Sea level in ocean reanalyses and tide gauges

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[1] Previous studies have noted the presence of interannual to multidecadal variability in tide gauge sea level records which is correlated with meteorological variability and which can overwhelm the signal associated with global sea level rise. This study examines the usefulness of using a set of seven ocean reanalysis and synthesis products in studies of sea level variability by comparing the tide gauges and reanalysis products at a representative set of 87 tide gauge station locations. The comparison is carried out for both a half-century base period and a century long-extended period. Treating the set of products as an ensemble of realizations obtained using different techniques, the results show generally good agreement for the half-century period with ensemble average correlations of 0.57 and RMS differences of 2.2 cm, reducing to a correlation of 0.5 for the extended period. A significant fraction of the difference between tide gauge sea level and product sea level is associated with meteorological forcing. These results support the conclusion that much of the interannual to multidecadal variability that appears in the tide gauge records is meteorologically driven. This suggests that ocean products have potential to be used to isolate this variability from the signal associated with the underlying global sea level rise.

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1. Introduction

[2] Coastal ocean tide gauge time series contain unique information about historical basin-scale variability as well as information about global sea level rise. They are also sparsely and unevenly distributed in space and time. Estimating the 20th century rate of global sea level rise, and even more so any possible acceleration early in the century, must contend with the presence of strong interannual to multidecadal variability, which observational studies suggest is the result of wind-driven ocean dynamics [*Miller and Douglas*, 2007; *Kolker and Hameed*, 2007; *Woodworth et al*., 2010; *Sturges and Douglas*, 2011]. Ocean reanalyses/syntheses that take account of indirect information such as surface meteorology and direct observations of ocean variables should be able to represent these processes and thus provide a reasonable estimate of regional sea level variability. As a first step toward integrating tide gauge and product sea level estimates, this study presents comparisons of seven reanalysis/synthesis products to 87 multidecadal tide gauge records during a 62 year base period 1950–2011 and a 111 year extended period 1900–2010. We examine their consistency and explore the extent to which the products can be used to augment the limited sampling of the tide gauge network.

[3] Since 1991 continuous remotely sensed sea level with near-global coverage has been provided by a succession of satellite altimeters with centimeter accuracy [*Leuliette et al*., 2004]. Prior to this date, the primary sources of information are the coastal and island tide gauge records [*Woodworth and Player*, 2003]. These tide gauges measure sea level relative to a ground datum, and thus revised local reference tide gauge sea level involves both land motion and oceanographic processes. Major contributions to the former include postglacial isostatic adjustment and earth loading changes, but many other effects may dominate locally. The latter includes a wide variety of interesting interannual to multidecadal basin-scale phenomena with amplitudes ranging from centimeters to tens of centimeters [e.g., *Ezer*, 1999; *Tsimplis et al*., 2006; *Church and White*, 2006; *Koerper et al*., 2009; *Yin et al*., 2011; *Hu et al*., 2011; *Qiu and Chen*, 2012].

[4] The case can be made that much of this variability is locally or remotely wind forced [*Kolker and Hameed*, 2007; *Woodworth et al*., 2010; *Sturges and Douglas*, 2011]. For example, sea level along the west coast of the United States shows both equatorially forced ENSO signals that propagate poleward as coastal waves and decadal variability forced by changes in the local wind systems associated with the Pacific Decadal Oscillation (PDO) of North Pacific winter climate [*Clarke and Van Gorder*, 1994; *Minobe*, 1997; *Miller and Douglas*, 2007]. In the eastern North

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Table 1. Ocean Product Sea Level Comparison to Tide Gauge Sea Level[a]

Product	Time Span	Resolution	η_{obs}	COR	ΔRMS	EOF1
CERFACS[b]	1962–2001	$2° \times 2°$ 31L	No	0.51	0.96	+6
ECMWF ORA-S4[c]	1958–2011	$(0.3° - 1°) \times 1°$ 29L	Yes	0.59	0.78	+10
GECCO[d]	1952–2001	$1° \times 1°$ 23L	Yes	0.52	0.91	+6
INGV[e]	1962–2001	$2° \times 2°$ 31L	No	0.58	0.84	+9
MOVE/MRI[f]	1949–2007	$(0.3° - 1°) \times 1°$ 50L	Yes	0.57	0.82	+7
POAMA2[g]	1960–2011	$(0.5° - 1°) \times 1°$ 25L	No	0.56	0.82	+8
SODA 2.2.4[h,i]	1871–2010	$0.25° \times 0.4°$ 40L	No	0.57	0.84	+7

[a]Statistical comparisons at the 87 tide gauge station locations are computed over the base period 1950–2010 (or shorter for those products which do not span the full period). Three products assimilate satellite sea level (η_{obs}). The data were smoothed by 2 year running filter prior to computing statistics. The average correlation (COR) and RMS difference normalized by the standard deviation of the tide gauge sea level (ΔRMS) were computed over the full station set. The first three empirical orthogonal eigenfunctions of the tide gauge time series over the full time period explain 52%, 10%, and 5% of the variance. These numbers become 38%, 17%, and 7% for the products with the shortest time span (CERFACS and INGV). The final column shows the increase in variance explained by the first EOF of the difference between tide gauge sea level and product sea level relative to the tide gauge sea level.
[b]*Daget et al*. [2009].
[c]*Balmaseda et al*. [2013].
[d]*Kohl and Stammer* [2008].
[e]*Davey* [2005].
[f]*Usui et al*. [2006] and *Tsujino et al*. [2011].
[g]*Yin et al*. [2011].
[h]*Carton and Giese* [2008].
[i]*Giese and Ray* [2011].

