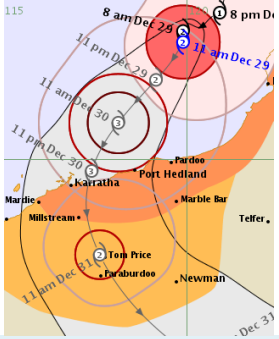
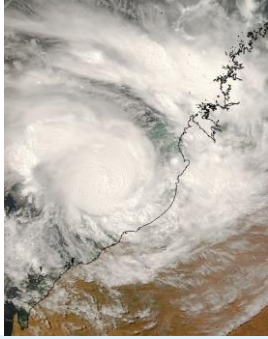
Australian Government
Bureau of Meteorology





Improving Tropical Cyclone Forecasts for North West Australia

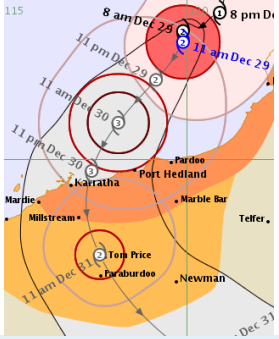
Jeff Kepert, Saima Aijaz, Andrew Burton, Noel Davidson, Jim Fraser, Diana Greenslade, Alister Hawkesford, Zhendong Huang, Xingbao Wang, Yi Xiao, Harvey Ye, Stefan Zieger

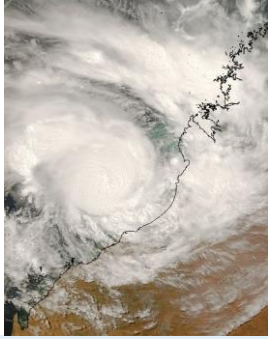
Thanks to Shell, Woodside, Inpex and Chevron

25 – 27 July 2017

Australian Government
Bureau of Meteorology

Why?



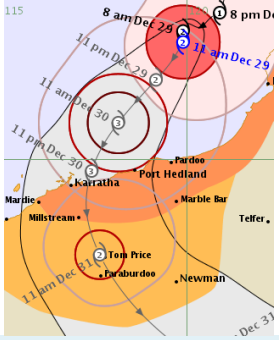


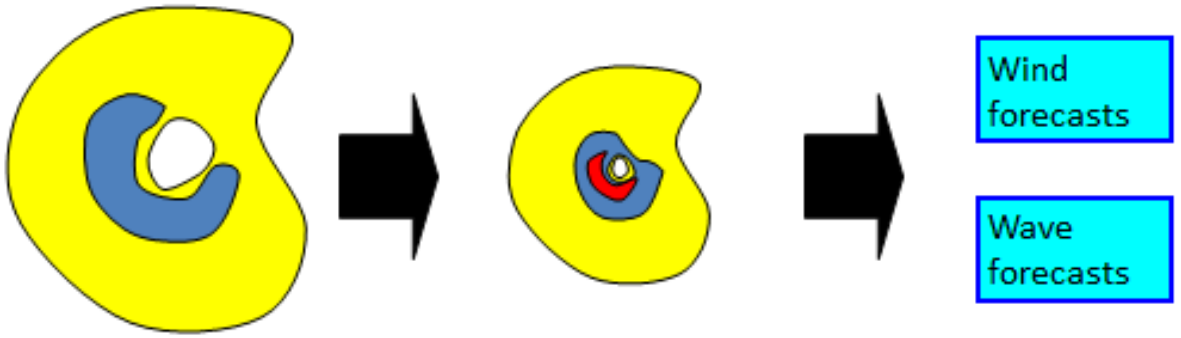
- The best TC data set for industry decision makers
- The best TC data set for weather service providers

- "Hard" numbers to enable industry to manage tropical cyclone risk in a safe, economical, efficient and effective manner
  - What is the likely intensity?
  - What is the highest feasible intensity?
  - What is the risk that wind / wave / rain thresholds will be exceeded?
  - What is the most likely time that those thresholds could be exceeded?
  - What is the earliest time that those thresholds could be exceeded?
  - Is the threat increasing or decreasing?
- Combine bias-corrected ensemble + high-resolution deterministic

Australian Government
Bureau of Meteorology

Probabilistic Wind Guidance





Raw model wind field

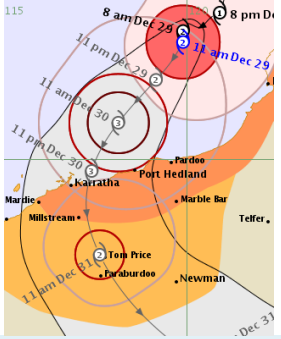
Bias-corrected wind field

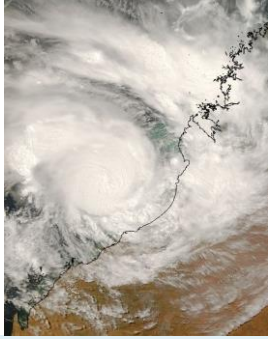
Downstream processing

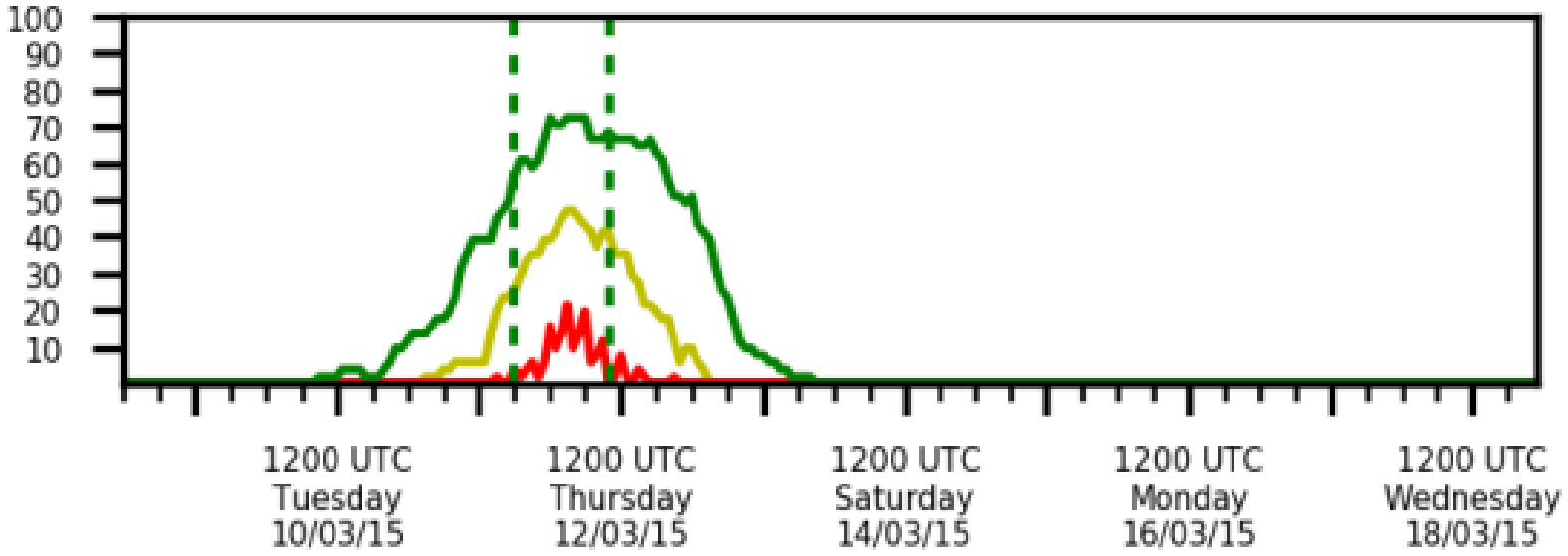
- Ensemble prediction the best way to develop alternative scenarios & likelihood.
- But TCs are too weak because of low resolution (computer limitations).
- Solution:
  - Diagnose TC biases in ensemble from ECMWF
  - Remove TCs and replace with bias-corrected synthetic TC
  - Rerun wave predictions using bias-corrected model

