Real-Time Altimetry from ERS-2

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Abstract

Since November 1995, NOAA has been generating "Real-time Geophysical Data Records" (RGDRs) for ERS-1 and ERS-2. ESA's Fast-Delivery altimeter data arrive at NOAA within 6 hours of acquisition, are combined with JGM-3 orbits produced by the Delft Univ. of Technology, and are enhanced with several environmental corrections. The operationally computed orbits are generated with a 2-3 day lag. To create RGDRs within 12 hours of acquisition, we use a predicted orbit extension to each orbital solution. The RGDRs contain orbit errors of ~50 cm, so are most useful for short-arc mesoscale studies. Results from two such applications are presented: monitoring of the Gulf Stream region and the Gulf of Mexico Loop Current.

A refined data set, the "Interim Geophysical Data Records" (IGDRs), can be computed within 3 days using the most precise part of the Delft orbits. These data have orbit errors of ~10 cm, and are suitable for large-scale interannual monitoring. The IGDR data will soon be assimilated into a coupled ocean/atmosphere model running at NOAA, as is currently being done with near real-time TOPEX altimetry.

Keywords: operational altimetry, mesoscale oceanography, western boundary currents

1. INTRODUCTION

One of the great advantages of working with altimetry data from the ERS satellites is the timeliness with which the Fast-Delivery data are received. Beginning in November, 1995 the NOAA Laboratory for Satellite Altimetry began generating near real-time products from ERS-1, and has continued since May, 1996 with ERS-2.

These "Real-Time Geophysical Data Records" (RGDRs) are based on ESA's Fast-Delivery "URA" product,which is received at NOAA within 6 hours of satellite acquisition. Since the URA data contain only crude satellite state vector information, the most important step in RGDR production is the addition of orbital information from ephemerides computed by the Delft Institute for Earth-Oriented Space Research. In order to produce RGDRs on a daily basis (within 12 hours of satellite acquisition) it is necessary to utilize a predicted extension to the computed orbits. After applying the predicted orbit, NOAA enhances the RGDR with improved geophysical corrections and makes the data available to select real-time users.

If the timeliness of data production is relaxed to three days, it is possible to use the highest precision part of the Delft JGM-3 orbits, rather than the predicted phase. In this case one obtains an "Interim GDR" (IGDR), another standard NOAA ERS product. Converting an RGDR into an IGDR simply entails replacing the predicted orbit with the best part of the computed orbit, and adjusting the height data accordingly.

In this paper we discuss the preparation of the NOAA data sets and illustrate a few current uses. The RGDR data have relatively large orbit errors, so are most suitable for mesoscale studies with explicit orbit error removal. We show examples from the Gulf of Mexico and Gulf Stream regions. The IGDR data are sufficiently accurate to monitor sea level on monthly time scales without removing orbit error, as shown in comparisons with tide gauges. The IGDR data will soon be assimilated into an operational ocean model at NOAA, along with near real-time TOPEX analyses.

2. ALTIMETER DATA PROCESSING

The production of the NOAA RGDRs is shown schematically in Figure 1. ESA's Fast-Delivery URA product is encoded and delivered via the Global Telecommunications Network to the U.K. Met. Office, then on to NOAA, within 6 hours of acquisition. Concurrently, Delft provides JGM-3 orbits twice weekly. These are comprised of a computed segment plus a predicted extension. NOAA combines the altimeter range data with the predicted orbit to produce "sea heights", relative to the WGS84 reference ellipsoid. The following geophysical corrections are then added: solid and ocean+load tides from the Univ. of Texas CSR 3.0 tide model [Ref. 1]; wet and dry troposphere corrections based on the NOAA National Centers for Environmental Prediction (formerly NMC) operational weather model; a second wet troposphere correction derived from Special Sensor Microwave Imager (SSM/I) measurements of total precipitable water vapor; and an ionosphere correction from the IRI90 model [Ref. 2].

In the future, the Fast-Delivery data will likely carry water vapor measurements from the on-board ATSR/M radiometer. This would be a significant improvement that would eliminate the need for the SSM/I correction currently used in the RGDR and IGDR data sets.

