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**Initialization, Prediction and Diagnosis of
the Rapid Intensification of Tropical Cyclones using
the Australian Community Climate and Earth System Simulator, ACCESS**

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LONG TERM GOALS

1. Improved initialization and skilful prediction of Tropical Cyclone (TC) track, structure and intensity.
2. Improved prediction of Rapid Intensification (RI).
3. Improved understanding of the mechanisms of TC structure and intensity change, particularly Rapid Intensification.

APPROACH

The plan is a 4-part, inter-connected program of: (a) basic research into initialization of realistic TC structures using the state-of-the-art 4-dimensional variational data assimilation system (4D-VAR) from ACCESS (Australian Community Climate and Earth System Simulator), which is an implementation of the UK Meteorological Office's NWP system, (b) high-resolution forecast experiments on prediction of TC structure and intensity, with particular focus on Rapid Intensification, using ACCESS, (c) Diagnosis of the mechanisms of TC intensity and structure change (environmental influences, vortex structure, internal processes), and (d) transitioning of a validated TC assimilation and prediction system into operations, to provide forecast guidance on TC track, intensity and structure change over the Indian and Pacific Ocean basins.

OBJECTIVES

The main long and short term objectives are:

- (a) To develop and apply ACCESS-based numerical systems to perform nested, high-resolution data assimilation, initialization and forecast experiments for rapid and slow intensification events.
- (b) To use the outcomes from (a) to investigate assimilation, prediction and dynamics of environmental influences and internal structure change during rapid intensification events.
- (c) To explore advanced hybrid ensemble-4DVAR data assimilation techniques to better initialize and validate TC structures (including the intense inner core and storm asymmetries) consistent with the large scale environment (LSE) of TCs.
- (d) To use sensitivity experiments and ensemble techniques to (i) understand the variability in simulations of RI, and (ii) estimate the highly anisotropic, flow dependent error covariances required for effective TC data assimilation.
- (e) To use idealised, synthetic TC structures in initial conditions, to investigate the sensitivity of RI prediction to vortex structure.
- (f) To investigate the use of additional data sources and new assimilation techniques for initialization of intense TC vortices without the use of a synthetic vortex.

WORK COMPLETED

Development of ACCESS-TC was built on core NWP systems of the UK Met Office, initially implemented at BoM by CAWCR and NMOC (Puri et al., 2012). The system is called the Australian Community Climate and Earth System Simulator, ACCESS. Its unique features are (i) the use of a 4DVAR system for initialization (Rawlins et al., 2008), (ii) advanced numerics, and (iii) sophisticated parameterization of physical processes. ACCESS has been configured for operational and research applications on Tropical Cyclones. ACCESS-TC consists of 5 components: (i) vortex specification, (ii) 4DVAR initialization, (iii) high-resolution prediction with the Unified Model, (iv) track and intensity verification, and (v) structure change diagnostics. The base system runs at a resolution of 0.11° and 50 levels, although higher-resolution forecasts have been made. The domain is re-locatable and nested in coarser-resolution forecasts. Initialization consists of 5 cycles of 4DVAR over 24 hours and forecasts to 72 hours are made.

Without vortex specification, initial conditions usually contain a weak and misplaced circulation. Based on estimates of central pressure and storm size, vortex specification is used to filter the analysed circulation from the original analysis, construct the inner-core of the storm, impose motion asymmetries consistent with the past motion of the storm, merge the synthetic vortex with the large scale analysis at outer radii, and locate it to the observed position. Vortex structure (Weber, 2011, personal communication) is based upon the Chan and Williams (1987) profile, but calibrated against thousands of reconnaissance observations from the North Atlantic.

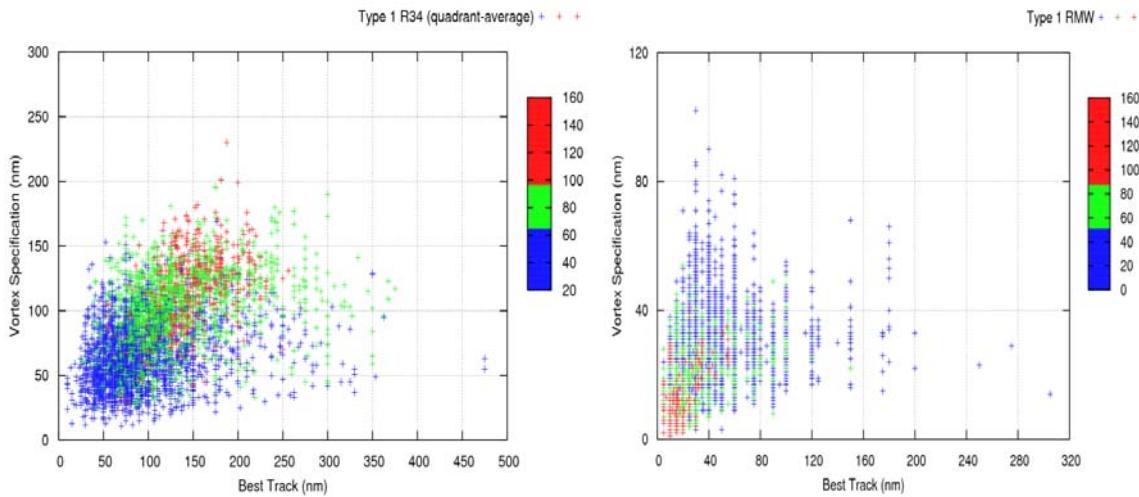


Figure 1: Scatter plot comparison between values of r_{34} and r_m from subjective estimates and from the vortex specification.

Validation of the idealized structures is presented in Fig. 1 which shows a comparison between values of r_{34} (azimuthal-mean radius of gale force, 34 knot winds) and r_m (azimuthal-mean radius of maximum winds) from subjective estimates in an extended best track data set (Demuth et al., 2006) and from the vortex specification. Both subjective and objective estimates are consistent and show that generally stronger storms have larger r_{34} and smaller r_m . However the variability in estimates for a given intensity is similar from both methods and so small intense and large weak storms are represented reasonably well. The mean absolute differences between objective and

subjective estimates for r_m and r_{34} for all storms are 15.8 and 40.5 nm. For category 3 to 5 storms these reduce to 6.9 and 40.2 nm. The differences are likely within the observational errors for these parameters and so we suggest that the vortex structures used in ACCESS-TC are the best that can be achieved without actual reconnaissance observations or assimilation of new data sources (eg, rainfall estimates).

Using all available conventional observations and only synthetic surface pressure observations, the 4DVAR builds a balanced, intense 3-D vortex with a well-developed secondary circulation. Figure 2 shows an example of the initialization for TC Yasi off the northeast coast of Australia. The diagram shows (i) observed and forecast tracks and intensities for TC Yasi from base time 00UTC 31 January 2011, (ii) north-south cross-sections of zonal and meridional wind and vertical motion at the initial time of the forecast following the application of 4D-VAR over 24 hours in 5 cycles. Note first that the forecast skill for both track and intensity is rather encouraging. The 60-hour track error near landfall is around 100km and the forecast has skill in predicting the intensification but does not forecast the rapid intensification just prior to landfall. Initialization of the primary circulation can be seen in the zonal wind cross-section, which reveals an inner-core with a low-level azimuthal-mean v_m of approximately 35 ms^{-1} at an r_m of approximately 50km on the equatorward side of the storm. The initialized secondary circulation can be seen in the north-south cross-sections of meridional wind and vertical motion, with (a) radial inflow (outflow) concentrated mostly in the boundary layer (upper troposphere) and extending to at least 1000 km from the centre of the storm, and (b) ascent focussed at small radii on Yasi's equatorward side.

