FIFTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 0.2e: **Present and imminent applications of geostationary infrared imagery to tropical cyclone analysis and forecasting**

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Abstract: Application of infrared (IR) imagery from geostationary satellites to the estimation of tropical cyclone structure, intensity, and forecast evolution is discussed. Present state-of-the-art methods for measuring wind structure and vertical shear, estimating current intensity, and predicting intensity change are introduced, and imminent future directions are discussed. The potential for combining IR imagery with multisensor/multiplatform satellite data is considered.

0.2e.1: **Introduction**

Infrared (IR) imagery from geostationary satellites is arguably the workhorse of tropical cyclone (TC) diagnosis and forecasting because of the high spatial and temporal resolution of the data, and because the regularity of sampling allows for continuous global monitoring of TCs. On the less positive side, IR imagery is often severely limited at giving *direct* information about TC inner-core structure and evolution because upper-level cirrus clouds are opaque at typical IR wavelengths. This is especially problematic in TC scenes that often display a central dense overcast (CDO), and much of the structure of the eyewall and surrounding rainbands becomes obscured.

Although TC diagnosis and forecasting is challenged by the presence of upper-level cirrus, the regularity of IR data and the volume of images that currently exist in archival data sets allow for calculation of *indirect* relationships between cloud-top temperatures (T_b) and intensity. For example, the subjective and objective versions of the Dvorak technique (Dvorak 1975, 1984; Velden et al. 1998; Olander et al. 2002) use the general characteristics of T_b fields to infer TC intensity. Recently, the SHIPS model (DeMaria and Kaplan 1994, 1999) has begun incorporating IR derived parameters into its multivariate set of intensity predictors, and an increase in intensity forecast skill has resulted (DeMaria et al. 2002). The daily variability of T_b fields in TC scenes was recently considered by Kossin (2002) and new relationships between T_b and periodic convective variability were uncovered. These results were forthcoming because of the recent availability of a large IR data archive (Zehr 1998).

The obscuring effects of the CDO can also be somewhat overcome through multispectral satellite methods that incorporate geostationary IR data to deduce TC wind fields at multiple levels (Velden et al. 1997, Velden 1997). These methods have been very successful and the resulting wind products are currently widely used. An example of satellite-derived wind fields in Tropical Storm Isidore (2002) in the Gulf of Mexico, and Hurricane Luis (1995) using rapid-scan imagery is shown in Fig. 0.2e.1. Figure 0.2e.2 is a montage of products that are based on multispectral satellite methods: vertical wind shear within varying layers, shear tendency, low-level vorticity, reduced surface winds, and a product based on a method of detecting intrusions of Saharan dust into TCs that was recently developed at the University of Wisconsin-Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) (Dunion and Velden 2002). The interaction of Saharan dust with TCs is hypothesized to affect TC intensity.

Using satellite-derived winds and wind shear at multiple levels, a version of the UW-CIMSS experimental vertical shear product (Gallina and Velden 2000, 2002) is being tested during the 2002 Atlantic hurricane season. This product is generated automatically and disseminated to a select group of scientists. In addition to giving information regarding vertical shear, the product also provides a forecast of 24 h intensity change, insofar as it identifies conditions for intensification as either favorable, unfavorable, or neutral based on the environmental shear. Preliminary testing has been very positive. An example of this product is shown in Fig. 0.2e.3.

This paper briefly discusses some of the present and imminent "cutting-edge" applications of IR data to TC analysis and forecasting. Section 2 describes the current state-of-the-art in the estimation of TC intensity. In section 3, the application of IR data to the intensity forecasting problem is discussed.