Atlantic shifts in the wintertime position of the North Atlantic storm tracks, a phenomenon known as the North Atlantic Oscillation (NAO), is likewise observed to be correlated with alongshore winds and coastal sea level [*Woodworth et al*., 2010; *Sturges and Douglas*, 2011; *Calafat et al*., 2012].

[5] There have been a number of efforts to make spatial reconstructions of regional sea level based on tide gauge time series for example by using projections on stationary patterns generally obtained from altimetry [e.g., *Church and White*, 2011; *Meyssignac et al*., 2012]. However, the percentage of sea level variability explained by these projections is not high, raising doubts about the validity of this approach [*Christiansen et al*., 2010; *Ray and Douglas*, 2011].

[6] Ocean reanalysis/synthesis products offer a complementary approach to those described above by reconstructing the time evolving state of the ocean by using historical observations (e.g., temperature, salinity, and sea level) to constrain a numerical simulation of the fluid equations of motion [*Carton et al*., 2005; *Berge-Nguyen et al*., 2008; *Meyssignac et al*., 2012]. There are now over 20 global such products [e.g., *Xue et al*., 2012], but only a few of these extend back to the era before continuous satellite altimeter sea level observations (before 1991). These products almost uniformly lack key processes such as the contribution to ocean mass due to continental ice melt and river discharge and glacial isostatic adjustment [*Peltier*, 2004], and also lack the detailed effects of near-coastal circulation. Recently, *Hay et al*. [2012] has proposed to include earth motion in a data assimilation algorithm. However, their proposed approach lacks the complementary regional ocean dynamics needed to complete a model of regional sea level variability.

[7] As a preliminary attempt to explore the usefulness of reanalysis/synthesis sea level products in extending the value of the tide gauge sea level network here we compare sea level from seven products listed in Table 1 to a reference set of 87 tide gauge records. Our goal is to explore the similarities of the two types of sea level estimates and understand the extent to which the two can be combined to improve representation of regional sea level variability.

2. Data and Methods

[8] The tide gauge records used in this comparison are 87 of the 89 monthly revised local reference sea level tide gauge records of *Ray and Douglas* [2011] obtained from the Permanent Service for Mean Sea Level website. We eliminate two records that we deemed to be problematic for our purposes (Aberdeen and Argentine Islands). While chosen for their geographic distribution, the tide gauge stations still sample the oceans unevenly. Seventy five percent of the stations reside in the Northern Hemisphere. The southern Indian Ocean and South Atlantic are only sampled by three gauges each.

[9] After filtering to remove the ~10 cm climatological monthly cycle and correct for the ~1 cm inverted barometer effect using sea level pressure estimates from the 20th century reanalysis [*Compo et al*., 2011] the time series are smoothed with a 1 year running box-car smoother. Next, we remove a linear trend at each station with coefficients computed either for the 62 year base period (shortened depending on the length of the gauge time series) or the 111 year extended period, to reduce the effect of unmodeled land motion. This set of filtered tide gauge records is used in almost all comparisons described below.

[10] The seven reanalysis/synthesis products are listed in Table 1. Six of the seven use a sequential assimilation approach: Simple Ocean Data Assimilation (SODA) V2.2.4, National Institute of Geophysics and Volcanology (INGV), European Center For Medium Range Weather Forecasts Ocean Reanalysis System 4 (ECMWF ORA-S4), the Multivariate Ocean Three-Dimensional Variational Estimation/Meteorological Research Institute (MOVE/MRI), European Centre for Research and Advanced

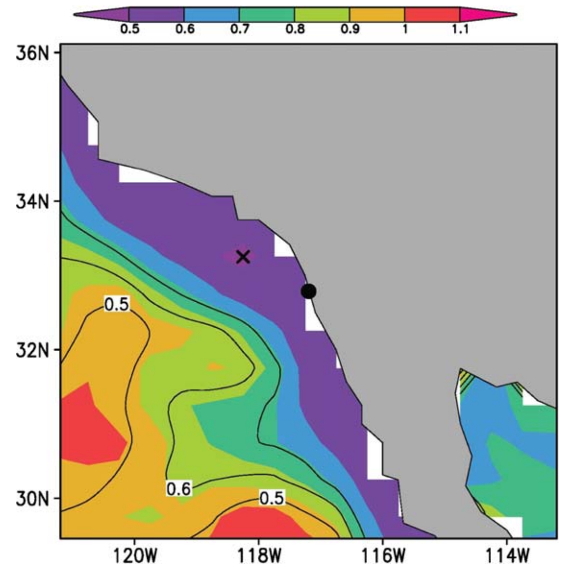

Figure 1. Normalized RMS difference (color) and correlation (contours) between SODA sea level and the tide gauge time series at San Diego, California (solid dot). The minimum normalized RMS difference of 0.48 occurs at the location indicated by the black cross. Note the alongshore orientation of the agreement.