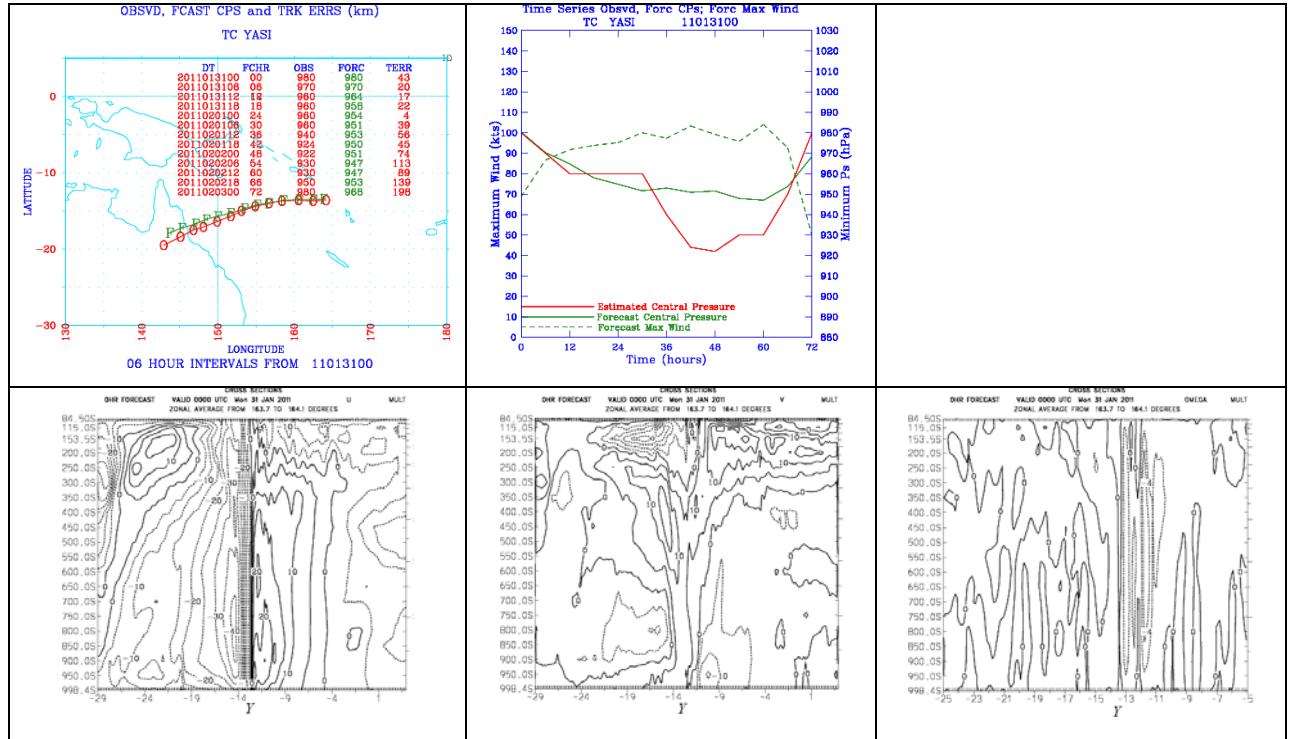


Figure 2: Top panels: Observed and 72-hour forecast tracks and central pressures for TC Yasi from base time 00UTC 31 January 2011. Lower panels: South-north cross-sections of zonal wind, meridional

wind and vertical motion through the initialized center of TC Yasi at 00UTC, 31 January 20111. Units are m/s and hPa/sec.

Using only synthetic surface pressure observations allows the 4DVAR to: (i) build the vertical structure, (ii) construct the secondary circulation without the constraints of imposed synthetic wind observations, and (iii) create a structure which is responsive to environmental wind shear without imposing constraints on the vertical-stacking of the circulation.

The system was declared operational in November 2011. Guidance is distributed in real-time not only to Australian Tropical Cyclone Warning Centres (TCWCs), but also to Weather Services with responsibilities over the west Pacific and eastern Indian Oceans. We believe that the guidance is now used in the consensus system developed at NRL and used operationally at JTWC. Support for the development and operational implementation of ACCESS-TC by NOPP/ONR is gratefully acknowledged.

VERIFICATION

As described in the previous Annual Report, verification has been very encouraging and this has continued during the 2011-2012 season for the Australian basin and during the 2012 season over the northwest Pacific (see Fig. 3). These statistics are competitive against long-term verification for the region. They also seem to compare favourably against other operational and model guidance for this season, but this needs to be quantified. A pleasing aspect is the comparable and consistent performance between the two basins. At 48 hours, the mean track and intensity errors over both basins is around 150 km and 12 hPa.

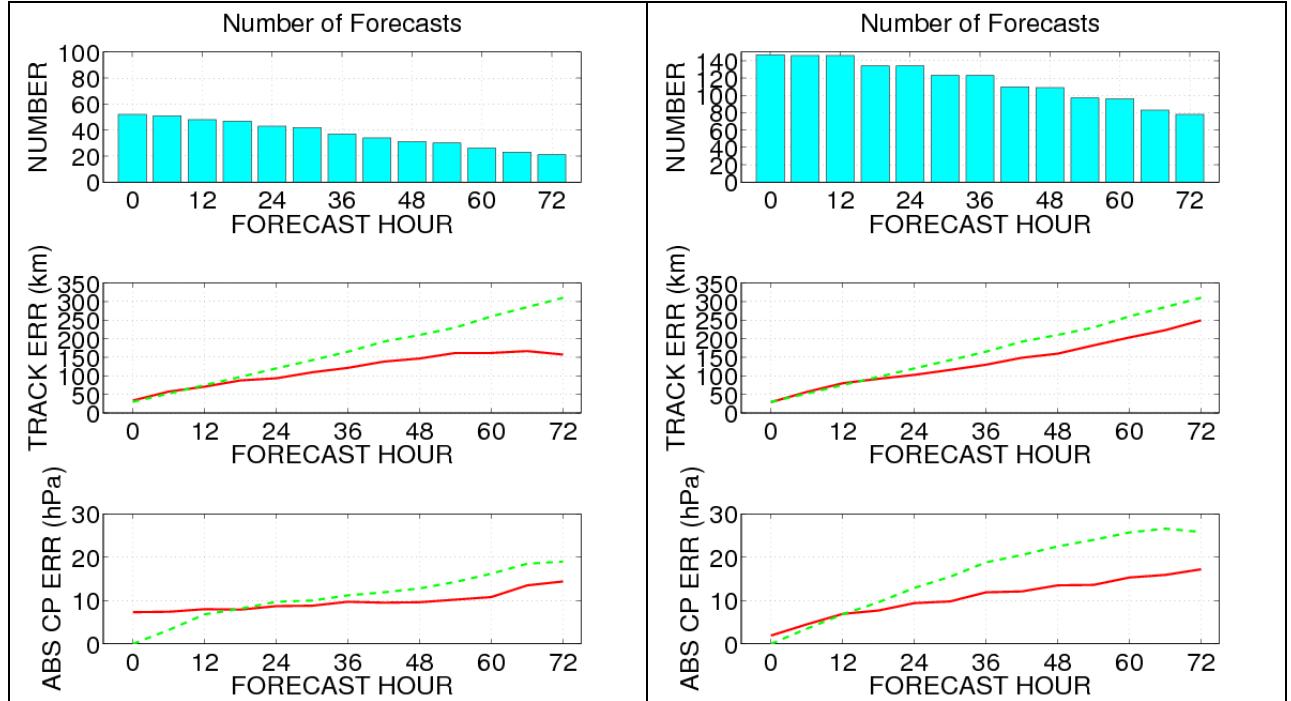


Figure 3: Verification statistics for operational ACCESS-TC. Left panel: 2011-2012 Australian Region (0° – 35° S, 80° – 180° E), 6TCs. Right panel: 2012 northwest Pacific, 16 TCs up until early October 2012. Vertical panels are: (top) number of forecasts, (center) mean track error, and (lower) mean absolute

central pressure error, every 6 hours to 72 hours. The dashed green curves on the center panel are approximate long-term mean (last 5 years) track errors and on the lower panel, mean absolute central pressure error using persistence as the forecast. For the northwest Pacific, forecast central pressures have been bias-corrected using the initialized minus observed value at $t = 0$.

