Auxiliary material:

Methods

We identified prominent dust plumes using true-color images from the MODIS sensor aboard the Terra and Aqua satellites, which make two to three passes over the Gulf of Alaska each day (http://modis.gsfc.nasa.gov/). We systematically screened every autumn image from 2003-2010 for potential events using the MODIS rapid response archive (http://rapidfire.sci.gsfc.nasa.gov/). We also screened every spring image from 2003, 2006 and 2010. We downloaded the MODIS Level 1B files for events with prominent dust plumes, and then constructed true-color images using the software hdflook (http://www-loa.univ-lille1.fr/Hdflook/hdflook_gb.html). Prominent dust events from 2003, 2005, 2006, 2009 and 2010 are shown in Figures A1-A5.

Hourly wind speed and direction data were obtained from a meteorological station at Middleton Island, near the continental shelf break in the Gulf of Alaska (59.432 °N 146.338 °W; http://cdo.ncdc.noaa.gov/qclcd/QCLCD; Figure A6). This site is positioned near the peak elevation of the island (< 50 m); given it's position in the ocean, winds measured here are far less impacted by topography than are wind measurements from most Alaskan meteorological stations. Similar data were also obtained from the Strawberry Reef USDA/SNOTEL station (60.2167 °N, 144.85 °W; Fig. A7; http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=1088&state=ak). Note that meteorological stations on the Alaskan coast are not closely positioned, especially given the variable winds expected in such mountainous terrain. Many such stations record hourly average wind speeds but not gust speeds. To our knowledge there are no available meteorological data that accurately record the wind gusts that are observed to occur in the Copper River valley and that cause resuspension of dust. We have installed a meteorological station that we expect is beginning to record such information. Average Upper Tsaina River daily snow depth (Fig. 2) was derived for 2004 – 2010 from USDA/NRCS/SNOTEL data (http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=1055&state=ak). Average Copper River discharge (Fig. 2) was derived from the Million Dollar Bridge data from 1989-1994 (http://waterwatch.usgs.gov/).

We calculated a sea level pressure (SLP) and wind vector composite from the NCEP-NCAR reanalysis (Kalnay et al., 1996) for an average "dust event" by averaging SLP and 1000 mbar wind vector anomalies for four representative dust events observed in MODIS imagery (Fig. 3a). The data used for this composite came from November 5, 2005, November 1 and 6, 2006, and October 29, 2009.

We collected dust during August, 2008, from a building located within the western terminus of the Copper River valley, where an exposed portion of the structure allowed dust to accumulate on surfaces. This dust was 1-2 cm thick and was estimated to have accumulated spanning 2-3 years by the building owner (L. Borer, personal communication, 2010). We took advantage of this unconventional collection method because it allowed collecting a sufficient quantity of dust to facilitate a variety of analyses. Quantitative mineralogy was determined by X-ray diffraction (XRD) using the methods and instrumentation outlined in Eberl (2004). The XRD data from the dust sample were fitted and converted to weight percent using the RockJock computer program, which has been shown to be accurate within 1-2 weight % (Eberl 2003). The same dust sample was analyzed by synchrotron-based X-ray absorption spectroscopy on beamline 11-2 at Stanford Synchrotron Radiation Lightsource for quantitative analysis of Fe species distribution and oxidation state in the dust sample using methods identical to those outlined in Schroth et al. (2009). Extended X-ray absorption fine structure (EXAFS) spectra were fit using a using least squares fitting of known standards using the SixPACK interface, which generated an error of less than 5% for each mineral phase (Webb, 2005). A combination of biotite, hornblende, goethite, ferrihydrite, hematite, and magnetite spectra provided the best fit (minimized residual) and generally agreed with XRD data. Fractions fit with biotite and hornblende are generalized as 'mixed valence silicates' in Table 1 that are representative of six-fold coordination of Fe substituted for Al in amphiboles and clays determined by XRD to be in the sample (i.e. chlorite, illite, biotite, hornblende, etc.; O'Day et al. 2004). Ferrihydrite and goethite are grouped together as hydrous ferric oxides owing to similarities in EXAFS spectra and variable crystallinity of these phases in natural environments XAS (O'Day et al., 2004). The iron (II/III) ratio was calculated based on the position of the centroid of the pre-edge feature (i.e. Lam and Bishop, 2008), but the uncertainty is not estimated for this measurement. The mineralogy and Fe solid-phase speciation reported for this single dust sample are similar to those observed in both glacial flour dust source material (Schroth et al., 2009) and in suspended particles collected from glacially-fed tributaries of the Copper River (Schroth et al., unpublished).