Training in Scientific Computation (CERFACS), and the Predictive Ocean Atmosphere Model for Australia-2 (POAMA2). The seventh, the Consortium for Estimating the Circulation and Climate of the Ocean (GECCO) uses a 4D-variational assimilation algorithm. Three use forcing provided by ECMWF (INGV, ECMWF ORA-S4, and CERFACS), three use the NCEP/NCAR reanalysis of *Kalnay et al*. [1996] (POAMA2, MOVE/MRI, and GECCO) and one (SODA) uses the 20th century reanalysis of *Compo et al*. [2011]. Three include altimeter sea level observations beginning in 1991 (ECMWF ORA-S4, MOVE/MRI, and GECCO) and thus might be expected to show improved agreement with the tide gauge records. SODA is unusual in that it spans the full 20th century.

[11] Each product sea level is monthly averaged and is filtered in the same way as the gauge records including removal of linear trends at each grid point. For most products, the instantaneous spatial global average of sea level is required to be constant by the model numerics. The one exception is ECMWF ORA-S4. For consistency, ECMWF ORA-S4 sea level is filtered to remove its instantaneous global average.

[12] The numerical models underlying the reanalysis/synthesis products do not properly resolve nearshore processes that we know influence the tide gauge records [e.g., *Hong et al*., 2000]. This limitation is particularly evident in the coarser resolution products (Table 1). To partially compensate for this limitation, we shift the location of the product time series by up to 3° from the location of the corresponding station by choosing the point within this geographic range whose sea level time series minimizes the RMS difference with the tide gauge record. For example, the minimum RMS sea level difference between the tide gauge and SODA at San Diego occurs for a grid point 60 km northwestward along the coast (Figure 1). The product sea level time series from the shifted locations (calculated separately for each product and each station) are used in the comparisons described below. The impact of this procedure is relatively small at open ocean islands and near straight coast lines (usually less than 10%), but in areas with complex coast lines or strong currents such as stations in the subarctic North Atlantic, or near the southeast Asian coastline, the differences may be up to 50%.

[13] We summarize our comparisons using two statistics: correlations at zero time lag and signal-to-noise ratios, defined as the RMS difference normalized by the standard deviation of the individual tide gauge records. These standard deviations are provided in supporting information Table S1. Of course, the two statistics contain similar information when the record and product variances are the same (Figure 2, bottom right).

3. Results

[14] The correlations between the product and tide gauge records are summarized in Figure 2. Correlations in the tropical Pacific are generally greater than 0.6 with normalized RMS differences in the range 0.2–0.6. The cause of these relatively high correlations and low RMS differences is evident when we compare all product time series at La Libertad, Ecuador (2.2°S, 80.9° W) all of which show a pronounced 4–8 cm ENSO signal (Figure 3). ENSO signals are also apparent in records further poleward along the west coast of North and South America, for example at San Diego (32.7°N, 117.2°W). Correlations are lower for some of the more southerly stations in the western Pacific that do not have a pronounced ENSO signal including Townsville I, Australia (19.2°S, 146.8°E) and Wellington II, New Zealand (41.3°S, 174.8°E) (see Figure 3). The reduced correlations in the central tropical Pacific in GECCO is due to the weakness of several El Niños (e.g., 1976/77, 1987/8, 1991/2) in that product.

[15] In the tropical Indian Ocean, where ENSO is only one of several sources of sea level variability [e.g., *Nidheesh et al*., 2012] the correlations are again high along the equator but lower along the coasts (Figure 2). A consistent conclusion from a number of other studies [e.g., *Clarke and Liu*, 1994; *Shankar and Shetye*, 1999; *Han and Webster*, 2002] is that river discharge and monsoon rainfall affect sea level at these coastal stations, processes that are evidently poorly represented in the products.

[16] In the North Atlantic Ocean, correlations are generally high on the eastern side of the basin south of 50°N where the NAO signal in alongshore winds is present. On the western side of the basin, sea level is coherent along the coast on the interannual time scale (compare Charleston, 32.8°N, 79.9°W, and Boston, 42.4°N, 71.1°W) reflecting the combined effect of wind stress curl over the North Atlantic and changes in the Gulf Stream system (Figure 4) [*Papadopoulis and Tsimplis*, 2006; *Sturges and Douglas*, 2011]. This coherence leads to high correlations for some products. Reassuringly, all products reproduce the sea level variability at Bermuda (where continuous hydrographic observations ensure that the products should properly estimate the steric component of sea level).

