Integrating satellite observations and modern climate measurements with the recent sedimentary record: An example from Southeast Alaska

Jason A. Addison, Bruce P. Finney, John M. Jaeger, Joseph S. Stoner, Richard D. Norris, and Alexandra Hangsterfer

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[1] Assessments of climate change over time scales that exceed the last 100 years require robust integration of high-quality instrument records with high-resolution paleoclimate proxy data. In this study, we show that the recent biogenic sediments accumulating in two temperate ice-free fjords in Southeast Alaska preserve evidence of North Pacific Ocean climate variability as recorded by both instrument networks and satellite observations. Multicore samples EW0408-32MC and EW0408-43MC were investigated with $^{137}$Cs and excess $^{210}$Pb geochronometry, three-dimensional computed tomography, high-resolution scanning XRF geochemistry, and organic stable isotope analyses. EW0408-32MC (57.162°N, 135.357°W, 146 m depth) is a moderately bioturbated continuous record that spans AD 1930–2004. EW0408-43MC (56.965°N, 135.268°W, 91 m depth) is composed of laminated diatom oozes, a turbidite, and a hypopycnal plume (river flood) deposit. A discontinuous event-based varve chronology indicates 43MC spans AD 1940–1981. Decadal-scale fluctuations in sedimentary Br/Cl ratios accurately reflect changes in marine organic matter accumulation that display the same temporal pattern as that of the Pacific Decadal Oscillation. An estimated Sitka summer productivity parameter calibrated using SeaWiFS satellite observations support these relationships. The correlation of North Pacific climate regime states, primary productivity, and sediment geochemistry indicate the accumulation of biogenic sediment in Southeast Alaska temperate fjords can be used as a sensitive recorder of past productivity variability, and by inference, past climate conditions in the high-latitude Gulf of Alaska.


1. Introduction

[2] High-latitude regions of the Northern Hemisphere are currently experiencing rapid environmental change as a result of combined forcing by natural and anthropogenic processes. In many regions of Alaska, observations include the rapid retreat of formerly advancing glaciers in both alpine and coastal settings [Molnia, 2007], thawing permafrost [Romanovsky et al., 2007], and widespread shifts in terrestrial [De Valpine and Harte, 2001] and marine [Mue- ter et al., 2009] biogeographic distributions. From a historical perspective, many of these changes are unprecedented and their future impacts are largely unknown due to relatively short instrumental records that span only the last 100 years. High-quality paleoclimate data sets are, therefore, essential for reconstructing earlier climate analogues to provide further insight into future conditions, yet the spatial coverage of such records is sparse.

[3] Long-term instrument observations are rare in the Gulf of Alaska sector of the Subarctic North Pacific Ocean, yet conditions here are an important component of Northern Hemisphere climate patterns with atmospheric teleconnections reaching as far east as the U.S. Atlantic Coast [Trenberth and Hurrell, 1994] and as far south as the Sonora Desert in northern Mexico [Latif and Barnett, 1994]. Gulf of Alaska precipitation, sea surface temperatures (SST), and fluvial discharge also show strong correlations...
to the Pacific Inter-Decadal Oscillation (PDO) index [Ebbesmeyer et al., 1991; Mantua et al., 1997; Trenberth, 1990]. There is strong evidence that the PDO strongly regulates the Gulf of Alaska marine ecosystem at multiple trophic levels [Beamish, 1993; Hollowed et al., 2001; King et al., 2000], likely through bottom-up environmental forcing [Gargett, 1997]. This decadal-scale North Pacific climate variability has further been extended to historic and ancient Pacific sockeye salmon abundances [Beamish and Bouillon, 1993; Finney et al., 2000]. Understanding high-frequency climate shifts in the context of high-latitude change is therefore critical to predicting future impacts on Gulf of Alaska resources and requires long paleoclimate data sets to supplement existing instrument networks.

In this paper, the last ~100 years of marine sediment from two coastal temperate (ice-free) fjords in Southeast Alaska are compared to modern climate observations to determine if these fjords are high-fidelity recorders of regional Gulf of Alaska climate dynamics. Fjord basins can preserve exceptional records of marine productivity [Gilbert, 2000], and as primary productivity appears to be forced by environmental conditions in the Gulf of Alaska [Gargett, 1997], temperate fjord sediment records thus offer a rare opportunity to reconstruct past high-latitude climate conditions if they are indeed sensitive to regional climate variability. To test this hypothesis, we examine two multicore-type sediment cores from Deep Inlet (56.965°N, 135.268°W, 91 m water depth) and Katlian Bay (57.162°N, 135.357°W, 146 m water depth), a pair of temperate fjords (Figure 1). Sediment accumulation rates in both fjords are very high (>250 cm/kyr; Addison [2009]), and offer an opportunity to investigate past Gulf of Alaska oceanography at exceedingly high temporal resolution. However, the preservation of highly resolved paleoclimate information is dependent upon the nature of sedimentation and post-depositional preservation. To understand the quality of the records preserved in Deep Inlet and Katlian Bay, we employ computed tomography (CT) scanning, scanning XRF geochemistry, linescan color imaging, and gamma-ray attenuated (GRA) bulk density analyses to describe the most recent ~100 years of accumulation. These results are then related to the modern cycle of sedimentation at work along the southeastern Alaska coast.

2. Methods

2.1. Site Overview

Deep Inlet and Katlian Bay are two temperate ice-free fjords located on Baranof Island in the Alexander Archipelago of southeastern Alaska (Figure 1). Deep Inlet was carved from the local Cretaceous Sitka Graywacke bedrock [Loney et al., 1975] by the extinct Cordilleran Ice Sheet [Kaufman and Manley, 2004], while Katlian Bay is located within the meta-sedimentary Kelp Bay Group.

Figure 1. SeaWiFS-derived net primary productivity measurements [Westberry et al., 2008] in the Gulf of Alaska during June 2007 (a), with black box indicating area over which values were averaged to generate the productivity time series in Figure 1g. Locations of the PFEL upwelling index site and the NOAA NOMAD buoys are indicated. Inset map (b) depicts location of cores EW0408-32MC and EW0408-43MC in Katlian Bay and Deep Inlet, respectively, along with locations of USGS stream gage stations and epicenter of M7.6 Sitka Earthquake.
Both fjords are connected to the Gulf of Alaska through Sitka Sound, a larger temperate fjord with a sill (likely a submerged Pleistocene terminal moraine) at approximately 130 m water depth. There are no modern tidewater glaciers along the coast of Baranof Island, nor are there any alpine glaciers in the high relief regions surrounding these fjords. Deep Inlet is 6 km long, 0.75 km wide, has a maximum depth of 91 m and is confined by a shallow sill at its mouth that is only 24 m deep. Several small unnamed streams drain directly into Deep Inlet, with the largest two forming a delta complex at the head of the fjord that have a combined drainage area of approximately 25 km². Katlian Bay is larger than Deep Inlet and is 7.5 km long, 1.5 km wide, and approximately 143 m deep. The sill at the mouth of Katlian Bay is also deeper than that of Deep Inlet, at a water depth of 47 m, with a deep scour pool lying just behind the sill. Katlian Bay also has a much larger delta at its head, generated by the confluence of four rivers that drain approximately 148 km² [Haight et al., 2006].