Australian Government
Bureau of Meteorology

TC Olwyn winds: EPS-BC



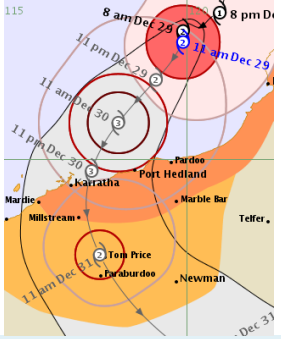


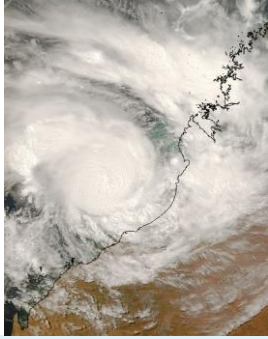


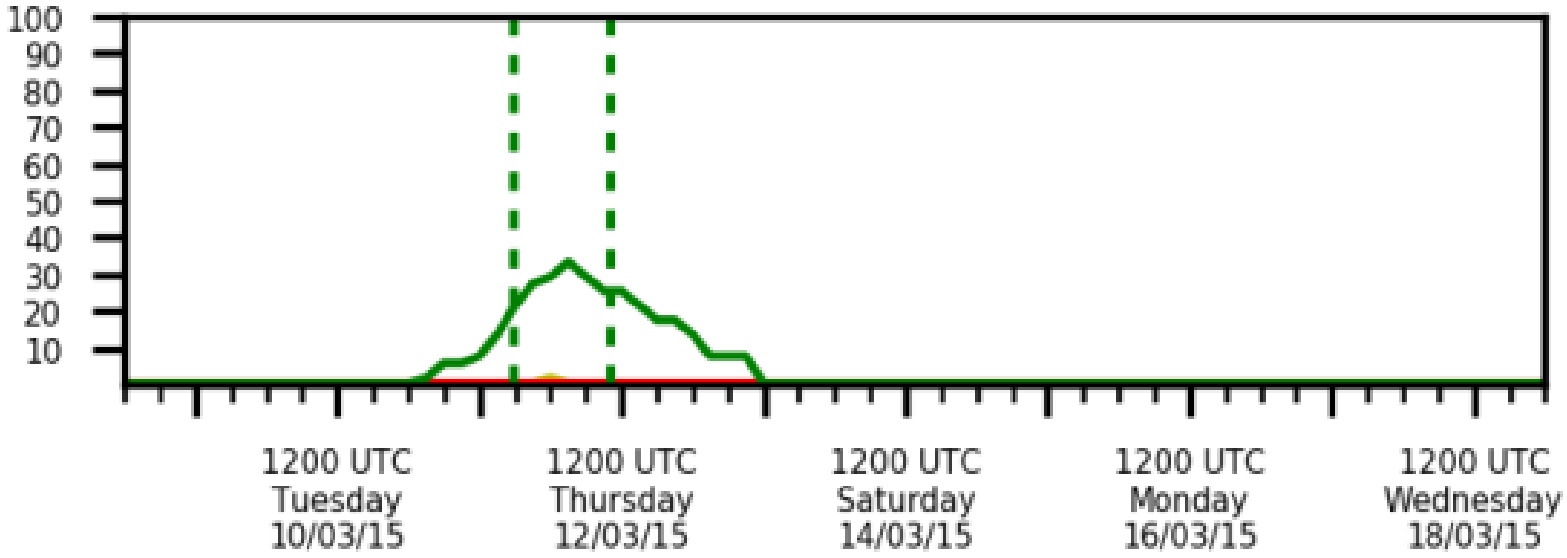
- Probability of gales/storm force/hurricane force at North Rankin in TC Olwyn.
- Forecast from bias-corrected ensemble prediction system (EPS-BC) from 66 hours (2 ¾ days) before.

Australian Government
Bureau of Meteorology

TC Olwyn winds: raw EPS



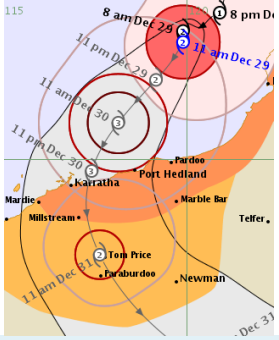




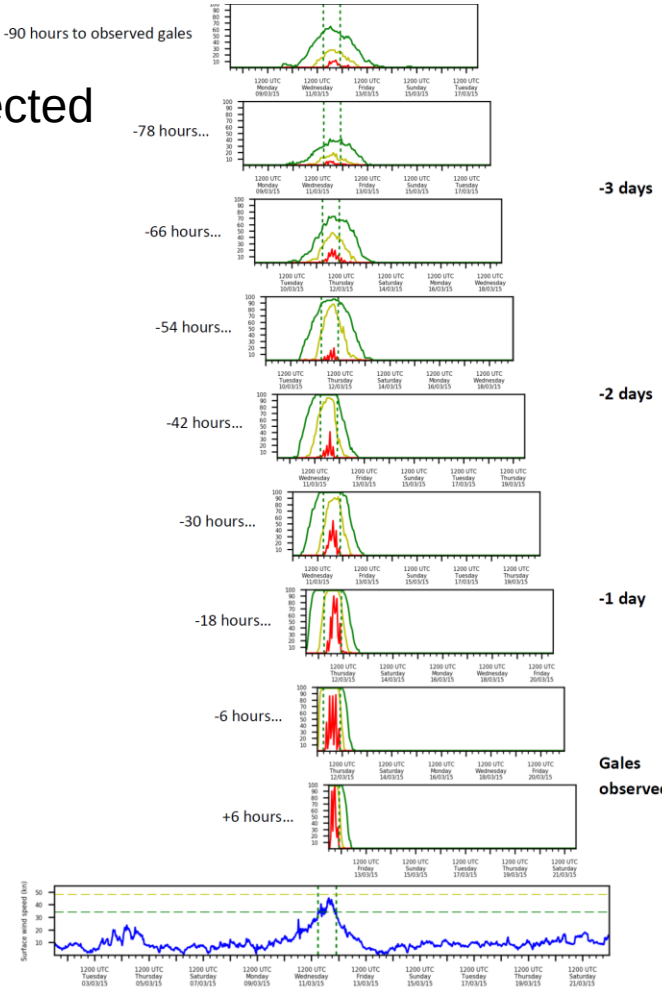
- Same plot, from uncorrected EPS system.
- Weaker indication of gales, almost no indication of risk of storm (50 kt) or hurricane (63 kt) force winds.
- TC Olwyn 60 kt at closest approach, max intensity 75 kt 12 hours later.
- The risk of storm or hurricane force was not zero!

