Validation of Sea levels from coastal altimetry waveform retracking expert system: a case study around the Prince William Sound in Alaska

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Abstract This paper presents the validation of Coastal Altimetry Waveform Retracking Expert System (CAWRES), a novel method to optimize the Jason satellite altimetric sea levels from multiple retracking solutions. The validation is conducted over the region of Prince William Sound in Alaska, USA, where altimetric waveforms are perturbed by emerged land and sea states. Validation is performed in twofold. First, comparison with existing retrackers (i.e. MLE4 and Ice) from the Sensor Geophysical Data Records (SGDR), and second, comparison with in-situ tide gauge data. From the first validation assessment, in general, CAWRES outperforms the MLE4 and Ice retrackers. In 4 out of 6 cases, the value of improvement percentage (standard deviation of difference) is higher (lower) than those of the SGDR retrackers. CAWRES also presents the best performance in producing valid observations, and has the lowest noise when compared to the SGDR retrackers. From the second assessment with tide gauge, CAWRES retracked sea level anomalies (SLAs) are consistent with those of the tide gauge. The accuracy of CAWRES retracked SLAs is slightly better than those of the MLE4. However, the performance of Ice retracker is better than those of CAWRES and MLE4, suggesting the empirical-based retracker is more effective. The results demonstrate that the CAWRES would have potential to be applied to coastal regions elsewhere.

1. Introduction

An accurate coastal sea level measurement has been a great demand by the scientific community for various applications. For examples, the accuracy of 1 mm/year is desired for measuring sea level rises and of 10 cm is required for detecting eddies in the East Australian Current system. Nowadays, local coastal forecast systems such as BLUElink Ocean Model Analysis and Prediction System [OceanMAPSv1.0b; 1] are already exploiting the coastal altimetry data for operational applications. The parameter of sea level anomaly (SLA) is derived quantitatively from satellite altimetry observations. However, within 200 m isobaths, the altimetry SLAs are not assimilated in the system due to land contamination in coastal altimetry signals, and lower accuracy of geophysical and atmospheric corrections [1].

Issues regarding the altimetry data over coastal have becomes an overwhelm discussion by the scientists worldwide. They realized the needs of specific treatments for recovering the altimetry data over coastal, so that the accuracy of the data is as good as the open ocean. Specific treatment is needed to correct the corrupted altimetry signals due to the land contamination [cf. 2, 3]. This can be performed by 'retracking' waveform that applies the coastal retrackers [e.g. 4, 5-10] to correct the estimation of geophysical parameters (i.e. SLA, significant wave height and wind speed). Waveform retracking has been conducted over global oceans to improve the accuracy of the altimetry measurements. When retrieving SLAs near coastal, attention is also needed when applying the corrections of sea states (e.g. inverse barometer and sea state bias) and of atmospheres (e.g. wet and dry tropospheric, and ionospheric) because they are less accurate due to high variability of the ocean signals and land contamination [11]. The state-of-the-art about retracking and geophysical corrections can be found in the book *Coastal Altimetry* by Vignudelli [12].

Innovative ideas is continuously developing to provide alternative approach to better accuracy of altimetry data from corrupted waveforms near coastal. These include modification of the standard Brown model [e.g. 13] to fit the noisy coastal waveforms, retracking of multiple waveforms [e.g. 7, 9, 14] to exploit the inter-waveform properties, retracking of reduced gate of waveforms [e.g. 8, 15, 16, 17] to exclude the non-ocean signals, and retracking using multiple retrackers based on the expert system [e.g. 18, 19-21] to select the optimal retracker.

The Coastal Altimetry Waveform Retracking Expert System (CAWRES) developed by Idris and Deng [6] is designed to optimize the estimation of SLAs by selecting the optimal retracker via a fuzzy expert system, and to provide a seamless transition from the open ocean to the coasts (or vice versa), when switching retrackers, via a neural network approach. Through the system, the fuzzy expert system is exploited to improve the selection method of the retrackers by integrating information about the physical features of waveforms and the statistical features of retracking results. Validation of the CAWRES retracked SLAs over the region of the Great Barrier Reef in Australia has been reported in Idris [2]. It shows that the SLAs from CAWRES generally outperform those from conventional methods. The retracked SLAs have satisfactory agreement with in-situ tide gauges.