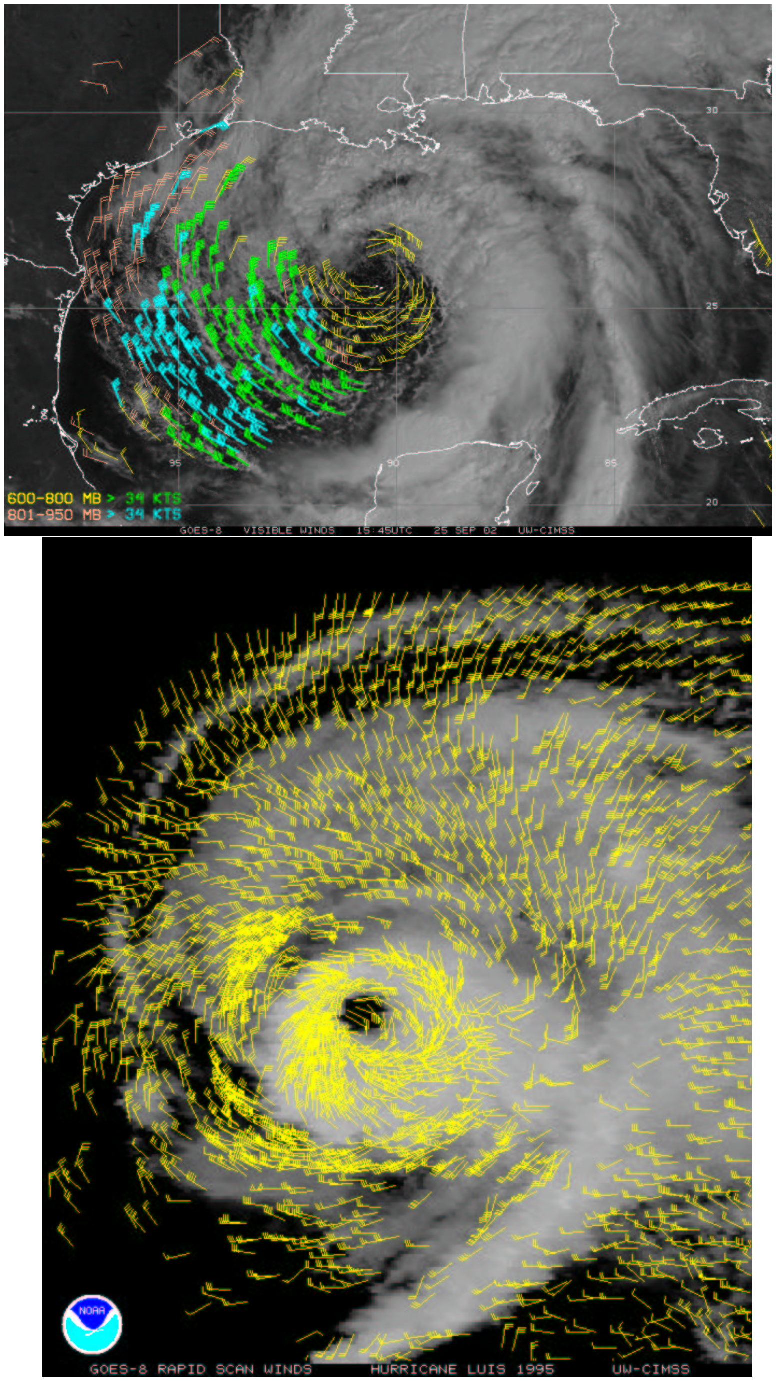

Figure 0.2e.1: Satellite-derived winds in (top) TS Isidore (2002) and (bottom) Hurricane Luis (1995).

0.2e.2: **Diagnosing tropical cyclone intensity using geostationary IR data**

The first widely applied method for estimating TC intensity using geostationary data was the Dvorak technique (Dvorak 1975, 1984). In response to the inherent subjectivity of the Dvorak technique, Zehr (1989) and Velden et al. (1998) developed the objective Dvorak technique (ODT)