Australian Government
Bureau of Meteorology

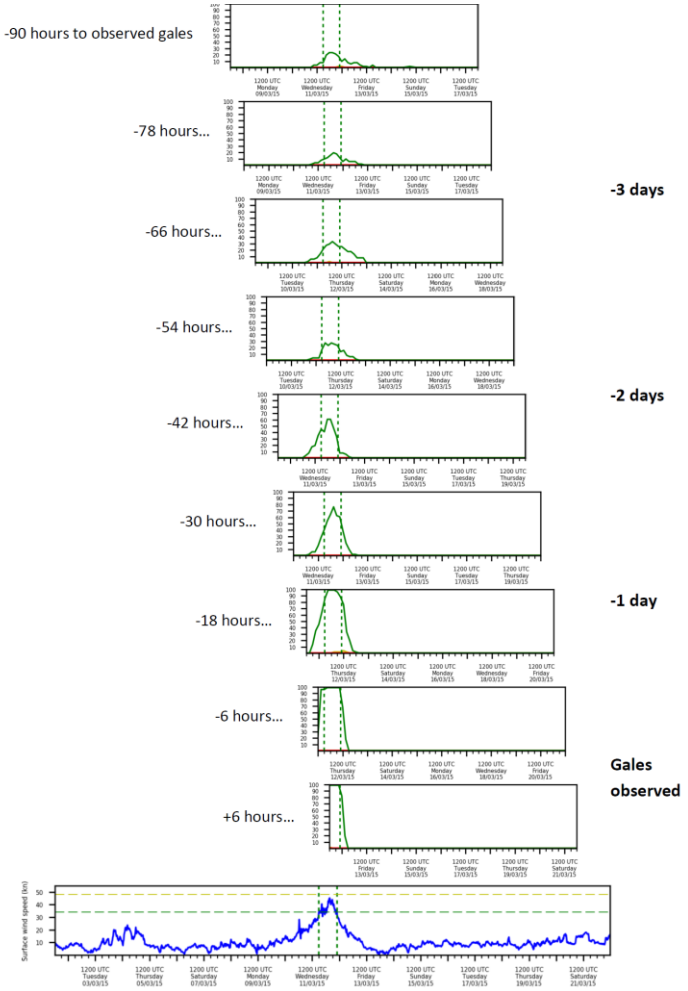
TC Olwyn winds



Bias-corrected

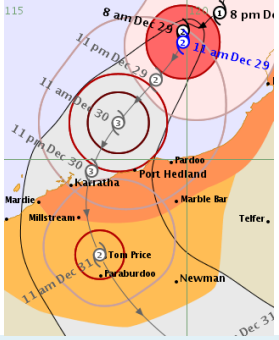


Raw

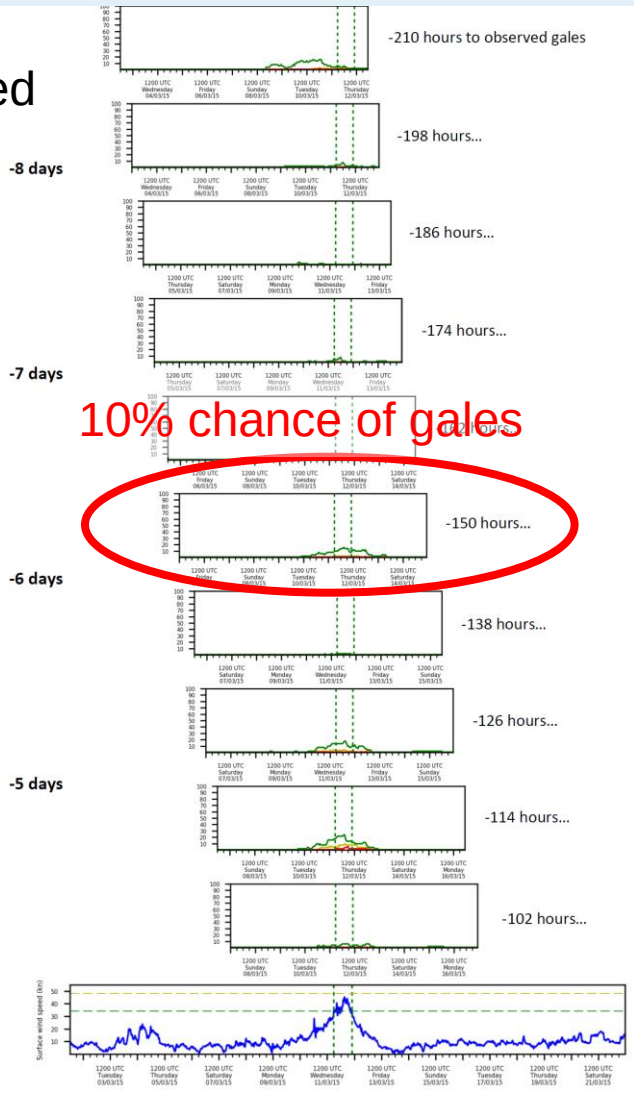


Australian Government
Bureau of Meteorology

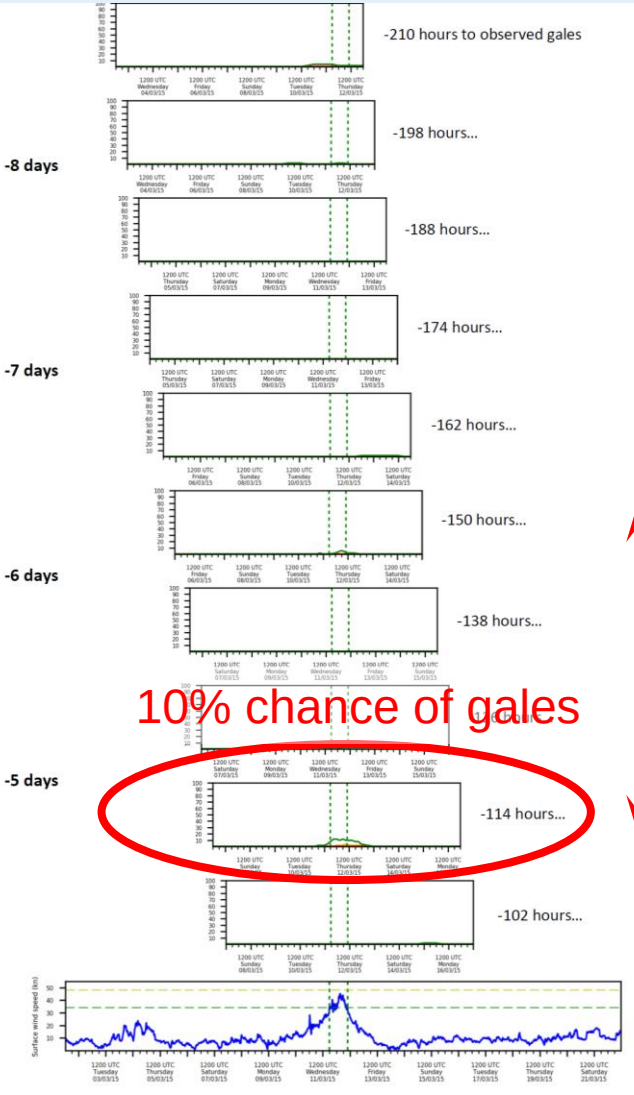
TC Olwyn winds, advanced warning



Bias-corrected



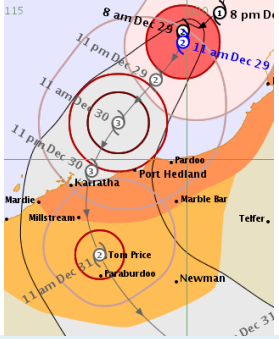
Raw

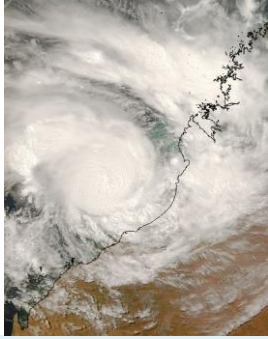


36 hr extra warning

Australian Government
Bureau of Meteorology

EPS-BC: flow-chart





Download EPS from ECMWF

Diagnose TC track, intensity, etc for each ensemble member

Cluster analysis of cyclones

Calculate bias-corrected intensity and size for mean of each cluster

Determine cyclone properties for each ensemble member

Insert new cyclones with bias-corrected properties into grids

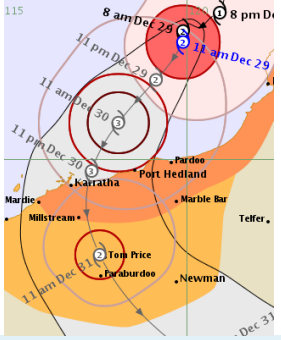
Calculate wind probability products

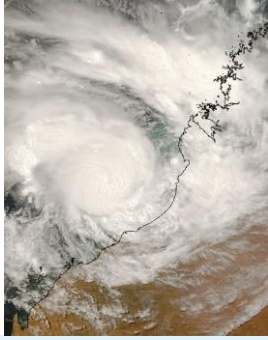
Run wave model on each ensemble member

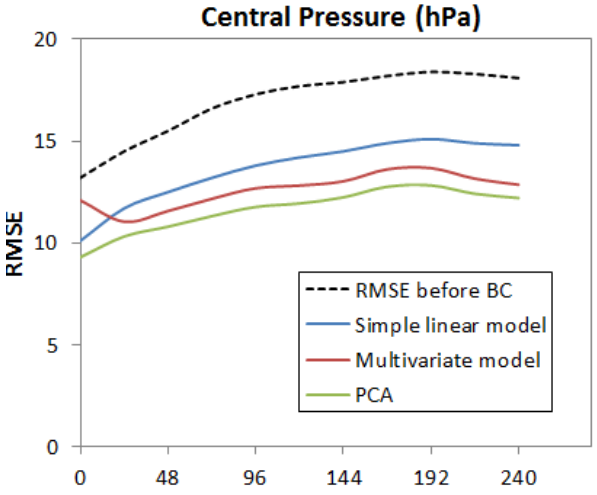
Calculate wave probability products

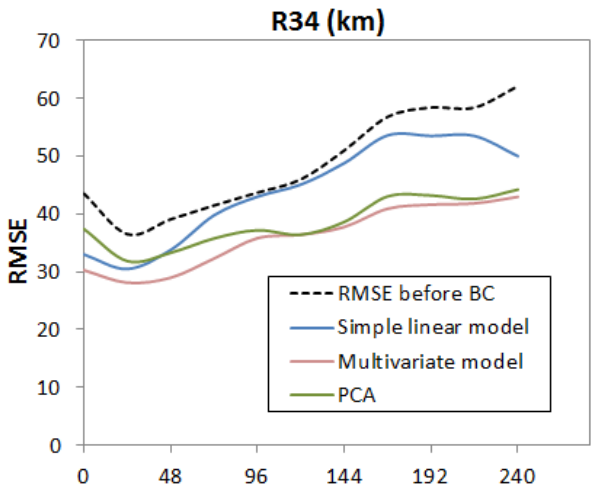
Australian Government
Bureau of Meteorology