In this paper, the validation of CAWRES is performed over the region of the Prince William Sound in Alaska, USA. The region is surrounded by steep and glaciated mountains, rough coastal sea states due to the notoriously stormy seas, and a complex hydrological system of freshwater from rivers and glaciers. The validation protocol is twofold: 1) comparison with existing retrackers from SGDR product and geoidal heights, and 2) comparison with tide gauge data. The comparison with tide gauge evidences to finding the accuracy and precision of the SLAs, while with the geoidal height, only the precision can be estimated.

2. Study Area and Data

The CAWRES has been applied to waveforms in the region of Prince William Sound (Figure 1). Waveforms in this area are highly perturbed by the mountainous terrain, varying ocean depth, complicated coastal geometry, and rough coastal sea states due to the notoriously stormy seas, and a complex hydrological system of freshwater from rivers and glaciers.

The Prince William Sound is a small (~100 km^2) semi-closed sea located in the northeast corner of the Gulf of Alaska. It is connected to the Northern Gulf of Alaska via two major passages: Hinchinbrook Entrance and Montague Strait, and has complex bottom topography and coastal orography. The maximum water depth, which is not shown, is about 800 m. To some extent, Prince William Sound also has the character of an estuary due to the strong runoff from snowmelt along the shoreline, especially in late summer/early autumn. The coastline is convoluted with many islands and fjords, several of which contain tidewater glaciers. It is surrounded by the Chugach Mountains, which reach a height of 4,300 m, and contain the most extensive system of valley glaciers in North America. With a shoreline length of about 6,900 km and a tidal range of 6-8 m, Prince William Sound has an enormously varied shoreline habitat of reefs, rocks, mud flats, eelgrass beds, wetlands, and cobble beaches [22]. Thus, altimetry data in this region can capture diverse patterns because of the mountainous terrain, the notoriously stormy seas, and a complex hydrological system of freshwater from rivers and glaciers.

The data used are Jason-1 and Jason-2/OSTM during the tandem mission. The Ku-band 20-Hz 104-sample waveform data are from January 2009 to December 2011, which corresponds to cycles 262 to 370 of Jason-1, and cycles 19 to 143 of Jason-2. Waveforms along one ascending pass (123) and two descending passes (28, and 104) of Jason-1, and two ascending passes (47, and 123) and one descending pass (28) of Jason-2 are investigated in the area of Prince William Sound (Figure 1).

In producing SLAs, environmental and geophysical corrections from SGDR products, and the DTU10 mean sea surface are applied to the altimeter range. The wet and dry tropospheric corrections are from the European Centre for Medium-Range Weather Forecasts (ECMWF) numerical prediction models, and ionospheric correction is from the General Ionospheric Model Map. The more accurate instrumental radiometer wet correction and dual frequency ionospheric correction are not used because of coastal contamination effects. The ocean tidal signals are removed using a pointwise tide modelling (Idris et al. 2014) rather than the global ocean tide model such as FES2004 and GOT4.8

because it better resolves the tidal signals in the study region. The sea state bias correction is not applied because it is not appropriate for waveforms near coasts. It is applied neither to coastal data, to avoid additional error, nor to open ocean data, to keep consistency of datasets in the area. The corrections have been interpolated from 1 Hz to 20 Hz.

