HURRICANE INTENSITY FORECASTING AT NOAA USING ENVISAT ALTIMETRY

John Lillibridge [(1)], Nick Shay [(2)], Mark DeMaria [(3)], Gustavo Goni [(4)], Michelle Mainelli [(5)], Remko Scharroo [(6)] and Lamar Russell [(7)]

[(1)] NOAA Lab. for Satellite Altimetry, 1335 East-West Hwy. E/RA31, Silver Spring, MD, 20910, USA
[(2)] University of Miami, Rosenstiel School of Marine and Atmospheric Sciences, Miami, FL 33149, USA
[(3)] NOAA Regional and Mesoscale Meteorology Branch, Fort Collins, CO 80523, USA
[(4)] NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL 33149, USA
[(5)] NOAA National Hurricane Center, Tropical Prediction Center, Miami, FL 33165, USA
[(6)] Altimetrics LLC, Cornish, NH 03745, USA
[(7)] U.S. Naval Oceanographic Office, Stennis Space Center, MS 39522, USA

ABSTRACT

NOAA's National Hurricane Center (NHC) has a number of skillful track guidance models, but only a limited number of intensity prediction schemes. The relatively low skill of intensity forecasts is due to the complexity of the problem, which involves a very wide range of scales, and interaction with the underlying ocean.

The empirical Statistical Hurricane Intensity Prediction Scheme (SHIPS) provides intensity predictions with accuracy comparable to those from the coupled three-dimensional GFDL hurricane model [1]. SHIPS was implemented at the NHC in 1996, and upgraded in 2004 to include upper ocean heat content (OHC) estimated from satellite altimetry. It is believed that hurricane intensification can occur over regions where OHC values exceed 50 kJ/cm^2, not just in regions of high sea surface temperature [2].

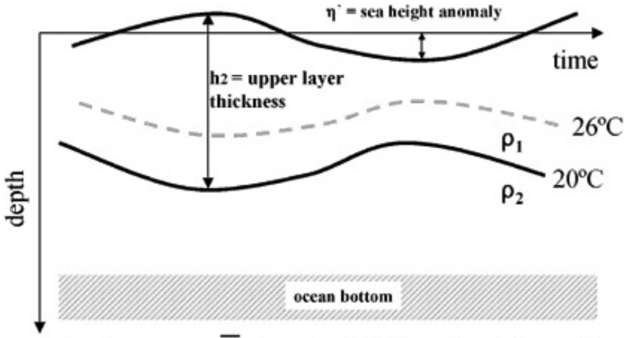
The OHC analysis presently incorporates sea surface height from Jason-1 and Geosat Follow-On. Envisat altimetry is expected to be included in the OHC analysis for the 2007 hurricane season. Efforts are underway to reduce the latency of Envisat data by including the Fast-Delivery Marine Abridged Record (FDMAR) products.

1. OCEAN HEAT CONTENT FROM ALTIMETRY

Early work on the development of tropical cyclones led to the concept of upper ocean heat content as an important quantity in storm intensification. OHC is defined as a heat anomaly, integrated between the sea surface (z=0) and the depth of the 26°C isotherm, D26, where ρ is sea water density and c_p is the specific heat of water, with a reference temperature of 26°C, Eq. 1:

$$\mathrm{OHC} = c_p \int_0^{D26} \rho \left[T(z) - 26 \right] \, dz \qquad (1)$$

OHC is estimated using a combination of sea surface height anomalies (SSHA) from altimetry and sea surface temperature (SST) from satellite-borne radiometric measurements. A two-dimensional baroclinic ocean model is used to estimate the depth of the 20°C isotherm (within the main thermocline) from the SSHA measurements, Fig. 1. The method is based on hurricane-season climatologies of the mean depth of the 20°C isotherm, and of the mean density difference between the two ocean layers. The depth of the 26°C isotherm is then calculated from the depth of the 20°C isotherm using the climatological relationship between these two depths. Finally, OHC is computed from the 26°C isotherm depth, along with measured SST values, using bulk vertical temperature gradients in the upper layer. Further details of this methodology are described in [2].



