure inland, relative humidity plummeted from 70-80% to well below 50% for less than a day (Figure 3A). Together, these data demonstrate that meteorological conditions rapidly shifted intermittently during autumn 2011 to those conducive to dust generation for brief time periods, and that even during a fall dominated by extremely wet and snowy conditions, glacial dust events can occur when the requisite meteorological conditions are present for as little as a day (e.g. only 22 hrs. below 70% RH during the 11/11 event, Figure 3A). Some of this may be due to the relatively small homogeneous grainsize of the glacial flour and the structure of the glacial hydrograph, which, upon recession of the glacial melt-derived component of the hydrograph in early fall (see Figure 2 from Crusius et al. 2011), produces expansive, extremely well-drained floodplains [*Brabets*, 1997]. These deposits can drain quickly (in less than a day) and transition to near surface soil moisture conditions conducive to generating glacial flour dust storms upon the onset of dry conditions and strong offshore winds, even when antecedent seasonal conditions have been very wet (Figure 2C).

Dust Season Fall 2012: Seasonal climatological conditions that dominated the dust season during the fall of 2012 were very different from the preceding fall. A strong and resilient pattern of high pressure was stationed over the Bering Sea and Alaskan mainland from October through December, with low pressure mostly positioned well to the south of its position in 2011, and near the British Columbia coast (Figure 2 A,B). The persistent northern high pressure and more southerly Aleutian Low suppressed precipitation and snowpack development in the region relative to the previous fall, which can be seen by the dramatic difference in the cumulative precipitation and snowpack depth between 2011 and 2012 during the peak dust seasons, (mid-October and early November respectively (Figure S1)). Furthermore, land-ocean pressure gradients were much stronger in 2012 relative to 2011 (Figure 2A,B), suggesting the fall period was dominated by strong dry offshore winds. Indeed, our meteorological monitoring station confirms the impact of these very different regional meteorological conditions of fall 2012 on the local drivers of dust generation, wind gust speed, orientation and relative humidity (Figure 3B,D). The persistence of a strong North to South, high to low pressure gradient (Figure 2B) produced strong (near or above 10 m/s) and dry (<60% relative humidity) northerly (mostly 0-45 degree) winds necessary to facilitate offshore transport of dust for extended periods of time (Figure 3B,D). Maximum wind gusts during 2012 were substantially stronger and mostly oriented from the crucial northerly 0-45 degree position for extended periods of time (Figures 3B,D). Thus, the persistent and elevated pressure gradients of fall 2012 produced conditions in the CRV that were ideal for almost continuous dust generation, in stark contrast to those measured during the same period in 2011.

Indeed, glacial dust events were consistently detected in the MODIS imagery dataset, sometimes directly over Middleton Island (Figure S3). We observed 29 events emanating from various GoA glacierized catchments between 10/1 and 1/1 with MODIS imagery, including a 9-day event from 10/20 through 10/28 during a period of consistent humidity values below 60% and northerly wind gusts close to or greater than 10 m/s (Figure 3B,D). Two brief events were detected on 11/1 and 11/7, which coincided with northerly wind gusts approaching 10 m/s and relative humidity values below 60%. Between 11/19/12 and 12/4/12, another prolonged event was detected via satellite almost daily, making it the longest continuous event that we have detected in the MODIS dataset. Again, this was a period of consistent northerly wind gusts around or above 10 m/s, with relative humidity well below 60% (Figure 3B). During both prolonged events, surface and 500 mb pressure distributions and gradients were broadly similar in structure with high pressure centered in the Bering Sea and Alaskan interior and low pressure to the south and east of the study site (Figure S1) A snowfall event that occurred on 12/15 raised the SNOWTEL-inferred snow depth above 40 inches at Mt Eyak, and snow was visibly covering the entire valley continuously from this point forward (visible in MODIS images). Persistent ubiquitous snowpack prevented subsequent severe dust storms, as dust storms were not detected for the remainder of the year. Yet two events occurred on 12/17 and 12/19 where blowing snow, perhaps bearing mineral Fe, was observed emanating from the CRV.