The verification statistics are encouraging, but forecast busts do still occur. During the 2012 season over the northwest Pacific, forecasts for Kai-Tak and Damrey during the early stages of their lives were not skilful by the standards indicated in the mean statistics. Our initial subjective impressions are that weak storms are difficult to forecast. This will be the focus of ongoing detailed investigations. Verification of track and intensity forecasts for some individual TCs are shown in Fig. 4.

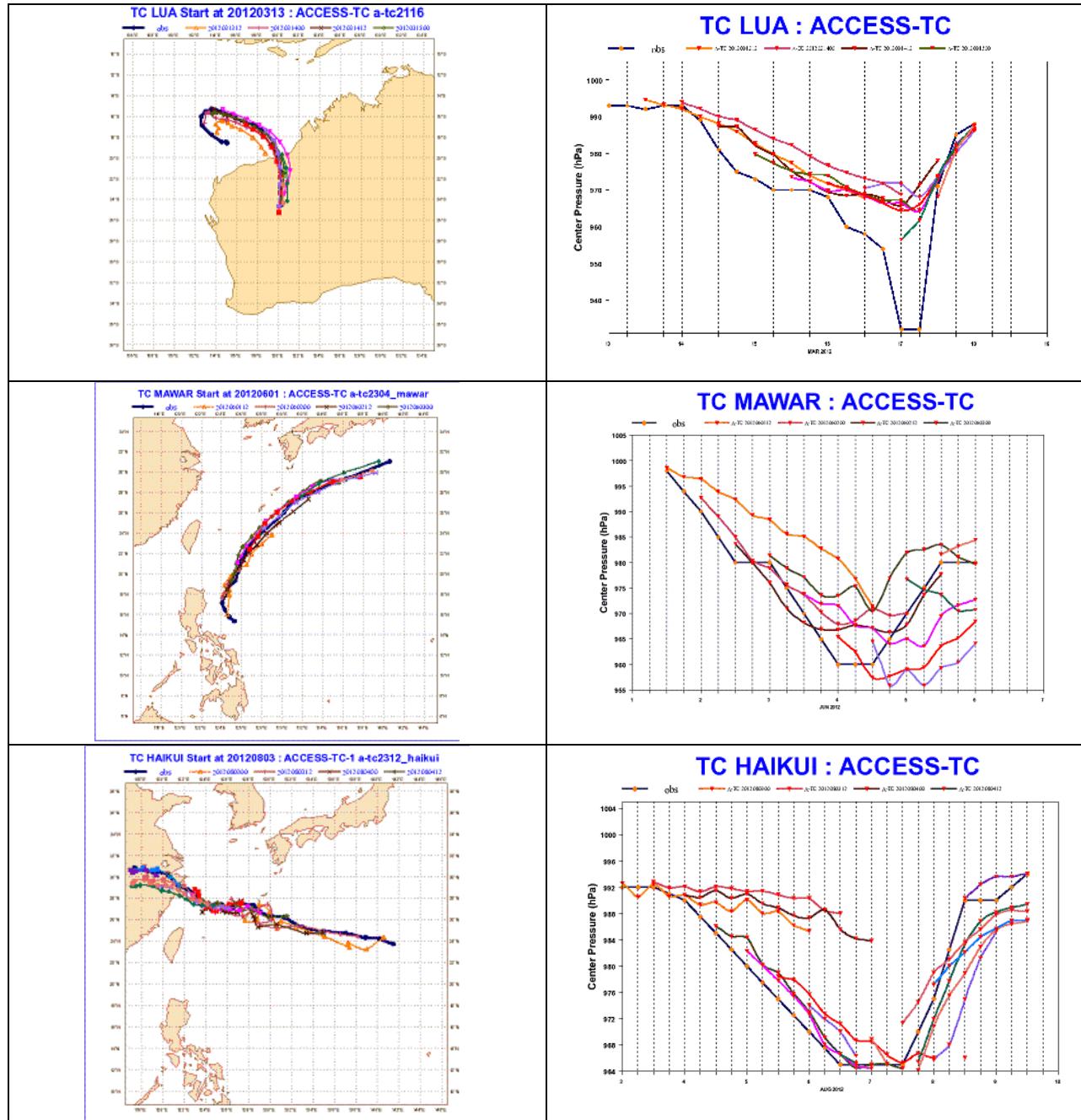
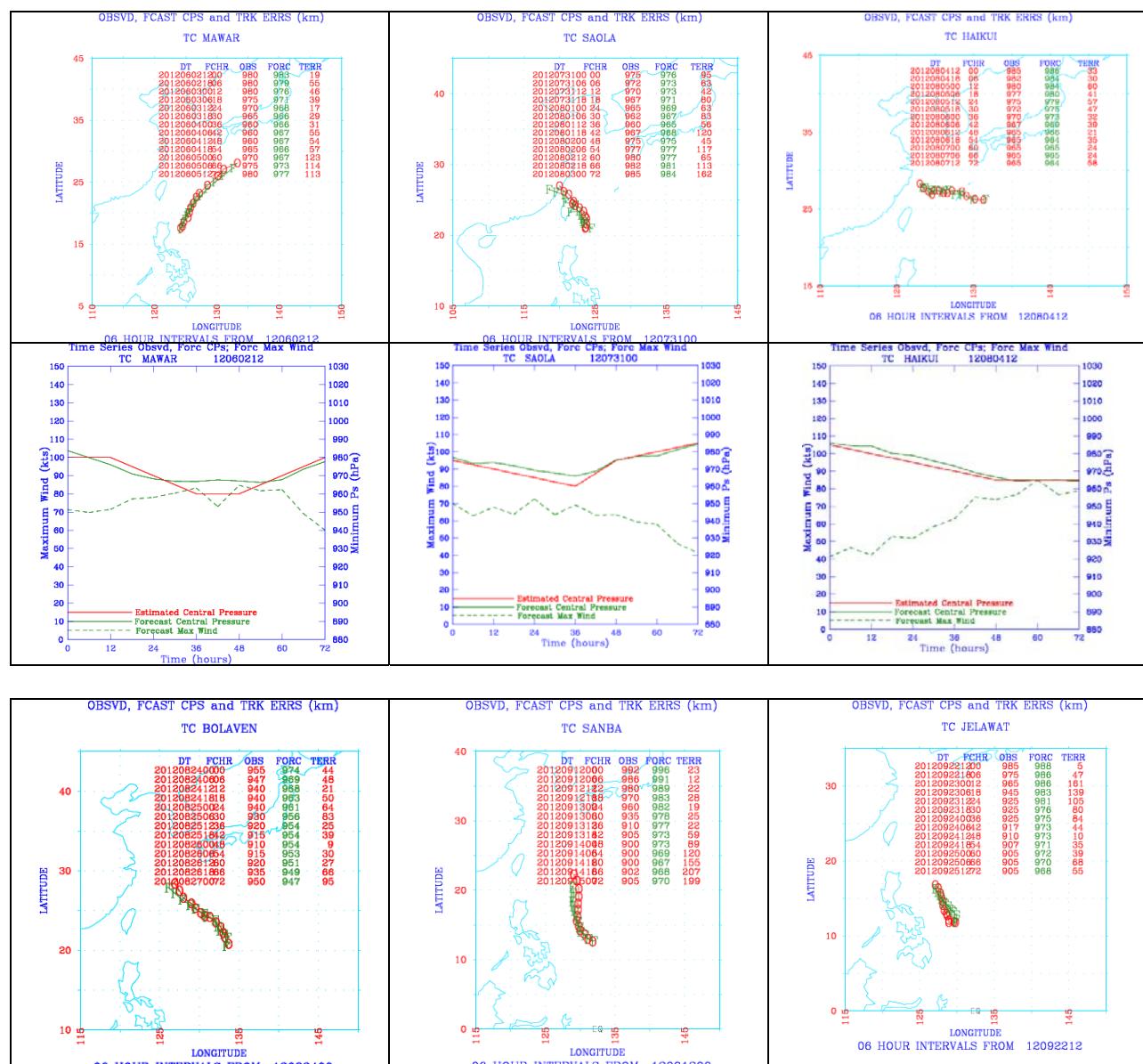