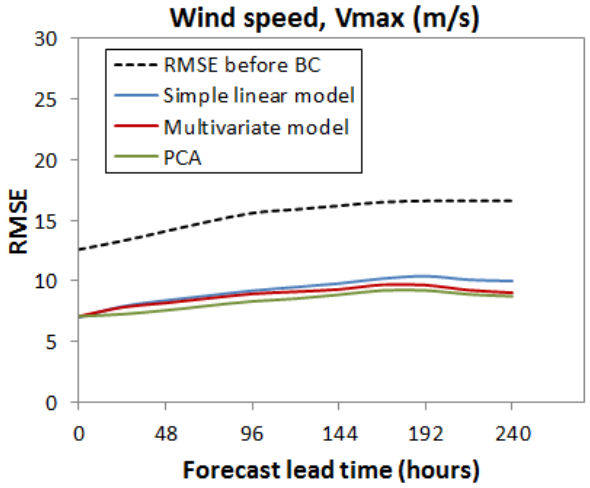
EPS-BC is more accurate

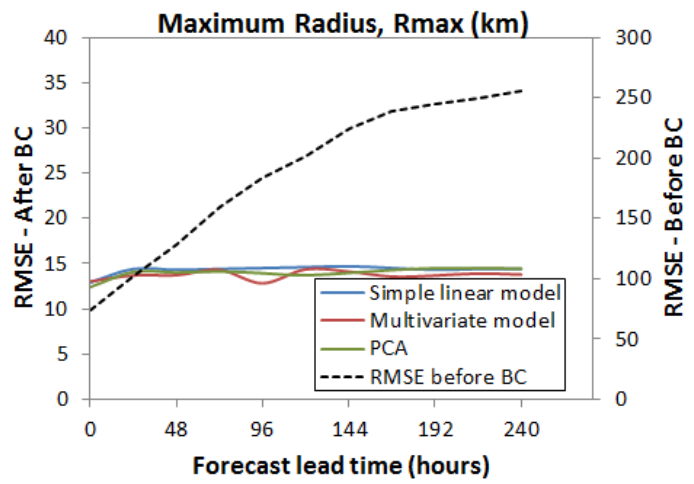






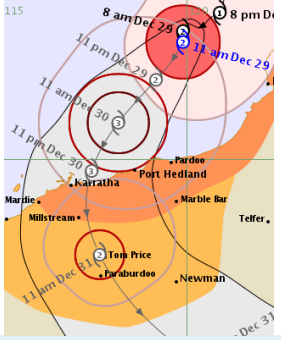


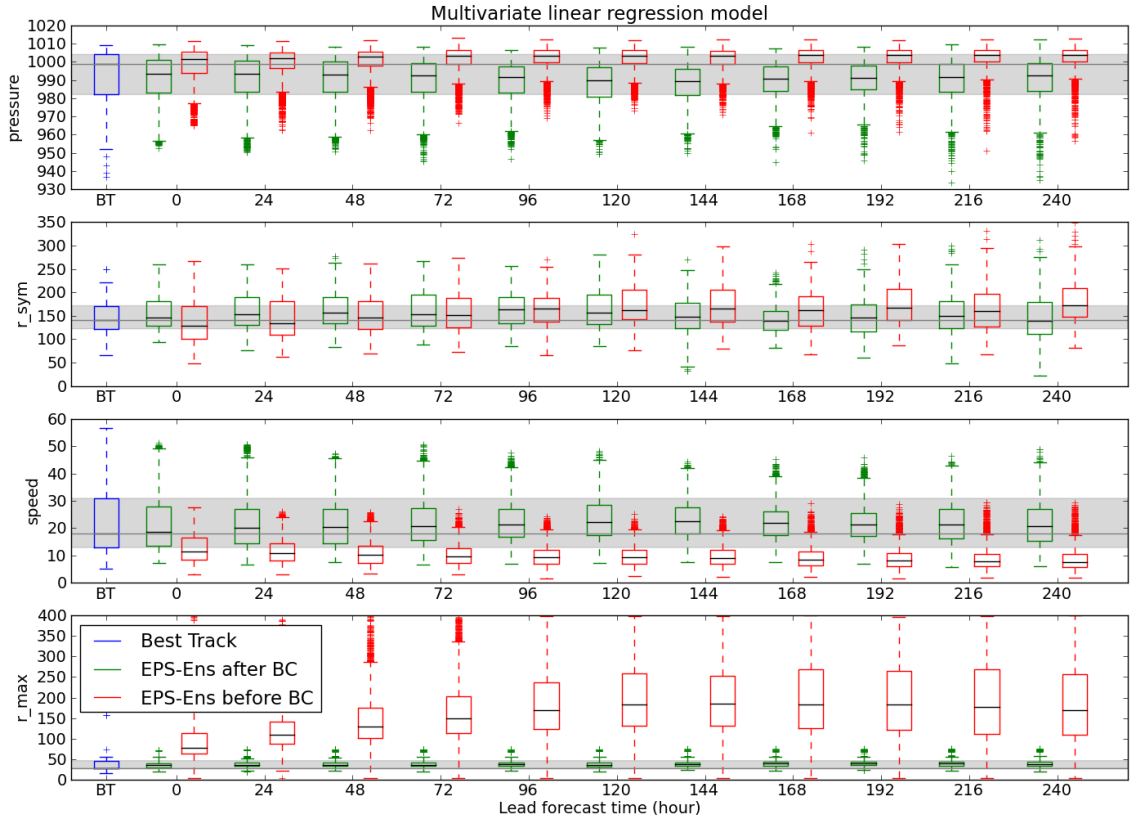




Australian Government
Bureau of Meteorology

EPS-BC: reflects climatology

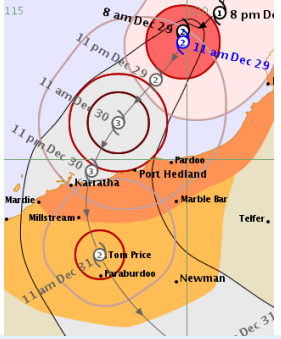


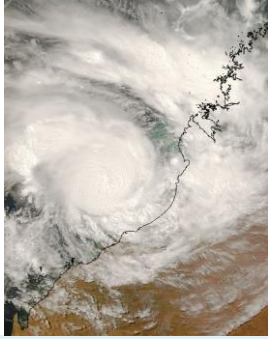


- Distribution of observed TC characteristics shown in blue and grey.
- The distribution of bias-corrected TC parameters (green) is much closer to climatology than the raw ensemble (red).
- Bias correction is leading to a more realistic distribution of cyclones.