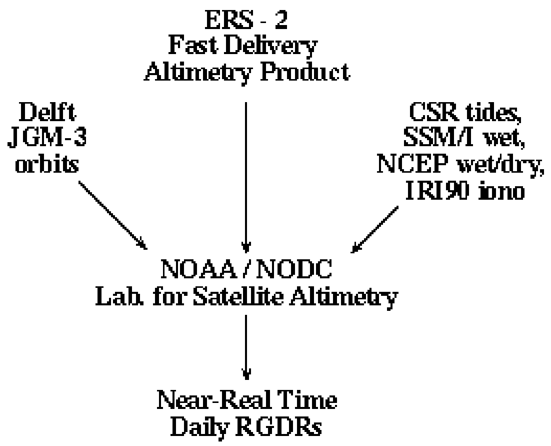

Figure 1. Data flow and processing for Real-Time GDRs.

The schedule of orbit generation at Delft, as well as the relationship between the computed and predicted phases, is shown in Figure 2. Each 12-day arc is composed of a 7 day computed phase (where actual SLR tracking data are used) and a 5 day predicted phase. The central 3.5 days of the computed phase (beginning one day into the arc) contains the highest precision part of each orbit. In post processing these 3.5 day segments are composited from successive orbital arcs to yield a continuous ephemeris. These precise orbits are then used to convert the RGDRs into IGDRs. At the time the orbits are generated, the most recent part of the precision orbit is 3 days old, and the orbit is within the first day of the predicted phase. Thus it is possible to generate RGDRs on a daily basis using a one day predicted orbit, and to generate IGDRs three days behind real time.

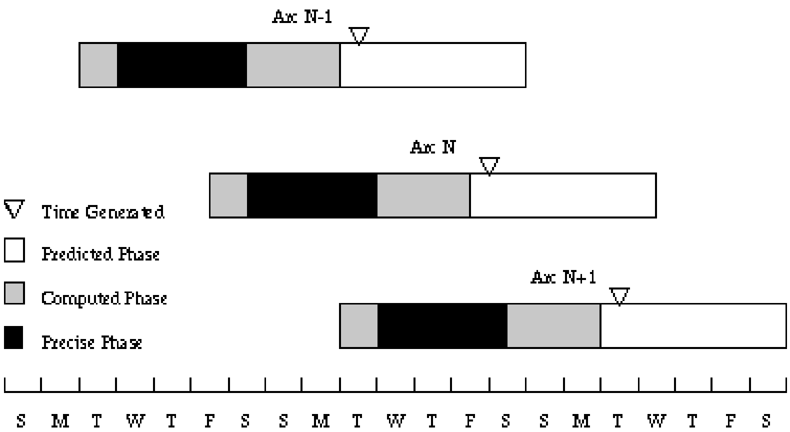

Figure 2. Timeline of Delft orbit generation. Arcs are produced each 3.5 days, and contain a 7 day computed phase and a 5 day predicted phase. The highest precision 3.5 days are used in IGDR production. The orbits are generated one day into the predicted phase, as indicated by the triangle.

The magnitude of the radial component of orbit error grows as the prediction time increases, as shown in Table 1 [Ref. 3]. Even in the worst case scenario of a five-day prediction, the expected orbit error remains below 50 cm. This is still acceptable for short-arc mesoscale studies where explicit orbit error removal is performed. By contrast, the orbit error of the high precision part of the orbits is estimated to be in the 10 cm range [Ref. 3], so that the IGDRs are suitable for interannual global circulation studies even without orbit error removal schemes.

Table 1. ERS-2 Radial Orbit Error: Predicted vs. Precise

Predicted Day Number	Mean Orbit Error (cm)	R.M.S. Orbit Error (cm)
1	13.4	14.6
2	17.9	19.1
3	22.9	24.6
4	29.0	31.5
5	35.5	39.4

3. REAL-TIME SEA LEVEL ANALYSES

Two examples of mesoscale studies using the RGDR data set are illustrated here. The Gulf of Mexico analyses are performed at the Univ. of Colorado Center for Astrodynamics Research, and are made available on their Gulf of Mexico near real-time web page:

http://www-ccar.colorado.edu/gom_nrt.html.

The Gulf Stream region studies are performed at the Delft Institute for Earth-Oriented Space Research, with daily updates on their Gulf Stream web page:

http://dutlru8.tudelft.nl/altim/gulfstream.

3.1 Gulf of Mexico

Because of the substantial orbit error present in the RGDRs, further treatment of the sea height data is required to derive accurate maps of sea surface topography. The Univ. of Colorado procedure blends ERS-2 and TOPEX altimetry, treating both data sets in a consistent fashion:

1. All TOPEX and ERS-2 data are referenced to the Ohio State University Mean Sea Surface 1995 [Ref. 4]. The data are treated as nonrepeat tracks and are referenced directly to the mean sea surface. This saves a significant amount of computation in the near-real-time processing.

