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Glacial isostatic adjustment along the Pacific coast of central North America

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ABSTRACT

We infer the GIA signal and its uncertainty along the central Pacific coast of North America using 680 sea-level index points and over 20,000 model runs sampling >700 (1-D) Earth viscosity models and 29 ice sheet reconstructions. Due to the large spatial extent and different tectonic settings of the study area, we divided it into three sub-regions (northern, central and southern) for which model parameters were inferred separately. Also, given that this region is tectonically active, the influence of this process (as well as sediment isostatic adjustment) was accounted for where possible by removing it from the data using published estimates. Our results indicate that it is not possible to produce an acceptable to for all of the RSL data with a single set of model parameters, suggesting significant lateral variability in viscous structure. Specifically, low viscosities (10^{19}–10^{20} Pas) are inferred in the upper mantle within the northern region (southwestern British Columbia and northwest Washington) compared to those inferred (2–5×10^{20} Pas) for the central and southern regions (extending from southern Washington to southern California). High quality model fits were obtained for all data except those from the northern region where no single parameter set was able to capture both the rapid and large RSL fall during the late glacial and the monotonic rise during the mid-to-late Holocene at all localities. This suggests the need for an Earth model that incorporates departures from a linear Maxwell rheology (as applied here) and/or lateral variations in viscosity structure. Using our optimal model parameter sets, we show that GIA is a significant contributor to both contemporary vertical land motion and relative sea level change in our study region and so should be considered when interpreting observations of these signals and for making future relative sea level projections. Model output of present-day vertical land motion at 483 GPS stations and sea-level change at 56 tide gauge stations is provided (with estimated uncertainty) so that these data can be used to study non-GIA processes more accurately.

1. Introduction

The Pacific coast of central North America is a geodynamically complex region. It is the location of an active convergent plate boundary, known as the Cascadia subduction zone, where the Juan de Fuca, Explorer and Gorda plates subduct beneath the North America plate. Furthermore, parts of this coastline were once covered by the Cordilleran ice sheet and were proximal to the Laurentian ice sheet during the peak of the last major glaciation, resulting in a considerable isostatic response in many areas. This complexity is reflected in a variety of data types, including geodetic measurements of 3-D land motion, instrumented (tide-gauge) and reconstructed observations of relative sea-level (RSL) change. Numerous studies have examined these data with the intent of better understanding the underlying processes and/or constraining models (Dragert et al., 1994; Hyndman and Wang, 1993, 1995; Smith-Konter et al., 2014; Veit and Conrad, 2016; Wang et al., 2003; Wang, 2007). A common issue that arises is the difficulty in removing the unwanted component signals from the data under consideration.

A number of studies have modelled reconstructions of RSL change in the vicinity of the Cascadia subduction zone to assess the accuracy of glacial isostatic adjustment (GIA) models and constrain input parameters, such as mantle viscosity structure (e.g. Clague and James, 2002; Dalrymple et al., 2012; James et al., 2000; James et al., 2009b; Muhs et al., 2012; Roy and Peltier, 2015). Roy and

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Peltier (2015) modelled RSL values along the pacific coast of North America, from Vancouver Island to Central California, using the ICE6G_C ice model combined with three different radial viscosity models. A comparison between their models and the compiled RSL histories (Engelhart et al., 2015) indicates that the models do not adequately fit the whole dataset. The discrepancies between their model output and the data were notably largest in western Vancouver Island, the southern part of Georgia Strait, and parts of the California coast. Roy and Peltier hypothesised that the majority of these discrepancies are associated with tectonic effects, although estimates of this contribution are not discussed. The authors suggest that data-model misfits in southern Georgia Strait, which is close to the Cordilleran ice margin, are associated with errors in the ice history and/or subsidence due to sediment loading.

In northern Cascadia, GIA studies using RSL observations and lake-shoreline tilt suggest low-viscosity values for the upper mantle ranging from 5×10^{18} to 5×10^{19} Pas (James et al., 2000, 2005). Adopting these relatively low viscosity values leads to present-day crustal uplift rates of ~0.1 mm/yr in southern Vancouver Island (James et al., 2009a) and 0.25 mm/yr in the northern Strait of Georgia (James et al., 2005). James et al. (2009b) found that an asthenosphere with viscosity range of 3×10^{18} Pas (for a 140 km-thick asthenosphere) to 4×10^{19} Pas (for a 380 km-thick asthenosphere) can fit the observations reasonably well. Their predicted present-day uplift rate over Vancouver Island is ~0.4 mm/yr which is larger than that estimated in previous studies.