Fe Transport and Deposition: It was unclear whether the brief dust events of 2011 would be detected in our aerosol measurements, as the events appeared on MODIS imagery to be minor, particularly compared to the 2006 event for which we had estimated Fe loading to the GoA [*Crusius et al.*, 2011]. It was also visually nebulous as to whether dust transport pathways directly impacted our observation station (e.g. Figure 1). However, upon examination of the aerosol time series of the bulk concentration of iron and aluminum on the filters collected during observed dust event intervals, it is evident that significant Fe deposition was occurring at our site, even when it was not visually apparent that the plume was impacting Middleton Island (nor was dust visible on filters) (Figure 4). During these intervals, Fe and Al bulk concentrations were 20 to 100 times higher than ambient background concentrations of Middleton Island air during conditions preceding the dust events (Figure 4). This confirms that our offshore Fe observatory is quite sensitive for capturing these events, and assuming a depositional velocity of 1 cm/sec [*Winkler and Rosner*, 2000], we estimate 4.02 mg/m^2 of aerosol-derived glacial iron was deposited around the Middleton Island region of the GoA over the course of the 2011 fall during these relatively minor and short-lived events.

Upon retrieval of samples spanning the fall of 2012, dust was clearly visually observable on filter surfaces (Figure S4), confirming that extensive dust deposition was occurring in the northern region of the GoA, and further suggesting that significantly more atmospheric glacial Fe was being deposited offshore in 2012 relative to 2011. Indeed, ten of the filters collected from 10/12 through 12/23 bore more than twice the amount of Fe measured during the strongest event of 2011 (400 ng/m^3), and four filters had more than ten times that threshold (Figure 4). Furthermore, on every filter collected from 10/12/12 through 12/23/12, Fe concentrations were comparable to or higher than events of 2011 (>80 ng/m^3) and elevated relative to ambient background concentrations (<10 ng/m^3). This demonstrates that for a period of over two months, there was not a single 4 day period when the air at Middleton Island was not enriched in aerosol glacial Fe derived from the Alaskan coast; a remarkable observation considering that this coastline is part of the largest contiguous temperate rainforest in the northern hemisphere, and that this time period coincides with the traditional ‘wet season’ in coastal Alaska. Furthermore, our estimate of 102 mg/m^2 of glacial Fe deposition in the Middleton Island region of the GoA indicates that over our relatively short ~2.5-yr. monitoring period, there was 25-fold variability in the deposition of aeolian glacial iron to offshore waters around Middleton Island during peak dust season, controlled by differences in seasonal weather patterns driven byvariability in the position of the Aleutian Low. While our dataset cannot detect a direct biological response to the marine ecosystem, considering the well-documented Fe limitation of much of the offshore GoA [*Boyd et al.*, 2007], relatively high solubility of Fe in glacial flour [*Schroth et al.*, 2009], and the observed response of offshore plankton populations to atmospheric Fe input from volcanic ash [*Hamme et al.*, 2010], it is likely that such variability has an impact on marine ecology and offshore Fe cycling in certain regions of the GoA. Furthermore, to predict how glacial flour iron dust deposition may vary under climate change scenarios, an understanding of the Aleutian Low dynamics is clearly necessary, as the magnitude, and the spatial distribution of the glacial aerosol Fe flux in this region over time will be highly dependent on the positioning, severity and persistence of this regional meteorological feature.

Fe solubility leaches of glacial dust-bearing filters following the protocols of *Schroth et al.* 2009 confirm that Fe fractional solubility is characteristic of CRV glacial flour (Figure S2), as the solubility for each of the 3 different events was similar to that observed for glacial flour parent material in our earlier work [*Crusius et al.*, 2011; *Schroth et al.*, 2009]. Furthermore, the remarkable similarity in solubility in all sequential leaches suggests that the fractional solubility of CRV glacial flour dust is quite consistent across events of variable magnitude and duration, and characteristic of a dust dominated by mixed valence Fe-silicate species [*Schroth et al.*, 2009]. Similar fractional solubility between previously published estimates of glacial flour parent material and these offshore glacial aerosols also suggest that there is minimal atmospheric processing that alters the solubility of dust loads between the CRV source and this offshore location. This is likely due to the close proximity to the dust source and therefore minimal time available for atmospheric processing, [*Hand et al.*, 2004], and the relatively pristine low elevation air mass that is transporting these dusts, in contrast to more polluted air masses observed elsewhere [*Mahowald et al.*, 2009]. It is possible, however, that the solubility of glacial dusts could be altered with either more transport time or when sourced from glacial river floodplains draining catchments bearing bedrock with Fe phases of a different solubility [*Schroth et al.*, 2009]. Yet it is also well-established that three successive Mili-Q™ leaches significantly underestimates total solubility of Fe in glacial flour from the CRV and that the total fractional solubility of Fe in these glacial flour dusts is much higher [*Schroth et al.*, 2009], particularly when these dusts are exposed to organic ligands in the marine environment [*A. M. Aguilar-Islas et al.*, 2010]. If we assume a total iron fractional solubility 10% [*Crusius et al.*, 2017; *Schroth et al.*, 2009], we estimate that 0.4. mg/m^2 and 10.2 mg/m^2 of soluble Fe was deposited across this region of the GoA during dust seasons of 2011 and 2012 respectively. This confirms that even relatively small glacial flour dust storms in the GoA are a significant source of relatively soluble Fe to offshore Fe-limited waters, with the potential to play an important role in offshore phytoplankton ecosystem structure and influence primary productivity in Fe-limited waters.