2. Along-track "loess" filtering is used to remove orbit and environmental correction errors. Loess filtering is a running least squares fit of a tilt plus bias, within a sliding window. The window width is approximately 15 degrees of latitude, to retain mesoscale signals.

3. A fast, multigrid preconditioned Cressman analysis is used for interpolation to a quarter-degree grid [Ref. 5].

4. Finally, a model mean is added to the sea surface height anomaly to produce an estimate of the total dynamic height.

An example of the dynamic topography derived from this method is presented in Figure 3. Here a clear image of sea surface temperature in the Gulf of Mexico (courtesy of Frank Muller-Karger, Univ. of S. Florida) is shown with overlaid contours of dynamic height based on the ERS-2/TOPEX analysis. A large meander in the Loop Current, in the SE corner of the Gulf, is well mapped by the altimeter derived sea surface. Even less energetic cyclones and anti-cyclones are clear in the surface topography, in excellent agreement with the surface temperature field.

The primary benefit of altimetry is that it is an all- weather, and all-season, data source that can be used to continuously monitor the Loop current and its associated eddies. This is a significant advantage over monitoring with infrared imagery, which is often hampered by cloudy conditions. In the summer months (June - October) a shallow warm water surface layer masks the thermal signature of the Gulf's deep circulation, while the altimetric measurements remain unaffected.

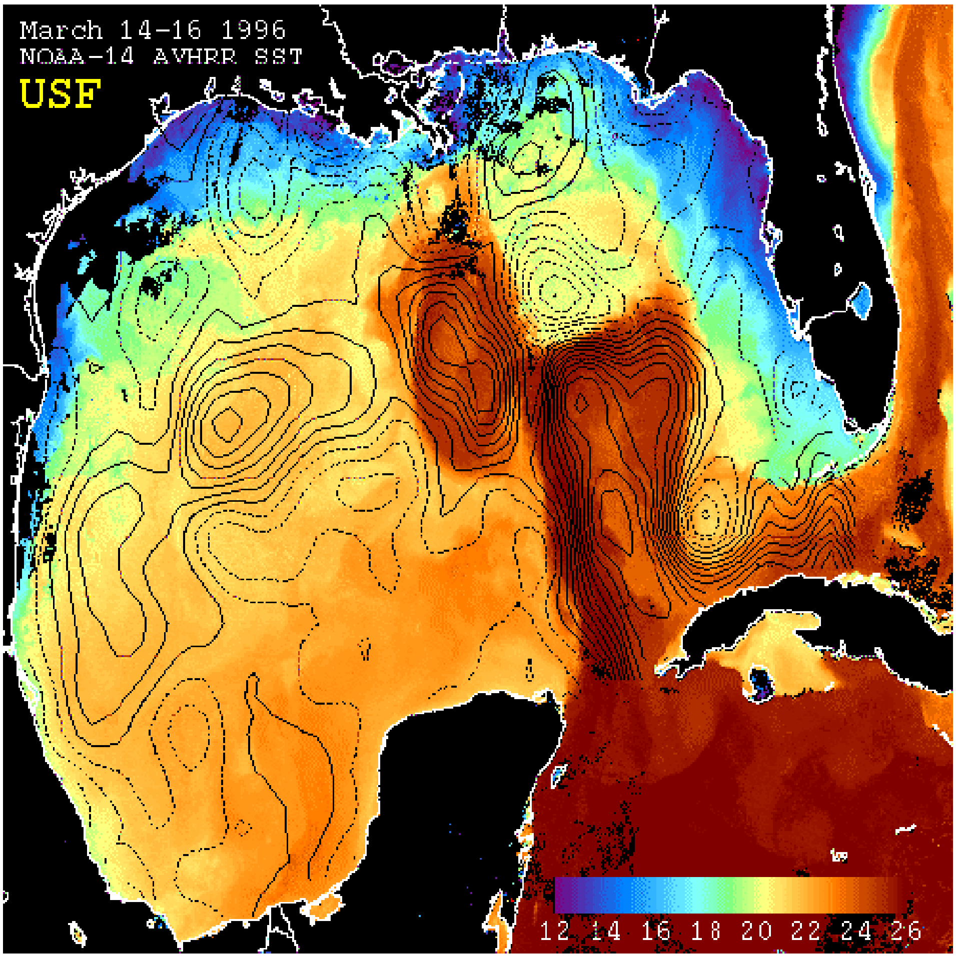

Figure 3. Sea surface temperature image of the Gulf of Mexico for March 14 - 16, 1996 with overlaid contours of dynamic topography from ERS-2 + TOPEX (10 cm contour interval). The large meander in the Loop current is evident in the dynamic topography.