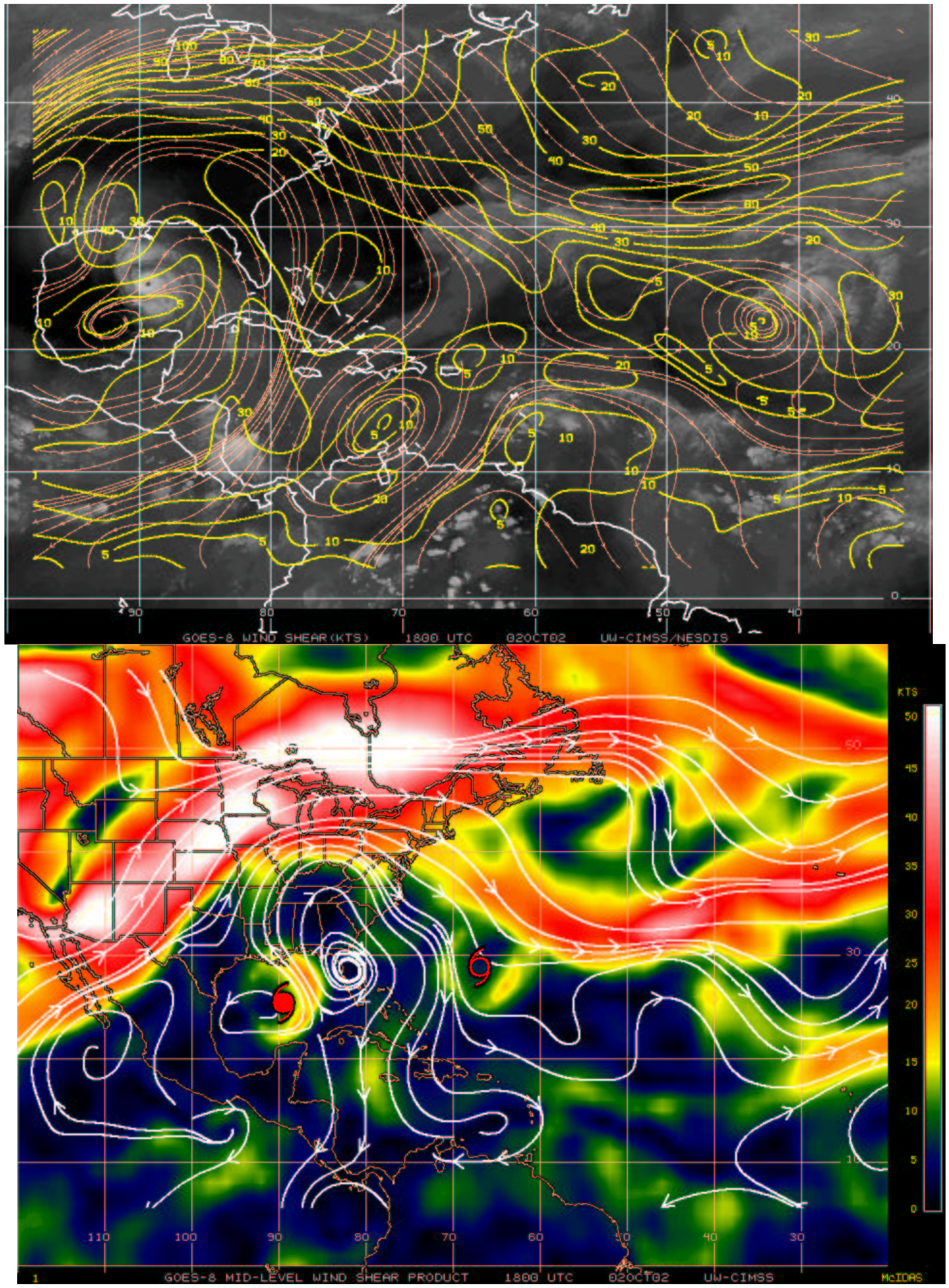

Figure 0.2e.2: A montage of products based on multispectral satellite methods. (Top) Vertical wind shear and (bottom) mid-level shear in Hurricane Lili (2002). Continued on following page ...

that is currently employed by various forecast centers and provides an objective method that is competitive with the subjective Dvorak technique. In response to feedback from forecasters in operational centers, various ways to improve the performance of the ODT are presently being explored under the umbrella of the advanced ODT (AODT, Olander et al. 2002). For example, improvement of the ODT in the case of weaker systems (below Category 1) is being addressed using various scene-typing schemes and objective curved band analyses.

