The Coupled Hurricane Intensity Prediction System (CHIPS)

The Coupled Hurricane Intensity Prediction System (CHIPS; see Emanuel et al., 2004) is based on a simple axisymmetric hurricane model that assumes that the interior flow is in gradient and hydrostatic balance, and that saturated moist entropy (the moist entropy air would have were it saturated at its given temperature and pressure) is constant along surfaces of constant absolute angular momentum. This is equivalent to assuming that the saturated potential vorticity is zero everywhere. The partial differential equations are phrased in a coordinate system in which the square root of the angular momentum (or “potential radius”) plays the role of the radial coordinate. This has several advantages: First, above the boundary layer, nonlinear advection is absorbed into the coordinate transformation so that, aside from vertical advection of actual moist entropy, the equations are linear. Second, and most importantly, this coordinate transformation yields high resolution in the all-important eyewall region, while sacrificing horizontal resolution in the outer regions of the storm, where it is less important.

The assumption of zero saturated potential vorticity in the interior is equivalent to assuming that the troposphere is always neutral to slantwise moist convection, i.e. that convection keeps the temperature lapse rate close to moist adiabatic on angular momentum surfaces. This means that most of the time dependence enters though the boundary conditions at the surface and the troposphere. The lower boundary condition is applied to actual moist entropy which is affected by radial advection by the Ekman flow, surface fluxes, and convective downdrafts. The upper boundary condition has a single time-dependent process: radial advection of entropy.

A Sawyer-Eliassen type equation is solved for the radial and vertical velocities. As with the rest of the model, this equation is in potential radius coordinates.

Convection is parameterized according to the assumption of boundary layer quasi-equilibrium. Here it is assumed that the import of low entropy air into the boundary layer from the middle troposphere balances radial advection and surface enthalpy fluxes. This balance is “soft” in the sense that the convective mass flux is relaxed towards it equilibrium value over a fixed, specified time scale.

CHIPS needs to know the value of the moist entropy in the middle troposphere in order to know what values are imported to the boundary layer via downdrafts, and this is represented by values at a single level in the vertical representing the middle troposphere. *CHIPS is very sensitive to this middle level moist entropy* (derivable from the relative humidity in the middle troposphere). A time-dependent equation for middle level moist entropy is integrated along with the boundary conditions. This equation considers radial advection, vertical advection by the vortex-scale vertical velocity, and convective fluxes.

Because CHIPS is an axisymmetric model, it cannot explicitly account for environmental wind shear, which is an important control on storm intensity. For this reason, the effects of environmental shear are parameterized in the model in terms of the shear itself and the model’s axisymmetric wind and convective mass fluxes. (See Emanuel et al., 2004, for details.) This parameterization is based on the “ventilation” hypothesis that the main effect of shear is to import dry air into the storm’s core at middle levels.

The atmospheric component of CHIPS is coupled to a very simple ocean model consisting of a series of independent one-dimensional ocean columns strung out along the forecast track. The only physics in this model is vertical mixing, which is parameterized according to the hypothesis that a bulk Richardson number is held constant during the mixing. The mixing reduces the sea surface temperature, which is fed back into the atmospheric model. Since the latter is axisymmetric, an average value of SST at the given radius in front of and behind the storm is used. While the unperturbed SSTs are derived from the operational GFS analysis, the mixed layer depth and sub-mixed-layer thermal stratification needed by the ocean model are at present taken from Levitus monthly mean climatology. Thus ocean eddies and other anomalies are not accounted for. But the ocean coupling is important and has a strong effect on the intensity forecast, particularly for high intensity events.

CHIPS is an intensity-only model and must be given a forecast track, which for operational forecasting, is the official NHC or JTWC forecast track, depending on the region.

CHIPS is initialized in a unique way. Large-scale initial conditions are derived from the latest GFS operational gridded fields. These include the potential intensity, which is the critical thermodynamic input to CHIPS. This is calculated from the analyzed SST together with the full vertical column profiles of temperature and humidity. So as to reduce the spurious influence of any GFS rendition of the tropical cyclone on the potential intensity, the latter is lagged 5 days before input to CHIPS. As it is a slowly changing field, this is not considered a serious problem.