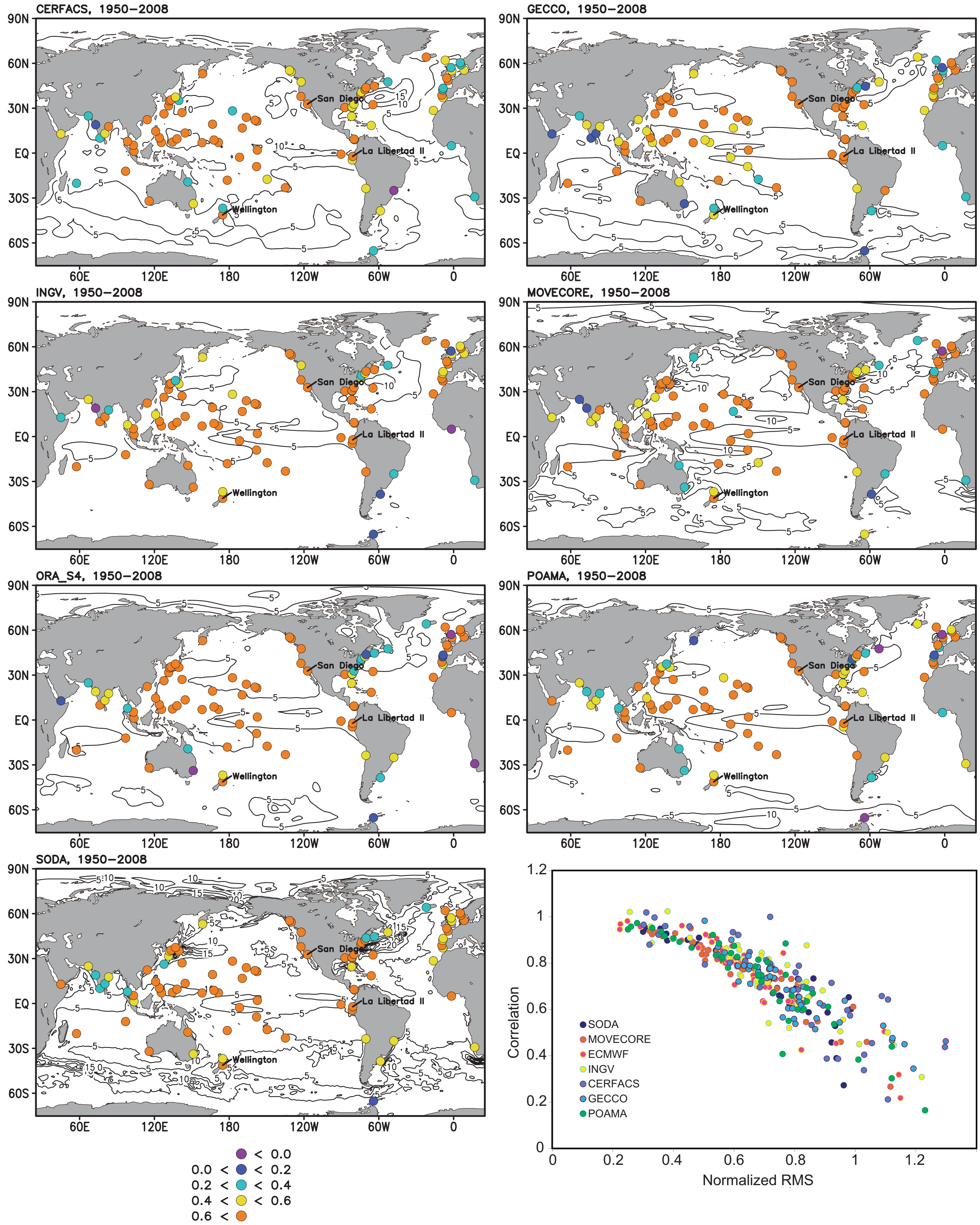

Figure 2. Correlations tide gauge and reanalysis sea level at 87 stations (location indicated by circle position, magnitude by color) for the base period. Contour lines show RMS variability. Scatter diagram of correlation versus normalized RMS difference for all stations and products (top right). The normalizations are provided in a supporting information Table S1.