Spring 2013: While available data and modeling from the coastal GoA region suggests that little dissolved or particulate Fe is transported much beyond the shelf break [*Ana M. Aguilar-Islas et al.*, 2016; *Crusius et al.*, 2017], and much of the dissolved Fe supplied to surface waters from autumn dust events could persist until spring phytoplankton blooms because the residence time of dissolved Fe in the ocean is ~1 yr. [*Hayes et al.*, 2015; *Moore and Braucher*, 2008], a biological impact of glacial flour dust remains unverified. Some uncertainty stems from the fact that events typically occur in fall, when phytoplankton productivity is decreasing with light availability. However, while examining the MODIS images during our time series, ten minor events were detected that occurred in winter and early spring 2013 that visually appeared to be blowing either snow, mineral dust, or both offshore (e.g. Figure S5 A,B,C), well before river ice break-up, the onset of significant snowmelt or a significant increase in river levels. The strong offshore winds and frequent periods of relatively low humidity during March and April of 2013 confirm that conditions in the source area were conducive to snow blowing offshore (SI Figure 4). While these events clearly occur at a lower frequency and are less dramatic (more difficult to visually detect from MODIS) than those in the fall, they are occurring as light and stratification are becoming more conducive to phytoplankton blooms offshore [*Henson*, 2007; *Strom et al.*, 2016], and therefore have potential to impact offshore ecosystem dynamics. Since the CRV tends to be blanketed in a particularly deep snowpack during the spring, enhanced by aeolian redistribution of snow sourced elsewhere in the catchment, it was unclear whether mineral dust is being transported or if it is just Fe-poor snow during these spring events. However, the iron and aluminum aerosol time series collected during the spring of 2013 confirms that there was significant enrichment of both Fe and Al in our filters during some spring sampling intervals, and offshore aerosol Fe deposition was comparable in scale (4.28 mg/m^2) to the events of fall, 2011(Figure 4). This indicates that these springtime events characterized by blowing snow also bear a fraction of potentially bioavailable iron (Figure 4) and atmospheric deposition of glacial Fe offshore can occur for a prolonged period of time during the spring, which contributes to Fe supply in some regions of the offshore GoA. It should be noted that the spring is also a period when the impact of Asian dust on our record should be more pronounced [*Holzer et al.*, 2005], as it has been detected in high elevation snow/ice records of the GoA's coastal mountains [*E Osterberg et al.*, 2008; *Zdanowicz et al.*, 2006]. We did not detect a systematic shift in Al:Fe ratios between fall and spring that might be anticipated if aerosol provenance had changed (Supplementary Table S1). Further examination of the relative contribution of Asian and Alaskan dust sources to GoA Fe budgets across time and space and using other more powerful provenance proxies (eg stable lead isotopes) is certainly warranted, but beyond the scope of this study.