$$h_2(x,y,t) = \overline{h}_2(x,y) + [1/\overline{\epsilon}(x,y)]\,\eta'(x,y,t)$$

$$\overline{\epsilon}(x,y) = [\overline{\rho}_2(x,y) - \overline{\rho}_1(x,y)] \,/\, \overline{\rho}_2(x,y)$$

Figure 1. Two-layer model used to calculate depth of 20°C isotherm, h_2, from SSH anomaly, η. Assuming no motion in the lower layer, variations in h_2 about it's mean are scaled by the density difference between layers, ε.

It has been demonstrated in previous studies [2], [3], that OHC is a more useful quantity than SST alone for predicting hurricane intensification. Of course there are many other factors, such as favorable upper-level wind shear, that will influence the development of a tropical cyclone. But OHC provides a better estimate of the store of heat available to fuel the storm than SST, and is more useful as a forecasting tool since altimetry can 'see' regions of high heat content even when SST is nearly uniform in regions such as the Gulf of Mexico, Fig. 2. In this figure the intensification of Hurricane Katrina is observed after crossing regions of high ocean heat content in the Loop Current and a warm core eddy in the Gulf of Mexico. The SST field shows no significant warm features.

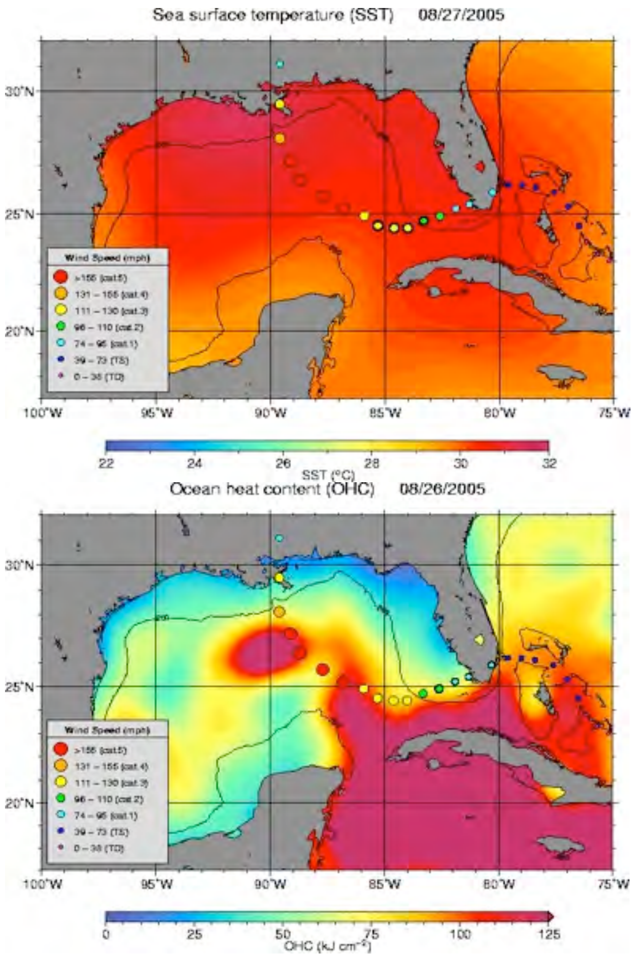


Figure 2. Comparison of fields of SST (top) vs. OHC (bottom) on 26/27-Aug-2005 during the passage of Hurricane Katrina. The SST field is nearly uniform in late summer, and doesn't reveal the Loop Current and warm core eddy features seen in OHC. These features were associated with Katrina's growth to a Category-5 storm.

2. ENVISAT ALTIMETRY FOR OHC

Presently Jason-1 and Geosat Follow-On (GFO) altimetry data are used operationally to create maps of OHC for intensity forecasts at the NHC. The Joint Typhoon Warning Center (JTWC), which forecasts tropical cyclones in the Western Pacific, is currently using OHC data based on Jason-1, GFO and Envisat, but only in an experimental mode. We plan to include Envisat in the blend of altimetry data used by the NHC for the 2007 hurricane season, and are working to get OHC into operations at the JTWC.