Temperature and salinity hydrocast data from Deep Inlet and Katlian Bay show a three-layer water column (Figure 2), which is characteristic of the “reverse estuary” circulation pattern common to temperate fjords [Syvitski et al., 1987]. Both fjords contain brackish surface mixed layers derived from fluvial discharge and surface runoff, which overlie intermediate zones that are freely exchangeable with waters from the open Gulf of Alaska (Figure 2d). The bottom waters below the sills in southeastern Alaskan ice-free fjords tend to exhibit dissolved oxygen depletion (either seasonally or permanently), depending on the rate of oxygen-renewal events [Burrell, 1989]. These dysoxic-to-anoxic bottom waters limit sedimentary bioturbation and enhance organic matter preservation [Skei, 1983].
2.2. Modern Climate Observations

[7] A collection of regional instrument-derived data sets is used to assess modern climate parameters and marine primary productivity, as neither Katlian Bay nor Deep Inlet contain sediment traps or instrumented moorings. The location and intensity of the Aleutian Low atmospheric pressure cell is described by the North Pacific Index, which is the monthly area-weighted sea level pressure (SLP) over the region 30°–65°N latitude and 160°E to 140°W longitude [Trenberth and Hurrell, 1994] with coverage beginning in AD 1899. The Aleutian Low is of special significance in this study, as it has been identified as one of the major drivers of North Pacific regional environmental change [Trenberth, 1990]. The coastal upwelling index for 57°N, 137°W from the Pacific Fisheries Environmental Laboratory (PFEL; [Schwing et al., 1996]) has been calculated for AD 1946–2010 and is based on estimates of Ekman transport driven by regional geostrophic wind stresses. Monthly mean surface air temperature (SAT) and monthly total precipitation observations for Sitka, Alaska (AD 1948–2010 at the Rocky Gutierrez Airport; AD 1922–1989 at the Sitka Magnetic Observatory) are from the NOAA National Climate Data Center. SST are from two different sources, a pair of instrumented NOMAD buoys at Cape Edgecumbe (56.612°N, 136.065°W) and the Fairweather Grounds (58.237°N, 137.986°W) maintained by the National Data Buoy Center with coverage from AD 2001 to 2010, and the satellite-based 1° × 1° NOAA Optimum Interpolation v.2 SST data set with coverage since January 1981 [Reynolds, 1988; Reynolds et al., 2002]. Monthly USGS stream discharge rate data from the Baranof Island area are sparse and discontinuous between AD 1915 to present, with a large data gap between 1957 and 1976. Most discharge measurements are from Sawmill Creek (site 15088000), but this record is discontinuous with several breaks in data coverage (Table 1). A combination of gage stations at Starrigavan Creek (site 15087618), the lower Indian River (site 15087700), and Bear Cove (site 15088200) contain data coverage between AD 1999 and 2008. Discharge data from the USGS stations are used in this study after normalization by drainage area.

[8] Net primary productivity (NPP) estimates are from SeaWiFS ocean color reflectance spectra and the carbon-based productivity model (CbPM) of Westberry et al. [2008]. The CbPM algorithm differs from traditional SeaWiFS-based estimates of net productivity that use a combination of chlorophyll concentrations and parameterizations to account for changing light, nutrient, and temperature conditions [Behrenfeld and Falkowski, 1997]. Instead, the CbPM approach relates NPP to (i) phytoplankton carbon biomass measured using SeaWiFS particulate backscattering coefficients, and (ii) phytoplankton growth rates derived from SeaWiFS chlorophyll:C ratios [McClain, 2009]. For this study, NPP values are averaged at monthly time-steps between October 1997 and October 2007 using the SeaDAS 6.1 image processing software (SeaDAS Development Group, NASA) for the grid box shown in Figure 1a, which includes 181 individual NPP nodes. The grid box covers approximately 31,000 km² of ocean surface area and is intentionally large to minimize the contributions from localized anomalies related to high turbidities in near-shore waters [International Ocean-Colour Coordinating Group, 2000]. Due to extensive cloud coverage and/or low light levels during the winter in Southeast Alaska, there are no data for the months November to January.

2.3. Sediment Core Collection and Description

[9] The cores considered in this study were collected by the R/V Maurice Ewing in September 2004 (Figure 1). Both EW0408-32MC and EW0408-43MC were collected using the Oregon State University (OSU) multicore rig in Katlian Bay and Deep Inlet, respectively. EW0408-32MC is 38 cm long, and EW0408-43MC is 61.5 cm long. Following retrieval, both cores were analyzed shipboard using a GEOTEK Multi-Sensor Core Logger (MSCL) at 1 cm intervals; data from GRA wet bulk density measurements are considered in this paper. The cores were then split, lithologies described, and linescan images were collected using the MSCL GEOSCAN 3-CCD camera, which yielded RGB images with a pixel resolution of 100 pixels/cm. 137Cs and excess210Pb data for both EW0408-32MC and EW0408-43MC have been presented previously [Walinsky et al., 2009], with minimum detectable activity limits of 0.15 dpm·g⁻¹ for 137Cs. All EW0408 cores are archived at the OSU Core Lab.

2.4. CT Scans

[10] Computed tomography (CT) provides rapid nondestructive three-dimensional mapping of a material’s X-ray attenuation variability at submillimeter spatial scales that can be used to identify changes in sedimentary facies [Duliu, 1999; Ketcham and Carlson, 2001; St-Onge and Long, 2009]. CT imaging was performed at the OSU Veterinary College using a Toshiba Aquilion 64-Slice instrument. Axial (0.5 mm slices), coronal (longitudinal; 0.5 mm slices), and sagittal (transverse; 1.0 mm slices) images were collected using a source radiation of 120 keV and 400 mA. CT measurements are expressed as Hounsfield units (HU), which are a measure of a material’s X-ray mean absorption coefficient relative to that of water, which in turn reflects a combination of bulk density, effective atomic number, mineralogy, and porosity [Boespflug et al., 1994; Boespflug et al., 1995] and were extracted from the CT scans using the software program ImageJ [Abramoff et al., 2004]. HU numbers were then calibrated to wet bulk density using the low-resolution (e.g., every 1 cm) GEOTEK GRA density measurements.

