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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

Michael J. Reeder[*], Noel E. Davidson, Craig H. Bishop[#], Jeffrey D. Kepert,
Peter Steinle, Kevin J. Tory and Yimin Ma

Centre for Australian Weather and Climate Research, CAWCR
A partnership between CSIRO and the Bureau of Meteorology,
Melbourne, Australia

[#] Naval Research Laboratory, Monterey, CA.

[*]School of Mathematical Sciences, Monash University, Melbourne, Australia.
michael.reeder@monash.edu.

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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) very 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., 2010). 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. So far five components of ACCESS-TC have been developed: (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^{o} 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. Using all available conventional observations and only synthetic surface pressure observations, the 4DVAR builds a balanced, intense 3-D vortex with a developed secondary circulation. Figure 1 shows an example of the impact of the initialization for TC Anthony off the northeast coast of Australia. The top panels show observed and forecast track and intensity without and with vortex specification. The impact on track is clearly evident. The lower panels show the analysed 500 hPa wind field without and with vortex specification. Note that with vortex specification, and using only surface pressure observations, the 4DVAR has built the vertical structure, here illustrated by the cyclonic circulation at the observed location. 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.

Satellite imagery is used to validate initial conditions and forecasts from ACCESS-TC. Figure 2 shows 85GHz imagery from the NRL web site and 500 hPa vertical motion for a TC Yasi forecast from the base time of 00UTC 31 January 2011, prior to it undergoing RI. The diagrams illustrate that the 4DVAR has effectively built the secondary circulation in a way which is generally consistent with the observed cloud banding, and the consistency between observed and forecast banding is preserved during the forecast.