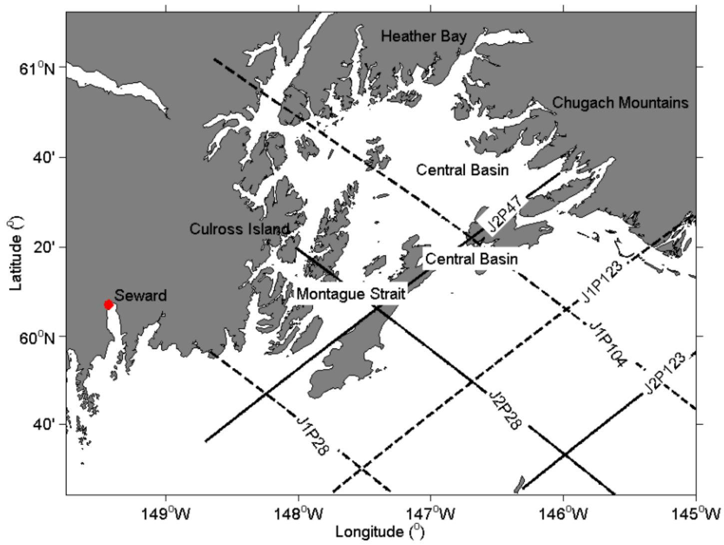

Figure 1. Jason-1 and Jason-2/OSTM satellite passes in Prince William Sound, Alaska. The red star shows the tide gauge station.

The quality and consistency of sea levels derived from the CAWRES is compared with in-situ measurements of geoid height and tide gauges. The geoidal height is based on the Earth Gravitational Model 2008 (EGM2008) with 2.5 minute resolution (http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08wgs84.html). The tide gauge data are from the University of Hawaii Sea Level Centre (http://ilikai.soest.hawaii.edu/uhslc). It is the hourly sea level data from Seward (60.072°N, 149.3°W) stations (see Figure 1). The assessment with tide gauge merits to finding the accuracy and precision of the SLA estimates, while with the geoidal heights, only the precision can be computed.

3. Validation of Retracked Sea Level from CAWRES

The quality of retracked sea levels from CAWRES is assessed by comparing the results with other existing retrackers available from the SGDR product (Section 3.1). The accuracy of the results are also compared with tide gauge data (Section 3.2).

3.1 Comparison with Existing Retrackers in the SGDR Product

Comparison between the CAWRES retracked sea surface heights (SSHs) with existing retrackers from the SGDR product is performed. The retrackers from SGDR product are the MLE4 and Ice retrackers. The parameter of SSHs is used to enable comparison with geoid height. It is realized that both datasets are relative to difference ellipsoid. However, conversion of reference ellipsoid is not performed because the impact on the analysis is assumed to be insignificant, as the STD and IMP are computed over a short SSH profiles (~10 km from the coastline) or small areas.

Three assessments are carried out: 1) the standard deviation of difference (STD) between retracked sea level with respect to geoid height and the improvement of percentage (IMP) of the sea levels; 2) the STD between 20 Hz retracked SLAs and its average 1 Hz SSHs, hereafter called ‘the noise STD’; and 3) the percentage of reasonable sea levels after removing outliers with predefined editorial criterion.

The IMP can be computed using Equation 1 [23],

$$IMP = \frac{\sigma_{raw} - \sigma_{retracked}}{\sigma_{raw}} \times 100 \quad (1)$$

where σ_{raw} and $\sigma_{retracked}$ are the standard deviation of the difference between raw SSHs and geoid heights, and retracked SSHs (e.g. CAWRES or Ice) and geoid heights, respectively. The raw SSHs are the SSHs retracked by the MLE-4 retracker because it is the standard retracking solution for the ocean.

Table 1 and Table 2 show that CAWRES improves the precision of the MLE4 SSHs over the region in 4 out of 6 passes. The IMPs are improved up to 33% for Jason-1 and 54% for Jason-2. However, deterioration in precision is found in pass 104 of Jason-1 and pass 47 of Jason-2, where the CAWRES retracked SSHs have negative IMPs (-7% and -22.2%, respectively). This suggests that the MLE4 retracked SSHs have a better precision than those of the CAWRES in both passes. Although deteriorations are recorded in both passes, results in Figure 2 show that the CAWRES recovers more (up to 70%) data than the MLE4 retracker. The percentage near the coast is extremely large (up to 70%), suggesting that the CAWRES retrieves more data than those of the MLE4 retracker. This also indicates that the CAWRES has extended the SLAs much closer to the coastline than those of the MLE4 retracker.