[11] Semiautomated lamination thickness measurements were made on contrast-enhanced linescan and CT images of EW0408-43MC using the WinGeol lamination software [Meyer et al., 2006]. After initial processing of the extracted RGB transect data by the WinGeol algorithm and boundaries between sublaminae were automatically assigned, each sublamina boundary was evaluated and corrected by hand when necessary. Three separate downcore transects were measured and the mean depth of each boundary was recorded.

2.5. Scanning XRF Geochemistry

[12] Semiquantitative geochemical data were collected on u-channel samples from EW0408-32MC and EW0408-43MC using an Avaatech XRF core scanner [Richter et al., 2006] at Scripps Institution of Oceanography. The u-channel
### Table 1. Pearson Correlation Coefficients for Sitka Regional Climate and SeaWiFS Productivity Measurements

<table>
<thead>
<tr>
<th></th>
<th>PFEL Coastal Upwelling Index</th>
<th>Sitka SAT (Spliced)</th>
<th>Cape Edgecumbe NDBC Buoy SST</th>
<th>Fairweather Grounds NDBC Buoy SST</th>
<th>NOAA Optimum Interpolation SST</th>
<th>Sitka Precipitation (Spliced)</th>
<th>USGS Fluvial Discharge (Sawmill Creek)</th>
<th>SeaWiFS Net Primary Productivity</th>
<th>Beginning Date of Record</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Pacific Index</td>
<td>0.76</td>
<td>0.54</td>
<td>0.55</td>
<td>0.47</td>
<td>0.52</td>
<td>−0.18</td>
<td>0.32</td>
<td>0.66</td>
<td>AD 1899</td>
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<tr>
<td>PFEL Coastal Upwelling Index</td>
<td>0.63</td>
<td>0.55</td>
<td>0.54</td>
<td>0.53</td>
<td>−0.22</td>
<td>0.25</td>
<td>0.63</td>
<td>AD 1946</td>
<td><a href="http://www.pfeg.noaa.gov/products/PFEL/modelled/indices/upwelling/upwelling.html">http://www.pfeg.noaa.gov/products/PFEL/modelled/indices/upwelling/upwelling.html</a></td>
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</tr>
<tr>
<td>Sitka SAT (Spliced)</td>
<td>−</td>
<td>0.89</td>
<td>0.93</td>
<td>0.89</td>
<td>−0.09</td>
<td>0.57</td>
<td>0.69</td>
<td>AD 1922</td>
<td><a href="http://cdo.ncdc.noaa.gov">http://cdo.ncdc.noaa.gov</a></td>
<td></td>
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<tr>
<td>Cape Edgecumbe</td>
<td>−</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.16</td>
<td>0.44</td>
<td>0.67</td>
<td>AD 2002</td>
<td><a href="http://www.ndbc.noaa.gov">http://www.ndbc.noaa.gov</a></td>
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<tr>
<td>NOAA Optimum Interpolation SST</td>
<td>−</td>
<td>−</td>
<td>0.99</td>
<td>0.99</td>
<td>0.10</td>
<td>0.37</td>
<td>0.53</td>
<td>AD 2001</td>
<td><a href="http://www.ndbc.noaa.gov">http://www.ndbc.noaa.gov</a></td>
<td></td>
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<tr>
<td>Sitka Precipitation (Spliced)</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>0.10</td>
<td>0.37</td>
<td>0.53</td>
<td>AD 2001</td>
<td><a href="http://www.ndbc.noaa.gov">http://www.ndbc.noaa.gov</a></td>
<td></td>
</tr>
<tr>
<td>USGS Fluvial Dischargeb</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
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<td>0.56</td>
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<td></td>
</tr>
<tr>
<td>SeaWiFS Net</td>
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<td>−</td>
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<td>−</td>
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<td>−0.13</td>
<td>−</td>
<td>AD 1922</td>
<td><a href="http://cdo.ncdc.noaa.gov">http://cdo.ncdc.noaa.gov</a></td>
<td></td>
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</tbody>
</table>

*Bold face indicates significant correlation at the 0.01 level. Italic numbers are population size.

bUSGS gage station at Sawmill Creek (site 15088000).

surfaces were lightly scraped to expose a less oxidized layer of sediment and then covered with 4 µm thick SPEX Certi Prep Ultralene® foil to prevent excess drying or contamination of the sediments during analysis as the XRF sensor moved downcore. Both cores were analyzed at 10, 30, and 50 keV energies for 10, 20, and 30 s, respectively, where the 10 keV energy level was used to detect the elements Al through Fe, 30 keV was used for Cu to Bi, and 50 keV measured Cd to Ba. A thick Cu filter and a Pd filter were placed in front of the Rh X-ray source for the 30 and 50 keV scans, respectively, to limit the lower energy bremsstrahlung and improve the signal-to-noise ratio. Measurement slit size for EW0408-32MC was 10 × 2 mm, while EW0408-43MC was analyzed using a smaller 10 × 0.2 mm slit size.

X-ray spectra were quantified using the WinAxil software package (Canberra Industries, Inc.), where an iterative nonlinear least square fit (based on a Gaussian function) was used to model both Kα and Kβ peak areas. The postprocessing also removed the bremsstrahlung background and corrected for escape- and sum peaks. The resulting data were then converted into total counts for each detected element, and a χ² goodness-of-fit parameter (D-area) was calculated. All scanning XRF element intensity measurements were then normalized by count times and converted to centered natural-log ratios (clr) [Aitchison, 1982; Pawlowsky-Glahn and Egozcue, 2006; Welte and Tjallingii, 2008] prior to compositional analysis. This data treatment helps to eliminate the effects of physical changes in the sediment matrix and scanner setup (e.g., grain size, water content, core surface topography, water, and/or air bubbles that accumulate under the foil). Lighter elements, generally those obtained in the 10 keV scan, are most affected by the presence of water beneath the foil surface while elements with higher atomic masses (such as those obtained in the 30 and 50 keV scans) are not as affected, and can more reliably be reported without much mathematical manipulation [Kido et al., 2006; Tjallingii et al., 2007; Ziegler et al., 2008] (see also supporting information). Clr-transformation of X-ray intensities also have the added benefit of correcting the constant-sum issue for compositional data [Aitchison, 1986] and are linearly proportional to concentrations for most elements [Welte and Tjallingii, 2008]. All scanning XRF element intensities considered exceed the 3σ lower limit of detection (LLD), calculated as LLD = 3 × (σc/i), where c = total number of counts for element j and i is the count time in seconds [Potts, 1987]. Visual inspection of representative X-ray spectra from selected samples in both cores was also used to confirm high signal-to-background intensities for key elements.