The Univ. of Miami group has made an assessment of the benefit of including Envisat data by comparing altimetric OHC to *in situ* observations based on XBT and CTD temperature profiles in the Gulf of Mexico, Fig. 3. The *in situ* measurements of OHC, and the depths of the 20°C and 26°C isotherms, are shown by the color filled background compared to the altimetry estimates shown by black contours. The upper panels, based on Jason-1 and GFO, are then compared to the potential improvement by the addition of Envisat in the lower panels.

Although there are some areas where the combination of three altimeters improves the agreement with *in situ* data, the incremental gain is generally not large. We believe this is due to using a one-cycle 35-day averaging window for the Envisat data. More careful study is required, for example with 10-day or ½-cycle 17-day averaging windows, to maximize the additional sampling provided by Envisat.

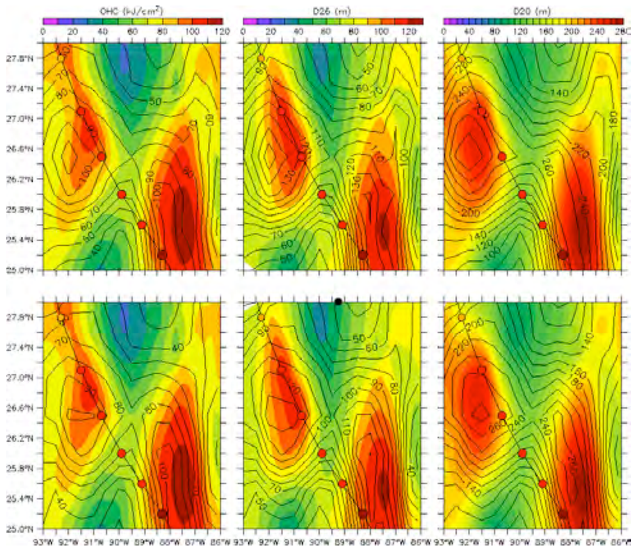


Figure 3. Fields of OHC (left), 20°C isotherm depth (middle) and 26°C isotherm depth (right) based on in situ values (in color) compared to altimetry (black contours) in the Gulf of Mexico prior to Hurricane Rita. The upper panels are based on Jason and GFO, the lower panels on Jason, GFO, and Envisat.

However, the present situation of using only Jason-1 and GFO has degraded significantly. The batteries on GFO have reached their end-of-life and can no longer sustain the radar altimeter when the satellite is in the eclipse portion of each orbit. The OHC analysis should be relying more heavily on Envisat data now, to augment the reduced GFO operations.

3. OHC AND INTENSITY FORECASTING

At the NHC, forecasters avail themselves of a variety of information to predict both track and intensity changes in hurricanes. Here we illustrate three primary uses that benefit from the inclusion of the altimetric OHC fields: statistical intensity models; coupled hurricane-ocean dynamical models; and qualitative use of OHC maps themselves by the forecasters.

3.1 The SHIPS & STIPS models

The SHIPS model [1], uses several "predictors" to forecast intensification. Notably the predictors include SST, as well as relevant meteorological parameters. In 2004 altimetric OHC was added as a predictor in the operational model at the NHC, and there was overall improvement in the model forecast skill. The improvement is expressed as a percentage reduction of error in the maximum surface wind speeds observed in the storm. For example, if the observed wind speed was 100 knots, and the SHIPS forecast was for 50 knots without, and 60 knots with OHC, the error would be reduced from 50 knots to 40 knots representing an improvement of 20% (10 knots out of the 50 knot error).

The JTWC is running an experimental version of its Statistical Typhoon Intensity Prediction Scheme (STIPS), which includes OHC input, in parallel to its operational model running without the altimetric predictor [4].