Table 1. STDs and IMPs between the Jason-1 retracked SSHs and the geoid heights.

Pass	**MLE4 retracker**	**CAWRES**		**No. of points**
	STD (cm)	**STD (cm)**	**IMP (%)**	
28	34	31	8.8	25,020
104	43	46	-7	53,362
123	46	31	32.6	62,262

Table 2. STDs and IMPs* between the Jason-2 retracked SSHs and the geoid heights.

Pass	**MLE4 retracker**	**CAWRES**		**Ice retracker**		**No. of points**
	STD (cm)	**STD (cm)**	**IMP (%)**	**STD (cm)**	**IMP (%)**	
28	65	30	**53.8**	54	16.9	54,487
47	45	55	-22.2	69	-53.3	36,120
123	12	11	**8.3**	15	-25	38,019

*The highest IMPs are indicated by bold numbers.

When compared to SGDR Ice retracker (Table 2), the IMPs (STDs) of CAWRES are always higher (lower), suggesting that CAWRES retracked SSHs are less noisy than those of Ice retracker. Along passes 47 and 123, Ice retracked SSHs show worse performance when compared to MLE4 retracked SSHs with -53.3% and -25% of IMPs.

Results in Table 3 show the number of reasonable SSHs and noise STDs of retrackers over the Prince William Sound region. When compare with SGDR retrackers, CAWRES presents the best performance in producing valid observations up to 84% and 85% for Jason-1 and Jason-2, respectively. The reasonable SSHs retrieved by the MLE4 are much less as ~54% and 71% of total dataset, respectively, while by the Ice retracker are ~72% for Jason-2. The same results can also be observed from Figure 2. This suggests that CAWRES is an effective method to enhance the spatial resolution of coastal altimetry data.

Beside the increment in the validity of the measurements, CAWRES also has the lowest noise STD when compared to the SGDR retrackers (Table 3). For Jason-1, CAWRES produces slightly smaller noise STD (46 cm) than the MLE4 retracker (48 cm), while for Jason-2, their values are similar (62 cm). The noise STD of Ice retracker is slightly higher (63 cm) than those of the CAWRES and MLE4 retrackers. However, it is realized that the difference in the noise STD of all retrackers is insignificant. Table 3 tells that, in general, CAWRES can spatially recover more SSHs than MLE4 (see also Figure 2) and Ice retrackers, and meanwhile achieves similar data quality to MLE4 and Ice other retrackers. This, therefore, confirms that CAWRES outperforms the SGDR retrackers over the tested region.

Table 3. Number of reasonable SSHs and noise STD of retrackers over the Prince William Sound region

Jason-1 missions			
Retracker	**Total number of SSHs**	**Numbers of reasonable SSHs (%)**	**Noise STD (cm)**
CAWRES	139,380	117,165 (84.06)	46
MLE4	139,380	75,145 (53.91)	48
Jason-2 missions			
CAWRES	135,680	115,221 (84.92)	62
MLE4	135,680	96,562 (71.17)	62
Ice1	135,680	97,668 (71.98)	63

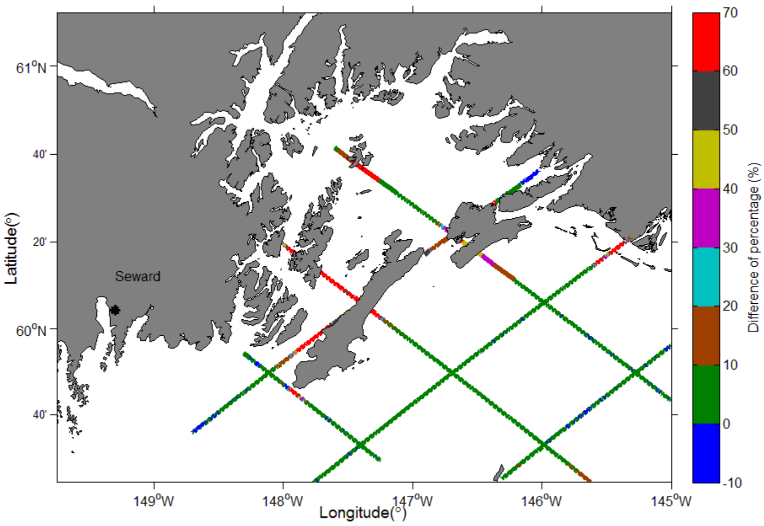

Figure 2. Spatial plot of the difference of SLA data recovered (in percentage) by the CAWRES and the MLE4 retracker. A positive value means the CAWRES retrieves more data than the MLE4 retracker