Further evidence of the quality of the real-time analyses is seen in comparisons of surface drifter tracks with the dynamic topography maps. Figure 4 shows a portion of several drifter tracks (courtesy of P. Niiler, W. Johnson, and the Minerals Management Service) overlaid on a map of dynamic topography for the same time period.

A large meander in the Loop Current in the SE Gulf is clearly shown in the dynamic topography, and the drifter track confirms its location, flowing along the contours. Animation sequences available at the Gulf of Mexico web page demonstrate the evolution of the dynamic topography in the Loop Current, with surface drifter tracks corroborating the location of energetic meanders and eddies.

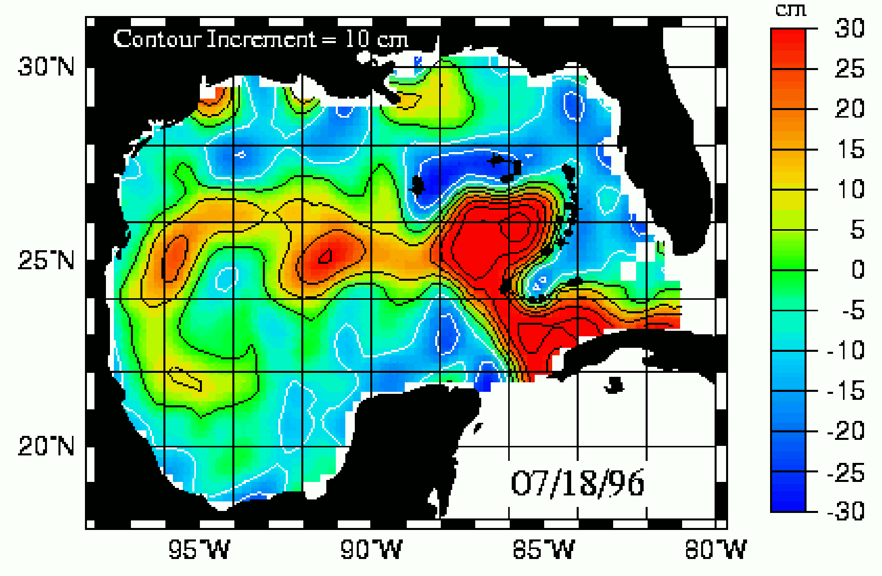

Figure 4. Blended ERS-2/TOPEX dynamic topography in the Gulf of Mexico on July 18, 1996, overlaid with surface drifter tracks (each square denotes a daily position).

3.2 Gulf Stream Region

The Gulf Stream analyses performed at Delft also incorporate an orbit error removal scheme, though the details differ from the Univ. of Colorado procedure.

1. The RGDR sea surface heights are combined with environmental corrections, and a surface fitting technique is applied to reduce the residual orbit error. This yields sea surface height anomalies relative to a predefined mean sea surface (based on ERS-1/2 only).

2. The anomalies are averaged into 7-km along-track bins and the relative dynamic topography is determined by interpolation. To reconstruct both large and mesoscale features from the along-track data, the altimeter data are interpolated both in space and time using the method of Successive Corrections [Ref. 6]. In the temporal domain, a Gaussian weighting function is applied with a time sigma of 7.5 days. The spatial sigma varies from 2.25 degrees in the first iteration to 0.55 degree in the fourth iteration.

3. After computing the relative dynamic topography, a "mean" dynamic topography (derived from three years of TOPEX data) is added to obtain an estimate of the total dynamic topography.

This method yields daily maps of surface velocity vectors in and around the Gulf Stream. An example showing current vectors, color coded with current speed is shown in Figure 5. The lack of a high resolution mean topography (in step 3. above) causes the Gulf Stream to appear somewhat blurred. Nonetheless, these maps are useful for identifying the location of large meanders, warm-core rings, and cold-core rings in the current system. The analysis provides information on the structure of the Gulf Stream even when cloudy conditions would obscure visible or infrared imagery.