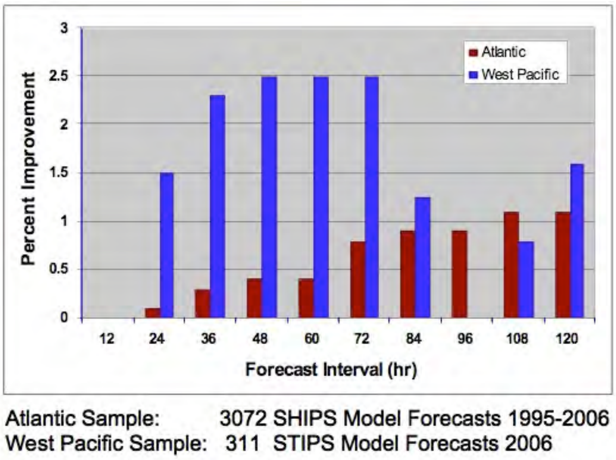


Figure 4. Increase in skill of SHIPS model with the inclusion of OHC, as a function of forecast interval. The N. Atlantic sample shows a small but significant improvement of about 1%, with more improvement at longer lead times. A smaller sample of 311 storms in the W. Pacific shows a larger improvement at short forecast intervals, from the JTWC STIPS model.

In Fig. 4 the improvement in the statistical models after including OHC is shown as a function of forecast lead time. This is based on a sample of 3072 Atlantic tropical cyclone forecasts, as well as a smaller sample of 311 forecasts in the W. Pacific. The improvement is on the order of a few percent, and generally increases for longer lead times. It appears that the model is more effective for the Pacific storms, but a larger sample of forecasts is needed to confirm this.

Although the improvement from the addition of OHC to SHIPS appears small, the gains are much greater for Category-5 hurricanes during the 2003-2005 hurricane seasons, Fig. 5. The only Category 5 storm whose intensity forecast wasn't improved was Isabel. The remaining Category-5 storms showed improvements of several percent, with the average reaching 5% at 84 hours.

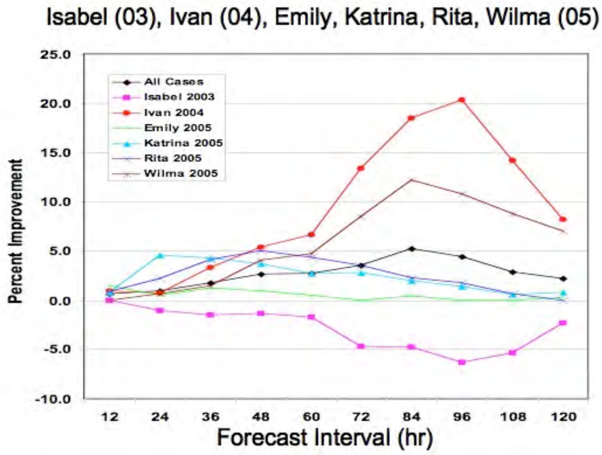


Figure 5 Improvement in SHIPS forecast for individual Category-5 hurricanes from 2003-2005. For these large hurricanes the role of OHC has a much larger impact.

In a preliminary study by the Naval Research Laboratory, the skill of STIPS forecasts was assessed for cases where typhoons tracked across the 'cold wake' formed during the passage of an earlier typhoon (B. Sampson, 2007, personal communication). The air-sea interaction and mixing associated with tropical cyclones creates these cold wakes, but in many cases the wake's SST signature quickly disappears. The loss of OHC after the passage of an earlier typhoon impacts subsequent typhoons passing over the wake, as they are robbed of heat energy to fuel them. The intensity forecasts for these 'cold-wake' typhoons is appreciably better when OHC is used in STIPS, Fig. 6. The improvement in the STIPS intensity forecasts is in the range of 6-8%, vs. a typical rate of 1-2% for all the W. Pacific storms analyzed. Although this analysis is based on a small sample size (N=39) it shows a promising and potentially important benefit from the inclusion of OHC.