Conclusions and Implications: Our comprehensive analysis of meteorological and aerosol time series conclusively demonstrates that there is dramatic inter-annual variability in glacial dust storm severity and occurrence, driven by the duration and persistence of regional fall pressure gradients, with profound impact on the quantity and distribution of dust-derived glacial iron deposited offshore in the GoA. When the Aleutian Low feature is persistent and northerly during the fall, dust transport offshore can be almost completely suppressed, with minimal offshore deposition of glacial Fe from this source. Conversely, when strong high pressure persists for extended periods in the Bering Sea and interior Alaska with a more southern Aleutian Low, almost continuous fall dust activity and related offshore deposition of soluble Fe can occur in one of the wettest regions of the northern hemisphere. Yet even under persistent ambient wet conditions driven by a steady stream of low pressure systems, very brief windows of dry conditions and katabatic-enhanced strong offshore flow, even at daily timescales, can trigger detectable dust events that deliver significant loads of reactive glacial Fe well offshore. The variability of the track and frequency of these low pressure systems, the strength and position of the Aleutian Low, must exert a strong control on the spatial and temporal variability of glacial dust and related iron deposition offshore in the GoA over time, which could be driven by climate drivers operating on multiple timescales (e.g. El Nino Southern Oscillation, Pacific Decadal Oscillation, North Pacific Gyre Oscillation) [*Di Lorenzo et al.*, 2013; *E C Osterberg et al.*, 2014]. This variability could have implications for offshore phytoplankton biomass and species distributions, and profoundly impact offshore Fe cycling. Dusts of the CRV appear to have relatively consistent fractional solubility characteristic of the Fe mineralogy of this catchment, and while this does not appear to vary in time, it would presumably vary in space/provenance due to heterogeneity of catchment lithologies along the variable geology of the coastal GoA catchments. Considering the large spatial extent of the glacierized GoA coast, it is also likely that regional weather patterns that promote dust emissions from the CRV can activate different glacierized floodplains depending on the particular configuration of pressure and associated wind fields. This agrees with the analysis of historical MODIS imagery which indicates that particular floodplains that generate dust across the GoA's catchment can vary by weather event. Interestingly, aerosol Fe deposition is also detected during the spring at Middleton Island, suggesting that springtime events could contribute Fe to offshore blooms as light and thermal conditions offshore become more conducive to bloom development, which warrants additional investigation. As is the case in many such studies, as we attempt to project changes to nutrient and related ecological dynamics in this region in response to a changing Anthropocene climate, it is important to consider the dramatic inter-annual variability observed in this study, and more importantly, the drivers of such variability and how they are projected to change in response to global climate warming.

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Supporting data and additional methodological information are included as text, 1 table and 5 additional Figures in an SI file.