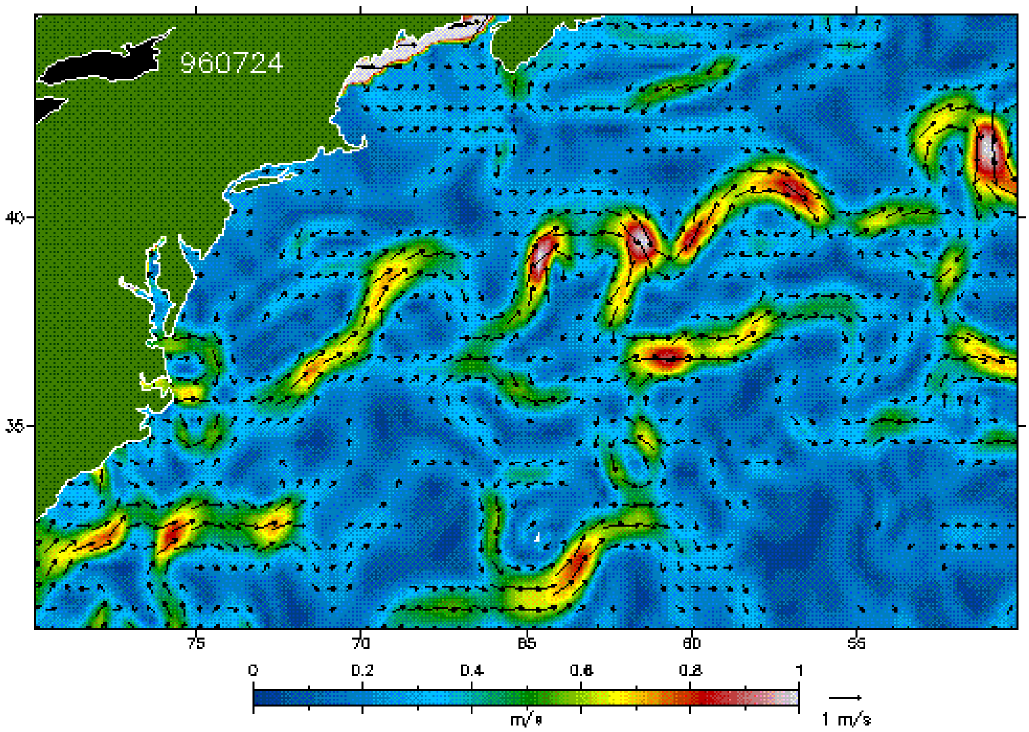

Figure 5. Surface velocity vectors in the Gulf Stream region on July 24, 1996. The magnitude of the velocities are shaded to indicate regions of high current speed.

The RGDR-based velocity estimates also correspond well with weekly composites of sea surface temperature (courtesy JPL/PO-DAAC); Figure 6. The location of the current axis, and several cyclonic and anti-cyclonic eddies, is apparent in the temperature data and is in good agreement with the velocity vectors.