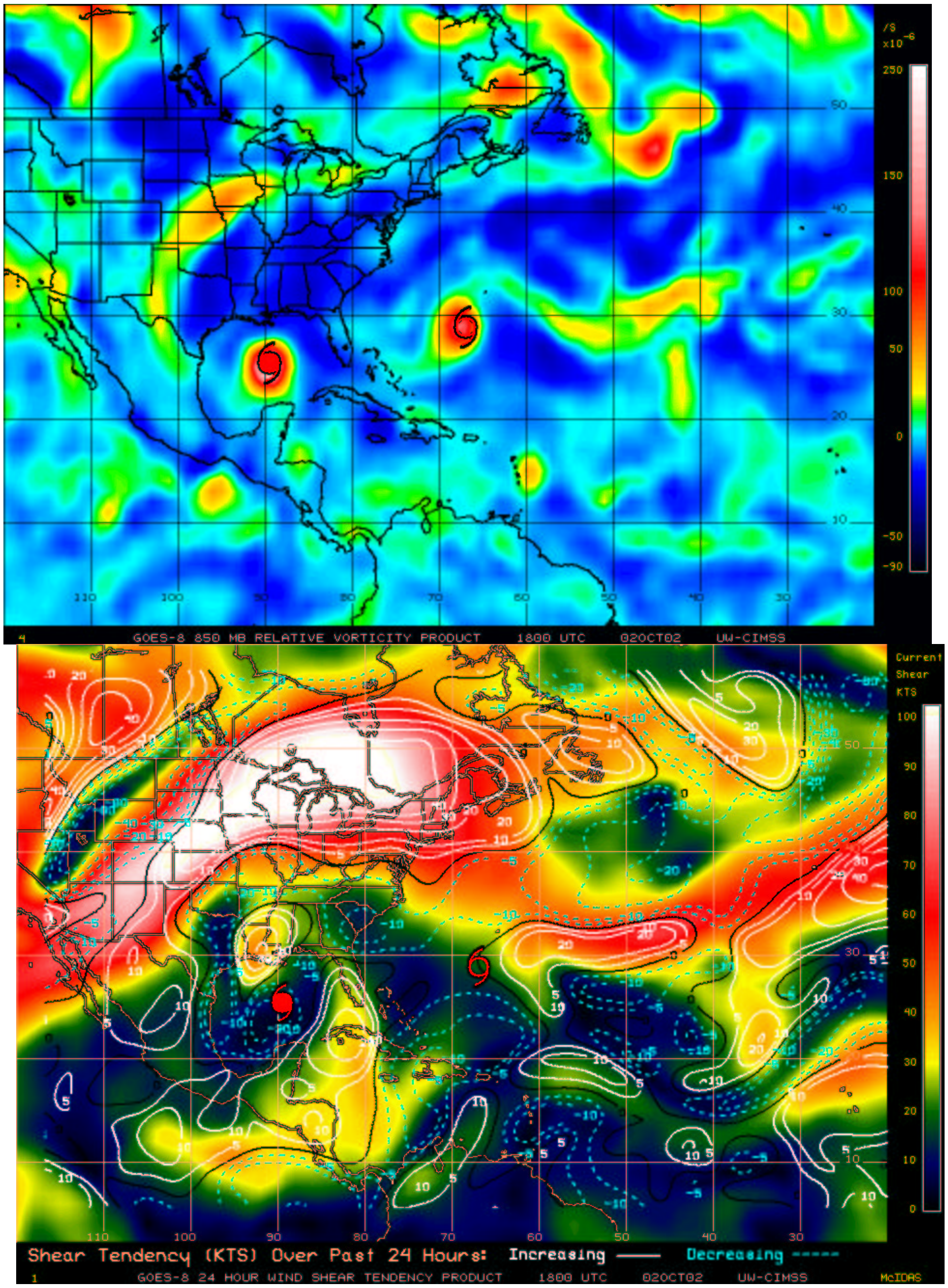

Figure 0.2e.2: ... continued. (Top) Vorticity and (bottom) 24 h vertical wind shear tendency in Hurricane Lili (2002) Continued on following page ...

The subjective, objective, and advanced objective Dvorak techniques all relate particular IR-derived parameters to current TC intensity. Put another way, these methods are based on *correlations* between IR imagery features and TC intensity. For example, it is accepted that colder cloud tops (i.e., deeper convection) in the TC eyewall region correlate well with greater intensity. These correlations have historically been empirically determined by means of human experience.

This section introduces a new approach that builds on empirical foundations, and considers more