Australian Government
Bureau of Meteorology

EPS-BC



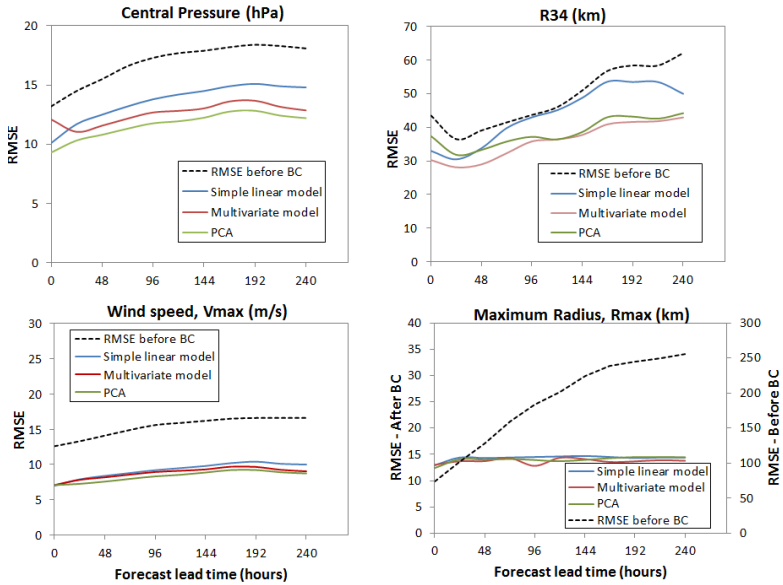


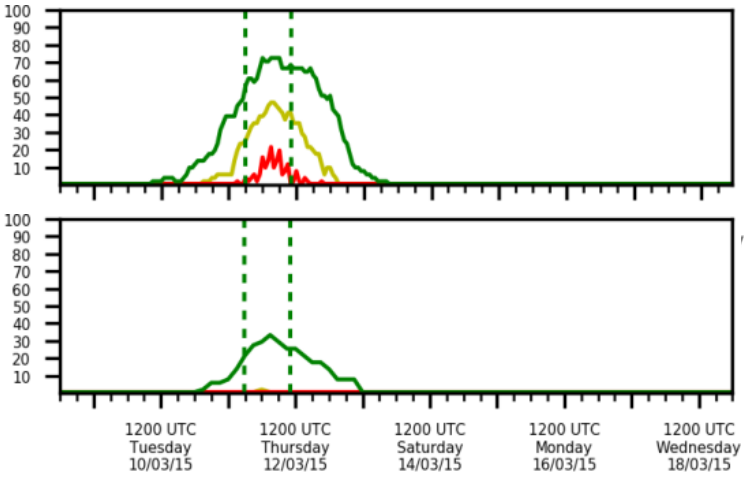
Benefits

- Objective warning of risk of severe wind events is given sooner
- Users will be able to mitigate earlier and with greater confidence

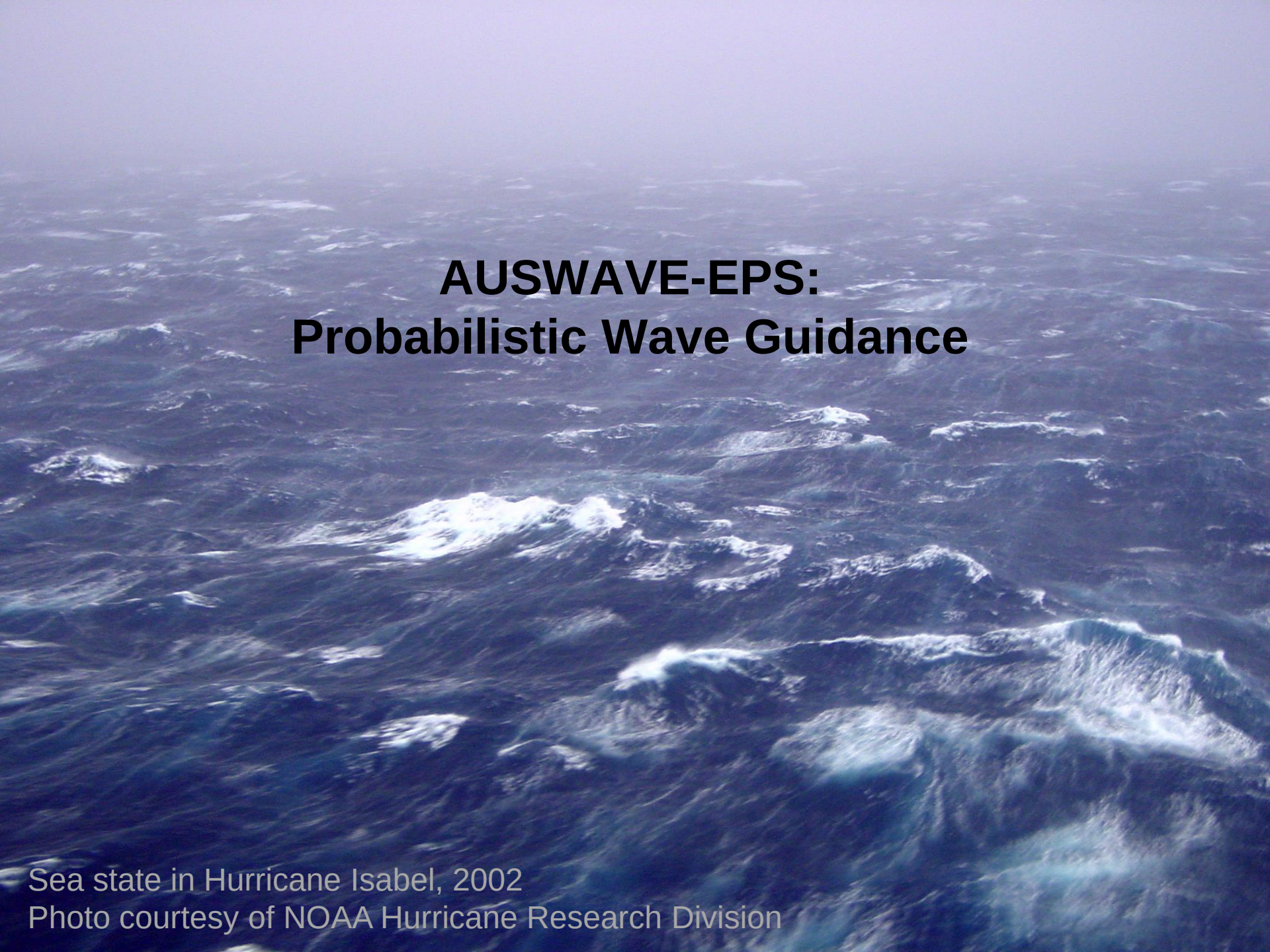
Improvements

- Forecast TC parameters are more accurate
- Spread-skill relationship and other probabilistic forecast skill measures are improved



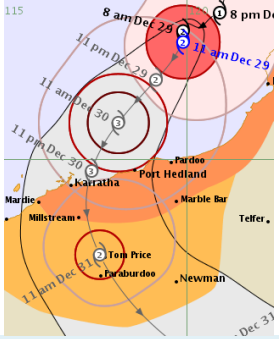


AUSWAVE-EPS:
Probabilistic Wave Guidance

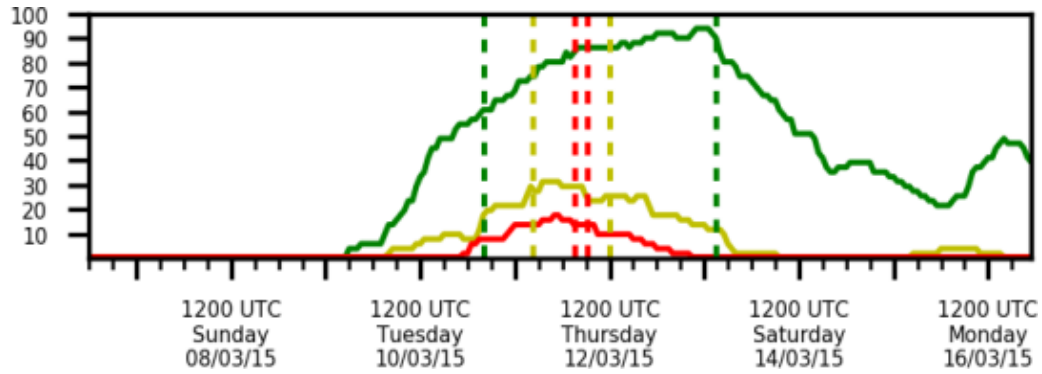


Sea state in Hurricane Isabel, 2002
Photo courtesy of NOAA Hurricane Research Division

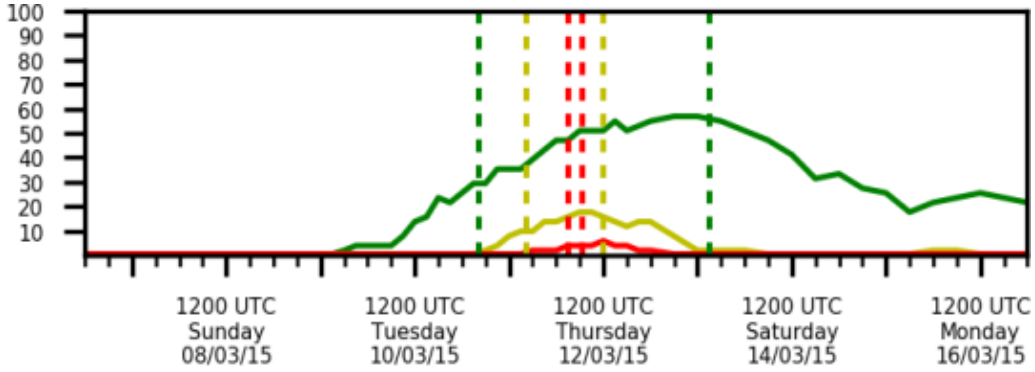
AUSWAVE-EPS: TC Olwyn



Bias-corrected



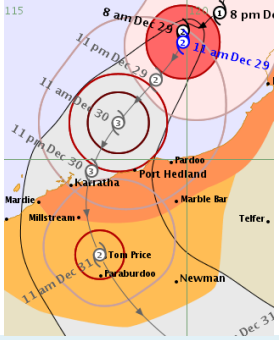
Raw

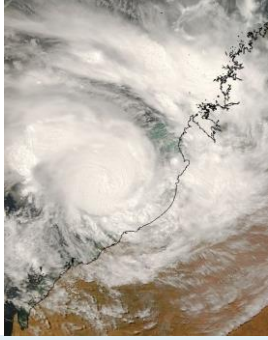


- 5-day wave forecasts of Hs for TC Olwyn at North Rankin
  - Green = p(Hs > 2m)
  - Yellow = p(Hs > 4m)
  - Red = p(Hs > 6m)
- AUSWAVE-EPS indicates markedly higher probability of large waves
- Max observed Hs was 6.8 m