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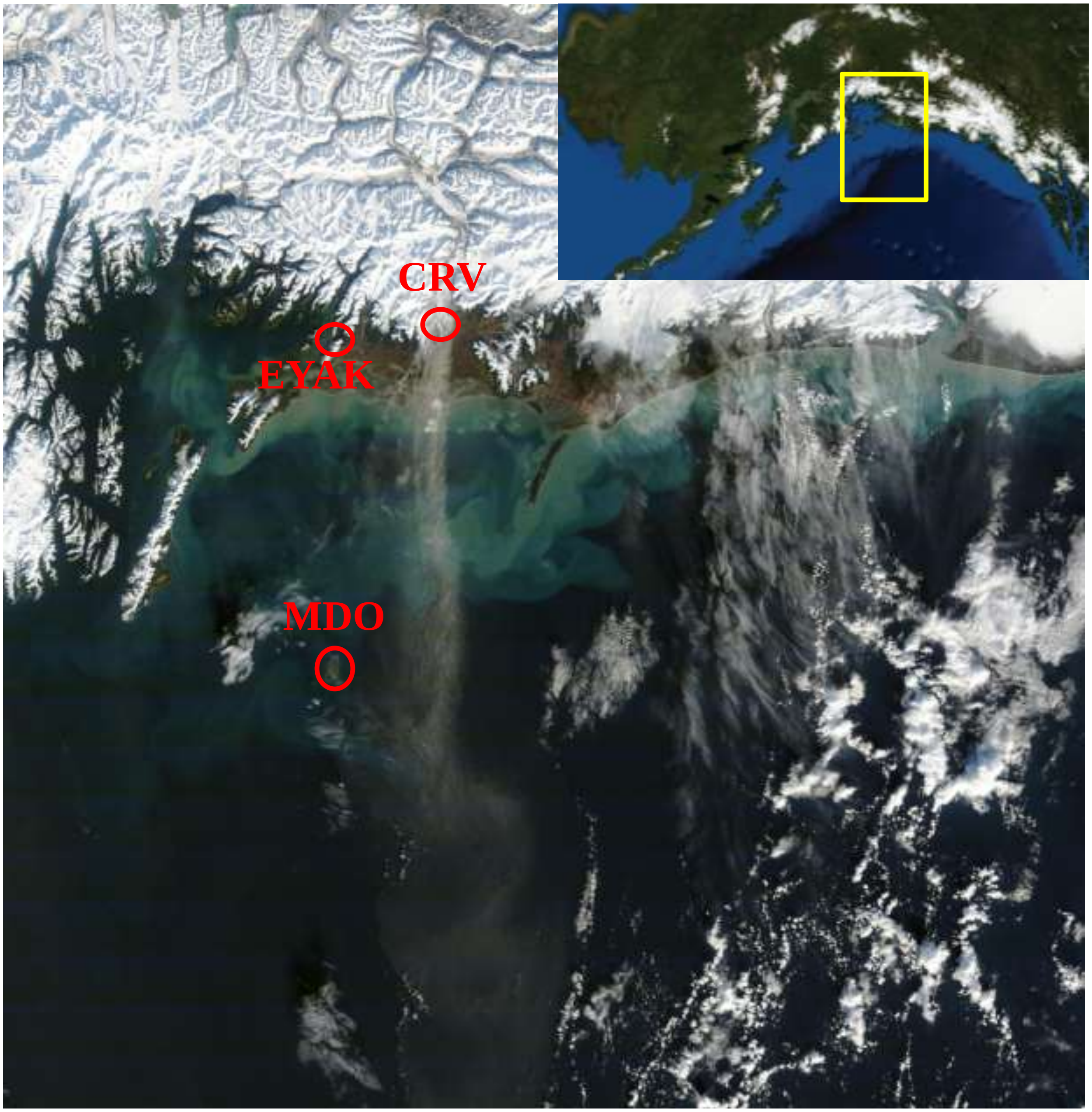
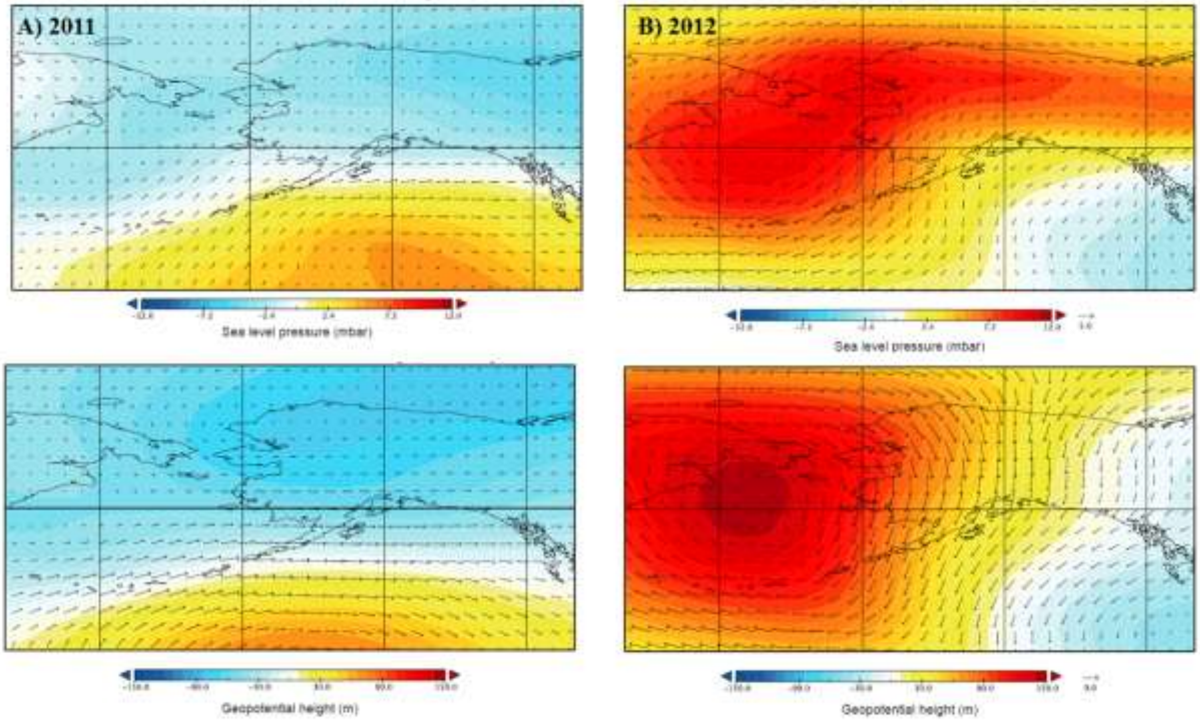
393 

