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Estimation of freshwater runoff into Glacier Bay, Alaska and incorporation into a tidal circulation model

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ABSTRACT

Freshwater discharge is one of the most critical parameters driving water properties within fjord estuarine environments. To date, however, little attention has been paid to the issue of freshwater runoff into Glacier Bay, a recently deglaciated fjord in southeastern Alaska. Estimates of discharge into Glacier Bay and the outlying waters of Icy Strait and Cross Sound are therefore presented. Existing regression equations for southcentral and southeastern coastal Alaska are applied to Glacier Bay to arrive at the estimates. A limited set of acoustic Doppler current profiler (ADCP) measurements generally support the predictions of the regression equations. The results suggest that discharge into the bay ranges from a few hundred to a few thousand $m^3\ s^{-1}$ during a typical year. Peak discharges can be much higher, approximately 10,000 $m^3\ s^{-1}$ for the 10-year flow event. Estimates of the seasonal variation of discharge are also obtained and reveal a broad peak during the summer months.

The hydrologic estimates are then coupled with a barotropic tidal circulation model (ADCIRC – ADvanced CIRCulation model) of Glacier Bay waters. This coupling is achieved by treating the entire coastline boundary as a non-zero normal-flux boundary. Numerical simulations with the inclusion of runoff allow for the estimation of parameters such as the estuarine Richardson number, which is an indicator of estuary mixing. Simulations also allow for the comparison of Lagrangian trajectories in the presence and absence of runoff.

The results of the present paper are intended to complement a comprehensive and recently-published dataset on the oceanographic conditions of Glacier Bay. The results will also guide continuing efforts to model three-dimensional circulations in the bay.

1. Introduction

Freshwater input is one of the most critical parameters driving water properties within fjord estuarine environments (Pickard and Stanton, 1980). Fjord environments are characterized by high rates of stored and direct precipitation and a great degree of spatial and temporal variability in input levels can be expected within these estuaries. The runoff of freshwater to fjords influences critical hydrologic properties that have important biological implications, such as water column stability and flow dynamics as well as the introduction of suspended and dissolved materials (including sediment and nutrients) that can greatly alter water column properties. As a result, the spatial and temporal patterns of freshwater entering fjords are important in influencing primary productivity, aggregation and availability of prey, distribution of species, as well as dispersal of planktonic organisms, including larval stages of many benthic invertebrates and fishes.

The runoff of freshwater to the fjord environment not only has an influence on local estuarine dynamics, but can also be a significant contribution to regional coastal circulation and oceanographic properties. Contribution of freshwater discharge to the Alaska coastal current, excluding the contribution from the Copper River and glacier ablation, is estimated to have a mean value of roughly 23,000 $m^3\ s^{-1}$ (Royer, 1982). Estimating freshwater discharge from different sources is of particular interest, given the recent rapid wastage of Alaska glaciers, which can substantially contribute to rising sea level (Arendt et al., 2002; Larsen et al., 2007).

Much of our understanding of freshwater input within the high latitude environment of Alaska has come from southcentral Alaska and has focused on runoff to the northern Gulf of Alaska (Royer,

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1979, 1982, 2005; Royer et al., 2001; Wang et al., 2004; Royer and Grosch, 2006) with less attention having been paid to the southeast (Neal et al., 2002). For example, Royer (1979, 1982) is credited with the first extensive work to estimate runoff into the Gulf of Alaska. His model used runoff data from the mouth of Resurrection Bay, offshore of Seward, Alaska (southcentral), to construct a spatially uniform annual hydrograph for the region (including southcentral and southeastern Alaska). Differences in annual hydrographs, however, might be expected between coastal and fjord environments as well as between southcentral and southeastern Alaska due to differences in surrounding watershed characteristics and precipitation patterns.

Less work has been conducted on the dynamics of freshwater input to fjord estuaries, despite the important ecological role of these areas, which act as important feeding, nursery, wintering, and breeding grounds, for the abundance of species, including those of commercial importance as well as those with threatened or endangered status. Much of our knowledge of the role of freshwater input on Alaskan fjord dynamics comes from Prince William Sound within the southcentral part of the state (Simmons, 1996; Gay and Vaughan, 2001; Wang et al., 2004); however, some work has been conducted in the southeast (Neal et al., 2002).

Understanding the role of freshwater input on fjord dynamics is of particular interest in Glacier Bay, a fjord with tidewater glaciers in southeast Alaska that has experienced rapid deglaciation over the past 250 years (Fig. 1). A long-term monitoring program of oceanographic conditions in Glacier Bay is one of the few such long-term programs in southeast Alaska (Etherington et al., 2007). Building upon our knowledge of this estuarine system will aid in our understanding of fjords in southeast Alaska as well as the dynamics of fjords undergoing deglaciation. Examination of oceanographic patterns within Glacier Bay indirectly suggests that freshwater discharge is the mechanism leading to the greatest degree of spatial and seasonal change in salinity and stratification (Etherington et al., 2007). Stratification (largely a result of salinity) is strong from spring through fall with a broad peak in summer months, illustrating the seasonal influence of freshwater discharge. It is hypothesized that these sustained stratification levels, in conjunction with deep-water nutrient renewal from strong tidal mixing, lead to sustained phytoplankton biomass from spring through fall in Glacier Bay, which in turn supports an abundance and diversity of higher trophic levels (Etherington et al., 2007). These observations and hypotheses related to freshwater input within Glacier Bay highlight the need for a more complete understanding of the role of freshwater input on this critical estuarine system.