2.6. Biogenic Silica, Total Organic Carbon, Molar N/C, and Organic Matter δ¹³C

Bulk sediment samples (1 cm thick × 2 cm wide) were collected every 5 cm from EW0408-32MC and EW0408-43MC, and biogenic silica (opal), total organic carbon (TOC), total nitrogen, and organic matter δ¹³C compositions were measured on homogenized carbonate-free splits according to the methods described in Addison et al. [2012]. Opal was measured using molybdate-blue spectrophotometry and a 0.1 M Na₂CO₃ extraction technique [Mortlock and Froelich, 1989]. TOC, molar ratios of TN:TOC (hereafter referred to as molar N/C ratios), and stable isotope analyses were performed at the Alaska Stable Isotope Facility (ASIF) using a Costech 4010 HCNS elemental analyzer coupled to a Finnigan DeltaPlusXP isotope ratio mass spectrometer (IRMS) on EW0408-32MC. A similar set of analyses were performed on EW0408-43MC by the USGS Isotope Tracers Project Lab using a Carlo Erba NA 1500 elemental analyzer and an Elementar (formerly Micromass) Optima IRMS. Several samples measured by ASIF were also measured by USGS to ensure data were of similar quality and that results would be directly comparable. Organic matter δ¹³C values are reported in permil units (‰) relative to the Vienna Peedee Belemnite (V-PDB), where δ¹³C = [(¹³C/¹²C)sample/(¹³C/¹²C)V.PDB] − 1) × 1000‰. Sedimentary δ¹⁵N data follow the same permil convention relative to atmospheric nitrogen. Replicate analyses of internal standards indicate standard deviations (1 σ) of approximately 1.0% for opal for both cores, and for EW0408-32MC (measured at ASIF; n = 5) 1 σ deviations for TOC were 0.88%, 0.012 for molar N/C ratios, 0.10‰ for organic matter δ¹³C, and 0.06‰ for sedimentary δ¹⁵N measurements, while the 1 σ deviations for EW0408-43MC (measured at USGS; n = 17) were 0.98% for TOC, 0.010 for molar N/C, 0.09‰ for organic matter δ¹³C, and 0.14‰ for sedimentary δ¹⁵N.

3. Results

3.1. Modern Climate Data

The monthly instrument data from Southeast Alaska compiled for the years AD 1998 to 2008 show evidence of strong seasonality in continental shelf waters (Figure 3). Low values of the North Pacific Index during the winter months indicate intensified Aleutian Low atmospheric dynamics in the eastern Gulf of Alaska (Figure 3a), which contributes to strong onshore winds and coastal downwelling (Figure 3b). Winter is also the period of minimum SAT and SST (Figures 3c and 3d). The peak in NPP occurs during the spring and summer (Figure 3g), due to a combination of the seasonal increase in solar insolation (Figure 3d), eutrophic zone thermal stratification, and a reduction in downwelling intensity. The maxima in precipitation and fluvial discharge follow in the autumn, with the peak flow season tending to occur between the months of September and December (Figures 3e and 3f).

The full suite of climate time-series data exhibit several significant correlations. All measurements of SST correlate at the 99% significance level with the longer Sitka SAT data (Table 1), and there is a significant correlation between Sitka SAT and the SeaWiFS-derived NPP record. A somewhat weaker correlation exists between Sitka precipitation and the Sawmill Creek discharge data, though it still exceeds the 99% significance level. The relatively small mountainous drainage basins adjacent to Katlian Bay and Deep Inlet offer little surface water storage area or groundwater discharge, thus favoring a rapid fluvial response to seasonal peaks in precipitation. Collectively, these results indicate that (i) the long Sitka SAT record is representative of local ocean SST conditions, particularly with regard to seasonality (Figure 4a) and (ii) the long Sitka precipitation record is likely a good indicator of regional precipitation that can be cross checked against the discontinuous USGS fluvial discharge network (Figure 5).

3.2. Modern Oceanographic Data

The full suite of oceanographic data exhibit several significant correlations. All measurements of SST correlate at the 99% significance level with the longer Sitka SAT data (Table 1), and there is a significant correlation between Sitka SAT and the SeaWiFS-derived NPP record. A somewhat weaker correlation exists between Sitka precipitation and the Sawmill Creek discharge data, though it still exceeds the 99% significance level. The relatively small mountainous drainage basins adjacent to Katlian Bay and Deep Inlet offer little surface water storage area or groundwater discharge, thus favoring a rapid fluvial response to seasonal peaks in precipitation. Collectively, these results indicate that (i) the long Sitka SAT record is representative of local ocean SST conditions, particularly with regard to seasonality (Figure 4a) and (ii) the long Sitka precipitation record is likely a good indicator of regional precipitation that can be cross checked against the discontinuous USGS fluvial discharge network (Figure 5).
Because of the short duration of SeaWiFS observations, a multiple (stepwise) linear regression model [Davis, 2002] was derived to extend the NPP record to the beginning of the Sitka weather observations in AD 1922 (Figure 4b). Using the available climate data from Table 1, data sets were selected for inclusion in the regression model if the probability of the resulting $F$-statistic was less than a significance level of 0.05, while data sets were excluded if the probability of the resulting model $F$-statistic exceeded the 0.10 significance level. For the period between AD 1922 and 1981, the stepwise approach identified both the Sitka SAT record and the North Pacific Index as key variables, such that

$$\text{SeaWiFS net primary productivity} = \frac{\text{Sitka SAT}}{C_{28,579}} + \frac{\text{North Pacific Index}}{C_{24,673}} + k_1$$

where $k_1$ is a constant of $-387.529$. When compared to the measured NPP data, equation (1) accounts for 60.8% of the total variance ($p < 0.01$). For the period between AD 1981 to 2009, the stepwise regression included the NOAA Optimum Interpolation SST data, where

$$\text{SeaWiFS net primary productivity} = \frac{\text{Sitka SAT}}{C_{28,017}} + \frac{\text{North Pacific Index}}{C_{24,719}} + \frac{\text{NOAA SST}}{C_{26,534}} + k_2$$

where $k_2 = -136.864$. This equation improved the fit between the modeled and measured productivity data, increasing the variance descriptor to 66.3% which is a significant improvement ($p < 0.01$) over the model derived from equation (1) (Figure 4b).

3.2. EW0408-32MC

This multicore sample recovered the sediment-water interface, and consists of very dark greenish-gray clay that contains diffuse centimeter-scale laminations visible in the
between 0.71 and 0.93 (Figure 7). Yields a range of marine-derived organic matter fractions of et al. values are of organic material, including mean opal concentrations of 27.4 mean opal concentrations (supporting information Table S1) indicate high concentrations of material. Mean molar N/C ratios are 0.094 molar N/C ratios are 0.094.<ref>Comparisons between clr element intensities that 
 elicited bioturbation in the CT images. Calibration of the linescan imagery (Figure 6), but which appear to be moderately bioturbated in the CT images. Calibration of the HU units from the CT scan against the low-resolution GEOTEK GRA wet bulk density measurements (n = 40, r = 0.59, p < 0.01) yields a mean bulk density of 1.08 ± 0.01 g/cm³.