In southern regions, including southern Washington, Oregon and California, a persistent subsidence has occurred following ice retreat. This has been interpreted as peripheral bulge (forebulge) collapse (Muhs et al., 2012; Reeder-Meyers et al., 2015; Reynolds and Simms, 2015). Although the northern regions proximal to the ice covered areas are affected more by GIA, the departure of sea level observations from the sea-level change due to meltwater addition (often termed eustatic or ice-equivalent sea level) can be interpreted as the imprint of GIA and tectonics in this region. Muhs et al. (2012) considered coral terraces on San Nicolas Island (offshore southern California) dated to MIS5. They adopted an upper mantle viscosity of 5×10^{20} Pas and found that the observations were compatible with lower mantle viscosity values in the range $5–10 \times 10^{21}$ Pas. Their results indicate a mean rate of uplift for San Nicolas Island of 0.25–0.27 mm/yr since MIS 5. Dalrymple et al. (2012) provided RSL model predictions for a few cities such as Pacific City, Waldport, Coos Bay, Eureka, and etc. based on the ICE-5G and ICE-6G models combined with the VM5a Earth model (Peltier and Drummond, 2008; Argus and Peltier, 2010; Peltier, 2010). These models generally predicted a higher rate of sea-level rise during late Holocene, resulting in the modelled curve being too deep compared to the observations.

The primary aim of this study is to constrain GIA model parameters for the Pacific coast region, extending from Vancouver Island to southern California. This work builds on those introduced above in several respects. Following Roy and Peltier (2015) we make use of the regional, quality assessed database of Engelhart et al. (2015) but extend this to include data from California (Reynolds and Simms, 2015). We explicitly consider and, where possible, correct for the influence of non-GIA processes on the RSL observations to arrive at relatively robust estimates of Earth viscosity structure. We consider a large range of Earth viscosity parameters (704 viscosity profiles) and ice histories (29 models) to sample parametric uncertainty more completely than in previous studies. In total, over 20,000 model runs were performed in carrying out the work presented below. A key contribution of this paper is the estimation of model parametric uncertainty. We provide spreadsheets of model output of present-day rates of vertical land motion and RSL change at 483 GPS stations and 56 tide gauge stations so that end users can remove the GIA signal and focus on that due to other processes such as tectonics. Finally, as indicated in past studies and confirmed here, there is strong evidence for lateral variations in Earth properties along the east Pacific coastline. All GIA studies to date (including this one), have applied a 1D (properties varying with depth only) Earth model. A second aim of this study is to provide a crude estimate of the lateral variations in Earth viscosity structure that will form the basis of a future study that explicitly considers lateral variations in Earth viscosity structure.

2. Methods

2.1. Observations

We have made use of two recently published compilations of sea-level records: one from Vancouver Island to Central California (Engelhart et al., 2015), and one from Central California to Southern California (Reynolds and Simms, 2015). The combined dataset is subdivided into 13 areas or sites (hereafter referred to as sites; Fig. 1). Sites 1–11 comprise the data compiled by Engelhart et al. (2015) and we have adopted the same criteria used by these authors (e.g. tectonic setting, distance from former ice sheet) to partition the data into the 11 sites. Site 12, Central California coast, comprises data from both Engelhart et al. (2015) and Reynolds and Simms (2015). The most southerly site, 13, uses data from Reynolds and Simms (2015) only. The total dataset consists of 178 freshwater indicators (upper limiting), 163 marine indicators (lower limiting), and 680 sea-level index points (SLIPs) to constrain past sea-level change in our study region. The number of each of these data types per site and the spatial distribution of SLIPs are shown in Table S1 and Fig. 1, respectively.

Based on the late-Quaternary ice coverage and tectonic setting of the study region, we divided the entire dataset into three subregions: northern (British Columbia and northern Washington), sites (1–7); central (southern Washington and Oregon), including sites 8, 9, and 10; and southern (California), including sites 11, 12, and 13. The northern region sites were once covered by the Cordilleran ice sheet with the southern margin extending, at most, to the area defined by site 7 (Clague and James, 2002; James et al., 2009a). The central region comprises the sites located south of the former ice sheet margin and north of the Mendocino Triple Junction. These sites have a similar tectonic regime and have experienced, in general, long-term crustal uplift due to the subduction of Juan de Fuca plate (Atwater, 1987; Burgette et al., 2009; Kelsey et al., 1996; Merritts and Bull, 1989; Muhs et al., 1992). In the southern region, which extends from the Mendocino Triple Junction to southern California, the primary tectonic boundary is conservative with strike-slip motion across the San Andreas Fault system (Brown, 1990; Crowell, 1962; Grove et al., 2010; Simkin et al., 2006).

Fig. 2 displays the sea-level data reconstructed for the 13 sites. The majority of the SLIPs in the northern region date to the pre-to-early Holocene and late Holocene. Data from the northern region record a rapid RSL fall immediately upon deglaciation of the Cordilleran ice sheet (from ~15 to ~12 ka); following this, sea levels rose gradually during early-to-mid Holocene followed by relatively stable values in the mid-to-late Holocene. At the central and southern sites, the reconstructions show RSL always below present and continuously rising during Holocene. The rate of sea level rise in the early-to-mid Holocene is higher than that in the late Holocene due, mostly, to the decrease in the rate of both meltwater input and peripheral bulge subsidence. For more discussion and details about the RSL reconstructions, please refer to Engelhart et al. (2015) and Reynolds and Simms (2015).