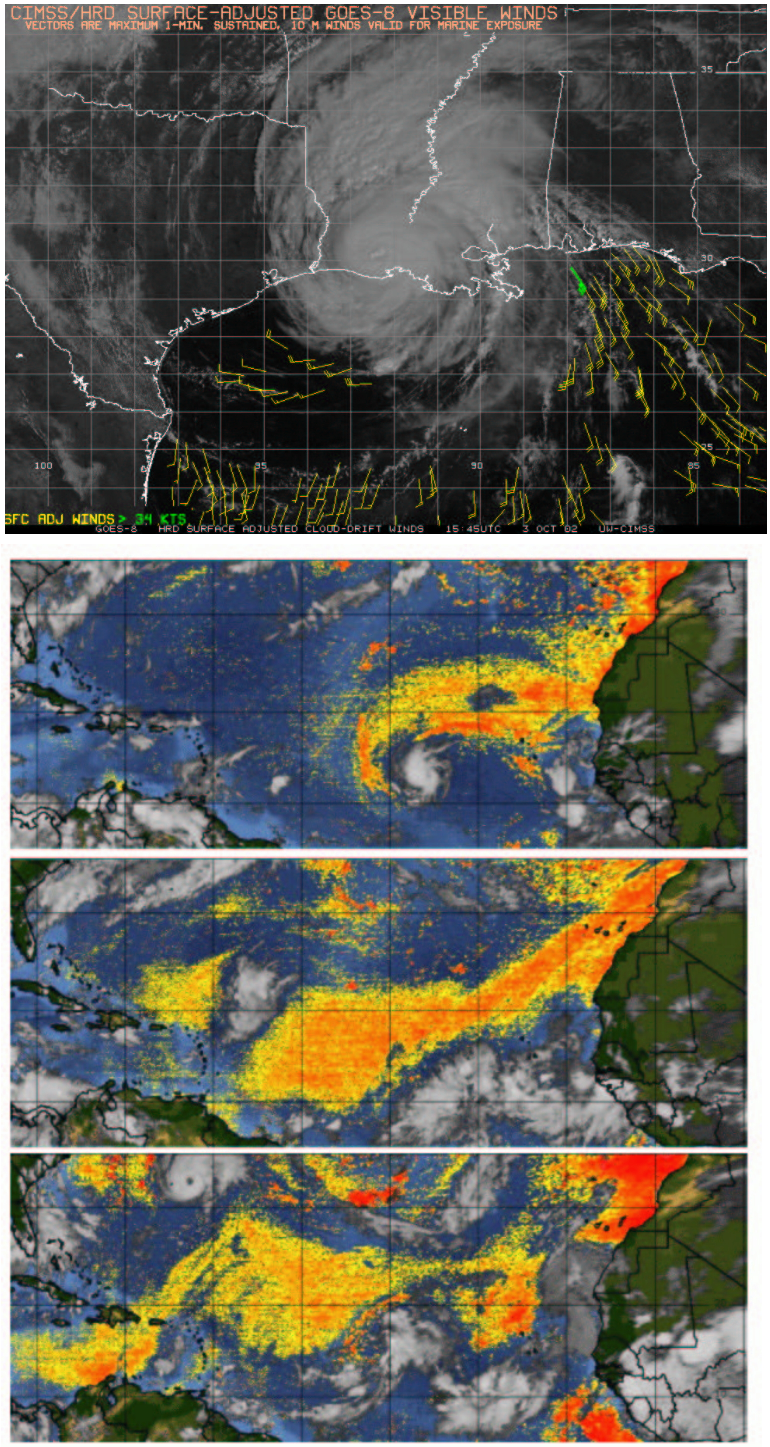

Figure 0.2e.2: ...continued. (Top) Surface adjusted winds and (bottom three panels) a new multispectral satellite product that captures the presence of Saharan air layers.

formal statistical relationships between IR-derived variables and TC intensity (Kossin et al. 2003). In particular, a multivariate linear model (multiple regression) is formed and tested. As a first step, the model predictors are the same as those used by the AODT. Mean sea-level pressure (MSLP)

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              TROPICAL STORM KYLE     18:00UTC     07October2002
   UW-CIMSS Experimental Vertical Shear TC Intensity Trend Estimates

     Current Conditions :
                   Latitude                      :   32:19:27 N
                   Longitude                     :   70:50:45 W
                   Intensity (MSLP)              : 1005.0 hPa
                   Max Pot Int (MPI)             :  971.7 hPa
                   MPI differential (MSLP-MPI)   :   33.3 hPa
                   CIMSS Vertical Shear Magnitude :    2.8 m/s
                                       Direction :  215.0 deg

     Outlook for TC Intensification Based on Current Env. Shear Values
     Forecast Interval :     6hr   12hr   18hr   24hr
                              F      F      N      N

     Legend :        VF-Very Favorable   F-Favorable   N-Neutral
                      U-Unfavorable     VU-Very Unfavorable

     --  Mean Intensity Trend (negative indicates TC deepening) --
               6hr            12hr            18hr            24hr
     VF  <-3.0mb/ 6hr   <-6.0mb/12hr   <-9.0mb/18hr   <-12.0mb/24hr
      F   -3.0 - -1.5    -6.0 - -3.0    -9.0 - -4.5    -12.0 - -6.0
      N   -1.5 - +1.5    -3.0 - +3.0    -4.5 - +4.5     -6.0 - +6.0
      U   +1.5 - +3.0    +3.0 - +6.0    +4.5 - +9.0     +6.0 -+12.0
     VU      >+3.0          >+6.0          >+9.0          >+12.0
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Figure 0.2e.3: An example of the experimental UW-CIMSS vertical shear product for Hurricane Kyle (2002). In addition to estimating shear based on satellite-derived winds, conditions for 24-h intensity change are indicated.

measured by aircraft reconnaissance (recon) is the predictand. Prelimary results suggest that the linear model is competitive with the existing AODT while streamlining the process considerably and reducing the number of decisions (e.g., scene type identification) that are made within the framework of the AODT.