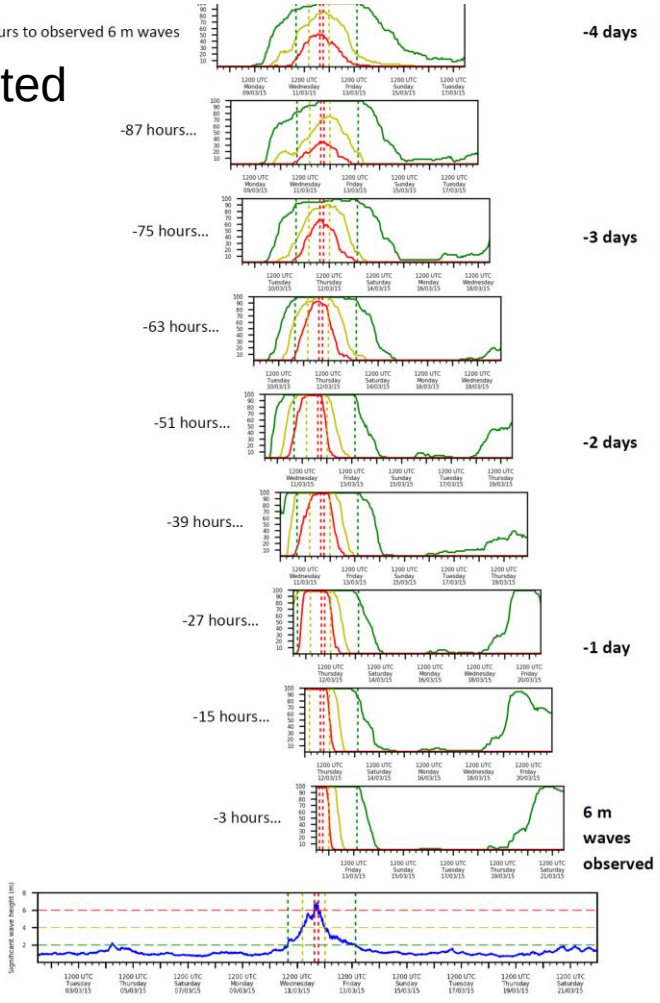
Australian Government
Bureau of Meteorology

AUSWAVE-EPS: TC Olwyn waves

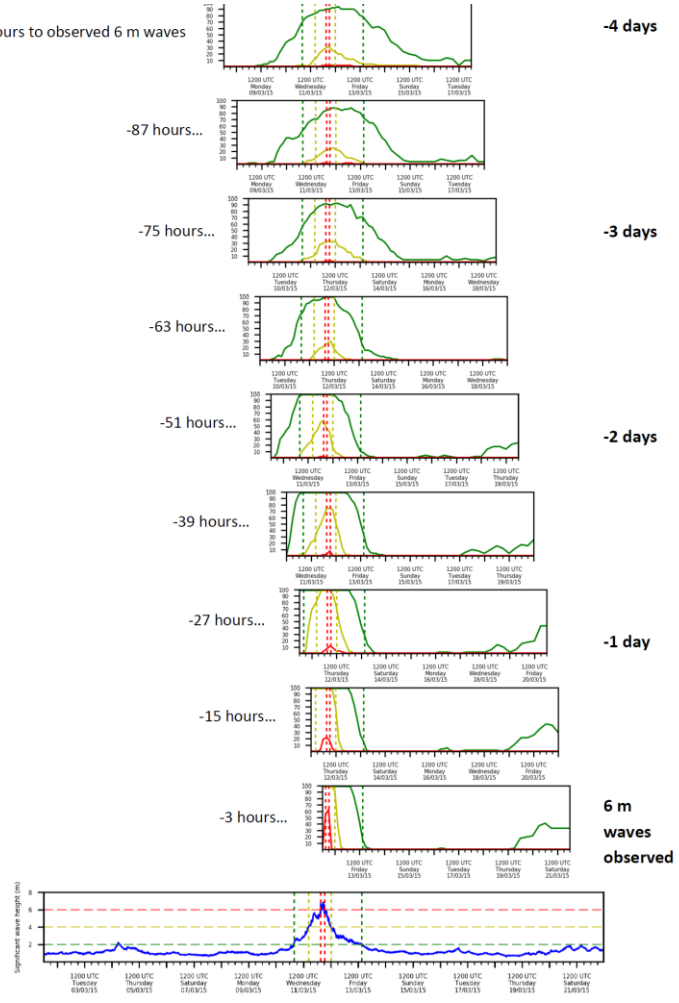




Bias-corrected

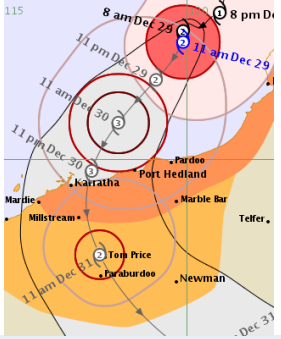


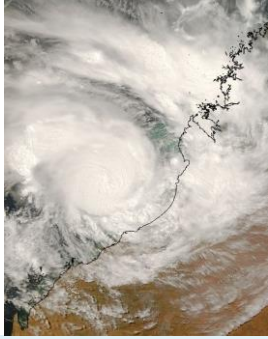
Raw



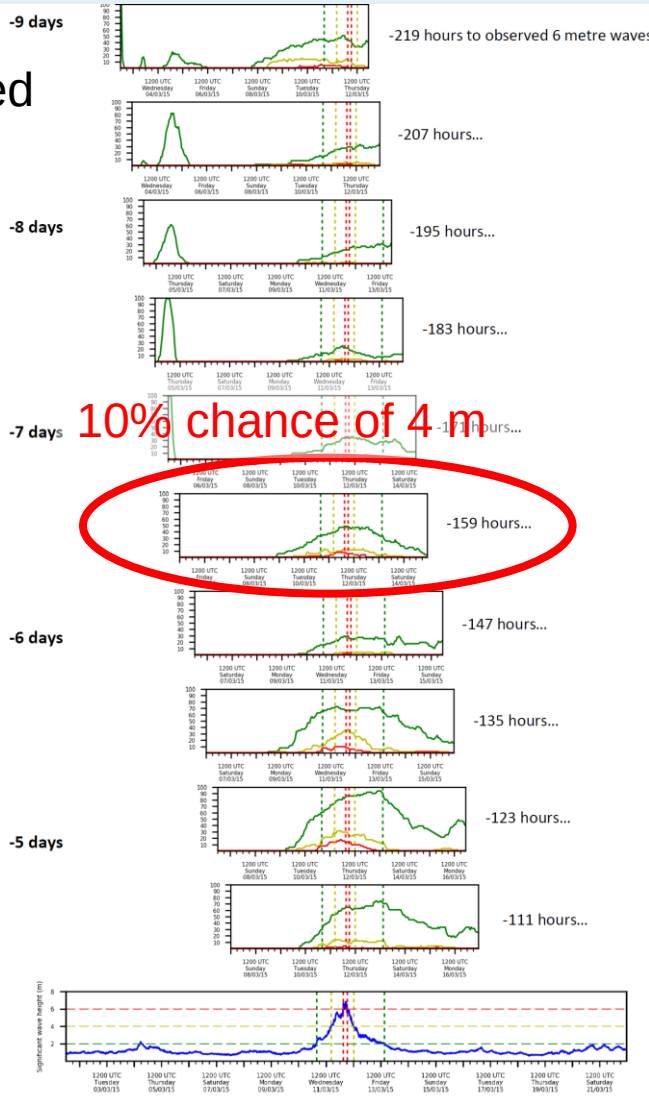
Australian Government
Bureau of Meteorology