Figure 4: Observed and forecast tracks and intensities for TCs Lua, Mawar and Haikui over the lives.

The quality of the track forecasts is clearly evident. Some encouraging skill for intensity forecasts is present, but we believe that somewhat higher resolution and improved representation of physical processes (moist processes, the boundary layer) is required. Our subjective assessment suggests forecast TCs are slow to intensify and slow to weaken. In our next upgrade, results suggest that this bias will be reduced.

ILLUSTRATIVE EXAMPLES of INTENSIFICATION

Figure 5 shows observed and forecast tracks and intensities from ACCESS-TC for six typhoons (Mawar, Saola, Haikui, and Bolaven, Ewiniar, Jelawat) during the 2012 season which underwent moderate to rapid intensification following the base times indicated.



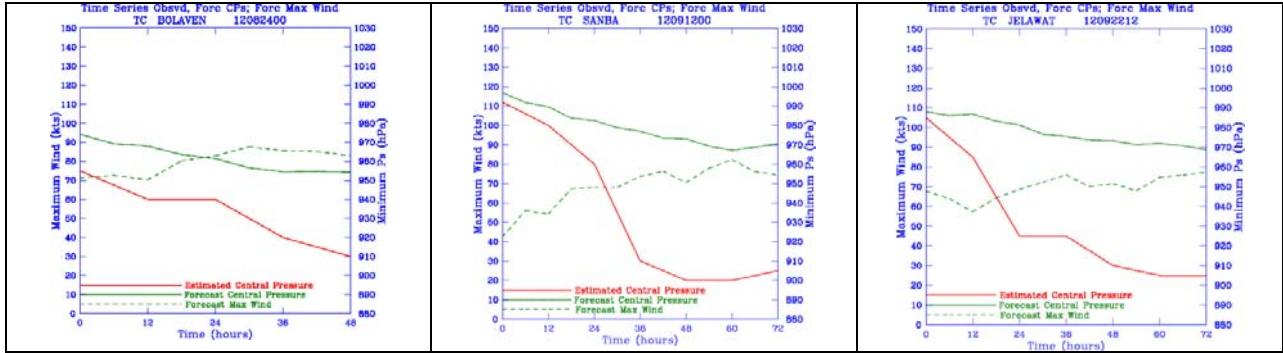


Figure 5: Observed (red ‘O’s) and forecast (Green ‘F’s) tracks and central pressures for TCs Mawar, Saola, Haikui (top panels, moderate intensifiers), and Bolaven, Sanba, Jelawat (lower panels, rapid intensifiers) from the base times indicated. The table in the track panels shows valid time of forecast, forecast hours, observed central pressure, forecast central pressure (hPa) and track error (TERR) in kms. The dashed curve on the intensity panels show forecast maximum wind in knots.

The forecasts of tracks are very skilful. For each case, intensification was predicted, but clearly the rapid intensification for the three rapid intensifiers was seriously underestimated. Since ACCESS-TC appears to have skill for moderate intensification, we believe that NWP system issues are significant in limiting the skill of RI forecasts. We currently believe that the two major issues are: (i) system resolution and (ii) physical parameterizations of boundary layer (sea spray, drag at high wind speeds) and moist processes. These are currently the focus of our attention, using the cases described here. Interestingly, there was also some evidence that Bolaven displayed secondary and tertiary eyewalls around 1200UTC, 26 August 2012. Given the encouraging forecasts from operational ACCESS-TC and our dynamical studies on secondary eyewall formation (Wang et al. 2012, and later discussion), we are very anxious to run very high-resolution forecasts for this event!!

TRANSITIONS

ACCESS-TC became operational in November 2011. Forecast track and intensity information is currently transmitted in real-time to JTWC and NRL, and also to other Weather Service Agencies with responsibilities over the eastern Indian and western Pacific oceans in both hemispheres. Forecasts are issued for named storms over the approximate domain $40^{\circ}\text{S} - 40^{\circ}\text{N}$, $70^{\circ}\text{E} - 200^{\circ}\text{E}$. Feedback from some operational Centers has been quite positive.

The next operational upgrade to ACCESS-TC is planned for November 2012 and will consist of (a) direct nesting in the enhanced ACCESS global system, (b) further refinements to the vortex specification (particularly the estimation of ROCI), and (c) possibly the use of enhanced observational data sets.

IMPACT/APPLICATIONS

We believe that ACCESS-TC forecasts are being used in the consensus forecast system at NRL/JTWC. From the current operational resolution of 12km, testing has also commenced on higher-resolution nested forecasts at approximately 4km and 1.5km. Although such high-resolution forecasts are unlikely to be run operationally in the next year, we anticipate that they will have important research, and eventually operational impacts. We hope that, in the future, the

high-resolution options may be used on TCs threatening the Australian mainland and for other dangerous storms.

Preliminary work has commenced on studying output from real-time and research versions of ACCESS-TC. The initial focus has been on structure diagnostics. Figure 6 shows radius-time sections of azimuthal-mean 10m tangential wind, radial wind and 500hPa vertical motion during the forecast for TC Yasi as it underwent intensification and landfall. Note (i) the horizontal extent of both the tangential and radial winds during the intensification, (ii) the growth in the size of the vortex (R_{34} increases) as it underwent intensification, (iii) the shrinking/contraction of the intense inner-core (R_{64} decreases) as the size increased, and (iv) the location of the non-steady ascent maxima which switch between inside and outside of the RMW as the intensification occurs. Further diagnostics are needed and planned in order to document and understand the many phenomena that can be seen from application of ACCESS-TC. We also plan to soon commence verification of R_{34} forecasts – a critical characteristic of storms.

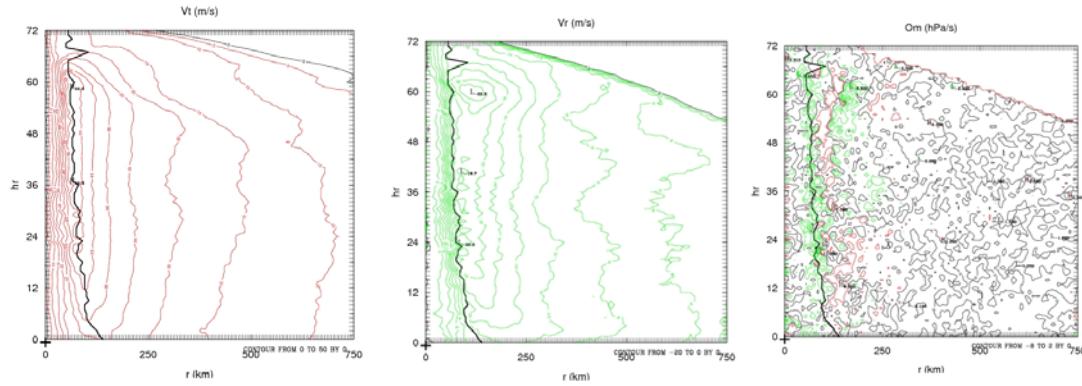


Figure 6: Radius-time hovmoller diagrams of tangential wind, radial wind and vertical motion during the forecast intensification of TC Yasi. Units are ms^{-1} for horizontal winds and hPa/s for vertical motion. The black line in each panel shows the azimuthal-mean RMW.