394 **Figure 1:** Location Map of Middleton Island Observatory station (MDO 59º25'17.20"N,
395 146º20'57.44"W) and Copper River Valley (CRV 60º40'29.44"N, 144º45'07.73"W)
396 meteorological station, and Mt Eyak Snowtel site (EYAK 60º33'N, 145º45') superimposed on
397 the largest glacial dust storm event of 2011 detected by MODIS on 11/2-3. The region is outlined
398 on the large scale inset Google Earth image of Alaska which includes regional glaciers and
399 bathymetry where the position of the continental shelf break near our monitoring site is evident.

400


A) 2011
B) 2012
Sea level pressure (mbar)
Sea level pressure (mbar)
Geopotential height (m)
Geopotential height (m)

(C)

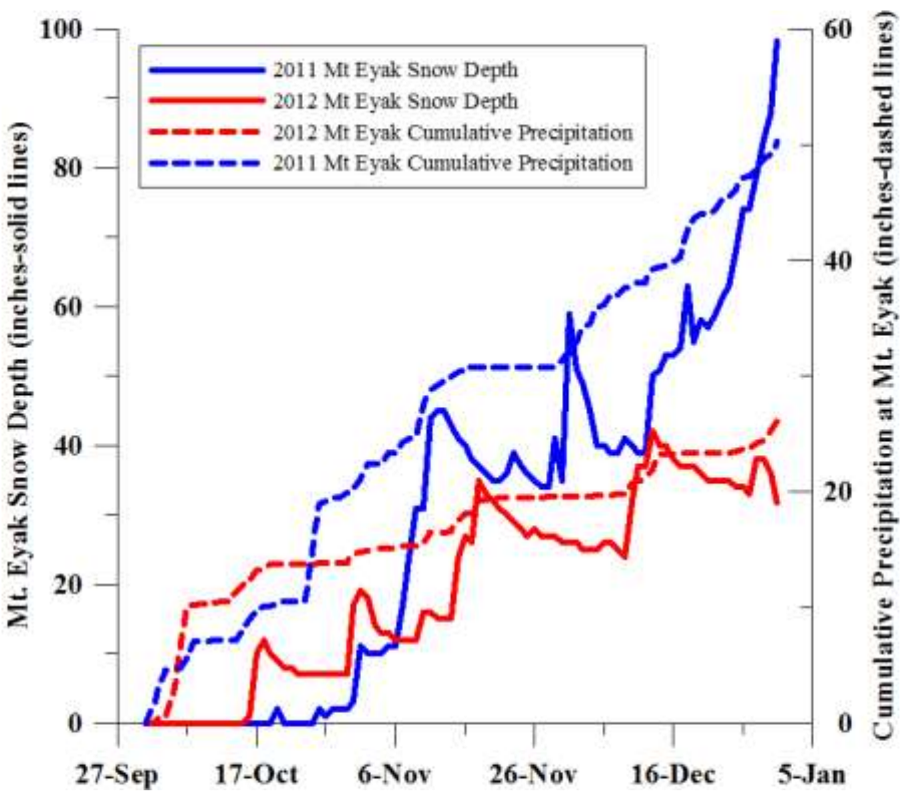

2011 Mt Eyak Snow Depth
2012 Mt Eyak Snow Depth
2012 Mt Eyak Cumulative Precipitation
2011 Mt Eyak Cumulative Precipitation
Mt. Eyak Snow Depth (inches-solid lines)
Cumulative Precipitation at Mt. Eyak (inches-dashed lines)
0
20
40
60
80
100
0
20
40
60
27-Sep
17-Oct
6-Nov
26-Nov
16-Dec
5-Jan

Figure 2: NCEP-NCAP reanalysis [Kalnay et al., 1996] for the GoA region, showing the average of surface wind and sea level pressure (top map) and 500/350 mb pressure and wind (bottom map) daily anomalies for **(A)** 10/01/201111-12/31/2011 and **(B)** 10/01/2012-12/31/2013, which are used to illustrate the variability of climatic drivers of dominant fall meteorology in the GoA region. **(C)** Cumulative water equivalent precipitation since 9/1 for 2011(blue dashed line) and 2012 (red dashed line) for the 9/1-12/31 time period for both years) at the Mount Eyak SNOWTEL site near Cordova, Alaska. Solid lines are measured snow depth at the same sites (2011 blue, 2012 red).