AUSWAVE-EPS: TC Olwyn waves

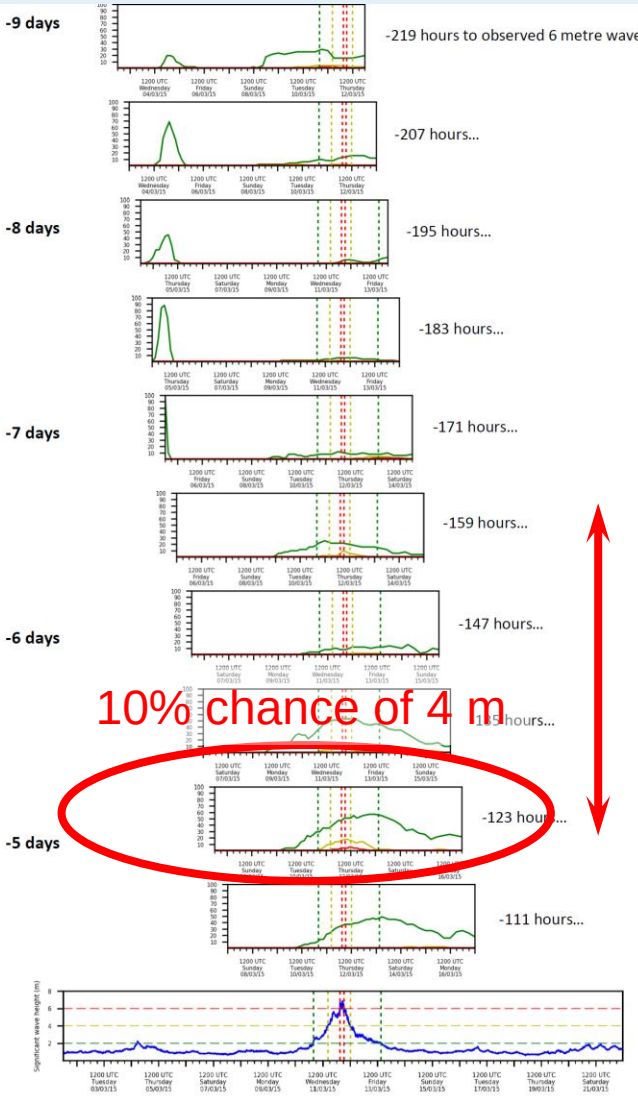




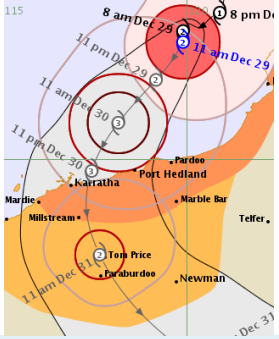
Bias-corrected

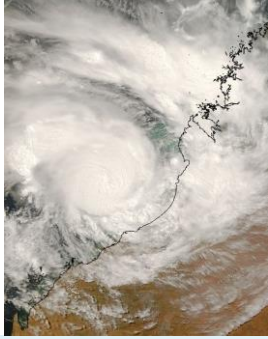


Raw

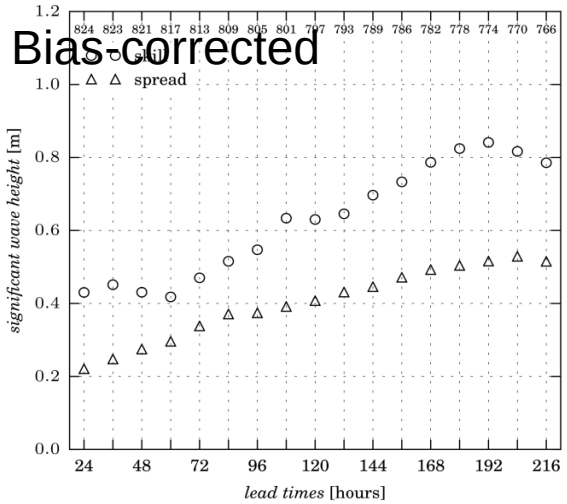


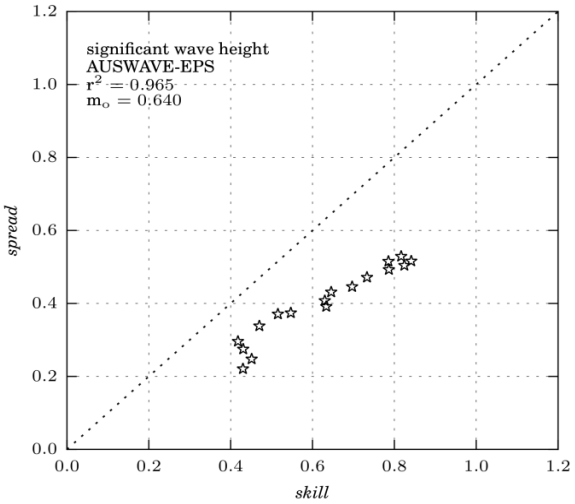
AUSWAVE-EPS: spread-skill



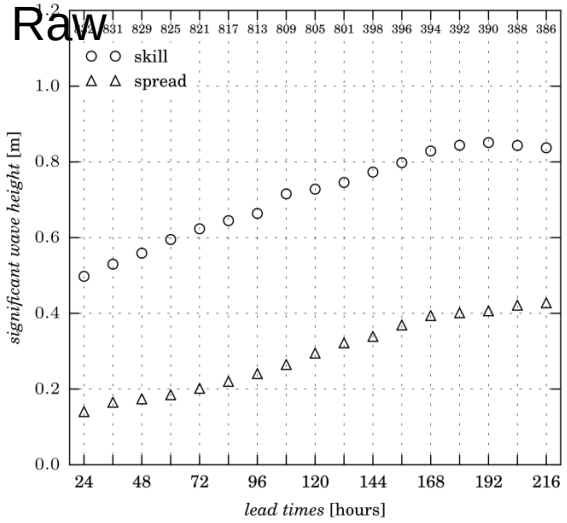


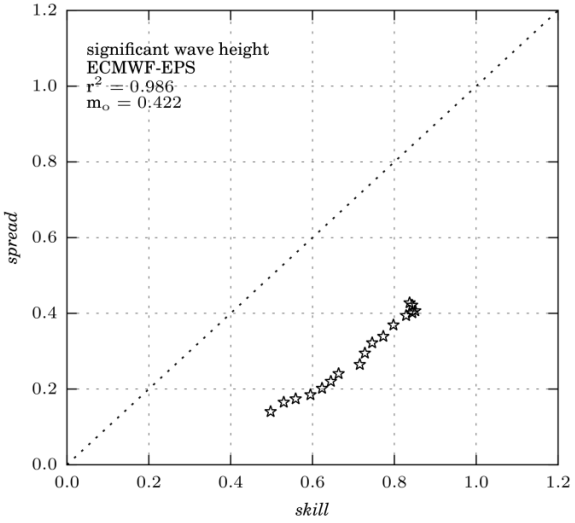
Bias-corrected





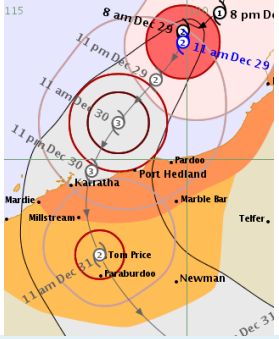
Raw

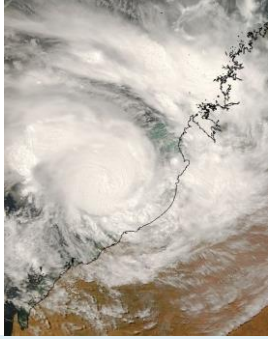




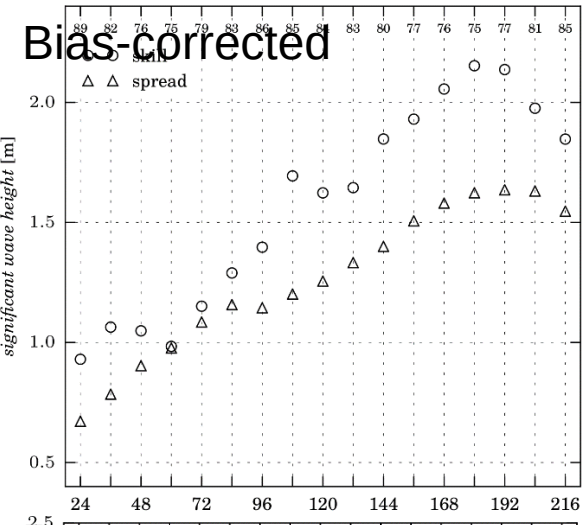
- Skill (RMSE, circles) is better in AUSWAVE-EPS
- Spread is higher in AUSWAVE-EPS
- Spread-skill relationship is closer to the ideal in AUSWAVE-EPS