RELATED PROJECTS

The NOPP/ONR Project sits within a much broader TC research program at CAWCR, and so benefits from inputs from the wider TC community at the Bureau of Meteorology. Specific projects directly related to the NOPP/ONR project are as follows.

1. The heat-engine paradigm for understanding tropical cyclone thermodynamics has shown that tropical cyclone intensity is sensitive to the sea-air fluxes, and prompted a substantial recent effort into improving our understanding of these fluxes at very high wind speeds. The turbulent fluxes in the remainder of the boundary layer have received less attention, although a couple of modelling studies have shown that the intensification rate, maximum intensity and storm structure are sensitive to the choice of parameterisation. While these studies do not analyse the reasons for these sensitivities, nor make recommendations as to which parameterisation methods are most suitable, they do clearly indicate that good forecasts of rapid intensification will require good representation of boundary layer processes. Accordingly, we have compared four methods of boundary layer parameterisation, representative of those in common use, in the diagnostic model of Kepert and Wang (2001). We found that one class of scheme failed to reproduce observations and had some theoretical deficiencies, and recommend that that type of scheme not

be used. Unfortunately, this class has been very popular for tropical cyclone simulation amongst MM5 users. Another class, K-profile parameterisations, were shown to be sensitive to misdiagnosis of the boundary-layer depth, a difficult problem in the tropical cyclone core. We consider them to be useable, but advise caution. The remaining two classes, local closures and higher-order closures, performed well in our tests. This work has now been published (Kepert, 2012).

2. Momentum, sensible and latent heat fluxes between the ocean and atmosphere are vital for the development and maintenance of tropical cyclones. Correct parameterisation of the air-sea exchanges, especially the ratio between the exchange coefficients for momentum and heat fluxes (Emanuel, 1995), will enhance model performance, including forecasting of rapid intensification (RI).

Improvements to the surface exchange parameterisation have been made for the ACCESS-TC model through (a) implementation of a variable Charnock parameter on near surface wind speeds to enhance the parameterization for momentum flux, and (b) implementation of a new scheme to include the effects of sea spray on heat and moisture fluxes. The Charnock (1955) relation is commonly used in NWP models for computation of momentum flux, which is dependent on momentum surface roughness length and which in turn is dependent on the Charnock parameter. A constant Charnock parameter is normally used but has been shown to be inconsistent in representing the correlation between near surface wind and momentum flux (Powell et al., 2003). Thus we have introduced a new expression for the parameter based on results from updated field programs (Andreas et al., 2012). The expression makes better representations of momentum flux for all wind ranges especially for the very high winds in hurricanes. Regarding sea spray, conventional NWP models normally use only interfacial flux parameterisations which are based on Monin-Obukhov similarity theory. Under high wind conditions (surface winds greater than 20 m/s, which are common in the core region of TCs) the spray contribution becomes increasingly important. In ACCESS-TC, we have implemented a modified spray scheme developed by Andreas et al (2008) with some modifications from Kepert (1996). The heat and moisture fluxes are mainly dependent on surface wind speed, sea surface temperature and humidity. The two implementations also enable us to make studies on ratios of the exchange coefficients from theoretical predictions (Emanuel, 1995)

Early results are encouraging and illustrated in Fig. 7 from a case study for TC Yasi with a control run (CtrTest) and a test with inclusion of sea spray and variable Charnock parameter schemes (SeaSpry). SeaSpry makes a better intensity prediction than CtrTest in comparisons with observed CP. Prior to 30 hours, the intensity changes from the two experiments, in terms of CP and Vmax, show small differences. After that time, it is clear that CP dips and Vmax increases much faster in the SeaSpry experiment than in the CtrTest run. When the TC core contracts (Rmax decreases) and the size increases (R34), the SeaSpry forecast produces a smaller, more intense core but a larger outer circulation compared to CtrTest. There are small and acceptable changes in the track forecasts.

As part of the NOPP collaboration, Drs. Jian-Wen Bao and Chris Fairall (NOAA, Earth System Research Laboratory) have kindly provided their sea spray parameterization. We are anxious to implement, test and intercompare their parameterization in ACCESS-TC on some of the above cases.

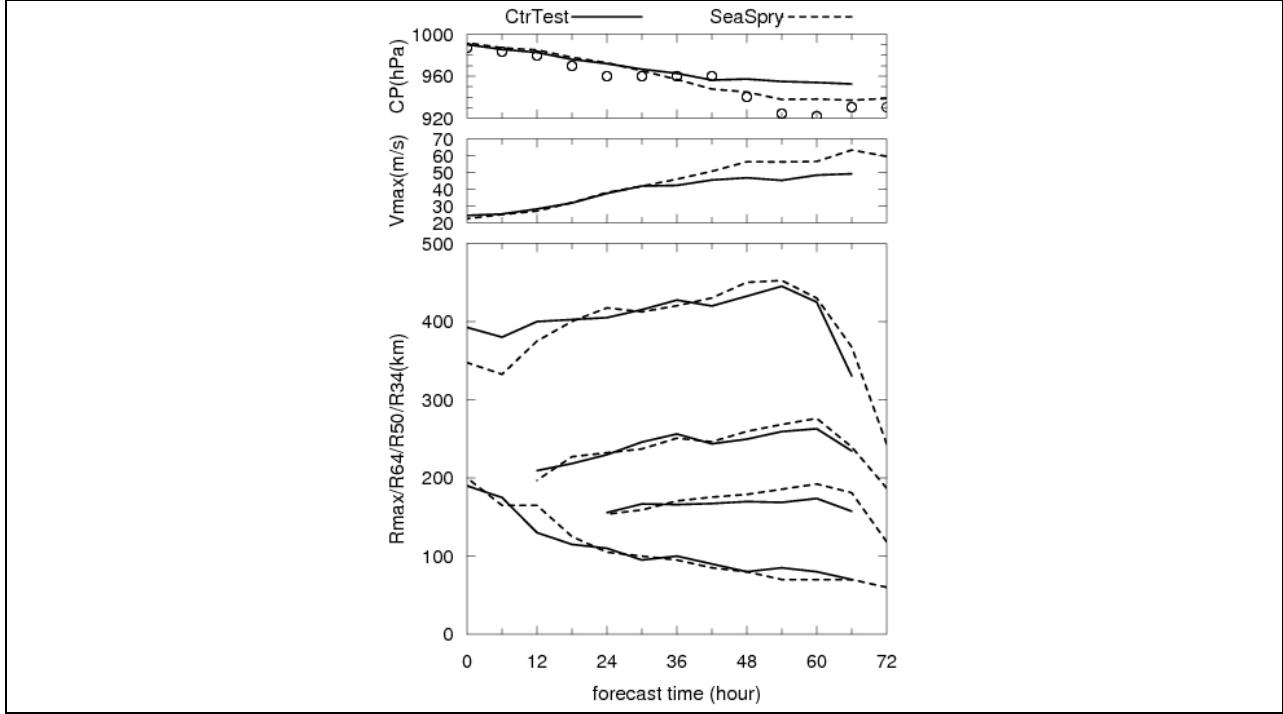


Figure 7: Time evolution of structure parameters for the control and parameterized sea spay forecasts for TC Yasi from base time, 12UTC, 30 January 2012. Note “o” in the top panel are estimated CP values.