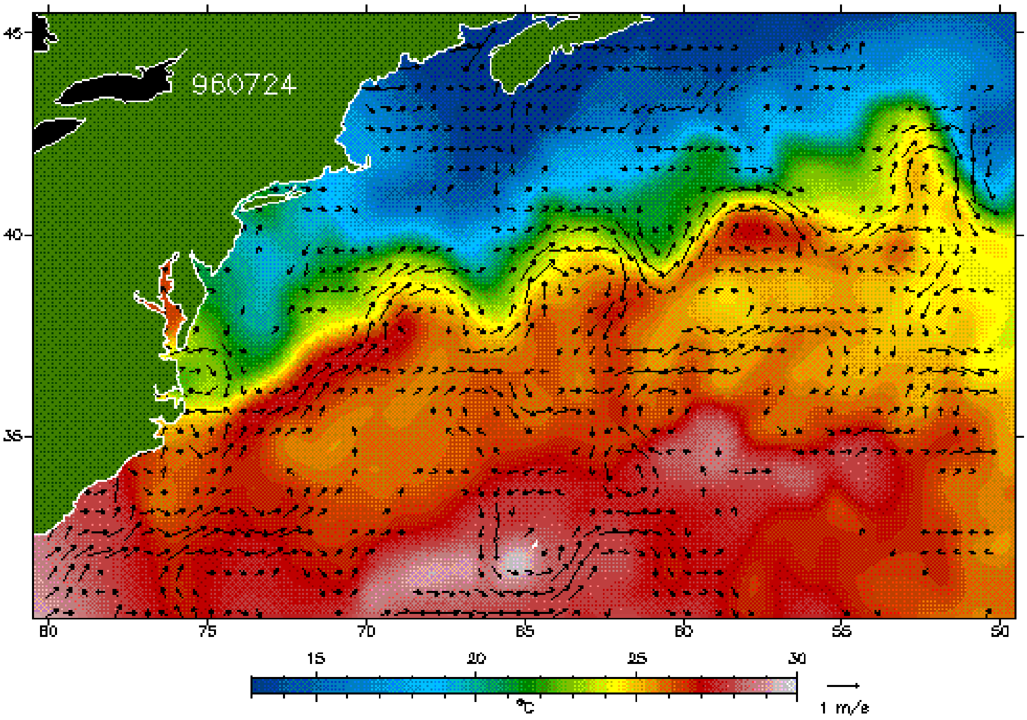

Figure 6. Sea surface temperature in the Gulf Stream on July 24, 1996, overlaid with velocity vectors from the Delft analysis. Note the correspondence of the Gulf Stream and associated ring and eddy features in the temperature and velocity fields.

4. DELAYED-MODE ANALYSES

The daily RGDR data are suitable for real-time mesoscale monitoring, but for larger-scale phenomena, which evolve on seasonal to interannual time scales, a more accurate data set is required. The definitive ERS altimeter data are ESA's Ocean Product Records (OPR), which are distributed some 6-8 months after acquisition. For applications that do not require the timeliness of the RGDRs, but do need data within a few days, the NOAA IGDRs fill the void. Although the IGDR data (currently) do not contain the ATSR/M measured wet troposphere, and have not been retracked like the OPRs, they are based on the highest precision part of the Delft orbits and are sufficiently accurate for many operational analyses. We intend to utilize collinear analyses from the ERS-2 IGDRs as input to a coupled ocean/atmosphere model being run by the Environmental Modeling Center at NOAA's National Weather Service. We are currently providing analyses from TOPEX with a similar 2-day lag, as inputs to the operational model. The addition of the ERS-2 data will provide better spatial coverage and an independent source of sea surface height information.

One way to assess the improvement in going from the predicted orbits (in the RGDRs), to the precise orbits (in the IGDRs), is to look at crossover differences within the 35-day repeat cycle of ERS-2. Figure 7 presents histograms of crossover height differences for cycle 12 (June-July, 1996). The r.m.s. of intra-cycle crossovers is reduced from 38.4 cm for the RGDRs to 19.4 cm for the IGDRs (Figure 7a). The IGDR crossovers have a smaller mean difference and a much tighter distribution. Figure 7b compares the IGDRs for Cycle 12 with the final-quality OPR data. The OPRs have a slightly tighter distribution, with an r.m.s. of 15.8 cm. The IGDR data are much closer to OPR quality than the RGDRs, due solely to using the precise portion of the Delft orbits.