[19] The carbonate-free organic element and δ¹³C data (supporting information Table S1) indicate high concentrations of organic material, including mean opal concentrations of 27.4 ± 2.0% and TOC values of 4.9 ± 0.5%. Mean molar N/C ratios are 0.094 ± 0.013, organic matter δ¹³C values are −21.9 ± 0.4‰, and sedimentary δ¹⁵N is 6.4 ± 0.2‰. Negative Pearson correlations exist between natural-log-transformed values of opal and TOC (n = 8, r = −0.90, p < 0.01), and natural-log-transformed values of organic δ¹³C and molar N/C ratios (n = 8, r = −0.894, p < 0.01). Applying a linear mixing model to estimate the fraction of marine-derived organic matter that uses a terrestrial end-member δ¹³C composition of −26‰ and a marine end-member δ¹³C ratio of −21‰ [Meyers, 1994; McQuoid et al., 2001; Walinsky et al., 2009; Addison et al., 2012] yields a range of marine-derived organic matter fractions of between 0.71 and 0.93 (Figure 7).

[20] Comparisons between clr element intensities that exceeded the detection limits of the Avaatech scanning XRF instrument show several coherent trends (Figure 8). Clr Al, Si, Ti, K, Fe, Ca, and Mn intensities exhibit rapid increases with increasing core depth between 0 and 12 cm that transitions to a more gradual increase that persists to the base. These similarities are reflected in the low covariance between most of these elements (supporting information Table S2). The profile of clr Ba is similar, but with a subsurface maxima between 7 and 17 cm depth. These trends generally contrast with those of clr Zn, Cu, Pb, Y, Zr, Rb, and Sr, which show an overall decrease toward the base of 32MC. Between 0 and ~21 cm depth, both clr Cl and S follow similar trends. Below 21 cm, S increases toward the base of the core, while Cl decreases. The intensity pattern of clr Br is distinct from any other element in 32MC, in that it oscillates between intervals of high and low intensities, superimposed on an overall linear decrease with depth.

[21] The radioisotope data for EW0408-32MC (Figure 6a) indicates several important features. The first-appearance datum (FAD) for ¹³⁷Cs activity occurs between 25 and 30 cm, and the FAD for excess²¹⁰Pb activity occurs below 35 cm (e.g., below the base of EW0408-32MC). A subsurface peak in ¹³⁷Cs activity occurs at 25 cm. The activities of the two uppermost excess²¹⁰Pb samples are approximately equal, as are the two uppermost ¹³⁷Cs samples, implying a surface mixed layer ~5 cm thick. Depth trends in both excess²¹⁰Pb and ¹³⁷Cs activity profiles suggest steady-state accumulation, with a maximum apparent accumulation rate of between 5 and 6 mm/yr for ¹³⁷Cs, and 3–6 mm/yr for excess²¹⁰Pb based on the constant initial concentration accumulation model [Nittouer et al., 1979]. A linear composite sedimentation model was developed from these data using a rate of 5 ± 1 mm/yr that places the core top at AD 2004 (date of collection), and the base at ~AD 1934. Combined with the CT-scan evidence of bioturbation (e.g., mottled fabric between 0 and 10 cm), these geochronology data indicate EW0408-32MC proxy data can be resolved at subdecadal but not annual time resolutions.

3.3. EW0408-43MC

[22] The sediment-water interface was not recovered in multicore EW0408-43MC, indicating an unknown volume of material was lost during core recovery. Both linescan and CT images of EW0408-43MC show parallel beds that vary both in color and HU value intensity (Figure 9). When the HU data are empirically converted into density values using the GEOTEK MSCL low-resolution bulk density measurements (n = 60, r = 0.68, p < 0.01), EW0408-43MC has a mean bulk density of 0.92 ± 0.03 g/cm³.

[23] Using a combination of color, HU, and relative bulk density, the stratigraphy of EW0408-43MC can be classified into four broad categories: (i) alternating thin light brown low-density (~0.88 g/cm³; CT-dark) sublaminae and dark brown/black medium-density (~0.92 g/cm³; CT-light) sublaminae; (ii) a thick normally graded unit with a coarse very high-density (~1.28 g/cm³) base between 12.4 and 14.7 cm depth, interpreted as a turbidite; (iii) a thick high-density (~0.96 g/cm³) unit between 32.8 and 42.0 cm depth with gradational contacts; and (iv) a bioturbated horizon between 18.7 and 24.7 cm. The repeating nature of the light brown and dark brown/black sublaminae suggests...
these are cyclical couplets whereas the higher density deposits appear to be episodic.

Organic geochemistry and isotope results for EW0408-43MC (supporting information Table S1) indicate extremely high concentrations of opal (mean 50.7 ± 8.0%) and TOC (10.8 ± 1.4%). Molar N/C ratios are also high (0.085 ± 0.005), as are organic matter δ^{13}C (-22.1 ± 0.5‰) and sedimentary δ^{15}N (6.1 ± 0.3‰). Negative Pearson correlations exist between natural-log-transformed values of opal and TOC (n = 12, r = -0.86, p < 0.01), and natural-log-transformed values of organic δ^{13}C and molar N/C ratios (n = 12, r = -0.97, p < 0.01). Using the same parameters to calculate the proportion of marine contributions as for EW0408-32MC (see section 3.2) yields a range between 0.63 and >1.0 of marine-derived organic matter (Figure 8), with the high value indicating that some samples had δ^{13}C values more enriched than the marine end-member value of -21‰.

The lithological complexity in 43MC is also reflected in the geochemical scanning XRF data (Figure 9). The clr-transformed intensities for Ti, Ca, Sr, and Fe follow similar patterns, with the highest intensities associated with the turbidite deposit and the other high-density units. These trends contrast sharply with those of Si, Al, Cr, Mn, Mo, Cu, Ba, and Zn, all of which have minimum intensities associated with the turbidite and high-density intervals, and
maxima associated with the low-density intervals. Both S and Cl show some similarities to the Si group as well, with maxima at 6, 17, and 28 cm depth. Clr Br is complex, as the lowest values are associated with the turbidite deposit, intermediate values occur within the low-density laminations, high values occur with the high-density unit between 33 and 42 cm, and the highest Br intensities are at the core top. The heterogeneity of EW0408-43MC is also reflected in the higher variance (supporting information Table S2), with the elements Fe and Al showing the greatest variance of any element in the scanning XRF data set.