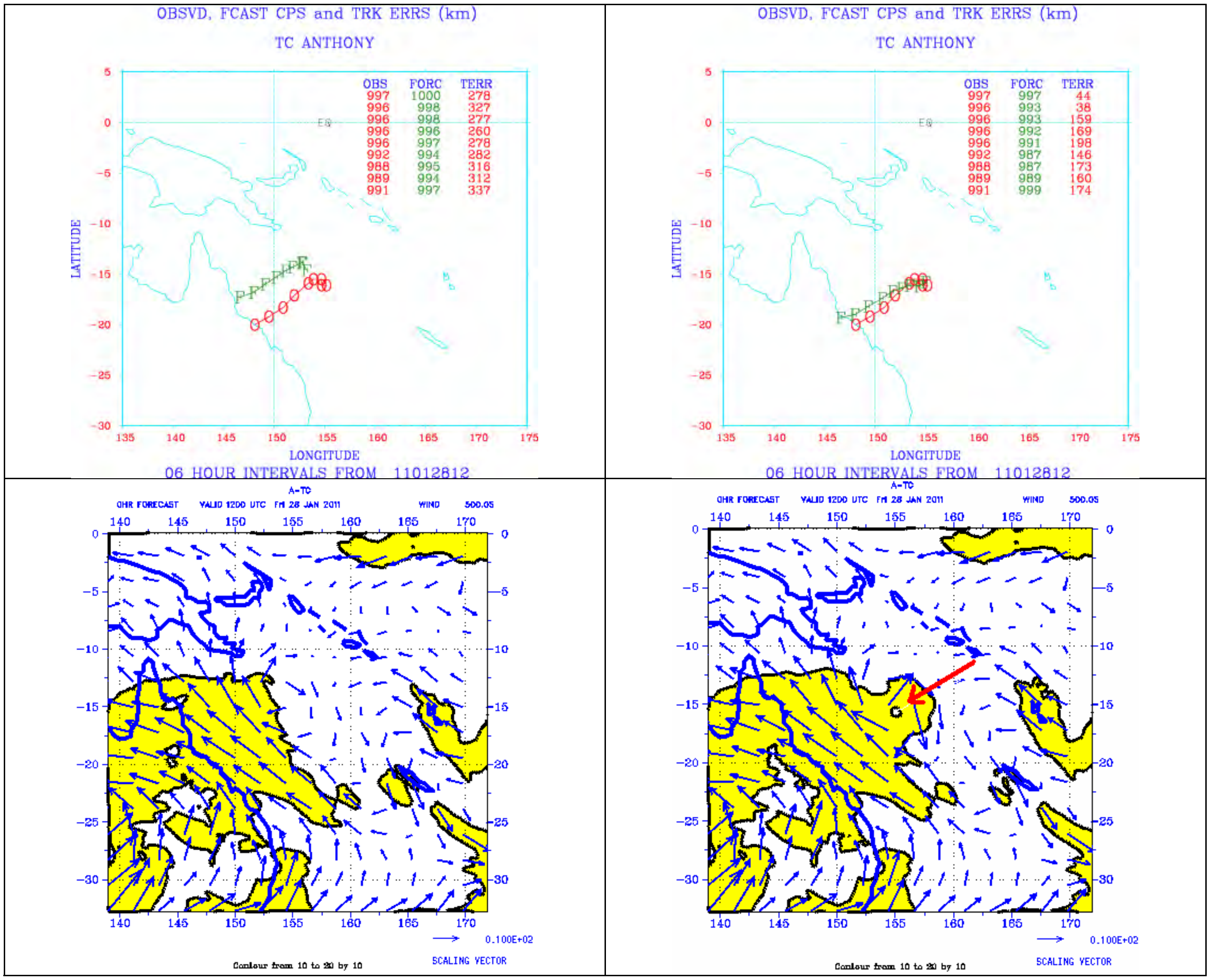

Figure 1: Top panels: Observed and forecasts tacks and intensities for TC Anthony from base time 12UTC 28 January 2011. Lower panels: Initialized 500 hPa wind fields. Left panels are without vortex specification, right panel are with vortex specification. Red arrow indicates cyclonic circulation built by the 4DVAR.