The environmental wind shear used by CHIPS is derived from the GFS 250 and 850 hPa winds after first filtering out the current storm's own wind field. This is done by filtering high spatial frequencies from the vorticity fields and then inverting the vorticity to derive filtered wind fields which are then used to calculate 250-850 hPa wind shear. Up until 2010, CHIPS used climatological temperature and relative humidity at 600 hPa to supply boundary conditions for its middle troposphere moist entropy field; beginning in 2010 the 600 hPs GFS fields were applied. Because the tropical cyclones in the GFS fields are usually too large, they produce excessive regions of high humidity near storms; for this reason, CHIPS uses the lowest humidity values within 2 GFS grid points of the GFS storm center.

Although the GFS fields are now used as boundary conditions on the middle-level moist entropy, this quantity is initialized by a different means. The storm is actually initialized at the beginning of its life regardless of how far back in time that was. The CHIPS storm is steered along the observed track up until the current time, and past GFS analysis fields are used to supply wind shear. But the middle troposphere moist entropy field is adjusted continuously in time so as to keep the CHIPS intensity close to the observed intensity from the beginning of the storm's life up to the current time. In effect, CHIPS makes use of the fact that storm intensity is more robustly estimated than middle-level humidity and uses the intensity information over time to estimate the initial middle troposphere moist entropy.

Since CHIPS needs an official track forecast to run, one must choose between waiting for the track forecast to issue and then making an intensity forecast, or using a 6-hour-old track forecast. In practice, we do both. In the first case, the track forecast is issued before GFS model fields for that forecast cycle are available, and thus one must wait for the GFS fields to runs CHIPS.

In addition to the main forecast, we run a limited 6-member ensemble. All ensemble members use the same official forecast track forecast but use differing initial intensities and/or enhanced or degraded shear. Here are the details; ensemble member 1 is defined as the control:

Ensemble member 2: Initial intensity is enhanced by 3 m/s. (During the initialization, the intensity increment is slowly ramped up over the previous 24 hours.)

Ensemble member 3: Initial intensity is weakened by 3 m/s. (During the initialization, the intensity increment is slowly ramped down over the previous 24 hours.)

Ensemble member 4: Initial intensity is as reported, but the intensity 12 hours before is enhanced by 1.5 m/s so as to produce a negative intensification anomaly at the initial time.

Ensemble member 5: Same as ensemble member 4 except that the initial intensification rate is enhanced rather than diminished.

Ensemble member 6: Initial intensity is enhanced as in ensemble member 2 and the environmental wind shear is set to zero at all forecast times. This is intended to give an upper bound on forecast intensity.

Ensemble member 7: Initial intensity is diminished as in ensemble member 3 and wind shear is enhanced by 10 m/s. This is intended to give a plausible lower bound on forecast intensity.

The good, the bad, and the ugly

CHIPS performance is usually comparable to that of other deterministic models, but it varies quite a bit from basin to basin and from year to year. As with other models, we occasionally upgrade the model and/or the initial and boundary conditions. Here we present examples of some of the worst and the best forecast skill evaluations in recent years.

We begin with the worst. Figure 1 shows the mean intensity forecast error defined as the absolute value of the difference between the forecast and the verification for the 2011 Atlantic season through September, comparing the CHIPS control and CHIPS ensemble mean with the official forecast and forecasts from other deterministic and statistical models. (The last forecast is just the arithmetic mean of CHIPS and GFDL.) Figure 2 shows the mean forecast intensity bias. These are all homogeneous comparisons; that is, the errors are accumulated only over forecasts for which all the guidance shown was available. (For this reason, we do not present evaluations beyond 72 hours even though CHIPS and a few other products extend to 120 hours, because some of the products extend only to 72 hours.) Clearly CHIPS has the largest errors at most lead times, and among the higher biases. (The 2011 Atlantic season is notable in that all guidance had positive biases.)