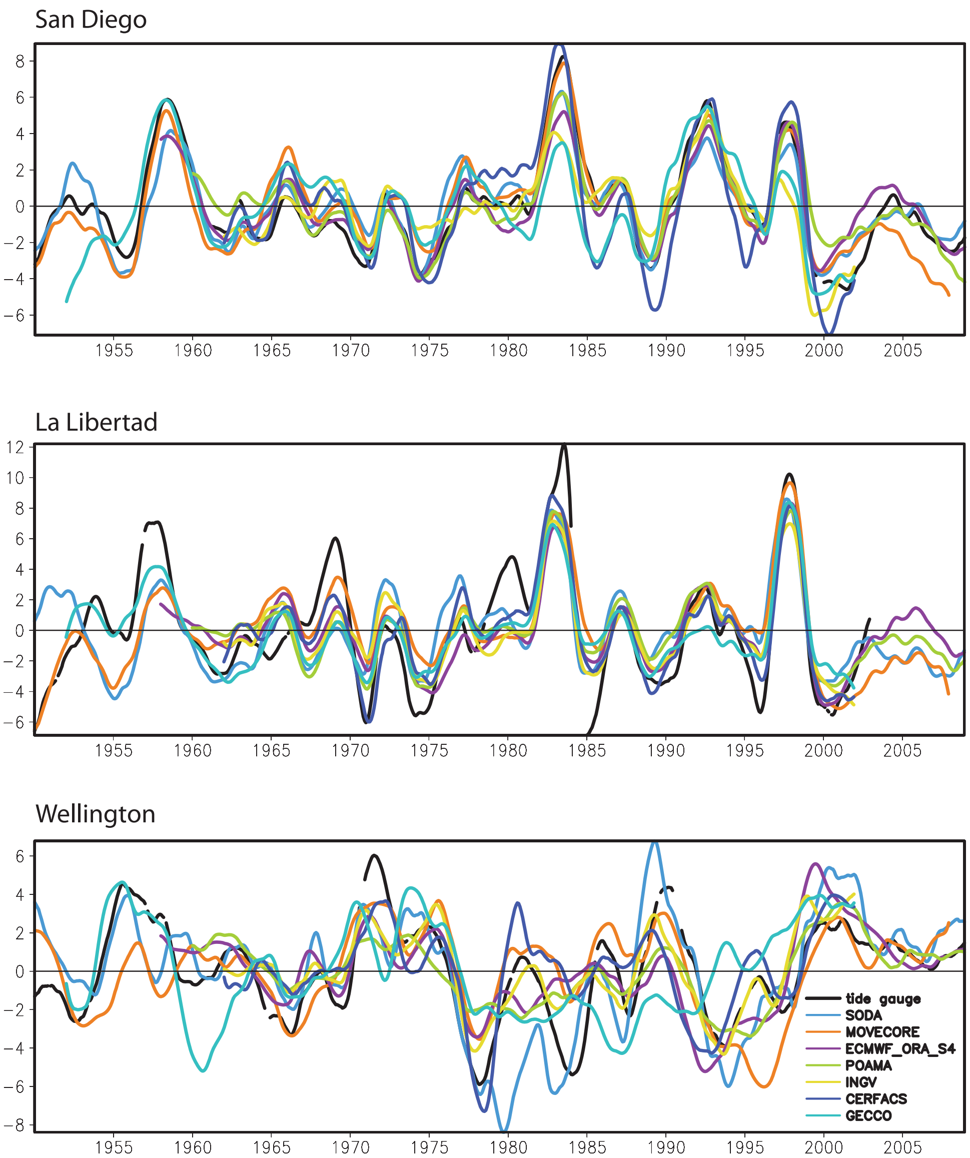

Figure 3. Comparison of Pacific tide gauge sea level (black) and product sea level (color) time series at three stations indicated in Figure 2. The average correlation is 0.75.

[17] Some information about the sources of sea level variability and also the sources of differences is apparent in the results of an Empirical Orthogonal Eigenfunction (EOF) analysis, here carried out weighting all 87 stations equally and without rotation. The First EOF of gauge sea level explains over 50% of the variability for the base period and can be qualitatively interpreted as the spatial mean since the spatial mean of the succeeding modes is negligible (Figure 5, top inset). The corresponding principal component time series shows the well-known nearly linear rise of historical tide gauge records of about 1.9 mm/yr, which can be obtained simply by averaging the gauge time series [e.g., *Church and White*, 2011] (Figure 5, top black). The first EOF of the difference between the tide gauge records and detrended SODA sea level increases the explained variance by7% (Table 1) over that of the first EOF of the gauges, but has little impact on the resulting trend in the first principal component (Figure 5, top blue). Similar increases in explained variance, which reflect reductions in uncertainty, are seen in comparisons using the other products.

[18] The second EOF, which explains 10% of the variance during the base period, has its largest projection in the Pacific sector, with a strong contribution from ENSO (Figure 5, bottom black) as well as a contribution associated with the recent high rate of sea level rise in the western tropical Pacific. As illustrated for SODA in Figure 5, any of the product sea levels reproduce much of this ENSO-related variability so that by subtracting any of the product sea level estimates from the tide gauge records we can remove most of the ENSO-related variability (Figure 5, bottom blue). In contrast, we do not have evidence that the products currently available properly model changes in sea level associated with mass transfer to the continents, such as discussed in *Boening et al*. [2012].