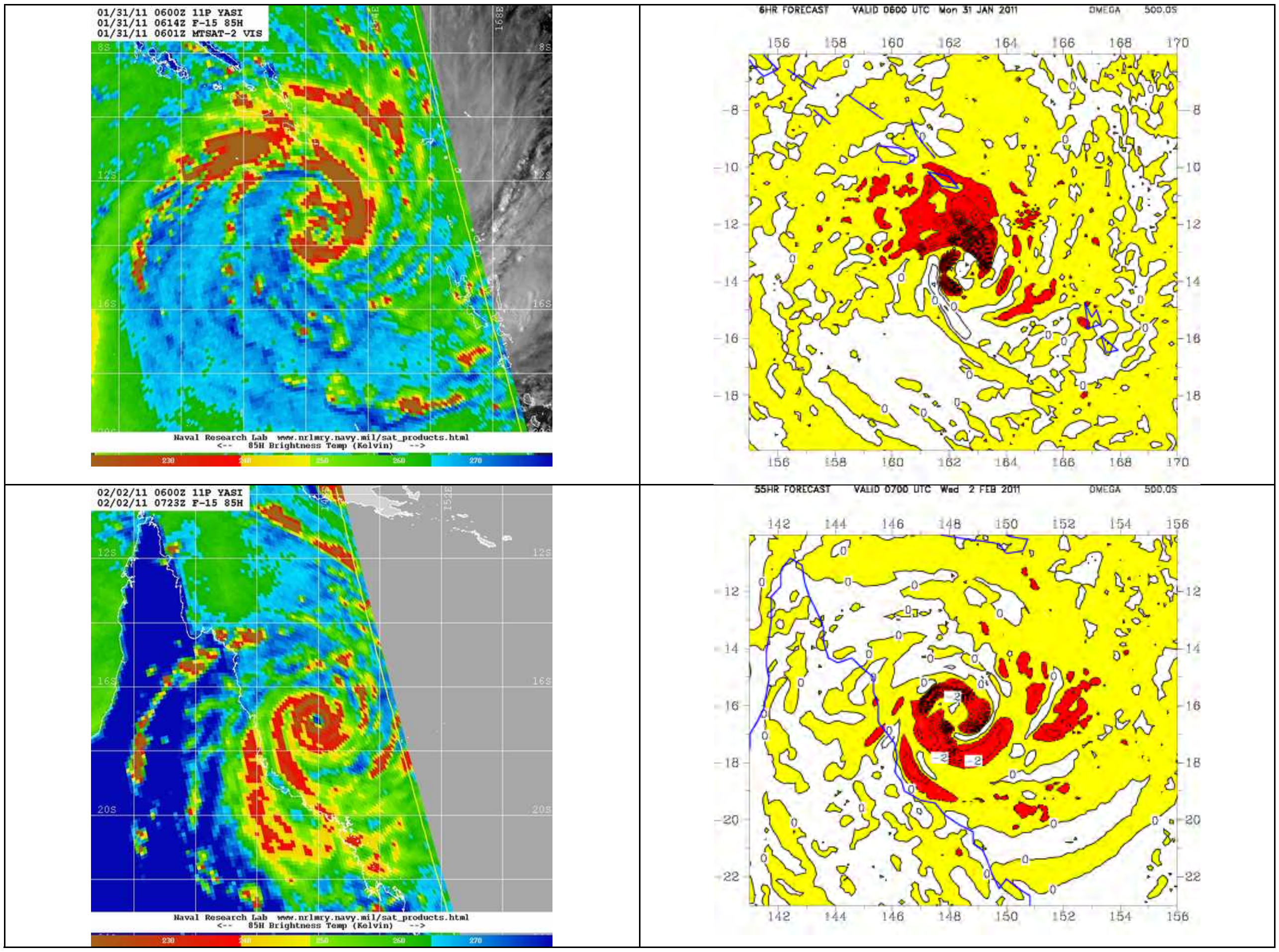

Figure 2: 85GHz Imagery from NRL web site (left panels) and ACCESS-TC 500 hPa vertical motion field at t = 6 (initialized with 4DVAR) and t = 55 hours for Yasi from base time 00Z, 20110131

RESULTS

Mean track and intensity errors for 11 Australian region storms during 2010-2011, run in hindcast mode, are shown in Fig. 3. These statistics are very competitive against long-term verification for the region. They also compare favourably against operational and model guidance for this season. However the verification sample is not homogeneous and real-time, so operational verification is required to fully validate the quality of the system, as discussed below.

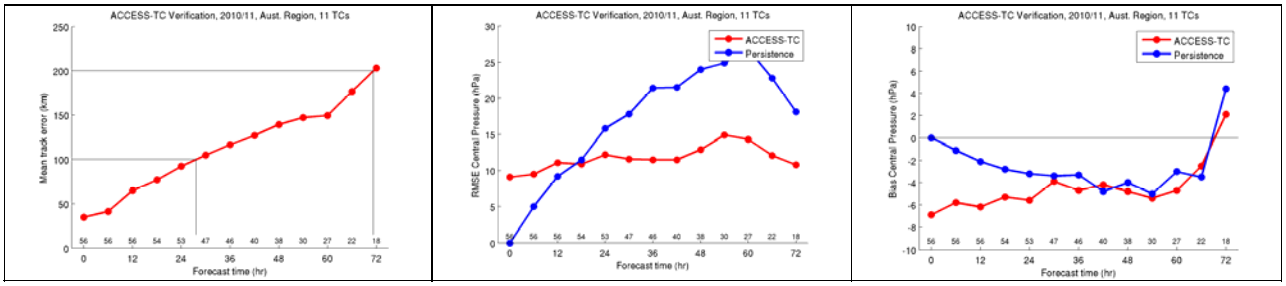

Figure 3: Verification statistics for 11 TCs from the Australian 2010-2011 season. Panels are mean track error (left panel), RMS central pressure error (center) and mean central pressure error (right), every 6 hours to 72 hours. The number of forecasts verified at each time is shown above the x-axis.

TRANSITIONS

ACCESS-TC has recently been implemented and run in real-time at the Australian National Meteorological and Oceanographic Centre, NMOC. Figure 4 shows the set of observed and forecast tracks and intensities for TC Ma-On (2011) over the northwest Pacific taken from those real-time runs. The quality of the forecasts is clearly evident, with the system guidance defining the track and intensity changes quite well.