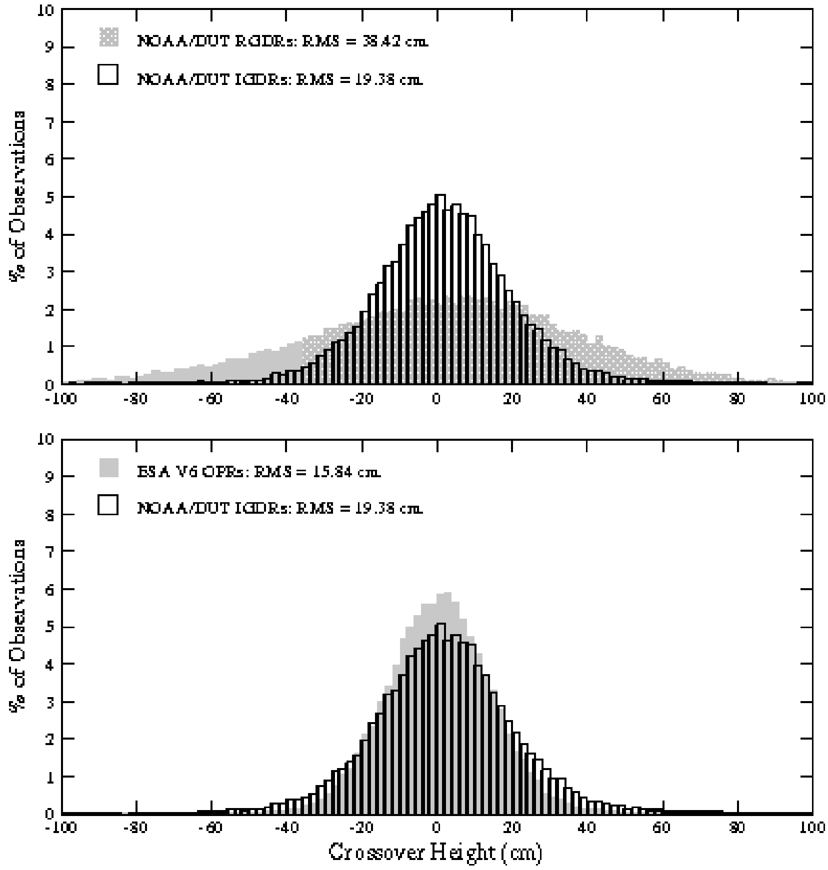

Figure 7. Histograms of crossover height differences within 35-day repeat cycle 12 (96/06/03 - 96/07/08). Top (7a) compares the IGDRs to the RGDRs; bottom (7b) compares the IGDRs to the OPRs.

The relative accuracy of the IGDR data can also be assessed via collinear analysis. The r.m.s. variability during 1996 is calculated in 1-degree along-track segments for the ERS-2 IGDRs and OPRs, as well as the highest quality TOPEX GDRs (Figure 8). In each case no orbit error removal was performed, and all passes with an r.m.s. deviation less than 50 cm (relative to a reference pass) were retained. For clarity, only the descending passes for ERS-2, and ascending passes for TOPEX, are shown. The missing IGDR data in the Indian Ocean is due to the delay in receiving data from the Prince Albert ground station; it is unavailable in the 2-3 day time frame. The increased spatial resolution of the ERS-2 data compared to TOPEX is apparent. Note that the background variability level in the quietest oceanic regions, such as the SE Pacific Ocean, is highest in the IGDR (bottom), less in the OPR (middle), and least in the Topex GDR (top). This reflects residual orbit error, which is highest in the IGDR data. Collinear "nests" containing bad passes also stand out as stripes of high variability. These remain in the OPR data even after editing based on orbit maneuver flags.