[19] Finally, we compare the subset of 45 stations that span at least 70% of the 111 year extended period

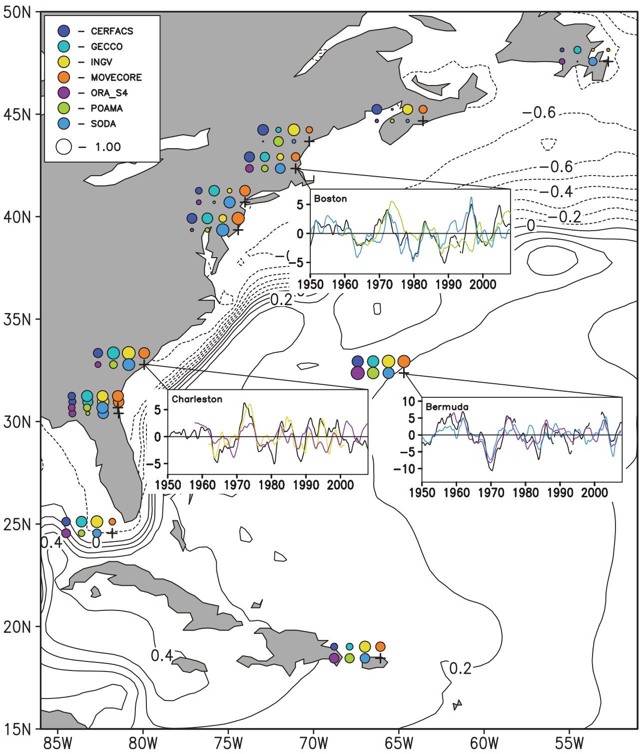

Figure 4. Expanded view of station correlations of detrended sea level in the western North Atlantic. Radius of each circle is proportional to the strength of the correlation. Three time series: tide gauge sea level (black), the product with the minimum correlation, and the product with the maximum correlation are shown for three stations: Boston, Charleston, and St. Georges, Bermuda. Contour lines show time-mean SODA sea level.

1900–2010 to SODA, the only reanalysis product available during this extended period. These stations are concentrated in the tropical and North Pacific and North Atlantic. For this extended period, the average correlation reduces from 0.57 to 0.50, while the normalized RMS difference increases from 0.84 to 0.95. Eliminating six stations with poor agreement boosts the centennial correlation to 0.55 and reduces the RMS difference to 0.87. Interestingly five of the six that are poorly correlated lie along the east coast of North America (Key West, New York, Boston, Portland, and Halifax).

[20] To illustrate the results of this comparison sea level variability at San Francisco (37.8°N, 122.5°W) is presented in Figure 6 (top) for the extended period 1900–2010, a period during which this tide gauge sea level rises monotonically on decadal timescales [e.g., *Sturges and Douglas*, 2011]. With the linear trend removed the gauge record has a residual 7.9 cm^2 variance with timescales ranging from interannual to multidecadal. SODA sea level explains roughly half of this variance, including virtually all of the ENSO-related sea level signal so that the difference between the two is dominated by a decadal to multidecadal fluctuation (Figure 6, middle).

[21] The residual difference, that is the difference between detrended tide gauge and SODA sea levels, seems to be at least partly associated with differences in the expression of PDO (discussed in section 1) in the gauge time series and the products in the eastern North Pacific. At San Francisco, the PDO index linear regression coefficient for the tide gauge record is 2.05 cm at zero time lag (the lag at which maximum variance is explained). The corresponding regression for SODA is 2.88 cm suggesting SODA overestimates the PDO contribution at this station. Removing the signal in the difference between these two time series associated with PDO reduces the unexplained variance by about 10% at San Francisco and other eastern North Pacific stations. The likely source of this difference is, we think, an error in the expression of PDO in the surface wind stress driving the reanalysis. The situation is different for ENSO, for which we find no systematic difference (although we note a peak in the residual coinciding with the 1982-3 El Niño!). After removal of the signals associated with PDO and ENSO, we are left with 4 cm^2 interannual sea level variance in the tide gauge records unaccounted for by the reanalysis product (Figure 6, bottom).

[22] Further north along the west coast of North America at Seattle (47.6°N, 122.3°W) the detrended gauge record variance, 6.7 cm^2, shows a residual difference from SODA sea level of 4.8 cm^2 (28% explained variance) which is reduced to 3.5 cm^2 after removal of the residual variance associated with PDO (zero time lag). Still further north at Ketchikan (55.3°N, 131.6°W) the detrended gauge record variance, 7.3 cm^2, has a residual difference from SODA sea level of 5.6 cm^2 and reduces still further to 4.6 cm^2 when the correlated PDO signal is removed. In the western North Pacific, SODA is less successful in explaining the variance of the few available gauges. One of the stations where the reanalysis product is most successful in explaining the tide gauge records is Aburatsubo (35.2°N, 139.6°E) where the detrended gauge variance of 4.9 cm^2 has a residual difference from SODA sea level of 3.7 cm^2 (24% explained variance).

[23] At Newlyn (50.1°N, 5.5°W) in the eastern North Atlantic the detrended tide gauge record variance, 4.1 cm^2, reduces to a residual difference from SODA of 2.5 cm^2 (in other words, SODA explains 39% of the tide gauge record variance). This residual further reduces to 1.9 cm^2 when the component of the signal correlated with the NAO index is removed [*Calafat et al.*, 2012 provides a recent discussion of this record]. Further north at Esbjerg (55.5°N, 8.4°E) the detrended tide gauge record variance is 13.3 cm^2, and the variance of the residual difference is 5.7 cm^2 (57% explained variance). In the Atlantic as well as the Pacific, the presence of climate signals in the difference between the tide gauge time series and the reanalysis product time series suggest that there is room for improvement in the reanalysis products.