3. The Environmental System Modelling (ESM) Program at CAWCR is conducting ongoing experiments on: (a) much higher-resolution configurations for all ACCESS-based systems, (b) advanced assimilation of satellite-based observations (eg, scatterometer, cloud motion vectors, satellite radiances), (c) improved parameterizations of moist processes, radiation and the atmospheric boundary layer, and (d) mesoscale data assimilation and prediction for high impact weather phenomena (eg, severe thunderstorms, fire weather). The TC research underway here will benefit from and give benefit to these related ACCESS research projects.

4. TC genesis is a major forecast issue in the Australian region, since numerous formations occur near the coast (Dare and Davidson, 2004). A TC formation diagnostic has been developed that identifies regions of low-deformation vorticity in which TCs are known to form. It is based on a modified Okubo Weiss parameter, termed OWZ (Tory et al. 2012). An assessment of 20-years of reanalysis data found that enhanced OWZ, aligned between the low- to mid-troposphere was present for 95% of observed TCs. With the additional requirement of enhanced moisture and moderate or weak wind shear sustained for about 48 hours, the combined conditions were shown to have good skill as a TC detector. The technique has also shown encouraging skill in real-time detection and tracking of potential developers from operational global analyses.

The detector is being developed and tested for two other applications:

- (i). Applied to global NWP forecasts the detector is being used to track potential developers and provide guidance on TC formation, which such models may not explicitly resolve.

(ii). Applied to global analyses the detector is being used to identify potential developers approximately 24 hours prior to genesis. When found, ACCESS-TC will be automatically triggered. We hope to test the system over the Australian and northwest Pacific basins, commencing December 2012.

5. Secondary Eyewall Formation and Eyewall Replacement Cycles are a natural way that strong storms change their internal structure and intensity. Understanding and prediction of this phenomenon is thus of major importance. Detailed diagnostics from a remarkable simulation (Wang et al., 2012) suggest that key linked aspects of SEF are: (i) a broadening of the swirling flow, (ii) the structure of the evolving secondary circulation, and (iii) the structure of the *Net Radial Force* (NRF) in the boundary layer (with largest contributions from the agradiant and frictional forces). These components are illustrated in Fig. 8, which shows five SEF/ERCs from the simulation and a conceptual model of the evolving azimuthal-mean structure of the storm.

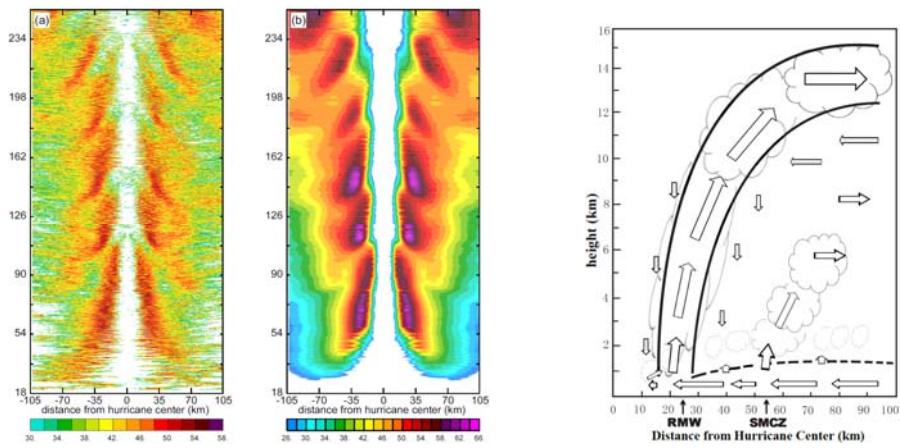


Figure 8. Radius-time Hovmöller diagrams of (a) radar reflectivity (dBZ), and (b) azimuthal-mean tangential wind (m s^{-1}) at 1 km height. The plot is based on 5-min frequency model output data. The legends for shadings are shown on the bottom of each panel.

6. Diagnostics suggest that TCs can have vastly differing structures. Large variability exists in, for example, RMW and R34. In order to improve prediction of structure and intensity some preliminary experiments have been conducted to understand how initial vortex structure may respond in different environments (Ma et al., 2012, Davidson and Ma, 2012). They suggest: (1) track forecasts are mostly, but not always, insensitive to the imposed structure; (2) in some cases specification of vortex structure can have a large impact on prediction of structure and intensity; (3) the forecast model mostly preserves the characteristics of the initial structure and so correct structure at $t=0$ is a requirement for improved structure forecasting ; (4) skilful prediction of intensity does not guarantee skilful prediction of structure; and (5) different initial profiles can sometimes change the timing of intensification. Thus correct initial vortex structure is an essential ingredient for more accurate intensity and structure prediction. In some cases, initial vortex structure can affect track, intensity and structure (Leroux et al., 2012) and so we continue to pursue sensitivity and understanding of the importance of initial structure on the evolving storm behaviour.

7. Large scale influences on Rapid Intensification and Extratropical Transition: RI and ET seem to be regularly associated with downstream amplification of Rossby waves. The left panels of Fig. 6 show hovmoller diagrams of stream function anomaly at 200 hPa during the RI of Katrina and Opal. These show the development eastwards of organized synoptic-scale troughs and ridges. RI occurred in association with the strengthening upper level ridge overlaying these storms, which may have also been influenced by latent heat release and divergence. The right panel shows for Opal, potential vorticity (PV) on the 330^0K isentropic surface (roughly through midlevels). Through these levels a PV connection between Opal and the midlatitude trough can be seen. This configuration seems favourable for intensification as cyclonic PV can be stripped from the trough and fed to the storm's vortex, while the anticyclone maintains a low shear environment. Further work is planned to quantify and study these processes in more detail.

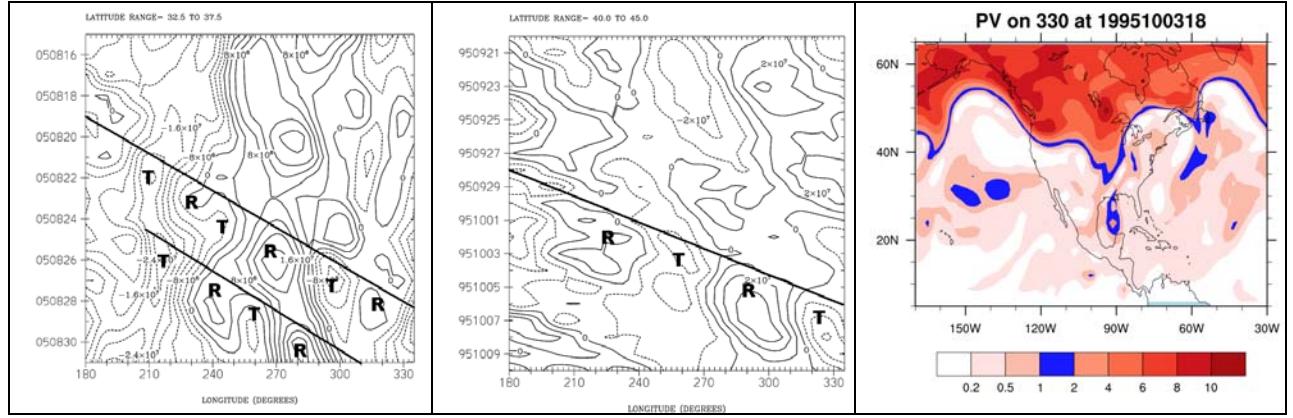


Figure 9: Left panel: Time-longitude section for the $32.5^0 - 37.5^0\text{N}$ band of 200 hPa stream function anomaly for the period 15 August to 31 August 2005. The longitudinal span is $180^0 - 330^0\text{ E}$. The 'T's and 'R's indicate where the troughs and ridges are amplifying. Center panel: Time-longitude section for the $40^0 - 45^0\text{N}$ band of 200 hPa stream function anomaly for the period 20 September to 10 October 1995. The longitudinal span is $180^0 - 330^0\text{ E}$. Right panel: Potential vorticity on the 330^0K isentropic surface at 1800UTC, October 3 1995.