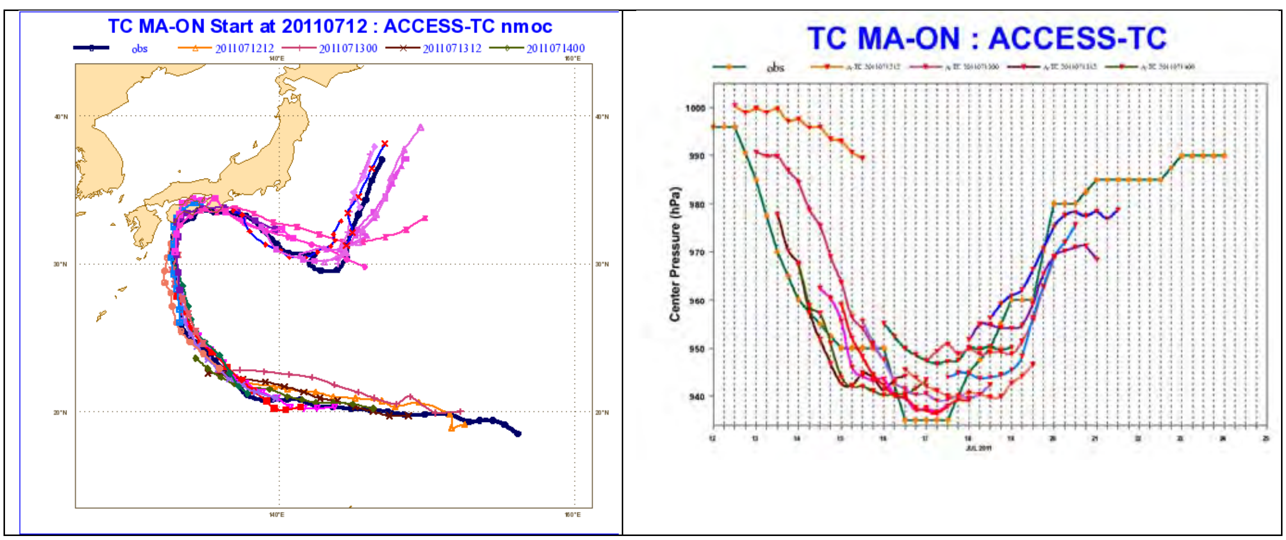

Figure 4: Observed and forecast tracks and central pressures for TC Ma-On from real-time forecasts from ACCESS-TC run at the Australian National Meteorological and Oceanographic Centre.

Mean verification statistics of real-time forecasts for 14 TCs run at NMOC over the NW Pacific for 2011 are rather encouraging and shown in Fig. 5. Based on these results and the robustness of the system, ACCESS-TC was declared operational on 11 November 2011. Forecast guidance will be distributed world-wide, including to JTWC, NRL and countries over the Pacific and Indian Oceans.

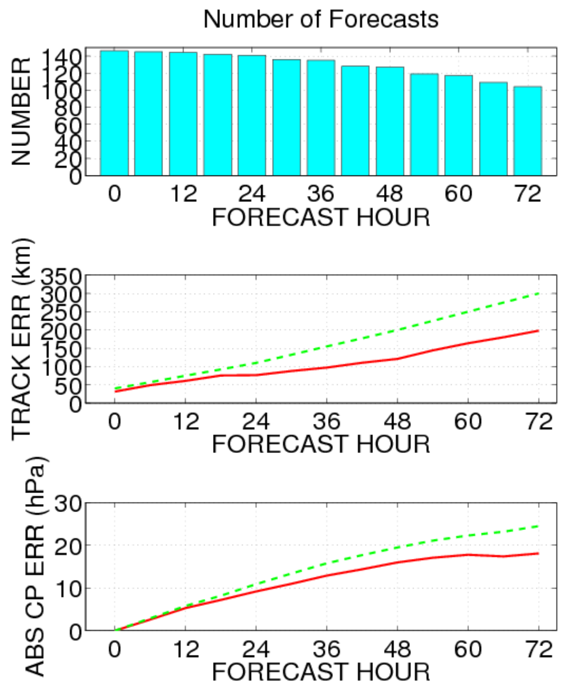

Figure 5: Verification statistics of real-time forecasts run at NMOC for 14 TCs from the NW Pacific 2011 season. Top Panel: Number of forecasts made at each lead time. Middle Panel: Mean track error at each forecast time (red curve) and for comparison the 3-year mean track error from the UKMO (green dashed curve). Lower Panel: Bias-corrected mean absolute central pressure error from ACCESS-TC (red curve) and from persistence forecasts (green dashed curve).