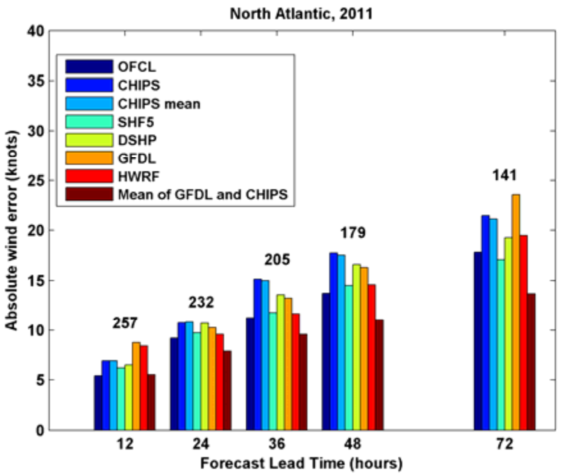


Figure 1: Mean absolute error as a function of lead time and model. The numbers in black above the bars show the number of forecasts.

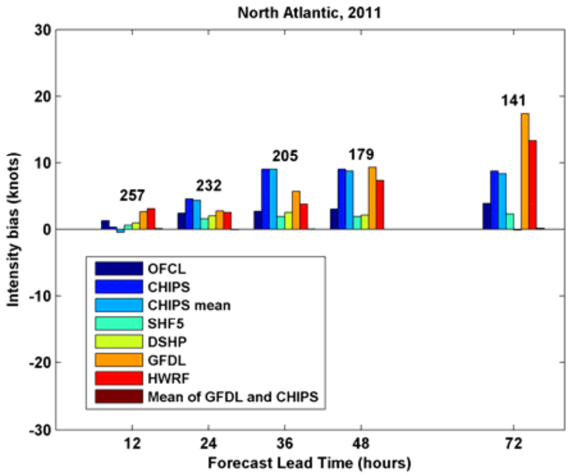
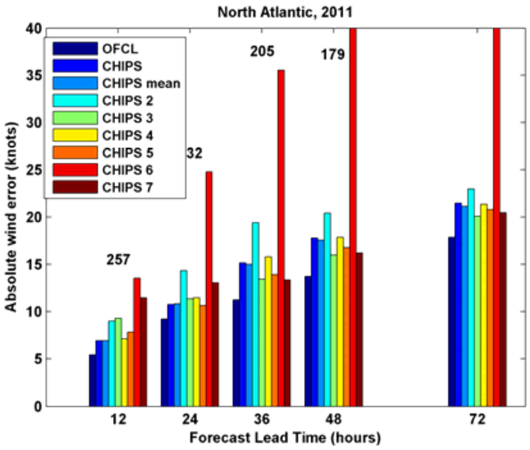


Figure 2: Mean bias as a function of lead time and model

Some insight into the source of the errors may be gleaned from Figures 3 and 4, which compare the various CHIPS ensemble members. Ensemble member 6, which has no shear, has a huge error and positive bias, while ensemble member 7, with enhanced shear, has a negative bias. (This suggests that the ensembles should be altered to add and subtract a smaller increment of shear than the 10 m/s used in these forecasts.) Ensemble member 3, with a low bias in the initial intensity, performs best in this case. This demonstrates the high sensitivity of CHIPS to shear and to middle level humidity, which is coupled to shear in the parameterization of shear effects.



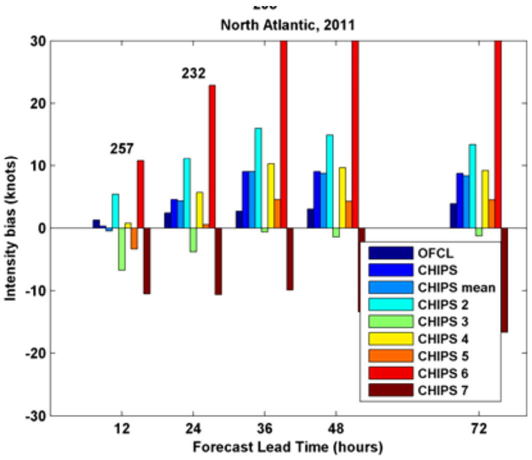


Figure 3: As in Figure 1 except for all 7 CHIPS ensembles, the CHIPS mean, and the official forecast.

Figure 4: As in Figure 2 except for all 7 CHIPS ensembles, the CHIPS mean, and the official forecast.