Results of a dependent test of the new regression-based method applied to a sample of 1624 IR images for which we have corresponding aircraft reconnaissance MSLP data is shown in Fig. 0.2e.4. Comparison of the first (top) and third panels in Fig. 0.2e.4 shows that when estimating MSLP based on a single image (i.e., with no information about previous IR scenes or intensities), the linear model outperforms the AODT. The root mean square error (RMSE) of MSLP estimated by the linear model is 13 mb while the RMSE of the AODT raw T-number MSLP is 17 mb. The linear model has reduced the outliers and has a more Gaussian distribution of error. Comparison of the second and fourth (bottom) panels shows that when MSLP estimated by the linear model (denoted as r-MSLP) is time averaged[1], the linear model is competitive with the CI-number based MSLP of the AODT. The RMSE for both methods are essentially equal, and the errors of the averaged r-MSLP again have a more Gaussian distribution. The AODT CI-number is formed using a combination of time averaging and application of rules, some of which are based on identification of scene types (the rules and scene types are employed in the AODT to mirror the rules in the

[1]Time averaging was performed using the same 12 h weighted mean that is used in the ODT and AODT. We plan on testing different averaging schemes, and may find that a shorter averaging period will perform just as well or better. Forecaster feedback has indicated a need for shorter averaging periods, particularly for capturing rapid intensity change events.

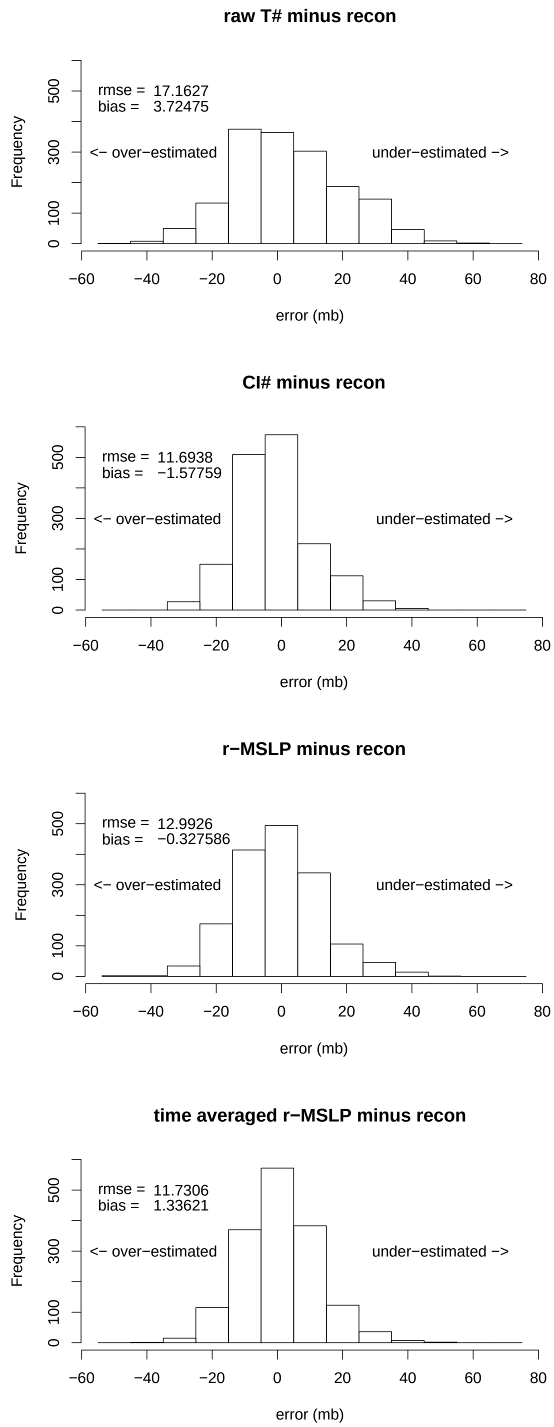

Figure 0.2e.4: Error analysis of MSLP (mb) estimated from the AODT raw T-number and CI-number versus reconnaissance (top two panels), and the regression based MSLP (r-MSLP) before and after time averaging (bottom two panels).

subjective Dvorak technique). Scene-type identification is one of the more difficult challenges that research on the AODT is actively addressing, but is *not required by the linear model.*

The results in Fig. 0.2e.4 are based on dependent testing of the entire sample of images that are concurrent with recon. An independent test of Hurricane Fran (1996) is presented here. We re-derived the regression coefficients for the entire sample minus Fran, and then tested the model on Fran (jackknife procedure). The results in Fig. 0.2e.5 demonstrate that the linear model (based