[26] Results of the radioisotopic analyses for the EW0408-43MC samples parallel the complex lithostratigraphy described above (Figure 6b). As the core barrel for EW0408-43MC over-penetrated during collection, there is no intact sediment-water interface. The presence

Figure 6. Geochronology results for (a) EW0408-32MC show a maximum apparent steady-state linear sedimentation rate of 5 ± 1 mm/yr by excess $^{210}$Pb, and an $^{137}$Cs subsurface maxima from the global fallout maxima during ~AD 1964 [Appleby, 2001]. These results indicate EW0408-32MC is a continuous record from ~AD 1934 to 2004. (b) EW0408-43MC over-penetrated and lost the most recent core-top sediments, and CT imagery reveals a non-steady-state lithostratigraphy (see text for discussion). The FAD of $^{137}$Cs occurs in the subsurface, indicating the interval between 45 and 50 cm corresponds to the early AD 1950s, supporting the inference that a hypopycnal plume deposit linked to cessation of low-flow conditions in Southeast Alaska occurred during the early 1950s (Figure 5). A relative varve count age-depth model anchored using both the hypopycnal plume deposit and a seismically generated turbidite (30 July 1972) indicates that EW0408-43MC spans ~AD 1940 to 1981, with a hiatus between AD 1956 to 1972.
of two episodic depositional units (e.g., the turbidite and the high-density unit between 32.8 and 42.0 cm depth) and the highly variable thicknesses of the laminated horizons (mean 7.6 ± 9.2 mm at 1 standard deviation) preclude the use of steady-state accumulation rate models to calculate age-depth relationships for EW0408-43MC. The episodic depositional horizons noted above tend to bracket anomalously low excess $^{210}$Pb and/or $^{137}$Cs activities, further supporting the interpretation that these deposits do not represent steady-state depositional conditions. The FAD of anthropogenically derived $^{137}$Cs occurs between 45 and 50 cm depth, which indicates the base is younger than ~AD 1900.

4. Discussion

4.1. Event Sedimentology and Geochemistry of EW0408-43MC

4.1.1. Sublaminae Couplets and Bioturbation Horizon

There is a high degree of geochemical overlap between the CT-light and CT-dark sublaminae, as well as the bioturbation horizon. This result is not unexpected as (i) the bioturbation horizon likely represents a mixture of these different sublaminae and (ii) the processes that lead to the generation of the CT-dark (e.g., marine phytoplankton) and...
CT-light (e.g., terrigenous material) sublaminae operate year-round in Southeast Alaska (Figure 3), though there is also a strong seasonal difference in the periods of maximum accumulation for these different components.

4.1.2. Turbidite (Seismite)
[28] Prior work by Walinsky et al. [2009] suggested that the upper 10.0–18.0 cm of EW0408-43MC was in nonsteady-state accumulation, possibly as a result of sub-marine gravity flows. The CT images support this interpretation, as indicated by the thick turbidite deposit between 12.4 and 14.7 cm (Figure 9). Using a combination of multivariate discriminant function analysis and ternary diagrams of key geochemical elements (Figure 10), the turbidite appears distinct from the other EW0408-43MC units, possibly as a result of being composed of coarser terrigenous clasts that were originally deposited upslope from the main fjord basin.

[29] While such deposits can result from aseismic processes [Syvitski et al., 1987], it seems more likely this turbidite is the result of slumping associated with a shallow M7.6 earthquake that occurred 30 July 1972 with an epicenter less than 20 km distant from the EW0408-43MC core site (Figure 1b) [Page, 1973; Schell and Ruff, 1989]. The 1972 earthquake also had an associated tsunami, suggesting the combination of slumping and tsunami backwash would be very likely to cause turbidite deposition, as was observed with the 1964 Good Friday earthquake (M9.2) in Port Valdez [Sharma and Burbank, 1973]. The turbidite also overlies the FAD of 137Cs in EW0408-43MC (Figure 6b), which supports the inference that the turbidite is younger than the early AD 1950s. The presence of scour-and-fill structures at the base of the turbidite indicates an erosive contact with the underlying laminae.

4.1.3. Hypopycnal Plume Deposit
[30] The second high-density unit between 32.8 and 42.0 cm in EW0408-43MC lacks both a coarse-grained basal unit and erosive contacts (Figure 9), which suggests this unit is not a turbidite. Instead, this deposit has the characteristics of a fluvial hypopycnal plume deposit, as the high density of the unit reflects a greater contribution of terrigenous sediment whereas the fine grain-size could be accounted for by settling of the suspended fluvial load as flocculated clastic mud [Syvitski et al., 1987; Ducassou et al., 2008]. The hypopycnal plume deposit describes a geochemical population that differs from the mixed sublamine/bioturbation populations (Figure 10), and both the CT bulk density and scanning XRF geochemical data show it is composed of three distinct subunits (Figures 9 and 10). The upper and lower subunits both have similar densities and geochemical compositions, while the middle subunit appears more similar to the sublamine/bioturbation compositions. Visual smear slide microscopy further indicates that the upper and lower subunits are composed of ~75% terrigenous clays (<4 µm), while the middle subunit is only ~50% terrigenous clays. All three subunits are also composed of biogenic components (predominantly diatoms and amorphous organic matter), with the middle subunit composed of much greater proportions of fragile Chaetoceros sp. diatom spores which are difficult to transport without fragmentation (J. Barron, personal communication) and suggests the middle subunit is a primary depositional feature. The internal stratification, stratigraphy, and geochemistry of the hypopycnal deposit thus suggests: (i) generation of the overall deposit differs from the normal sedimentation regime that generates the CT-dark/CT-light sublaminae; (ii) the thickness of the deposit (~10 cm) is due to rapid accumulation; and (iii) the upper and lower subunits are derived from allochthonous fine-grained lithic clays, while the biogenic-rich middle subunit is derived from autochthonous planktonic sources. Overall, these observations suggest that the hypopycnal deposit was deposited during a single autumn/winter flow season, but in detail, it appears to be composed of two different
“flushing” events separated by a late-season phytoplankton bloom. It is difficult to ascribe a single mechanism to the cause of such a bloom, but perhaps it was stimulated by the rapid influx of terrestrially derived nutrients to Deep Inlet from the first hypopycnal event.

Figure 9. Linescan imagery, CT scanning results, calibrated bulk density, organic elemental and isotopic analyses, and scanning XRF geochemistry for EW0408-43MC. Additional XRF element intensity data contained within online supplement. Note that the density record has been truncated.

Fluvial hypopycnal plume deposits require a strong salinity contrast between a low-salinity surface water mass and underlying saline waters, a condition that is common in temperate fjords (Figure 2). Precipitation and fluvial discharge records from the Sitka area suggest the most likely

Figure 10. EW0408-43MC scanning XRF intensity data by lithology. Both (a) multivariate discriminant function analysis and (b) centered ternary Fe–Ca–Br diagrams [Thio-Henestrosa and Martin-Fernandez, 2005] indicate that the geochemical composition of the turbidite is distinctive from the other units, while both sublaminae types and the bioturbation zone are geochemically similar. The hypopycnal plume deposit has been subdivided into three subunits, and geochemical analysis indicates the upper and lower subunits are geochemically similar, while the middle subunit is more similar to the biogenic-rich sublaminae composition.
period for such a hypopycnal deposit to accumulate in Deep Inlet would be associated with the resumption of high-flow conditions during the wet season of AD 1952 (Figure 5). This period is anomalous in that it received very low precipitation (two standard deviations below the annual mean) during the two preceding years, which resulted in an accumulation of fine-grained detritus and sediment in local stream beds. The return of normal high-flow conditions, therefore, would facilitate transport of this multイヤr accumulation of terrigenous material into coastal waters.