Additional discussion on the rate of deposition of glacial flour-derived dust

Wind speed data help us to constrain the rate of dust deposition from a single "snapshot" in time. If we assume the dust travels at an average speed of ~10 m/s, as suggested by data from Middleton Island during these dust events (Fig. 3C; Fig. S6), it would take ~14 hours for dust to travel the full ~500-km length of the visible plume from 6 November, 2006. Thus, in the absence of clouds, a sequence of daily "snapshots" from MODIS might capture most of the dust transported, with each daily snapshot capturing a different mass of dust with the assumption of no carryover from the previous day. Dust activity was intermittent during October-November, 2006 (see Fig. S6; see a time series at http://woodshole.er.usgs.gov/staffpages/jcrusius/research/CopperRiverDustNov2006B.htm).

As mentioned in the main body of the paper, particle concentrations during dust events were inferred primarily from MODIS data. Although the true-color images permitted the direct identification of dust events, the same data interpreted by the MODIS standard aerosol algorithm (Remer et al., 2005) did not yield any estimates of AOT. Upon consulting with members of the MODIS aerosol team, it was concluded that the algorithm was not designed to perform aerosol retrievals as these steep sun angles (during autumn). As a result, the aerosol code was modified to allow for such retrievals. These changes will be included in the next official release of the code (Collection 6). The resulting map of AOT shows dust plumes emanating from several locations along the GoA coast (Fig. S8b).

However, the CALIPSO satellite offers an independent check on the mass of the dust plume. The lidar on this satellite examines a swath only 70 m wide at the earth surface during each overpass, with the result that CALIPSO could examine only the leading edge of the November 6, 2006 dust plume (see Fig S9). Some of the profiles inferred from the lidar contained clouds that were at higher elevation than the dust and which obstructed the observation of dust underneath. Thus the flux of dust in the plume could not be estimated because the profile did not provide a complete measure of mass perpendicular to the direction of the flow. However, CALIPSO sampled dust in a clear sky interval approximately 70 km long where it was possible to derive the aerosol optical thickness (AOT). The estimate of AOT was carried out by grouping 30 consecutive backscattering (532 nm) profiles which approximate the length of a MODIS AOT pixel. These groups of profiles were then averaged and integrated across the entire column of air. To transform from integrated backscattering to total optical depth, an extinction-to-backscattering ratio (S) of 40 1/str was assumed. This is the value used by the CALIPSO science team when dust is identified in the scene under observation (Omar et al., 2010). The columnar mass concentration is derived by multiplying by 2.7 g m^{-2} (Koren et al, 2006) over the area spanned by the 30 profiles. The resulting concentrations derived from CALIPSO spanned values from 30.6 to 37.4 μg cm^{-2} (one outlier was excluded because of proximity to a cloud which led us to suspect it was contaminated). The corresponding mass concentrations for the same region, inferred assuming mass is proportional to the MODIS AOT were very similar, ranging from 27 to 40.5 μg cm^{-2} . By contrast, the dust concentrations estimated using the MODIS aerosol algorithm averaged 10.2 μg cm^{-2}, smaller (by a factor 3-4) than the CALIPSO-derived estimates. It is difficult to generalize the results stemming from this intercomparison of methods spanning such a limited region. However, these results tend to give credence to the higher dust flux estimates from our work that were inferred by assuming columnar dust concentrations are proportional to MODIS AOT (method two in the main body of the paper). It is also worth noting that all other prominent dust plumes were examined from 2006 and 2010.

This November 6, 2006 plume, although imperfect, offers the best overlap between the CALIPSO and MODIS retrievals.

The ideal dust deposition estimate might entail a modeling approach with knowledge of aerosol size distribution, a realistic wet deposition parameterization and realistic winds. Such information is not available in this case. The difficulty in modeling such an event is illustrated by our attempt to use HYSPLIT, an aerosol transport model (Escudero et al., 2006) . The standard wind files used by the model (GDAS wind data base with a 1x1 deg spatial resolution) did not include wind speeds high enough to trigger dust production in the model, and it became clear that the assimilated winds in GDAS do not have the spatial resolution to include the steep topography, as well as the katabatic winds initiated by cooling near the mountain glaciers.

The dust mass provided in the body of the paper relies on interpretation of the AOT (e.g. Fig. 1d) inferred from the MODIS data, and to a lesser extent the backscattering profiles from the CALIPSO satellite. We offer here an entirely independent check on this estimate, based on the likely wind erosion caused by a major dust storm. Given that we know the source area of this dust to be the Copper River floodplain, whose dimensions are fairly well constrained, we can estimate how much erosion of the exposed sediment would be required to yield the mass of dust inferred above. From MODIS images taken at high and low water stages we estimate an area of exposed floodplain sediments of 500 km^2. If we assume a total dust mass generated during the 2-week November, 2006 event was 50,000 tons ($5x10^{10}$ g), erosion of only 0.05 mm of sediment is required (assumes sediment bulk density = 2 g cm^{-3}). Assuming several times more sediment was eroded but rapidly re-deposited close to the source (e.g.

coarse material), erosion of several times more sediment might have been required. While highly uncertain, this is a plausible estimate of the amount of wind erosion caused by this event. In much of the western U.S., for example, wind erosion is greater than 0.1 mm yr^{-1} (Wilkinson et al, 2007).