IMPACT/APPLICATIONS

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 time series of central pressure, maximum wind, radius of maximum wind, and radius of 64, 50 and 34 knot winds for TC Ma-On as it underwent intensification, recurvature and transition. Note (i) the quality of the central pressure forecast, (ii) the growth in the size of the vortex (R34 increases) as it underwent intensification and transition, and (iii) the shrinking of the intense inner-core (R64 deceases) as the size increased. 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 R34 forecasts – a critical characteristic of storms.

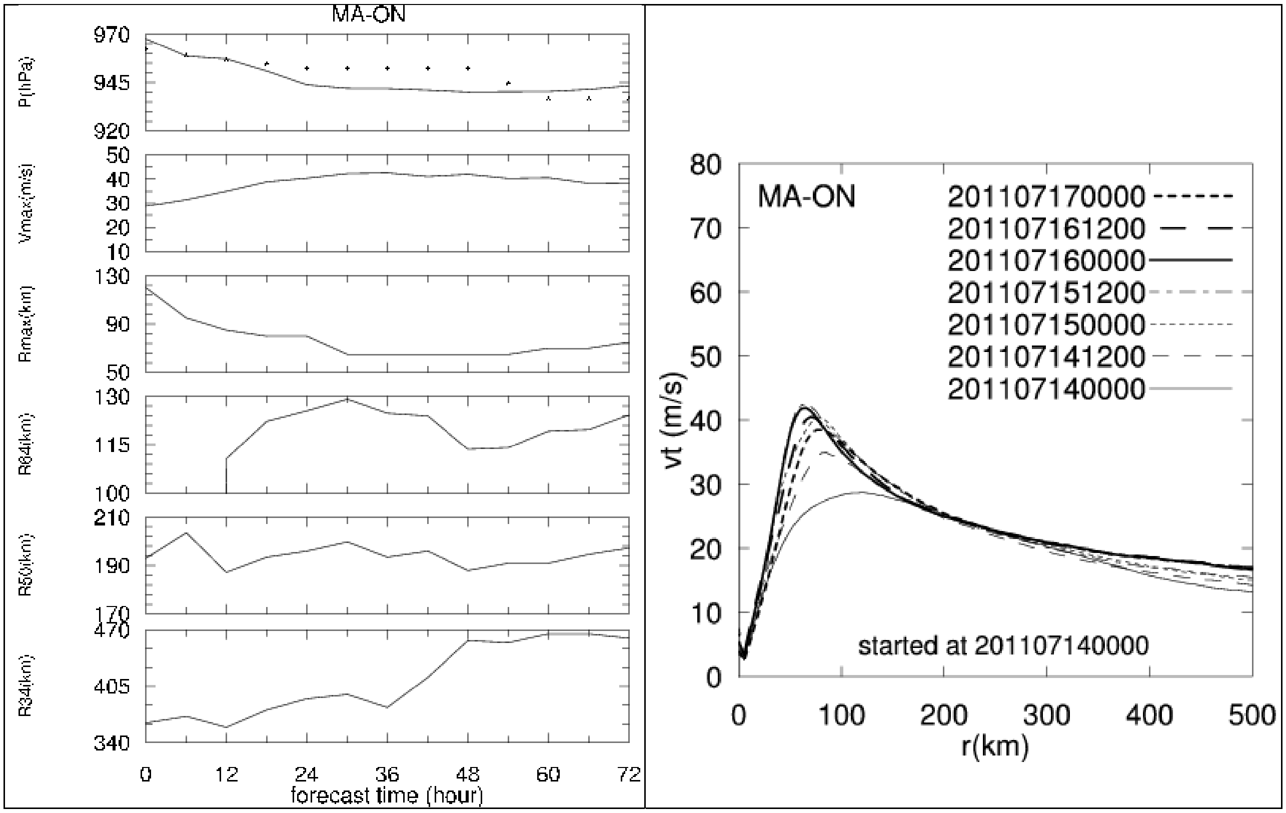

Figure 6: Left panel: Time series of forecast central pressure, maximum wind, radius of maximum wind, radii of 64, 50 and 34 knot winds for TC Ma-On from base time 00UTC, 14 August 2011. Symbols in the top left panel show estimates of central pressure. Right panel: Radial distribution of forecast azimuthal-mean tangential wind every 12 hours for TC Ma-On from base time 00UTC, 14 August 2011.