3.2 The Coupled GFDL/Princeton Hurricane Model

An independent intensity prediction model that is run by NCEP for NHC is based on the coupled GFDL atmospheric and Princeton ocean models. This is a purely dynamical (vs. statistical/dynamical) coupled model whose ocean state is initialized with climatological conditions. Recent work by Isaac Ginis, Univ. of Rhode

Island, has demonstrated that OHC fields can be used to initialize the ocean model, resulting in much more realistic mesoscale features, such as the Gulf of Mexico Loop Current and associated warm core eddies, Fig. 7.

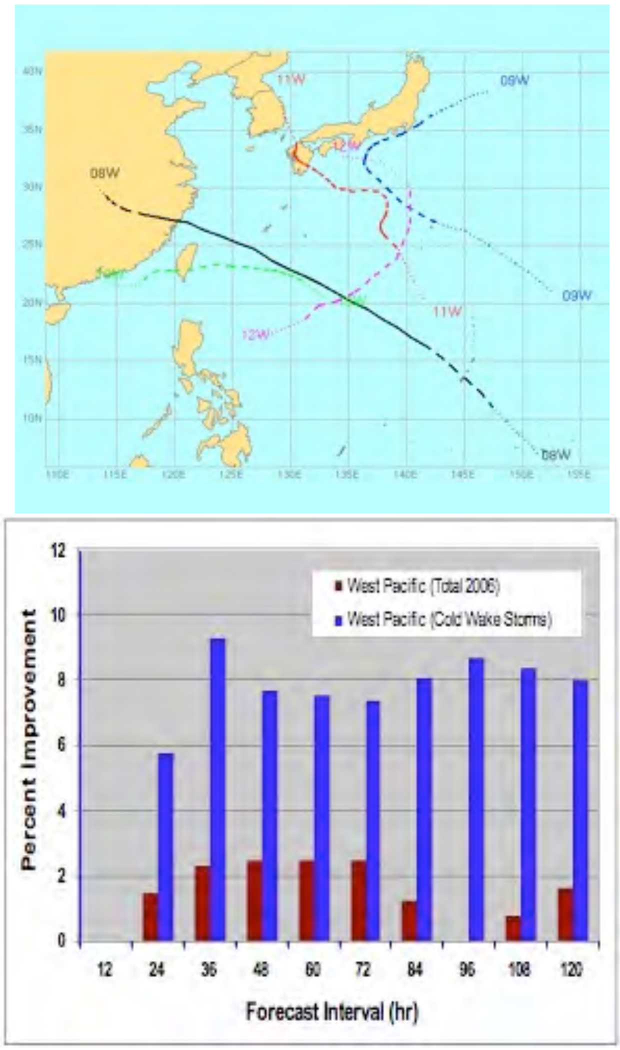


Figure 6. Analysis of "Cold Wake" typhoons from the W. Pacific 2006 season. The tracks of typhoons 8W-12W (top) show the storms crossing the tracks of earlier typhoons. The improvement in the STIPS intensity forecasts (bottom) illustrates that the inclusion of OHC which retain cold wake features is significantly greater than the averages over all 2006 typhoons.

This example, from Hurricane Rita in 2005, shows that the climatological initialization doesn't capture the mesoscale OHC features that fueled the intensification of Rita. The model initialized with OHC fields will properly drive the coupled atmospheric hurricane model, resulting in improved performance.

The improvement after assimilating OHC in the coupled model is shown in Fig. 8, in terms of the time series of minimum atmospheric pressure observed during hurricane Katrina. The observed values dropped to nearly 900 mbar on Aug. 28th, 2005, while the standard coupled model predicted a minimum pressure of only 930 mbar a day later. By assimilating OHC into the coupled model, the proper timing of minimum pressure was predicted, with a minimum value of 915 mbar, closer to the observed value.