8. Rainfall from TCs is being considered at both climatological and NWP timescales. As discussed in Dare et al. (2012), rain from tropical cyclones affects the northern coastlines of Australia, covering longitudes between 110 and 155E. Over the central north and the northeast (longitudes east of 130E), the mean contribution made by TCs to the total rain is approximately 10% during the wet season. However, the contribution from TCs increases west of 130E to mean values as large as 40%. A primary reason for this high percentage is that this region is relatively dry (total rain is not large). The standard deviation of TC contribution to the total rain also increases toward the west because during some years there is no rain produced here from TCs, while during other years it exceeds 80%. Understanding the behaviour of TCs and the amount of rain they produce is important in regions such as this because water resources are scarce and can benefit from TC rainfall. On the other hand, all coastlines from west to east face problems from TC rainfall such as flooding, and therefore benefit from improved forecasting of TC tracks and longevity after landfall. Some of the features described above are illustrated in Fig. 10.

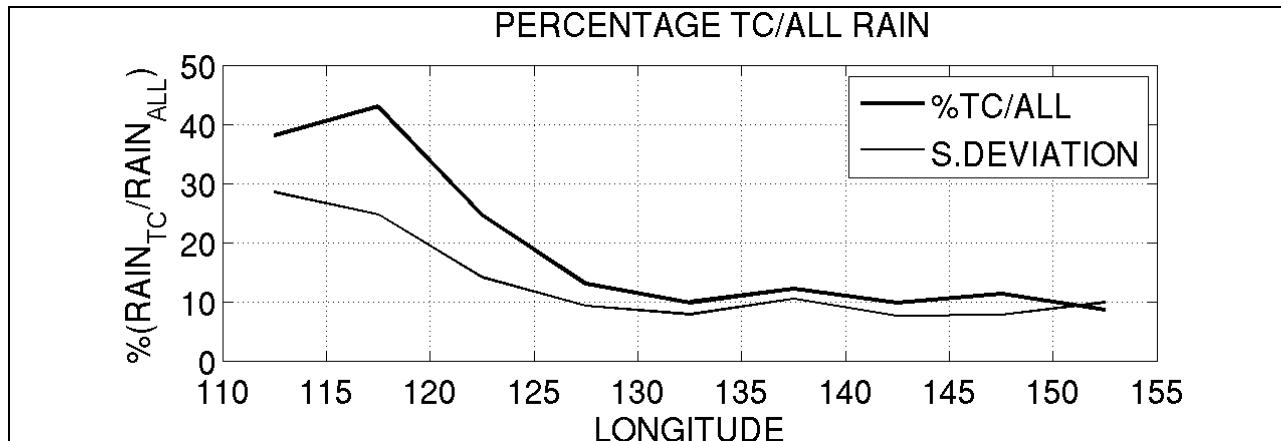


Figure 10: Mean and standard deviation of interannual percentage of all rain that is due to TCs within 50 km of the coast and within 5° longitude bands.

Evaluation of TRMM estimates of daily rainfall in tropical cyclones over the Pacific and Australian region is being conducted. Firstly, validation is performed over the Pacific using the Comprehensive Pacific Rainfall Database (PACRAIN). The evaluation is performed on two different terrain types: low-lying atoll sites (assumed to represent open-ocean conditions) and coastal and island sites (over land). TRMM is better able to estimate the intensity of TC heavy rain over ocean than over land. It is least skilful at coastal and island sites with high elevation, where it significantly underestimates heavy rainfall, suggesting that TRMM 3B42 is unable to capture orographic enhancement during TC landfall. Secodnly, evaluation is also performed over Australia, using a high quality rain gauge based gridded rainfall product from the Australian Water Availability Project (AWAP). The study period is from Jan.1998 to Dec.2011. It includes 96 tropical cyclones passing over Australia. The comparison show high correlation over space and time between TRMM estimates and AWAP analysis for rainfall from TCs at landfall. TRMM generally overestimates TC rain at low rain ranges but underestimates TC rain at high rain ranges. As illustrated in Fig. 11 averaged over all available TCs, within a radius of 500 km from the TC centre, TRMM agrees well with AWAP for moderate and strong TCs (CAT 3-5) but significantly underestimates TC rain within 200km of the TC center for weak TCs (CAT 1-2).

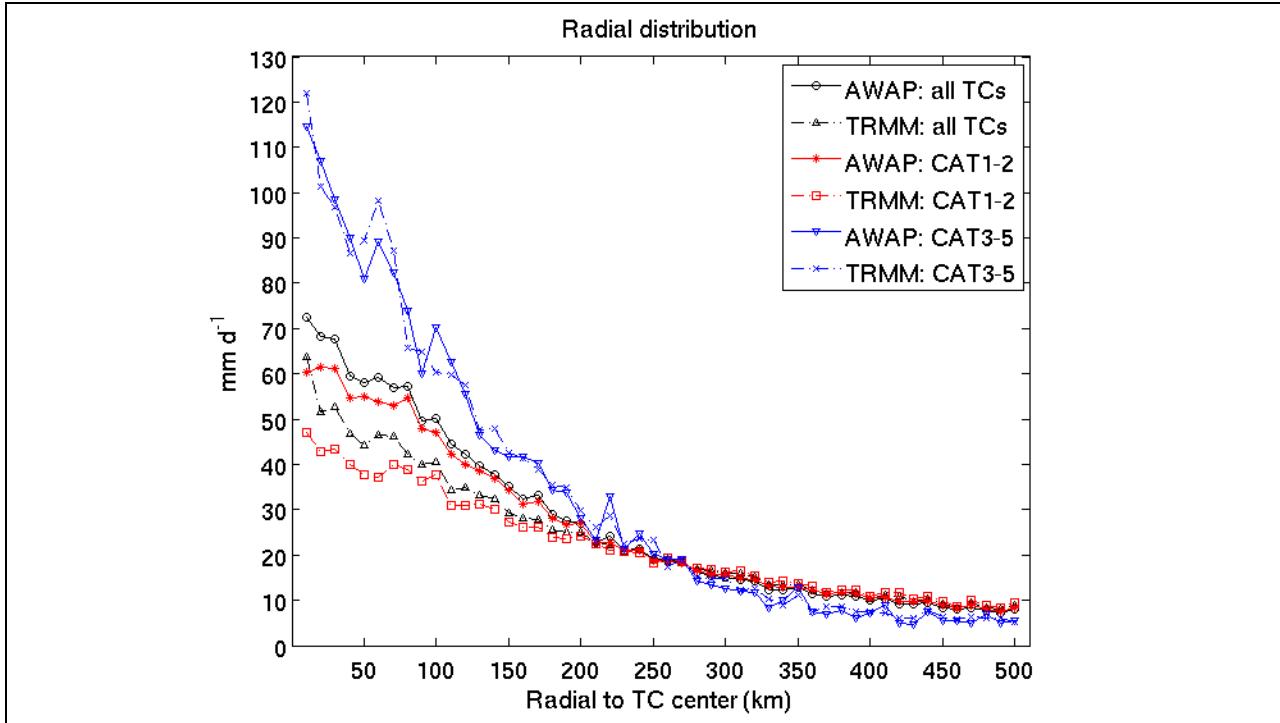


Figure 11: Radial distribution of mean rain within 500 km from TC center. Black line for all TCs rain, red line for rain from CAT1-2 TCs, blue line for rain from CAT3-5 TCs.