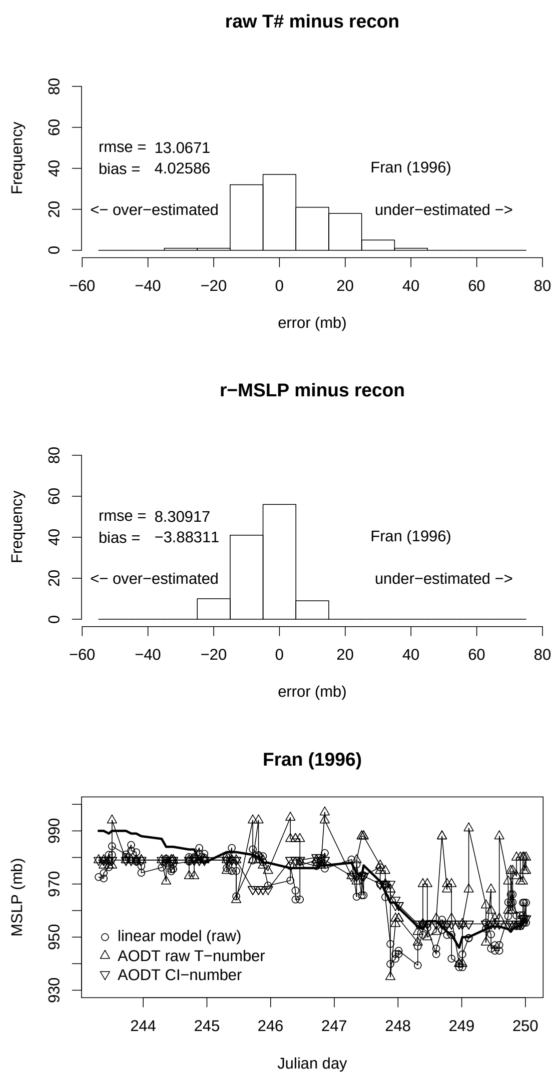

Figure 0.2e.5: Independent (jackknife) MSLP (mb) error analysis of the linear model applied to Hurricane Fran (1996), and comparison with the AODT. Error analysis of the raw T-number MSLP (top) and the regression-based MSLP (middle). (Bottom) Evolution of recon MSLP (thick line), raw T-number and CI-number MSLP, and the linear model-derived MSLP.

on a *single* image, i.e., with no time averaging), gives a better estimate of MSLP (RMSE = 8 mb) than the raw T-number derived from the AODT (RMSE = 13 mb). The biases for the two methods are comparable, but of opposite sign (negative error implies an overestimation of intensity). The bottom panel in Fig. 0.2e.5 shows the evolution of MSLP as measured by recon (thick black curve) and as estimated by the linear model and the AODT. Presently, we are calculating time averages of r-MSLP, but they are not available at the time of this writing. However, a time average performed on the r-MSLP curve in Fig. 0.2e.5 will result in greater accuracy.

At the time of this writing, a very limited independent testing has been performed, and it is not clear how well the linear model will perform in a variety of cases. Results of independent testing thus far have been very encouraging.

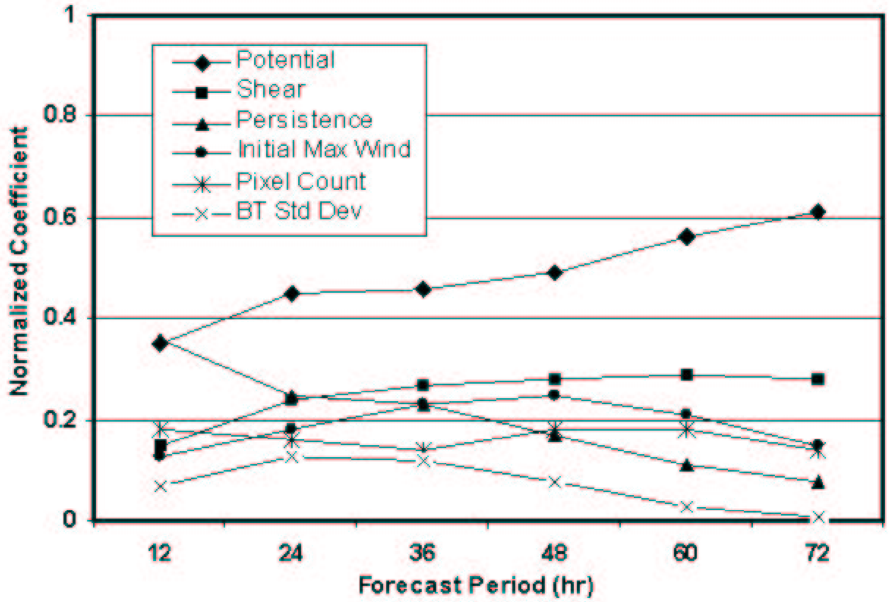

Figure 0.2e.6: Normalized regression coefficients at 12–72 h for the four most important predictors in SHIPS and for two predictors from the GOES-IR data (inner-core Pixel Count and Brightness Temperature Standard Deviation).