4.2. Construction of a Varve Chronology for EW0408-43MC

[32] The assignment of the turbidite and the hypopycnal deposit to specific periods allows the construction of a preliminary chronology for EW0408-43MC based on the hypothesis that the laminated couplets preserve the annual cycle of deposition in southeastern Alaska (e.g., varves). Since the CT-dark sublaminae are dominated by organic matter, and the peak in NPP in Southeast Alaska occurs between May and August (Figure 4a), the CT-dark sublaminae are designated as “0.5” year intervals (e.g., 1945.5, 1957.5, etc.). Similarly, as the CT-light sublaminae are composed primarily of detrital material from precipitation run-off and fluvial discharge which peaks in southeastern Alaska between September and December (Figure 5b), these units are designated as “0.0” year intervals (e.g., 1945.0, 1958.0, etc.) by convention.

[33] The gradational contact between the turbidite and the overlying CT-dark sublaminae supports the inference that the episodic deposition of the turbidite occurred during an interval of high organic matter accumulation (likely the summer diatom bloom; Figure 4a) without disrupting the continuity of the record following the deposition of the turbidite. To maintain continuity with the preliminary varve chronology, the contact between the overlying CT-dark sublaminae and the turbidite is assigned an age of AD 1972.5. The hypopycnal plume deposit is assigned an age of AD 1952.0, and as it has gradational contacts both above and below with adjacent CT-dark sublaminae, this unit is part of the continuous record.

[34] A time discontinuity in the EW0408-43MC varve record occurs between 14.7 and 24.7 cm. The upper depth discontinuity is due to the erosional scour at the base of the turbidite that removed an unknown number of underlying sublaminae. The lower discontinuity depth is at the base of the bioturbated horizon, which represents the maximum penetration depth of homogenization of several laminae couplets, thus obscuring the varve chronology for this interval as well. Combined, the turbidite scour and the bioturbation have effectively removed the time constraints on the laminae couplets between 14.7 and 18.7 cm. This gap in the chronology is constrained to between ~AD 1956 and 1972.5.

[35] The resulting chronology is presented in Figure 6 and represents the mean depth of each sublaminae measured from three downcore transects. This floating varve-based chronology places the core top age at ~AD 1981, the base of EW0408-43MC at ~AD 1940, and includes a hiatus between ~AD 1956 and 1972. The resulting EW0408-43MC chronology also explains the absence of key 137Cs horizons, including the lack of an AD 1963/1964 subsurface maxima (which would have been deposited during the hiatus), as well as the lack of an AD 1986 maxima related to the high-latitude deposition of radionuclide fallout from the Chernobyl accident [e.g., Sugai et al., 1994] due to over-penetration during core collection. Given the uncertainties associated with the generation of this age-depth model, the chronology for EW0408-43MC is likely accurate only to subdecadal timescales.

4.3. Shifts in Recent Primary Productivity and Sedimentary Br/Cl Ratios

[16] Few instrument data sets from Southeast Alaska are long enough to compare directly against the multidecadal record of sedimentation preserved in multicore samples EW0408-32MC and EW0408-43MC. The Pacific Decadal Oscillation record is based on statistical analysis of North Pacific Ocean SST and extends to the beginning of the 20th Century AD [Mantua et al., 1997]. It has been used in many studies as an estimator of the state of North Pacific climate regimes [e.g., Minobe, 1999]. Therefore, the PDO index is used in this study as a measure of North Pacific environmental variability, against which to compare the (i) derived measures of Sitka primary productivity and (ii) the geochemistry of the recent sedimentary record accumulating in Katlian Bay and Deep Inlet.

[37] Equations (1) and (2) allow an estimation of NPP from the long Sitka SAT, NPI, and SST records. NPP is not normally used as an estimator for export productivity, particularly in regions where particle export tends to be anticorrelated with biological activity such as in the Southern Ocean [Sarmiento and Gruber, 2006]. However, sediment flux studies in the high-latitude North Pacific Ocean [Francois et al., 2002; Whitney et al., 2005] show high particle export efficiencies, but low transfer efficiencies to the deep ocean (PEeff and TEeff, respectively, as defined by Henson et al. [2012]). Henson et al. [2012] use a global compilation of open-ocean sediment trap data [Honjo et al., 2008] to calibrate satellite estimates of PEeff and TEeff and show that the coastal Gulf of Alaska has (i) high levels of primary production; (ii) high surface particle export rates; (iii) high PEeff; and (iv) low TEeff. The shallow depths of the core sites in Katlian Bay (146 m depth) and Deep Inlet (91 m depth) minimize the impact of TEeff to this study, as a low TEeff would result in a skewed and/or discontinuous sediment record. The recognition that diatoms greatly increase rates of PEeff in high-latitude settings especially during bloom seasons [e.g., Buesseler, 1998], such as those that occur in the Gulf of Alaska, further supports the inference that surface productivity is comparable to the export productivity that accumulates beneath the shallow waters of southeastern Alaska temperate fjords. The elevated concentrations of diatom-bound opal in both Katlian Bay and Deep Inlet (mean 27 and 51%, respectively) also reflect this high PEeff. Sediment trap studies performed in other Northeast Pacific temperate fjords (Boca de Quadra: Burrell [1989]; Effingham Inlet: Chang et al. [2013]) show that the highest total biogenic fluxes occur during the late spring/early summer seasons, which is consistent with the SeaWiFS NPP observations for the Sitka region (Figure 2). The Chang et al. [2013] study measured opal, TOC, and CaCO3 fluxes, with the spring/summer opal flux nearly four times higher than during the subsequent autumn and winter seasons. Collectively, these observations suggest that SeaWiFS NPP can be used to
estimate export productivity in Katlian Bay and Deep Inlet in lieu of having direct sediment trap data, though these estimates should probably be considered only semiquantitative.

SeaWiFS observations between AD 1997 and 2009 (Figure 3) indicate the dominant peak in NPP in Southeast Alaska occurs between June and August (Figure 4a). Comparing deviations from the overall summer mean NPP shows multidecadal variability with periodicity similar to that of the PDO (Figures 11a and 11b). This result is not surprising as both the PDO and Sitka productivity anomaly data sets include an SST term, though there are subtle differences (e.g., the PDO is based on a North Pacific basin-wide SST mean, while the Sitka record is based on local SST conditions, and includes SLP and SAT terms). Therefore, this SeaWiFS-based estimator of NPP is likely a semi-independent estimator of regional Southeast Alaska productivity through the early 20th century. Together, the PDO index and the Sitka productivity estimate yield a modern data comparison of North Pacific climate regime state and export productivity, respectively, that correspond to the same time intervals that are preserved in EW0408-32MC and EW0408-43MC.