RELATED PROJECTS

The NOPP/ONR Project sits within a much broader TC research program at CAWCR, which includes projects on: 1. the development of the ACCESS-TC forecast system for operations and research, 2. understanding and prediction of intensity change, with a focus on genesis and rapid intensification, 3. rainfall in TCs, 4. understanding and prediction of TC Landfall, 5. the TC boundary layer, 6. development of a coupled ocean-atmosphere limited area model for TCs (CLAM-TC), and 7. TCs and climate.

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 been accepted for publication in *Monthly Weather Review*, subject to minor revision (Kepert, 2011).

2. Sensible and latent heat fluxes from the ocean are vital for the development and maintenance of tropical cyclones. Correct parameterisation of the air-sea exchanges will enhance model performance, including forecasting of rapid intensification (RI).

Improvements to the surface exchange parameterisation have been made to the ACCESS-TC model through implementation of a new scheme to include the effects of sea spray on heat and moisture fluxes. Conventional NWP models normally use only interfacial flux parameterisations which are based on Monin-Obukhov similarity theory. Under high wind situations (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 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. In addition, we have also modified the parameterisation for surface momentum flux to better represent high wind situations. That is, we have modified the expression for surface momentum surface roughness length for near surface winds to match surface stress measurements in high-wind hurricane situations (Powell et al., 2003).

Figure 7 shows, from a case study for TC Yasi (a major storm that devastated parts of the Australian coast), improvements in track and intensity from the new surface flux parameterization. The improved location and intensity at the initial time, also indicates that the new scheme has impacted on the initialization of the vortex. With the new scheme, the model predicts higher surface sensible and latent heat fluxes around the radius of high winds near the eye wall (not illustrated). This study is ongoing. More case studies and further diagnostics are planned in order to validate and understand the impact of the parameterization on forecasts of RI, and to determine whether these alterations lead to systematic improvements. This work will be reported in a journal article at a later date.

3. Diagnostics that provide insight into dynamical processes are of vital importance for understanding and predicting atmospheric processes. An understanding of vorticity and potential vorticity tendency can be particularly illuminating for TC genesis and intensity change studies. Potential vorticity (PV) tendency is often overlooked in TC research, because traditional forms of the equations do not offer much useful insight, beyond that PV is conserved in adiabatic flow, and friction and diabatic processes act as PV sources and sinks. Furthermore, when the traditional equation is applied to convective systems there can be very large cancellation between the dominant tendency terms, which casts doubt on the accuracy of the result.

Haynes and McIntyre (1987) provided a theoretical argument that revolutionised PV thinking. Their equations showed that a PV quantity is conserved on or between isentropic surfaces even when friction and diabatic processes are present. The implication of this result is profound, i.e., for most atmospheric systems PV is to a large extent horizontally conserved. In practice, however, the Haynes and McIntyre isentropic equations can be difficult to implement, the hydrostatic assumption is implied, and the conserved PV quantity is not strictly PV.

We re-derived PV tendency in geometric coordinates, and arrived at a true PV tendency equation that is valid for fully compressible, non-hydrostatic fluids, does not suffer from the cancellation problem of the traditional PV tendency equations, and retains the insight of the Haynes and McIntyre equations (Tory et al. 2012, recently accepted in JAS). These equations will be used in our investigation of TC structure change.