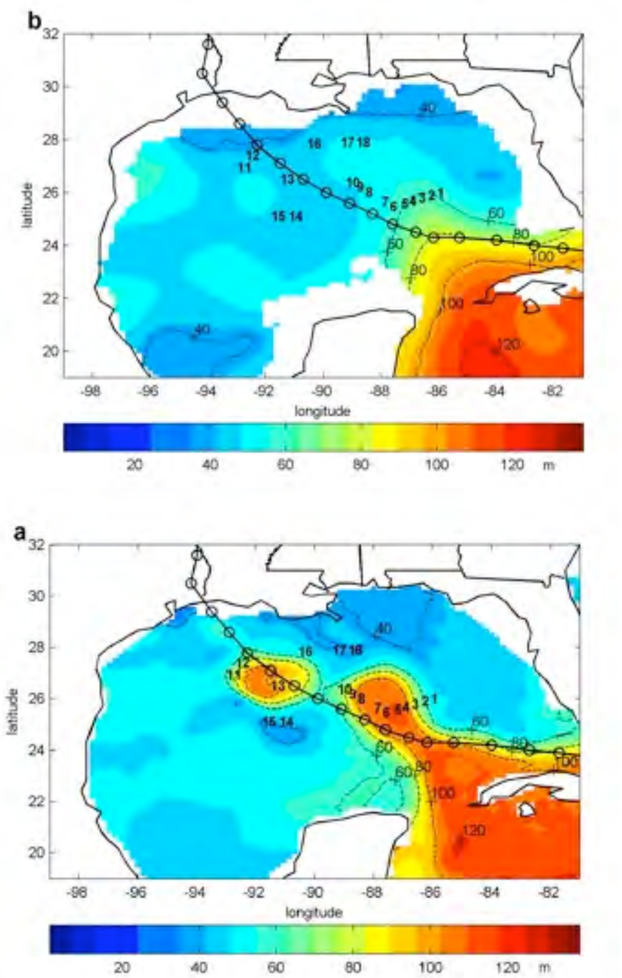


Figure 7. Depth of the 26°C isotherm from the GFDL coupled model before assimilation (top) and after assimilation (bottom) of OHC from altimetry. The overlaid track of hurricane Rita shows that the storm passed over regions of high OHC, that were not reflected in the operational model initialized by climatology.

3.3 Qualitative use by Hurricane Forecasters

Hurricane forecasters rely on a variety of information to help guide their intensity predictions. When tens or hundreds of thousands of lives may be impacted it is imperative that they receive the best available information in a timely fashion. The same fields of OHC that are used as predictors in SHIPS, and which can be assimilated to improve the dynamical hurricane models, are utilized by forecasters [5] in their original mapped form (e.g. Fig. 2).

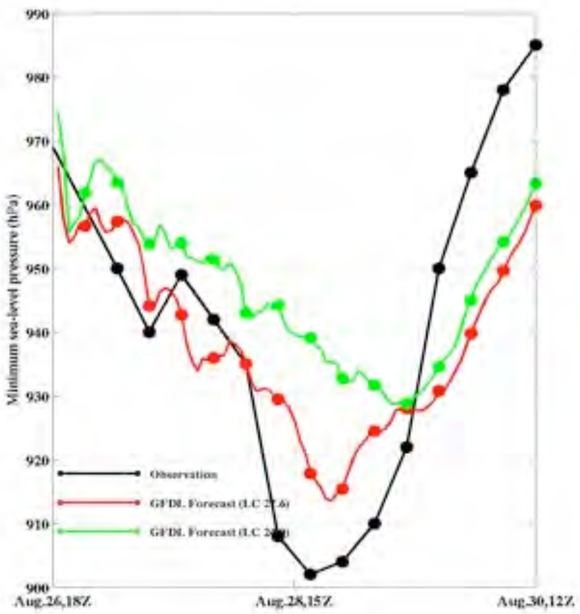


Figure 8. Time history of minimum surface pressure along the track of Katrina. Observed values are in black, GFDL model predictions without OHC are in green, and with OHC assimilation are in red. The addition of realistic OHC structure as seen in Fig. 7 results in better timing as well as minimum pressure values in the forecast.

Subjective use of the OHC maps provides a direct benefit to intensity forecasting. The following quotes demonstrate how the OHC fields helped guide the forecasters:

Katrina - "Katrina is expected to be moving over the Gulf of Mexico Loop Current after 36 hours, which when combined with decreasing vertical shear, should allow the hurricane to reach category four status before landfall. This pattern in combination with the high oceanic heat content … along the path of Katrina calls for additional strengthening".