4. Summary

[24] Most observation-based studies of 20th century sea level variability prior to the satellite era are based on sparse coastal and island tide gauge records. A purpose of this article is to highlight the fact that complementary information is available from ocean reanalysis/synthesis products (the terms are nearly synonymous) which derive sea level variability from other variables such as historical winds,

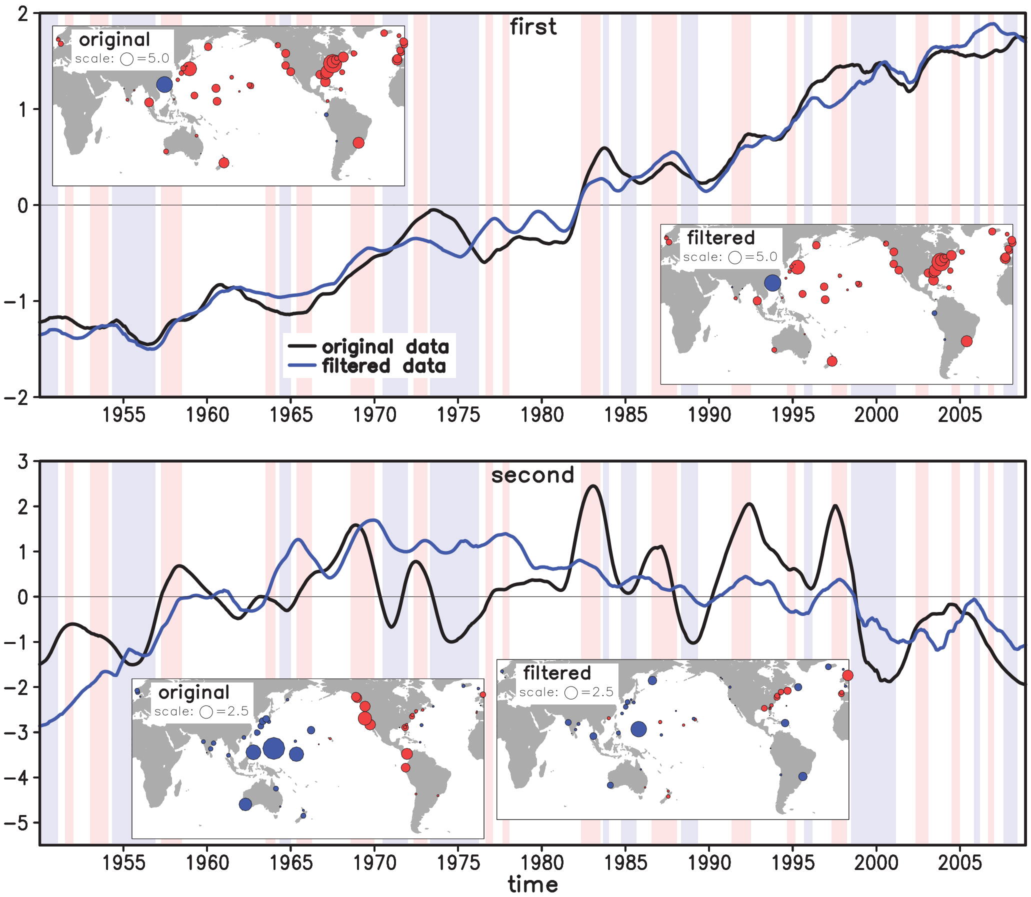

Figure 5. Comparison of the first and second Principal Component time series for the tide gauge sea level at 87 stations with the trends retained but after GIA correction (black) and for the tide gauge sea level minus the detrended SODA sea level estimates (blue). (top) First EOF (insets) and corresponding principal component time series. (bottom) Second EOF (insets) and corresponding principal component time series. Time series were smoothed with a 2 year running filter prior to the analysis. Vertical colored stripes indicate the phase of ENSO, red for El Nino. Inset circles show phase (red+, blue−).

ocean temperature, and ocean dynamics. In this study we explore the similarities and differences of these two types of sea level data sets.

[25] The 87 tide gauge stations we explore are approximately 1/3 of the available long tide gauge stations and have been selected based on a variety of criteria including confidence in the record and exposure of the gauge location to the open ocean. After filtering out the seasonal cycle and removing a linear trend [the characteristics of which are discussed in detail by *Ray and Douglas*, 2011] these tide gauge records show an average residual 2.8 cm variability during our 62 year base period (1950–2011). This variability includes well-described phenomena such as ENSO and some less-well understood signals. We compare these tide gauge records to sea level from seven reanalysis/synthesis products, three of which do assimilate satellite sea level available during the past two decades. The comparison shows average correlations in excess of 0.55–0.6 and RMS differences normalized by the standard deviation of the individual tide gauge records of 0.77–0.84.