3.2 Comparison with Tide Gauge Data

In comparison with tide-gauge data, the performance of CAWRES and SGDR retrackers is assessed by computing the mean values of temporal correlation and root mean square (RMS) error (Table 4) in the area near (<100 km) the Seward station. They are computed from Jason-1 (J1), Jason-2 (J2) and the combination of Jason-1 and Jason-2 (J1+J2) data. These values are not computed for the Jason-1 Ice retracker because it is unavailable from the SGDR products. Figure 3 shows the spatial plots of temporal correlation and RMS error of the retrackers over the region.

Results from Table 4 and Figure 3 show that there is a satisfactory agreement between the retracked SLAs from the CAWRES and the tide gauge. The mean value of the temporal correlations (RMS errors) of the CAWRES is slightly higher (lower) than that of the MLE4 retracker, suggesting that the SLAs from CAWRES are more accurate than those of the MLE4 retracker.

When comparing with the Ice retracker, it is seen that the temporal correlation (0.94) of Ice retracker is better than those of the CAWRES (0.86) and MLE4 retracker (0.85). It is noted that no significant difference in their RMS errors (~7 cm). This is an astonishing result as the Ice retracker is intended for hydrology and cryosphere applications, and not for Open Ocean or coastal applications. It, however, outperforms the MLE4 of an ocean retracker. A similar result has been found in the Arctic ocean by Jain et al. (2015), where the performance of the Ice retracker is found superior than the physical-based (i.e. MLE4) retracker in comparison with the tide gauge data. In the cryospheric areas, like in the Arctic and the Prince William Sound, the physical-based retrackers may be ineffective because the ocean usually have a significant presence of sea ice, thus affecting the accuracy of estimated SLAs.

From Table 4, it is realized that the accuracy of Jason-2 retracked data is better than that of Jason-1 data. This is partly due to a stable mispointing angle of Jason-2, while mispointing angle of Jason-1 is severe. That is, the Jason-1 slope of waveform trailing edge departed from the value expected for a nadir-pointing instrument [24], thus affecting the accuracy of the estimations.

The plot of the SLA time series from different retracking methods and tide gauge at nine locations around Prince William Sound is shown in Figure 4 (refer to Figure 3a for the distribution of the locations), along with their correlations and RMS errors. The retracked SLAs from the Ice retracker are not shown in Figure 4a to Figure 4e because they are unavailable from the Jason-1 SGDR products.

Based on results in Figure 4, in general, the performance of both CAWRES and MLE4 retrackers are almost equal with slight differences in the value of correlations and RMS errors. It is seen that in some cases (Figure 4a, b, and e), the correlation and RMS error of the MLE4 retracker are slightly better than those of the CAWRES, and vice versa (Figure 4c, g and h). However, the accuracy of Ice retracker is always better than those of the other two retrackers (Figure 4g-i), proving that it is the optimal solutions for retrieving accurate SLAs over the tested region.

The results shows that the CAWRES provides retracked SLAs that agree with tide gauge data at almost all locations with correlations $\geq$0.57 and RMS errors $\leq$23 cm, except for locations d and f (Figure 4d and Figure 4f), where the CAWRES shows disagreements. In such complicated locations, the CAWRES as well as the SGDR retrackers fail to produce accurate SLAs, mainly due to the extreme corruption of waveforms and data corrections (e.g., tides, wet and dry tropospheric delays). The SLAs retracked by the MLE4 are totally missing in Figure 4d, indicating that the MLE4 cannot fit waveforms at that coastal location. The SLAs near the coast retracked by the MLE4 (e.g., Figure 4c) and Ice retrackers (e.g., Figure 4f) are sometimes discarded as the waveforms are highly perturbed by emerged lands and coastal sea states.