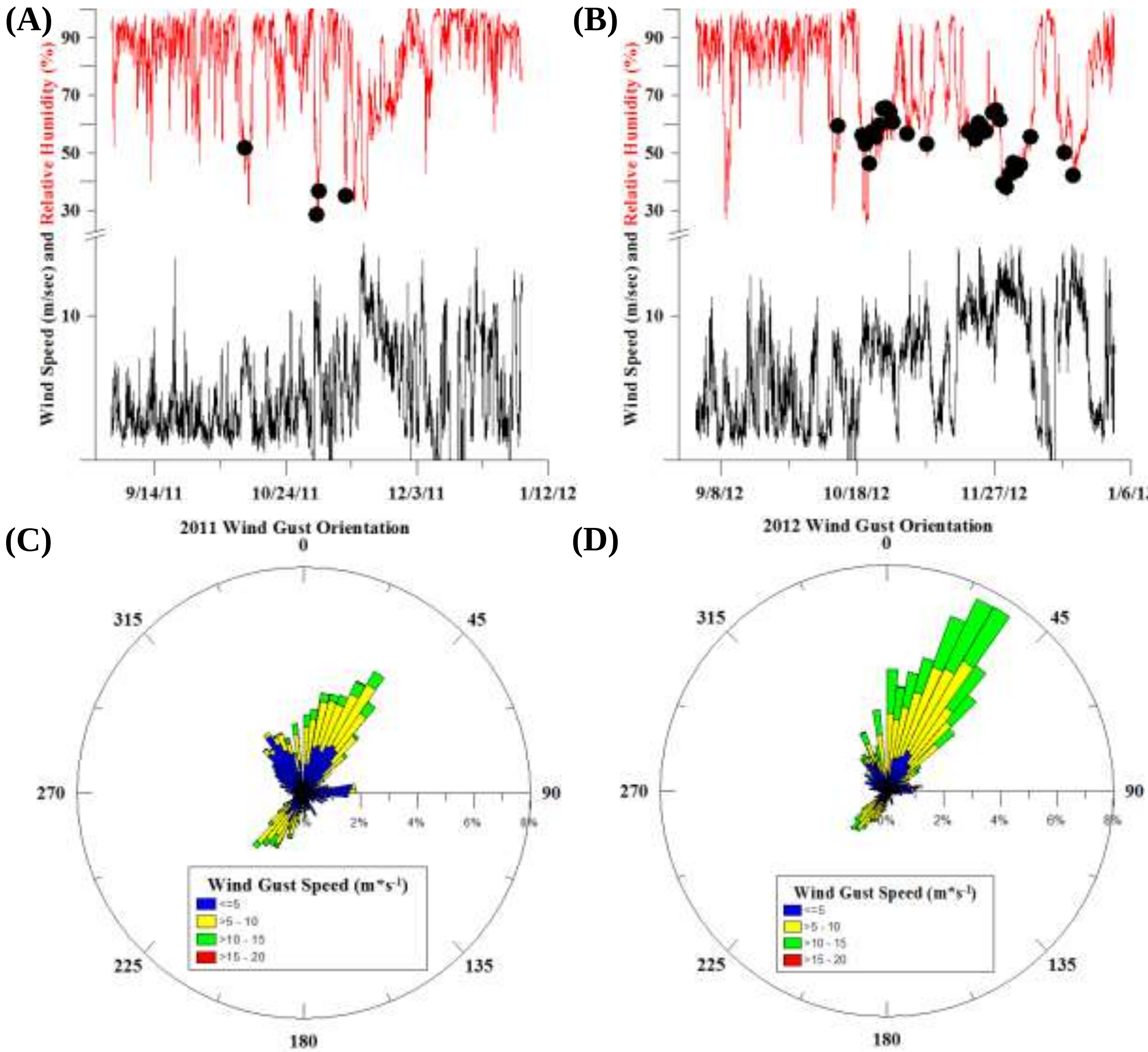


Figure 3: Copper River Valley hourly maximum wind gust speed (black line) and relative humidity (red line) spanning peak dust season (9/1-12/31) for 2011**(A)** and 2012**(B)**. Black dots embedded on the relative humidity time series represent days when dust events emanating from the Copper River Valley were detected with MODIS. Wind gust orientation rose diagrams are illustrated for fall 2011**(C)** and 2012**(D)**.