Figure 11. Modern (a) monthly Pacific Decadal Oscillation (PDO) index, (b) estimated Sitka net primary productivity from equation (2), and the clr-transformed Br/Cl ratio from (c) EW0408-32MC and (d) EW0408-43MC. PDO index from Mantua et al. [1997]. Thick dashed line indicates timing of North Pacific regime shift that occurred during the winter of AD 1976/1977.

4.4. Reconciling Discrepancies Between Traditional Productivity Proxies and the Br/Cl Ratio

The continuous Br/Cl ratio data from EW0408-32MC contains decadal-scale shifts superimposed over a decreasing linear trend from the core top toward the base (Figure 11). The high-resolution discontinuous data in EW0408-43MC also shows similar behavior. In particular, both cores show a shift in the Br/Cl ratio during the late AD 1970s. This period corresponds to the major North Pacific climate regime shift that occurred rapidly during the winter of AD 1976/1977 [Ebbesmeyer et al., 1991], which resulted in a significant shift in Gulf of Alaska marine ecosystem dynamics toward a higher productivity baseline [Beamish, 1993; Hollowed et al., 2001]. Both cores also show evidence of an earlier shift in their respective Br/Cl ratios during the early AD 1950s, another period of noted change in North Pacific climate and ecosystems [Mantua et al., 1997].

Biogenic fraction = opal + (2 \times TOC) + CaCO_3 \quad (3)

and treating CaCO_3 as a constant of 6.0% based on a mean concentration of surface samples from 10 temperate Southeast Alaska fjords [Walinsky et al., 2009], the mean biogenic content of EW0408-32MC is 43.2 ± 1.2% and EW0408-43MC is 77.2 ± 5.4%. Assuming authigenic precipitation of other sediment phases is negligible and that the lithic fraction represents the remainder of the bulk
sediment phases, there is a much greater lithic fraction present in EW0408-32MC than EW0408-43MC.

An unexpected result from EW0408-32MC is the opposite downcore trends between opal and the Br/Cl ratio (Figure 7). Downcore changes in opal are also similar to the low-frequency background for the lithogenic elements (e.g., Ti, Fe, and K) and wet bulk density, which is unexpected as the lithogenic and biogenic fractions are nearly equal in EW0408-32MC. The downcore shift in all solid-phase components can best be explained by changes in sediment porosity, which does not necessarily require changes in the relative concentrations of either biogenic or lithogenic phases (see supporting information for porewater model results). The opposite trend between opal and TOC is, therefore, assumed to be due to a combination of dilution by porewaters, as well as dilution of the remaining biogenic sediment phases by the greater contribution of opal (Figure 7a). Since Br/Cl is proportional to the TOC concentration in the sediment, the secular decline in the Br/Cl data downcore thus also reflects a combination of dilution by porewaters and opal.

The downcore plots of EW0408-43MC biogenic and lithogenic data (Figure 9) do not exhibit the same porosity-driven secular decrease as that found in EW0408-32MC. This result is likely due to (i) the lack of recovery of the sediment-water interface of EW0408-32MC where the exponential decline in porosity would be most pronounced and (ii) the much higher concentrations of opal and organic matter may create a gel-like rheology [Di Giuseppe et al., 2009] that differs in its response to burial and compaction from that of the clastic clays of EW0408-32MC.

4.5. Time-Series Analysis of EW0408-32MC

The continuous and steady-state accumulation of sediments in EW0408-32MC suggests this record is ideal for detailed time-series analysis. After removing the porosity-induced trend from the Br/Cl ratio data using linear regression, the resulting detrended Br/Cl ratio was analyzed using a modified sequential Student’s t-test algorithm [Rodionov, 2004, 2006] to test the occurrence of coherent “regime” states in the data (Figures 12a and 12b). Six regimes were identified, with shifts exceeding the 99% confidence threshold occurring in AD 1991 (±3 years), 1975 (±6 years), 1965 (±8 years), 1954 (±11 years), and 1941 (±13 years), all of which have been previously identified as regime shifts in the PDO. Analysis of the frequency domain of the detrended EW0408-32MC Br/Cl data shows a significant multidecadal peak with a period of 23 years/cycle (Figure 12c) which corresponds with known periodicities of North Pacific climate regime shifts [Mantua et al., 1997]. It should be noted that the short timescale of the EW0408-32MC record precludes the identification of longer PDO periods, such as the 50–70 yr periodicities found by Minobe [1999].

5. Conclusions

Modern instrument and paleoceanographic proxy data demonstrate the prevalence of low-frequency oscillations that dominate Gulf of Alaska climate. Bottom-up forcing of the marine ecosystem by changes in atmospheric and ocean climate conditions, particularly associated with the North Pacific regime shift in AD 1976/1977, is also expressed in the accumulation record of marine-derived organic matter in the
nearshore temperate fjords of Southeast Alaska. The characteristics of these ice-free fjords (low bottom water oxygen concentrations and high primary productivity) make them ideal depocenters for preserving high-quality paleoclimate archives, though they can also introduce complications, such as turbidite erosion and deposition, and episodic oxygenation of bottom waters. Despite significant differences in interfjord geomorphology such as sill depth and upland drainage basin physiography, reliable paleoclimate records can be extracted and cross-validated at a regional scale.

[46] The complex sediment deposition mechanisms that occur in temperate fjords necessarily require high-resolution scanning and imaging techniques that are normally beyond the scope of studies focused on traditional deep-water marine depocenters. Cryptic episodic deposition events discovered in surface sediments using such scanning techniques (e.g., turbidites, hypopycnal plume deposits, etc.) can be linked to modern records of seismicity, precipitation, or other instrument-derived data sets, and thus be utilized as chronostratigraphic horizons to supplement other chronometric techniques.

[47] Using a combination of ultra-high-resolution sediment core CT scanning and scanning XRF techniques, as well as radioactive nuclide and organic elemental analyses, a pair of short multicore samples from Baranof Island was found to record decadal-scale fluctuations in Br/Ci ratios, which reflect changes in marine organic matter accumulation. The pattern of changes in Br/Ci follows the same temporal pattern as that of the Pacific Decadal Oscillation, as well as an estimated Sitka summer productivity anomaly parameter calibrated with recent SeaWiFS observations. The correlation of North Pacific climate regime states, primary productivity, and sedimentary Br/Ci ratios indicate the accumulation of biogenic sediment in Southeast Alaska temperate ice-free fjords can be used as a sensitive recorder of past productivity variability, and by inference, climate conditions in the high-latitude Gulf of Alaska.

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