Additional discussion on the comparison to eddies as an Fe source

Note that our estimate of the maximum annual bioavailable Fe load to GoA surface waters from the Haida eddies (~170 tons/yr) is lower than the numbers presented in Johnson et al (2005) of 5000 tons/yr of total Fe exported from the coast. This is because our estimate considers only the "labile" iron (Johnson's 2005 definition) in the top 100 m plus Johnson's estimate of the vertical flux of "labile" Fe at 200 m. In other words, we assume that most of the total Fe, and most of the Fe present below 100 m is largely removed from the ocean by settling and by scavenging processes, and is not among the pools that are available to phytoplankton in surface water. We believe our estimate of the flux of "labile" Fe to surface water is a better comparison to our estimate of soluble Fe derived from the November, 2006 dust event.

Auxiliary material acknowledgements

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Auxiliary material figure captions

Fig. S1: MODIS true-color image for March 13, 2003. The white contour line is the 100-m depth contour, while the blue contour is the 500-m depth contour.

Fig. S2: MODIS true-color image for November 5, 2005. The white contour line is the 100-m depth contour, while the blue contour is the 500-m depth contour.

Fig. S3: MODIS true-color image for November 6, 2006. The white contour line is the 100-m depth contour, while the blue contour is the 500-m depth contour.

Fig. S4: MODIS true-color image for October 30, 2009. The white contour line is the 100-m depth contour, while the blue contour is the 500-m depth contour.

Fig. S5: MODIS true-color image for November 17, 2010. The white contour line is the 100-m depth contour, while the blue contour is the 500-m depth contour.

Fig. S6: Middleton Island hourly wind speed and wind vector time series for October and November 2006. Wind vector length is proportional to wind speed while the vectors point in the direction from which the wind originates. Colored bars along top indicate periods when dust was observed (yellow), the Copper River delta and proximal GoA was obscured by clouds (red), or when the region was cloud free, but no dust was observed (green) in MODIS imagery over the same time period. Vertical arrows denote the time of the satellite pass where significant dust was spotted in MODIS imagery.

Fig S7: a) Wind rose diagram illustrating relative frequency distribution of all available hourly wind speed and direction data (2006 to 2010) from the meteorological station at Strawberry Reef, located on an island just offshore of the Copper River delta (60.2167 °N, 144.85 °W). Note that winds in this location are almost certainly strongly influenced by local topography; b) Same as a), but spanning November 1-8, 2006 when significant dust was observed. Winds are predominantly from the north during the dust event, consistent with the wind observations from Middleton Island (Fig. 3c), the NCEP analysis (Fig. 3a), and the prevalence of dust at that time from multiple sources along the GoA coastline (Fig. 1b).

Fig. S8: AOT estimate for November 6, 2006; a) using old algorithm (no dust is inferred); b) after the algorithm was modified to account for the steep angle of view (as described in Auxiliary Material text).

Fig S9: The location of the CALIPSO track is presented as a line traversing the leading edge of the November 6, 2006 dust plume as visualized from this columnar dust mass map estimated from the MODIS data (full-plume view in a) and expanded view in b)). CALIPSO profiled this dust plume in two sections along the track separated by clouds (best visualized in b). The north end contained too many small clouds to permit an AOT estimate. Starting from the southern portion of b), the first group of pink pixels yield a mean mass concentration of 33.8 μg cm^{-2} as inferred from CALIPSO data (see auxiliary material text). These values are similar to the value of 33.2 μg cm^{-2} inferred using MODIS, assuming dust mass is directly proportional to AOT. Both of these sets of values are considerably higher than the corresponding values of 10.2 μg cm^{-2} derived from the MODIS aerosol algorithm.

Table S1: Quantitative mineralogy (XRD) and Fe speciation (EXAFS) of Copper River dust sample. See methods discussion. Mineral classes of 'mixed valence silicates' and 'hydrous ferric oxides' are grouped together due to similarity in spectral features associated with minerals that fall into those classes.

Mineral	**Wt. %**	**Speciation of Fe (EXAFS)**	**Wt %**
Quartz	26.3	Mixed Valence Silicates	74
Kspar	2.4	Magnetite	12
Plagioclase	37.0	Hematite	10
Calcite	4.1	Hydrous Ferric Oxides	4
Dolomite	1.8	**sum**	**100**
Amphibole (ferrotschermakite)	5.9		
Pyroxene	1.2		
Magnetite	0.2		
Clay Minerals		**Fe Oxidation State**	
Smectite (ferruginous)	2.9	Fe (II)	57
Biotite	4.3	Fe (III)	43
Chlorite	7.5		
Muscovite	3.7		
Vermiculite	2.7		
sum	**100**		