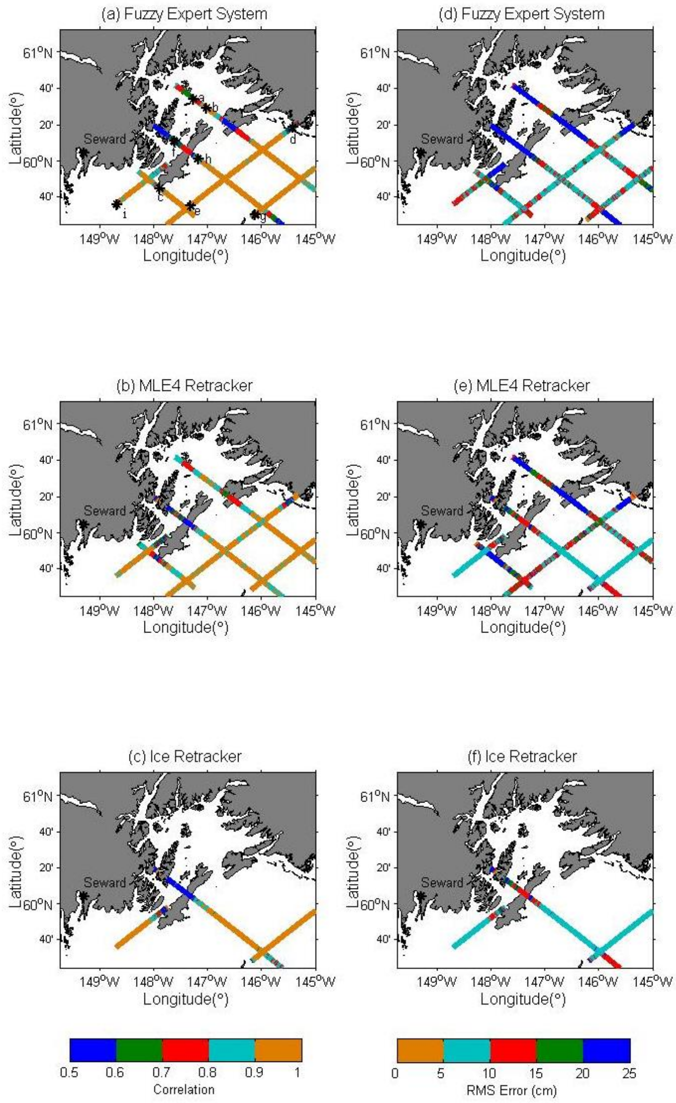

Figure 3. Spatial plots of the temporal correlation (left panels) and RMS error (right panels) of the sea level anomalies from the CAWRES and the Seward tide gauge station. The SLA time series at locations a-i (black dots in a) is shown in Figure 4.

Table 4. Mean of temporal correlation and RMS error in the area near (<100 km) the Seward tide gauge station

Mean temporal correlation						
CAWRES			**MLE4**			**Ice**
J1	**J2**	**J1+J2**	**J1**	**J2**	**J1+J2**	**J2**
0.84	0.86	0.87	0.60	0.85	0.67	0.94
Mean RMS error (cm)						
7	7	12	30	7	24	7