Now for the good: Figures 5-8 are the same as Figures 1-4 except they are for eastern North Pacific forecasts over the same period of time (through September, 2011). Here the CHIPS ensemble mean is the star performer, even beating the official forecast at large lead times. The CHIPS control is not far behind. In contrast to the Atlantic, ensemble member 7, with the high biased shear, has large negative biases and large absolute errors. This suggests that the GFS analyses of shear and/or mid-level humidity may be systematically different between the North Atlantic region and the eastern North Pacific. It is also possible, of course, that the official intensity estimates are biased in the eastern North Pacific relative to the Atlantic, perhaps owing to the absence of aircraft reconnaissance in the former region.

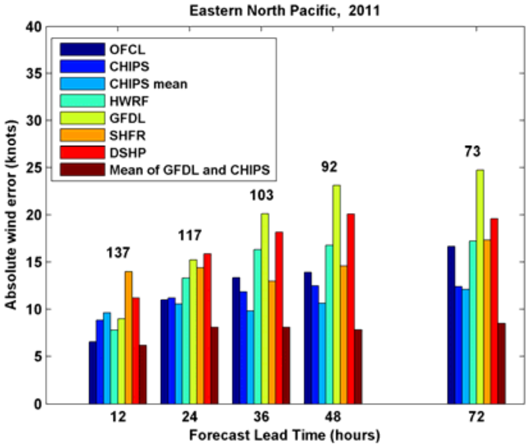


Figure 5: As in Figure 1 except for the eastern North Pacific

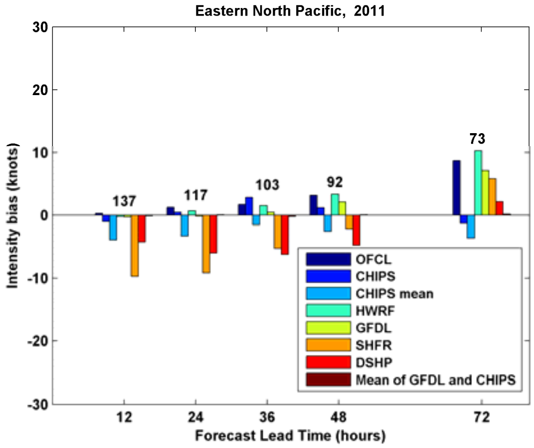


Figure 6: As in Figure 2 except for the eastern North Pacific

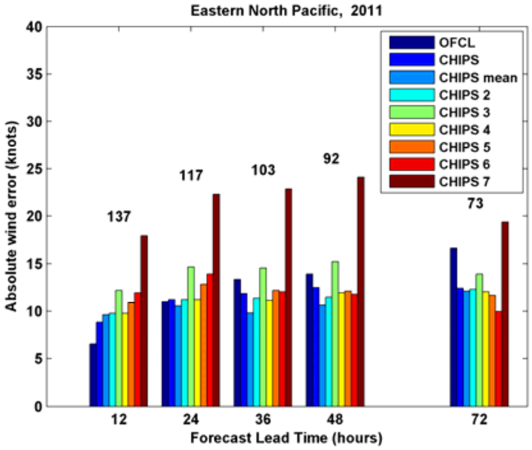


Figure 7: As in Figure 3 except for the eastern North Pacific

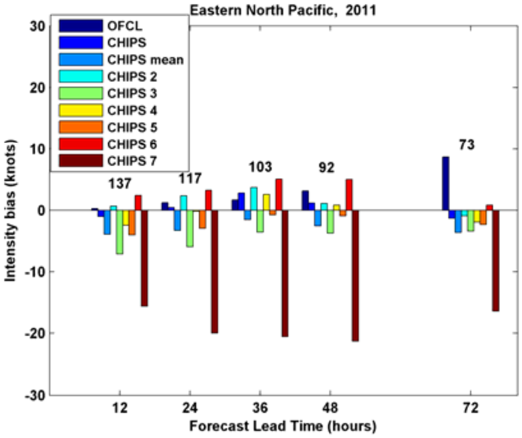


Figure 8: As in Figure 4 except for the eastern North Pacific

The better performance of CHIPS in the eastern North Pacific would appear to be related to systematically smaller values of shear there. This would suggest the CHIPS could be improved by improving the shear parameterization and/or the GFS-supplied evaluations of shear and middle tropospheric humidity.

Emanuel, K., C. DesAutels, C. Holloway, and R. Korty, 2004: Environmental control of tropical cyclone intensity. *J. Atmos. Sci.,* **61,** 843-858.