9. NRL has on-going research projects in ensemble forecasting, high-resolution coupled modelling of TCs, ensemble based data assimilation and 4D-VAR data assimilation. Each of these projects will benefit from and give benefit to the research activities described here. US Navy operations will also benefit from the improvements in operational TC forecasting that arise from this research. The project will not only focus on the prediction of the intensity (CP, VMAX) of storms, but on prediction of a set of vortex structure parameters (CP, VMAX, RMW, R34 and ROCI) and storm asymmetries, which will provide new and important guidance for naval ship operations and coastal activities. Some of this guidance is now available and being used at NRL and JTWC. Further improvements are planned.

FUTURE PROJECTS RELATED to RAPID INTENIFICATION

These include:

- Collaborative studies with UKMO to address some deficiencies in ACCESS-TC. These include: (a) the analysis of the environment of storms, (b) objective estimation of TC size used in the vortex specification, and (c) a systematic under-estimation in initialized and forecast intensity.
- Specification, Prediction and Validation of TC Structure (CP, Vmax, RMW, R34, ROCI):
 - Critical for prediction of track, intensity, structure, storm surge and rainfall
- Experiments with High Resolution Initialization and Prediction.

- Experiments with Ensemble Prediction
- Experiments with Revised and New Physics;
- Parameterizations and diagnostics for TC boundary layer and moist processes
- Enhancements with 4DVAR
 - Impact of extra observation types
 - Sensitivity tests on the application of inner and outer loops
 - Flow dependent and TC covariances.
- NWP and basic research applications from special experimental data sets:
 - TPARC/TCS08, PREDICT: Genesis and Rapid Intensification
- Rainfall in TCs
- Influence of Amplifying Rossby Waves on TC structure and intensity.
- Inner-core Dynamics

REFERENCES

- Andreas, E. L., L. Mahrt, D. Vickers, 2012: A New Drag Relation for Aerodynamically Rough Flow over the Ocean. *J. Atmos. Sci.*, **69**, 2520–2537.
- Andreas, Edgar L., P. Ola G. Persson, Jeffrey E. Hare, 2008: A Bulk Turbulent Air–Sea Flux Algorithm for High-Wind, Spray Conditions. *J. Phys. Oceanogr.*, **38**, 1581–1596.
- Chan, J. C. L. and R. T. Williams, 1987: Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: zero mean flow. *J. Atmos. Sci.*, **44**, 1257–1265.
- Charnock, H. (1955), Wind stress on a water surface. *Quart. J. Roy. Meteor. Soc.*, **81**, 639–640.
- Dare, R.A and N.E. Davidson, 2004: Characteristics of tropical cyclones in the Australian Region. *Mon. Wea. Rev.*, **132**, 3049–3065.
- Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.*, **52**, 3969–3976.
- Kepert, J. D. and Y. Wang, 2001: The dynamics of boundary layer jets within the tropical cyclone core. Part II: Nonlinear enhancement. *J. Atmos. Sci.*, **58**, 2485–2501.
- Kepert, Jeffrey D., 1996: Comments on “The Temperature of Evaporating Sea Spray Droplets”. *J. Atmos. Sci.*, **53**, 1634–1641.
- Puri, K. and co-authors, 2012: Implementation of the initial ACCESS Numerical Weather Prediction system. *Aust. Meteor. Oceanograph. J.* (submitted)
- Puri, K. et al., 2010: Preliminary results from Numerical Weather Prediction implementation of ACCESS. *CAWCR Research Letters*, **5**, 15 – 22. Available from <http://www.cawcr.gov.au/publications/researchletters.php>
- Powell, Mark D., Peter J. Vickery, Timothy A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones, *Nature* **422**, 279–283
- Rawlins, F., S. P. Ballard, K. J. Bovis, A. M. Clayton, D. Li, G. W. Inverarity, A. C. Lorenc, T. J. Payne, 2008: The Met Office global four-dimensional variational data assimilation scheme. *Quart. J. Roy. Met. Soc.* **133**, 347–362.

REFERANCES and PUBLICATIONS related to the project

- Chen, Y.J., E. Ebert, K. Walsh and N. Davidson, 2012: Evaluation of TRMM Daily Precipitation Estimates of Tropical Cyclone Rainfall using PACRAIN Data. *J. Geophys. Res.*, (submitted).
- Dare, R.A., N.E. Davidson and J.L. McBride, 2012: Tropical Cyclone Contribution to Rainfall over Australia. *Mon. Wea. Rev.*, (in press)

Davidson, N. E. and Y. Ma, 2012: Surface Pressure Profiles, Vortex Structure and Initialization for Hurricane Prediction. Part II: Numerical Simulations of Track, Structure and Intensity, *Meteorol. Atmos. Phys.*, **117**, 25-45.

Davidson, N.E., 2010: On the intensification and recurvature of Tropical Cyclone Tracy (1974). *AMOJ*, **60**, 169-177

Harper, B. A., J. D. Holmes, J. D. Kepert, L. M. Mason, and P. J. Vickery, 2011: Comments on “Estimation of Tropical Cyclone Wind Hazard for Darwin: Comparison with Two Other Locations and the Australian Wind-Loading Code”. *J. Appl. Met. Clim.*, in press.

Kepert, J. D., 2011: Choosing a boundary layer parameterisation for tropical cyclone modelling. *Mon. Wea. Rev.*, **140**, 1427-1445.

Kepert, J. D., 2011: Balance-aware localisation for atmospheric and oceanic ensemble Kalman filters. *Comp. Geosci.*, **15**, 239-250, doi:10.1007/s10596-010-9188-0.

Leroux, M-D., N.E. Davidson, Y. Ma and J.D. Kepert, 2012: On the rapid intensification of Typhoon Sinlaku during TCS08. *Mon. Wea. Rev.* (accepted).

Luo, Z., N.E. Davidson, F. Ping and W. Zhou, 2011: Multi-scale interactions affecting tropical cyclone track changes. *Adv. Mech. Eng.*, **2011**, Article 782590, 9 pp.

Ma, Y., M. Kafatos and N. E. Davidson, 2012: Surface Pressure Profiles and Initialization for Hurricane Prediction. Part I: Analysis of Observed and Synthetic Structures, *Meteorol. Atmos. Phys.*, **117**, 5-23.

Nguyen, C.M., M.J. Reeder, N.E. Davidson, M.T. Montgomery and R.K. Smith, 2011: Vacillation cycles during the intensification of Hurricane Katrina. *Quart. J. Roy. Met. Soc.*, **137**, 829-844.

Powell, M. D., J. D. Kepert, and E.W. Uhlhorn, 2010: Reply to “Comments on Estimating maximum surface winds from hurricane reconnaissance measurements” by J.F. Franklin. *Wea. Forecasting*, in press, doi:10.1175/WAF-D-10-05054.

Tory, K.J., R. A. Dare, N. E. Davidson, J. L. McBride, and S. S. Chand, 2012: The importance of low-deformation vorticity in tropical cyclone formation, *Atmos. Chem. Phys. Discuss.*, **12**, 1–43, 2012, www.atmos-chem-phys-discuss.net/12/1/2012/ doi:10.5194/acpd-12-1-2012

Wang, X., Y. Ma and N.E. Davidson, 2012: Secondary Eyewall Formation and Eyewall Replacement Cycles in a Simulated Hurricane: Effect of Unbalanced Forces in the Atmospheric Boundary Layer, *J. Atmos. Sci.*, accepted.