Rita - "The environment is conducive for strengthening and Rita, as Katrina did, will be crossing the Loop Current or an area of high heat content within the next 12 hour or so. This would aid the intensification process. The intensity forecast is based on the premise that the shear and reduced outflow will cause a gradual weakening, especially after Rita moves west of the Loop Current."

Ivan - "Thereafter the hurricane will be over the northwestern Caribbean Sea where there is high oceanic heat content and lower shear. So, Ivan is expected to intensify before reaching Cuba".

4. REDUCING THE LATENCY OF ENVISAT OHC

Presently, the blended fields being used to compute heat content at the NHC and JTWC are based on Envisat Intermediate Geophysical Data Record (IGDR) data, which has a typical latency of 3-4 days. Having the most up to date information on the ocean's mesoscale structure will benefit intensity forecasts. We are working to include the Envisat FDMAR data, with a latency of several hours, into the blend. The following analysis is based on Cycles 54-56 of the FDMAR data, 18-Dec-2006 to 02-Apr-2007.

Recent improvements in the Envisat ground segment's processing software have eliminated some of the issues that hampered the use of FDMAR data:

1. Ultra-Stable Oscillator (USO) anomaly correction files were routinely made available to users on 28-Jul-2006. It is essential to correct the ~5.5 m bias, and tens of cm of around-orbit variation in height, associated with the anomaly.

2. Instrument Processing Facility (IPF) Version 5.03, released 18-Sep-2006, implemented the 'peakiness' parameter in the FDMAR data, providing a desirable edit criteria for SSHA data affected by sea ice or rain.

3. Also in IPF 5.03, a status flag to indicate the quality of the real-time orbits in each 1-Hz FDMAR data record was added: bit #27 of the Measurement Confidence Data (MCD).

The FDMAR uses orbits from the on-board DORIS (Doppler Orbitography and Radiopositioning by Satellite) system's real-time DIODE (Détermination Immédiate d'Orbite par Doris Embarqué) processor [6]. When DIODE orbit data are unavailable, due to instrument or ground segment processing difficulties, a crude state-vector propagator orbit is used as a fall-back.

Our initial analysis of Cycles 54-56 shows an unexpectedly large amount of degraded data, where the propagator orbit is present rather than the higher accuracy DIODE orbit, Fig. 9. Here the ascending and descending passes are plotted separately, illustrating that there are persistent 'patches' where the DIODE data are missing, as well as a large number of full passes based on the poor propagator orbit. The percentage of good data are in the range of only 60-65 percent for cycles 55-56, and even lower in cycle 54 (presumably due to data availability issues in the ground segment).

It is hoped that the full passes of missing DIODE data, at least, can be rectified in the next upgrade to the IPF. The 'patches', however, are apparently due to an inherent, single-source-packet delay between the altimetry and

DIODE data within the telemetry, and this will not be easy to solve (P. Femenias, personal communication).