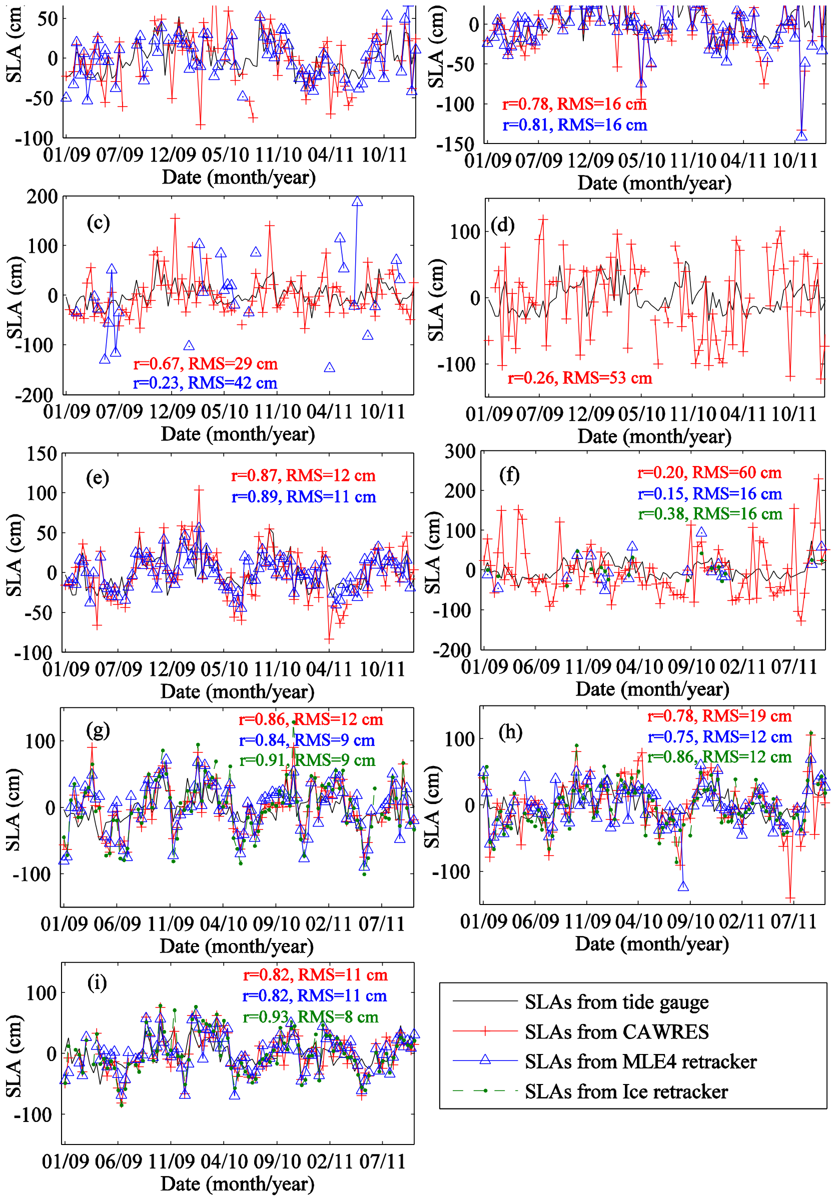

Figure 4. Time series of the sea level anomalies from different retracking methods and tide gauge at nine locations around the Prince William Sound (see Figure 3a). The retracked SLAs shown in a-e are from the Jason-1 mission, while the retracked SLAs shown in f-i are from the Jason-2 mission. The retracked SLAs from the Ice retracker are not shown in a-e because they are unavailable from the Jason-1 SGDR product. The retracked SLAs from the MLE4 retracker are unavailable in d. The temporal correlation (r) and RMS error of for each retrackers are also shown in each subplots.

4 Conclusions

The results over the tested regions emphasize that the retracked sea levels from the CAWRES are consistent with those of the geoid height and tide gauges. It reduces the STD of the MLE4 retracked sea levels by up to 15 cm for Jason-1 and 35 cm for Jason-2. It recovers 12-30% more data than the MLE4 and Ice retrackers over the regions. Although CAWRES improves the spatial resolution of the coastal altimetry data over those regions, sometimes, the quality of the retrieved SLAs is poor. Therefore, the CAWRES products should be used with caution. Analysis with tide gauge indicates that the retracked SLAs from Ice retracker outperform the CAWRES and MLE4 retracker, suggesting that the empirical-based retracker is more effective when over the ocean with significant presence of sea ice. With respect to the standard MLE4 retracker, CAWRES produces more accurate and precise SLAs. Current research is undertaken to compare the CAWRES SLAs with the Regional Ocean Model System (ROMS) over the Prince William Sound to identify their consistency.

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