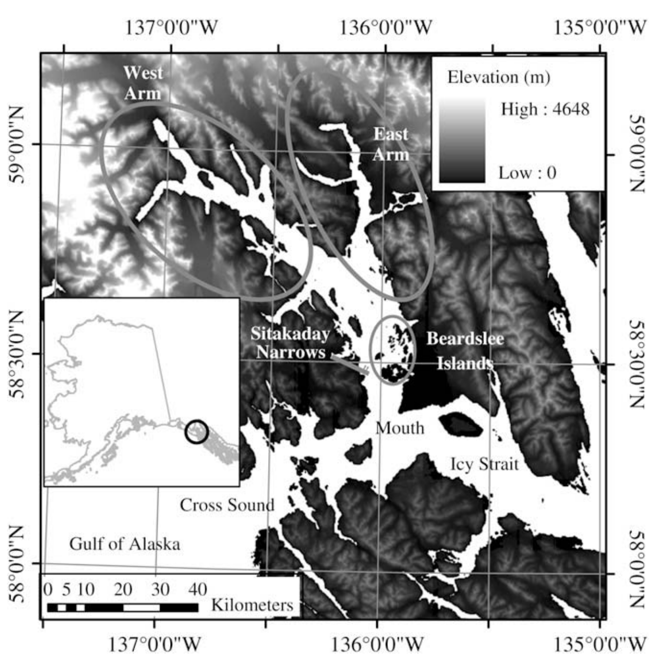

Fig. 1. Overview of Glacier Bay, and the outlying waters of Icy Strait and Cross Sound. Grayscale background indicates elevation and key place names are included. The inset shows the state of Alaska and the location (circle) of Glacier Bay.

The present manuscript seeks to advance this understanding by coupling estimates of freshwater input into Glacier Bay with highly-resolved simulations of the tidal flows in the bay. This work makes contributions in three areas. First of all, data and previous estimates of freshwater runoff into the bay are essentially non-existent. Second, published modeling studies and observations of tidal currents in the bay are extremely scarce. Cokelet et al. (2007) discuss an interesting but limited acoustic Doppler current profiler (ADCP) transect up the bay. The data reveal the strong spatial gradients in tidal speeds, with the lower bay having the highest speeds. Cheng et al. (2007) performed some preliminary modeling studies, but their simulations did not include freshwater runoff and did not include the outlying waters of Cross Sound and Icy Strait. Finally, the incorporation of freshwater runoff as boundary conditions to the tidal model presents some unique challenges in the case of Glacier Bay. In many estuarine situations (e.g. San Francisco Bay, Chesapeake Bay), the bulk of the freshwater input to the system is in the form of one or a few large, well-defined streams or rivers. In the case of Glacier Bay, the steep relief yields many hundreds of small, often ephemeral, streams that contribute flow to the bay. Focusing solely on the few largest streams would capture only a small fraction of the total drainage area to the bay and significantly underestimate the total freshwater flux.

The manuscript is organized in the following way. First, the characterization of the watersheds draining into Glacier Bay is discussed. Next, a set of regression equations developed for southcentral and southeast Alaska are adopted as a means of estimating freshwater discharges into the bay. Third, a limited set of stream gaging measurements are presented in order to assess the suitability of the regression equations. Finally, the tidal modeling of the bay is reviewed in detail, paying particular attention to the effects of the freshwater runoff.

2. Methods

2.1. Characterization of watersheds

Geographic information system (GIS) methods were used to determine the boundaries and the physical characteristics of the watersheds draining into Glacier Bay. Before proceeding, note that the terminology 'Glacier Bay' is often used to refer both to the waters in the bay proper (north of the bay mouth; Fig. 1) and the outlying waters in Cross Sound and Icy Strait. In this manuscript, 'Glacier Bay' will be used interchangeably with 'combined bay system' to refer to the overall domain shown in Fig. 1 and the term 'bay proper' will be used to focus attention on the waters north of the bay mouth.

The starting point for the characterization process was the digital elevation model (DEM) available from the United States Geological Survey (USGS) National Elevation Dataset (NED).[2] For Alaska, the nominal grid spacing for the NED is approximately 60 m. For the purposes of quantitative calculations of watershed characteristics (e.g. area) and for the tidal modeling, the DEM was projected onto the UTM Zone 8 coordinate system.

[2] National Elevation Dataset, http://seamless.usgs.gov (Accessed January 2007).