For future development, the multivariate linear model also allows for the easy inclusion of a broad variety of additional parameters. In particular, inclusion of microwave-derived parameters (e.g., Bankert and Tag 1997, 2002; May et al. 1997; Hawkins et al. 1998) seems to be a logical next step in the evolution of a hybrid model that incorporates multi-satellite sensor information to estimate TC intensity. Additional IR-derived parameters can also be easily tested in the model. Information regarding climatology, persistence, and synoptic-scale environmental predictors similar to those used in SHIPS (Statistical Hurricane Intensity Prediction Scheme; DeMaria and Kaplan 1999, DeMaria et al. 2002, 2003) may form significant parameters for estimating current intensity as well as forecast intensity, and can be readily included in the linear model.

0.2e.3: **Forecasting tropical cyclone intensity using geostationary IR data**

One of the most pressing problems in TC forecasting is the relatively low skill of current numerical weather prediction models in predicting TC intensity. While track forecasting has had a steady and significant improvement over the years, intensity forecasting progress has lagged far behind. To address this problem, a statistical method (SHIPS) was developed by DeMaria and Kaplan

(1994, 1999) and is currently employed by forecast centers for Atlantic and eastern North Pacific TCs. The method is based on a multivariate linear model that produces intensity forecasts that depend on environmental parameters such as sea-surface temperature and synoptic vertical shear values. This year, the experimental version of SHIPS (SHIPS-E) incorporates IR data (Demaria et al. 2002) as well as ocean heat content information from the TOPEX/Poseidon radar altimeter (Mainelli et al. 2002) as additional predictors of intensity change. Figure 0.2e.6 shows the significant contribution of the GOES-IR derived predictors to the linear SHIPS model (DeMaria et al. 2002). For the current 2002 Atlantic TC season, SHIPS-E has slightly greater skill than SHIPS (Fig. 0.2e.7), although neither model has performed well during this period (DeMaria et al. 2003). At the end of the season, a thorough analysis of SHIPS-E will be conducted.

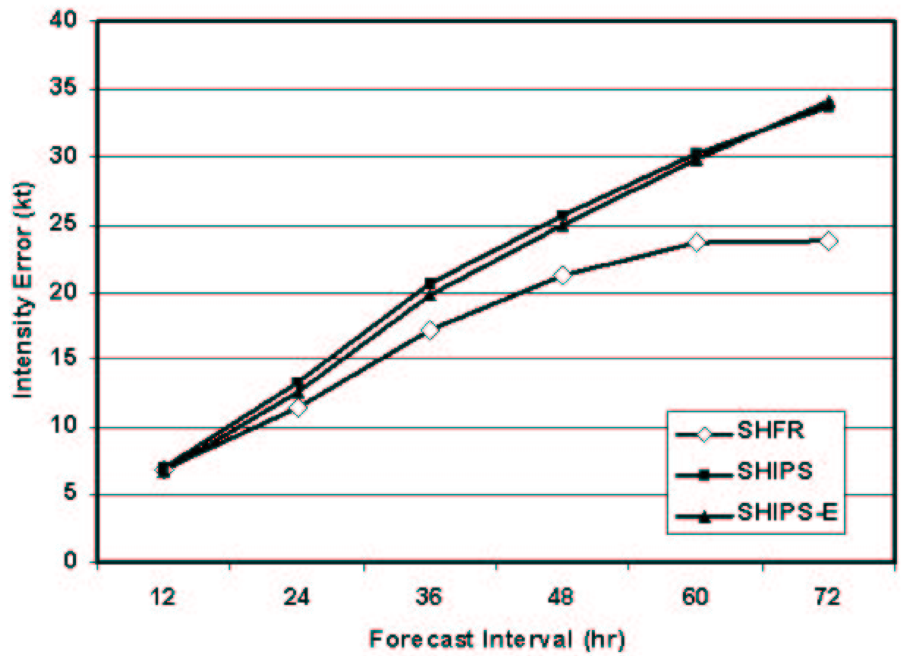

Figure 0.2e.7: Average intensity errors from the SHIFOR, SHIPS, and experimental SHIPS for the period 20 Aug to 26 Sep, 2002 (from DeMaria et al. 2003).

Future directions for further improvement of SHIPS will include testing of additional IR-derived parameters. The inclusion of predictors derived from the UW-CIMSS experimental wind shear product may also improve the skill and will be tested by the UW-CIMSS team in the near future. One of the possible advantages of predictors such as IR-derived or inner-core shear parameters is that they are not dependent on track forecasts as many of the other SHIPS predictors are.

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