[26] Agreement between the two types of sea level estimates is high in the tropical Pacific and along the west coast of North and South America due to the presence in both time series of a strong ENSO signal. The EOF analysis shows that little ENSO-related variability remains in the tide gauge minus product differences. The agreement is generally low at stations along the Indian subcontinent due to the influence on sea level of poorly modeled river discharge. A brief Intercomparison of the individual products shows correlations for CERFACS are somewhat lower and RMS differences somewhat higher (0.51 and 0.96) than for the others. GECCO also has lower correlations and higher RMS differences (0.52 and 0.91) then the rest, but this result is influenced by the presence of a handful of stations such as Cochin (10.0°N, 76.3°E) where the agreement is very poor.

[27] In the first-half of the 20th century, the number of tide gauge records declines, so that only 45 of the original 87 cover at least 70% of the 111 year extended period 1900–2010. In the second part of the paper, we compare this more limited set of tide gauge records to SODA, the only one of the products to span this extended period. The agreement is slightly lower when computed over the extended period than for the base period, but rises to an average correlation of 0.55 when the six gauges (out of 45) with the poorest comparison are eliminated. Interestingly,

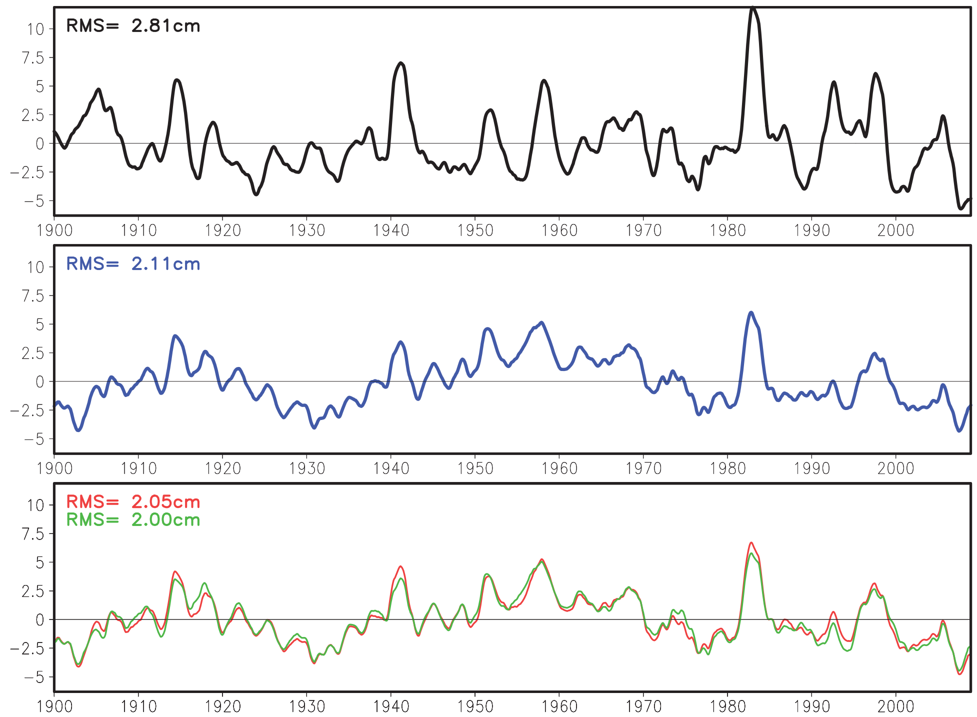

Figure 6. Detrended San Francisco (37.8°N, 122.5°W) sea level. (top) Tide gauge sea level; (middle) tide gauge minus SODA sea level; (bottom, red) tide gauge minus SODA sea level minus correlated PDO index time series (5 year lag); and (bottom, green) tide gauge sea level minus SODA sea level minus correlated PDO index time series (5 year lag) minus correlated Southern Oscillation index time series (no lag). RMS variability is shown in top left.

five of these six poorly correlated gauges lie along the east coast of North America. In the North Pacific, a significant amount of the variance of the tide gauge minus product differences is correlated with the index of the PDO (with a multiyear lag). In the eastern North Atlantic, a significant amount of the residual variance is described by the wintertime index of the NAO. We interpret the presence of these climate signals in the residual difference of the sea level estimates as indicating the presence of errors in the reanalysis products likely, we think, due to errors in surface forcing.

[28] In summary, because of their global coverage and their inclusion of ancillary data the reanalysis/synthesis products provide an important complement to the tide gauge records through the 20th century. While the currently available products do not directly address the problem of global sea level rise, by improving estimation of regional sea level variability they can be used to separate regional variability from the global rise signal in the tide gauge records. Tide gauge records, in turn, can be used to provide information about the accuracy of the products on long timescales, and as we have seen identify the presence of imperfectly represented climate signals.

[29] The fact that the tide gauge observations and the ocean products contain independent information about historical sea level suggests that an improved estimate can be made by including the gauge observations within the framework of the reanalysis. Such a modified assimilation product would then also require a model with regional land motion [e.g., as proposed by *Hay et al.*, 2012]. Such coupled ocean/land physics is also required to account for other geophysical measurements such as time-dependent gravity. One of the benefits of such an assimilation exercise may be that in addition to improving estimates of sea level we will learn about the interaction between motions in the ocean and solid earth.

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