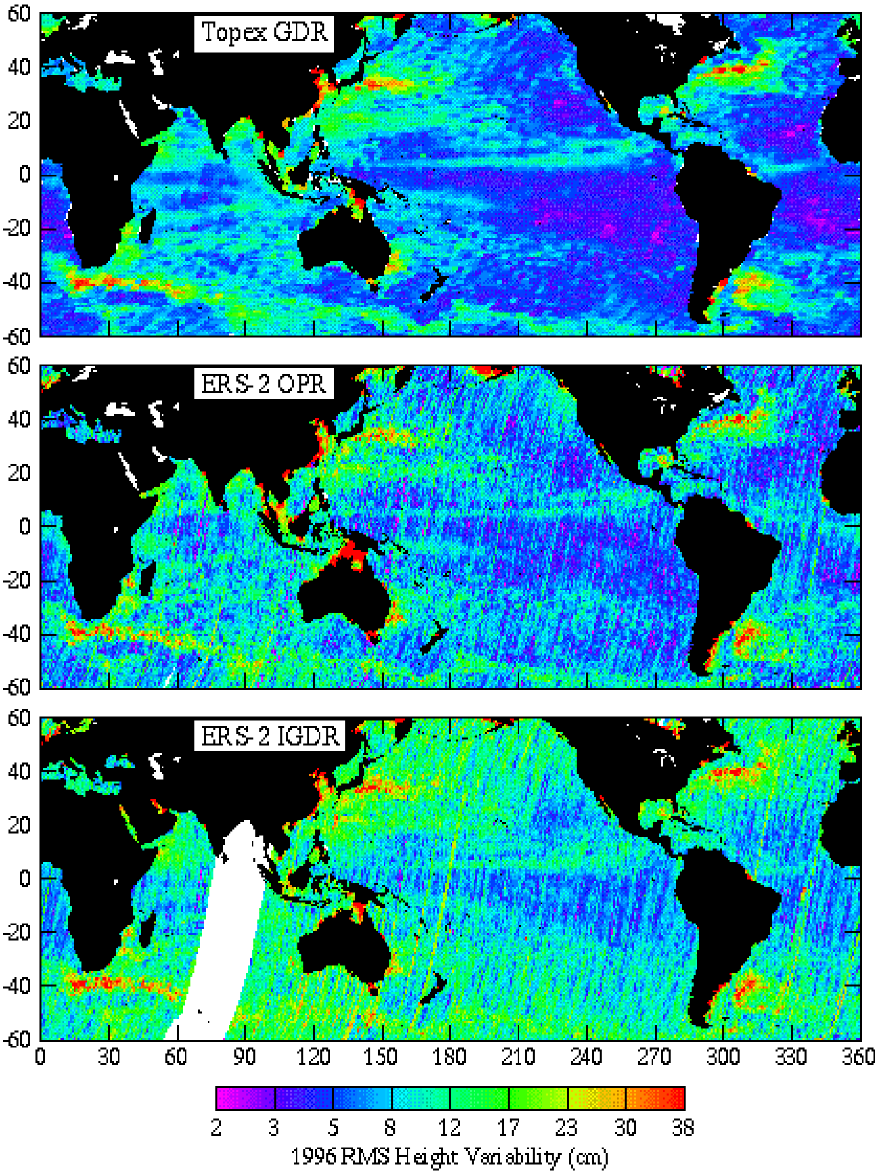

Figure 8. The r.m.s. height variability during 1996 from collinear analyses. The ERS-2 IGDRs have a higher overall level, particularly noticeable in quiet oceanic regions. The OPR variability is similar to the more accurate TOPEX GDRs. Stripes evident in both the OPR and IGDR data indicate residual orbit error or passes affected by maneuvers.

Despite the orbit error present in the IGDRs, their utility for studying large scale interannual signals is readily apparent. When monthly averages of sea level are computed, the ERS-2 IGDRs compare with tropical Pacific tide gauges nearly as well as TOPEX. An example from the equatorial tide gauge at Christmas Island in 1995-1996 illustrates this point (Figure 9). The r.m.s. fit of the two altimetry time series to the tide gauge data is nearly identical over this 18 month period.

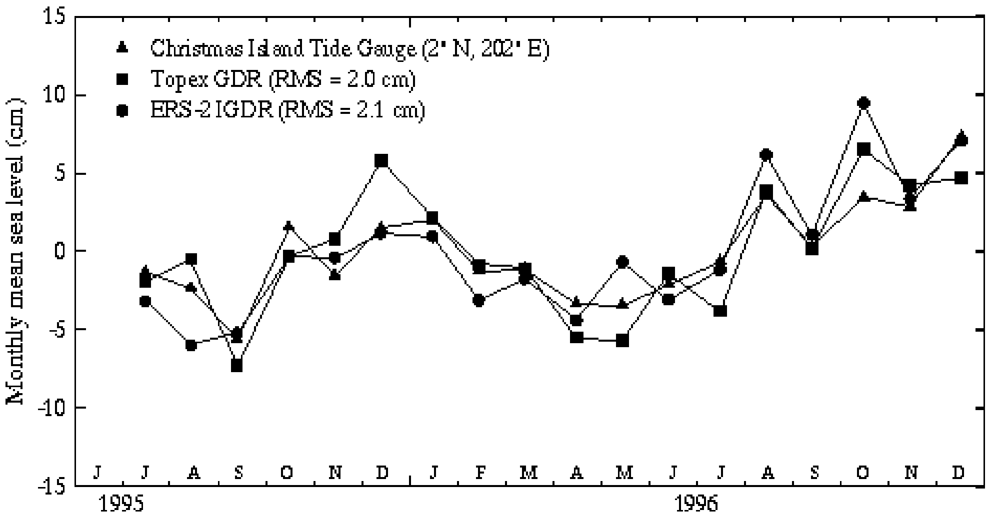

Figure 9. Monthly mean sea level from ERS-2 IGDRs and TOPEX GDRs, compared with tide gauge measurements at Christmas Island. The r.m.s. fit of the altimeter heights to the gauge heights is about 2 cm for this 18 month period.

5. CONCLUSIONS

The utility of the RGDRs for mesoscale current monitoring will improve when the on-board ATSR/M wet correction is available in real-time. Even now, their utility to seafarers and ocean-based enterprise is clear from the Gulf of Mexico and Gulf Stream examples shown above.

The IGDRs provide a compromise between the timeliness of the RGDRs and the precision of the OPRs. Monthly averages of IGDR data are quite accurate, but for assimilation purposes the level of residual orbit error is still quite high. We are exploring the method of Tai and Kuhn [Ref. 7], to reduce the orbit error in the IGDRs while retaining the large-scale, low-frequency oceanic signals. Alternatively, methods such as those of Le Traon, et. al [Ref. 8], which fit ERS-2 data to TOPEX, could be utilized to minimize the errors in the IGDR data. The hope is that the IGDRs can be made nearly as accurate as the real-time TOPEX data, so that both data sets can be assimilated into NOAA's coupled ocean/atmosphere model.

6. ACKNOWLEDGEMENTS

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