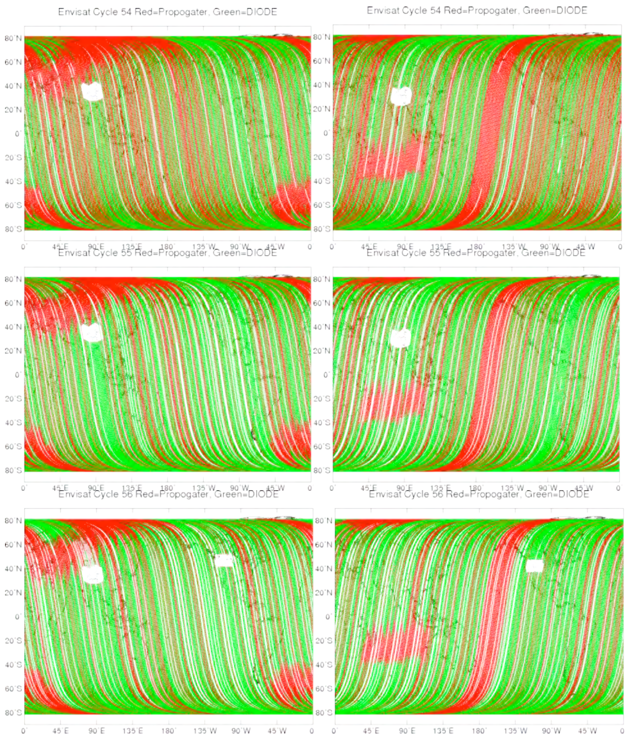


Figure 9. Distribution of real-time orbits for Envisat Cycles 54 (top), 55 (middle), and 56 (bottom) for ascending passes (left) and descending passes (right). The red points are from the crude state vector propagator, while the green points are based on the DORIS/DIODE onboard system. The white areas are where the RA-2 performs its calibration mode.

To assess radial orbit error in the FDMAR data, we difference the orbital heights from the IGDR (DORIS Medium-precision "MOE" orbits) with the DIODE orbits in the FDMAR, Fig. 10. The orbit differences have an amplitude of ~30 cm and are dominated by once and twice-per-revolution variations. This level of orbit error does not present a problem for the routine processing of the SSHA fields done at the Naval Oceanographic Office who supply the SSHA fields to the NHC. The data based on propagator orbits, with typical errors on the scale of meters, are problematic and likely would not be used.

5. CONCLUSIONS

Altimetry provides a valuable tool to produce global maps of upper ocean heat content. Fields of OHC improve the forecast skill of both statistical models such as SHIPS, and coupled dynamical models that are used operationally for tropical cyclone intensity forecasts. OHC seems to be particularly effective when forecasting large storms over regions of OHC in excess of 50-60 kJ/cm^2. 'Cold-wake' cyclones, which cross regions of low OHC due to previous storms, appear to benefit even more from the inclusion of OHC in the statistical models.

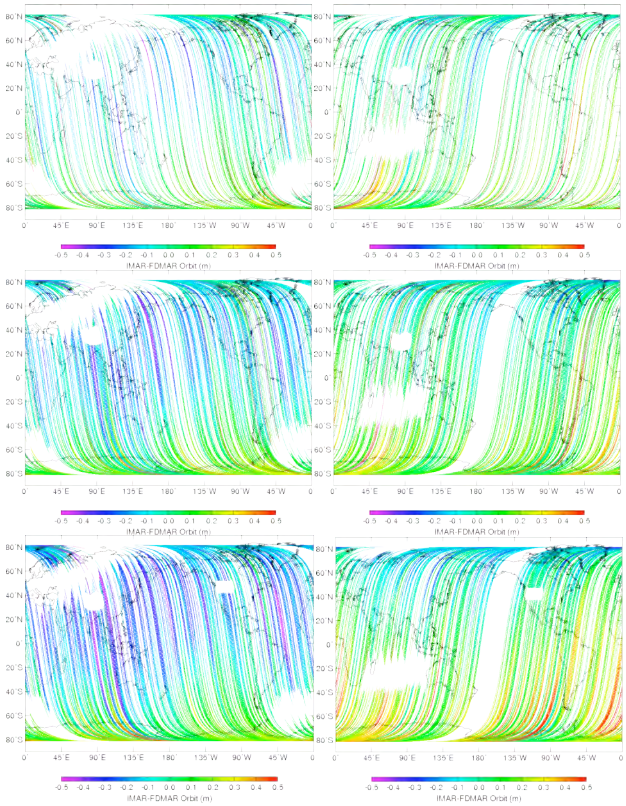


Figure 10. Differences in orbital altitude between the IGDR MOE orbits and FDMAR DIODE orbits. Points based on the propagator orbits in the FDMAR are excluded. The differences are attributed to radial orbit error in the DIODE orbits with a level of 20-30 cm.

Applying the USO corrections in the ground segment and, more importantly, increasing the percentage of passes based on DIODE orbits will increase the utility of the fast-delivery data. In the next several months we plan to add FDMAR data to our altimetry processing, so that it can be included in the OHC analysis done by the NHC.

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