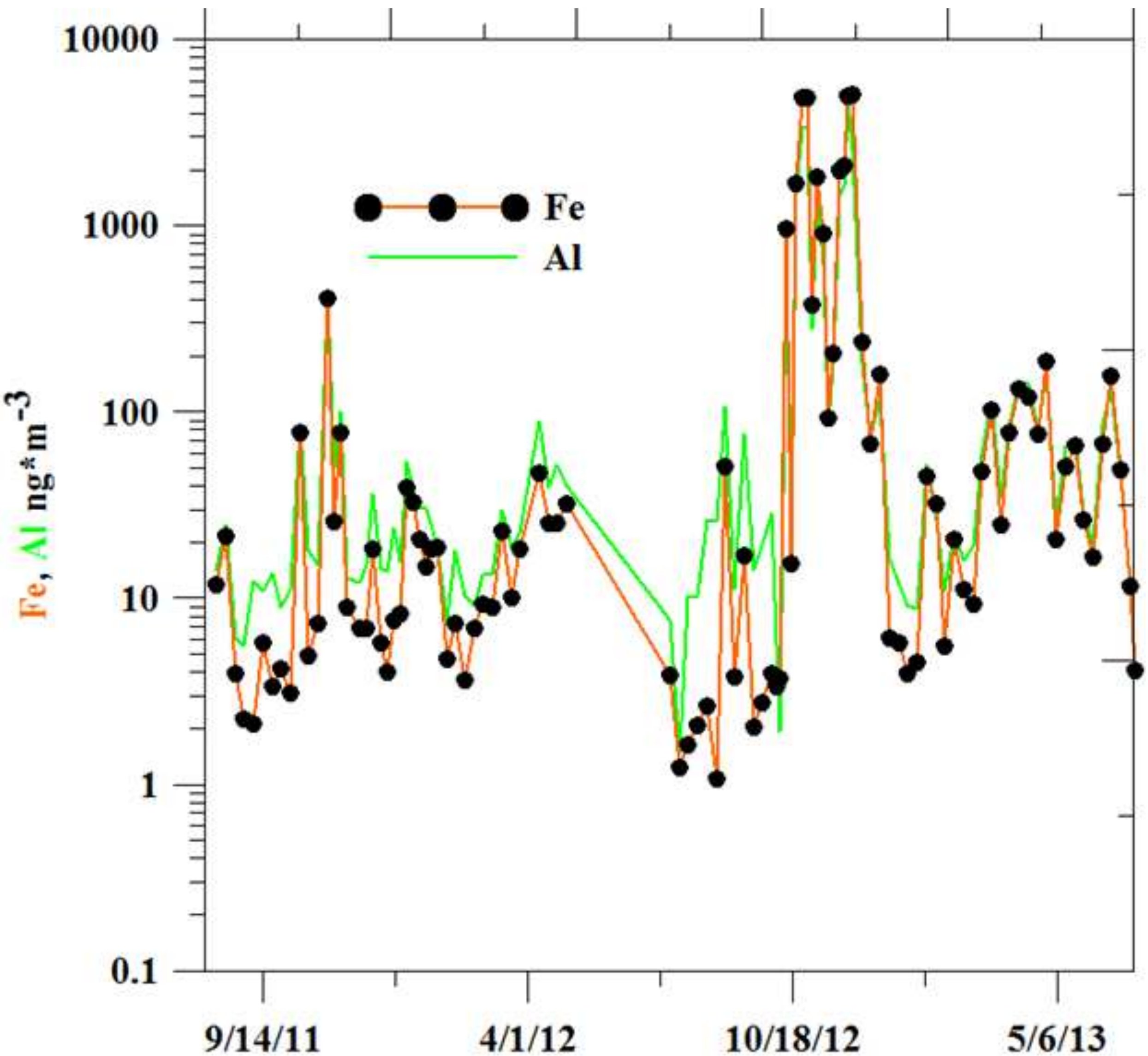


Figure 4: 2011-2013 time series of iron (orange) and aluminum (green) bulk concentration XRF data collected for this study at Middleton Island(note log concentration scale). Black dots embedded on the Fe time series indicate the midpoint of the sampling interval, but the concentration is representative of total Fe or Al collected on the filter over the sampling interval.