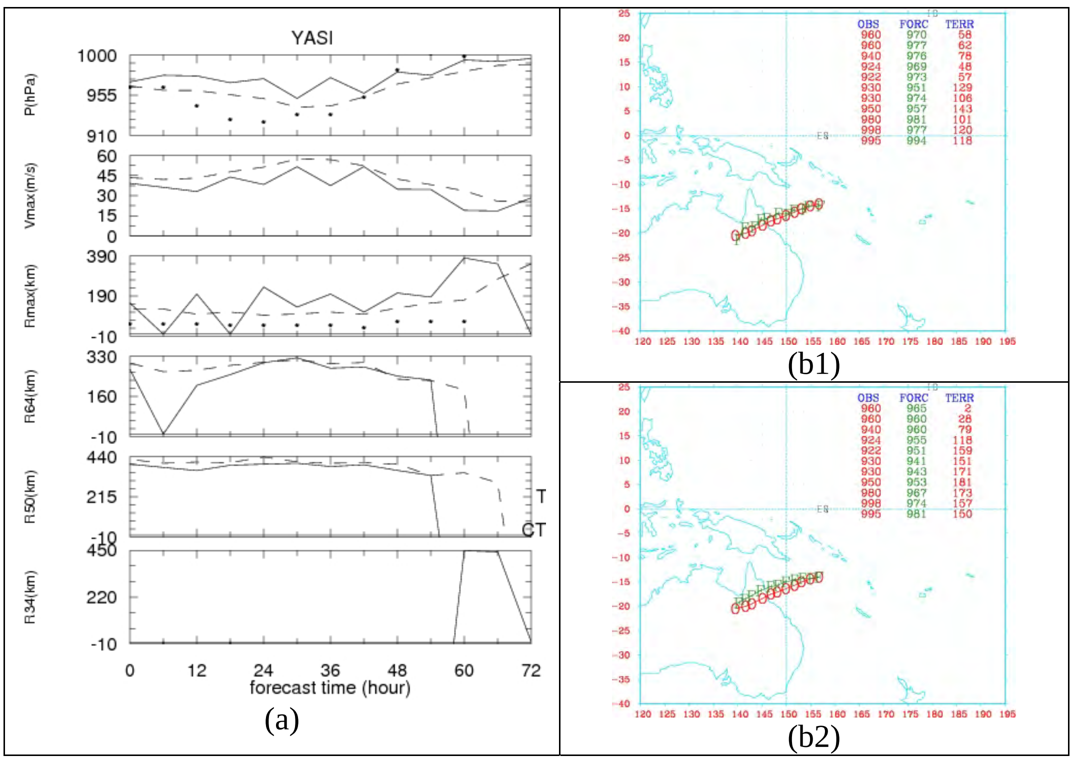

Figure 7. (a) Time series of forecast central pressure, maximum wind, radius of maximum wind, radius of 64, 50 and 34 knot winds, from the original air-sea surface exchange scheme (solid line) and spray route inclusive scheme (dashed line). In (a), the solid line refers to the original scheme and the dashed line is to the spray route scheme. The dot symbols in the top frame are operational estimates of central pressure. Panel (b1) plots the observed and forecast tracks and tabulates the observed and forecast central pressures (hPa) and track errors (km) at 6-hour intervals from the standard scheme. Panel (b2) is similar, except for the new scheme.

4. 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.

5. The High Impact Weather Team in the Weather and Environmental Prediction Program has a focus on TC and Fire Weather Research. The TC Team is focussing on: 1. the development of the ACCESS-TC forecast system for operations and research, 2. Understanding and prediction of intensity change, with a focus on genesis and rapid intensification, 3. Climate influences on TCs, and 4. Understanding and Prediction of TC Landfall. The research in this proposal is a necessary intermediate step on the way to achieving these objectives and hence is of great significance to the TC research program.

6. 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 will become available during November 2011.

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
    - Critical for TC prediction

- 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, 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.

Haynes, P. H. and M. E. McIntyre, 1987: On the evolution of vorticity and potential vorticity in the presence of diabatic heating and frictional or other forces. *J. Atmos. Sci.*, **44**, 828—841.

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, 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.

PUBLICATIONS related to the project

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.*, (in press)

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.

Luo, Z., N.E. Davidson, F. Ping and W. Zhou, 2011: Multi-scale interactions affecting tropical cyclone track changes. *Adv. Mech. Eng*. (in press).

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., J. D. Kepert, J. A. Sippel and C. M. Nguyen, 2012: On the use of potential vorticity tendency equations for diagnosing atmospheric dynamics in numerical models. *J. Atmos. Sci.* (in press).