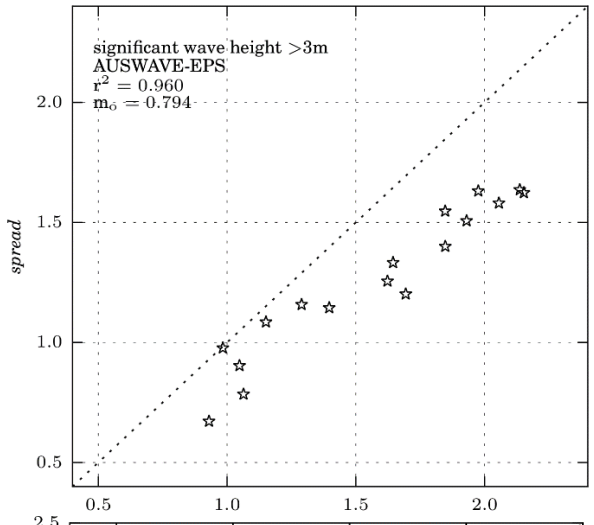
AUSWAVE-EPS: Hs>3m spread-skill



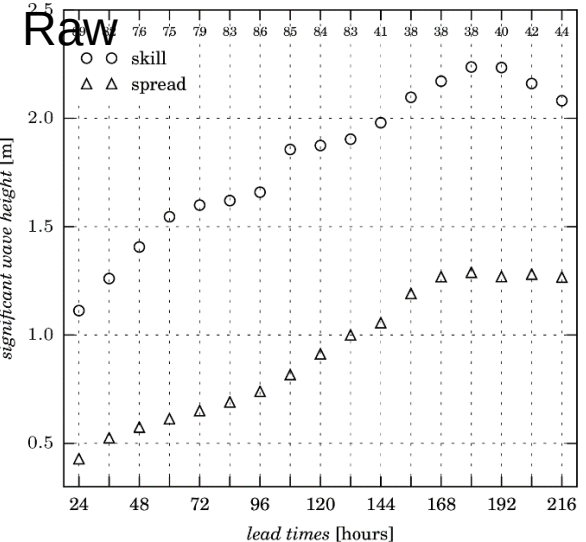


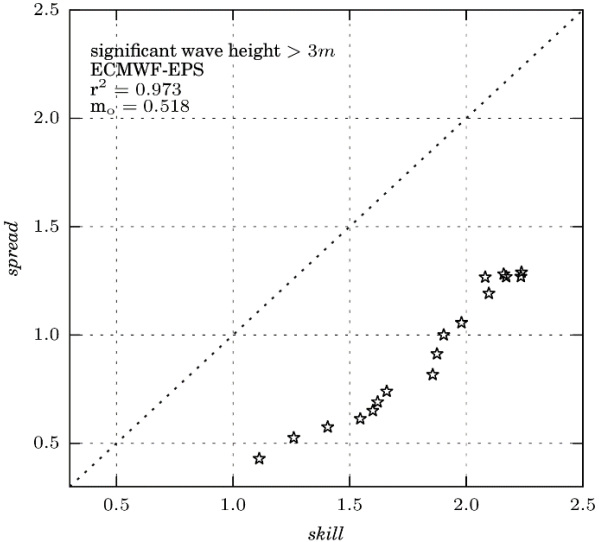
Bias-corrected





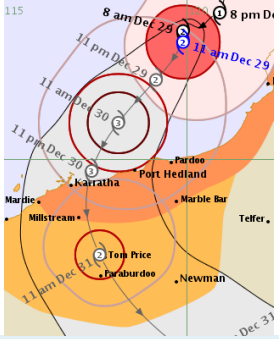
Raw

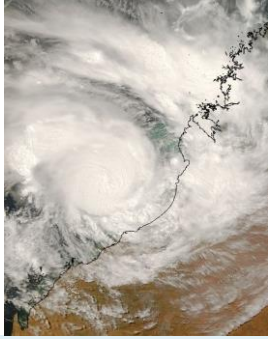




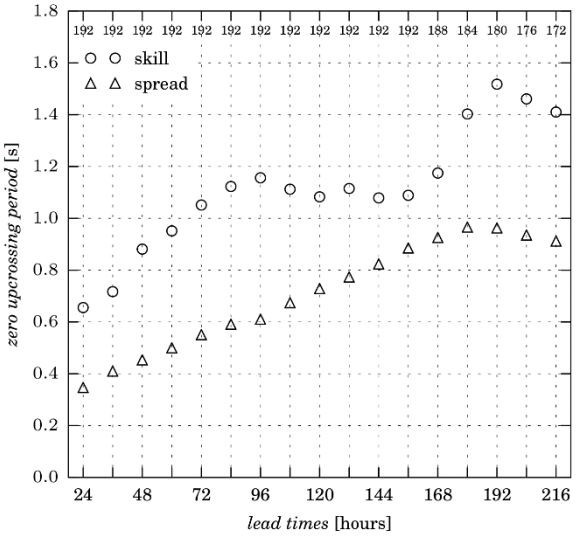
- Spread-skill with data restricted to Hs > 3m
- AUSWAVE-EPS has better skill and greater spread
- Spread-skill relationship very close to ideal 1-1 relationship

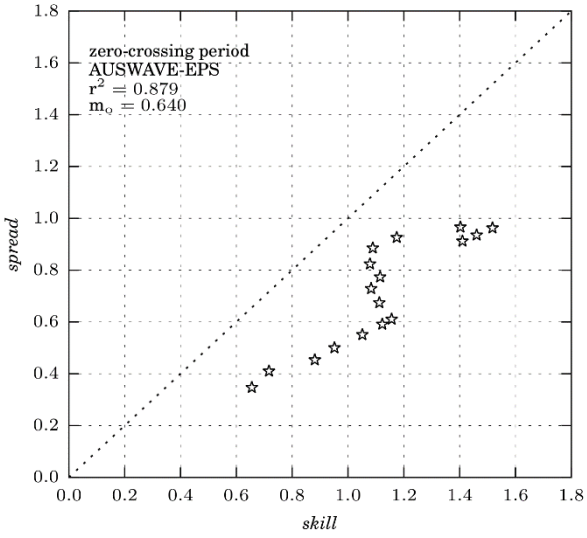
AUSWAVE-EPS: period spread-skill





Bias-corrected

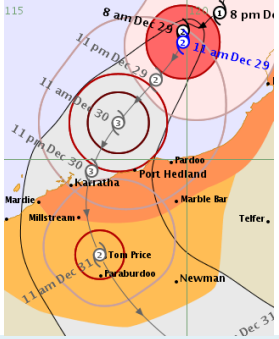


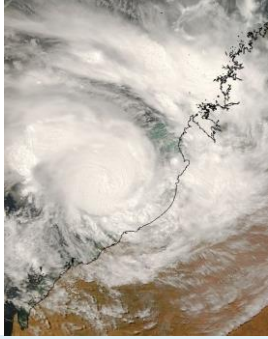


- Zero-crossing period
- AUSWAVE-EPS weakly underspread
- Data not available from ECMWF for comparison

Australian Government
Bureau of Meteorology

AUSWAVE-EPS: Brier skill score





Bias-corrected

Lead time	+24	+36	+48	+60	+72	+84	+96	+108	+120	+132
> 3.0m	84	81	79	80	87	86	93	103	106	104
N	*129*	*123*	*115*	*114*	*118*	*121*	*122*	*122*	*120*	*118*
> 4.0m	18	16	15	15	19	23	27	33	32	29
N	*28*	*25*	*25*	*25*	*25*	*28*	*28*	*28*	*28*	*28*
> 5.0m	7	9	8	8	10	13	15	17	16	16
N	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*
> 6.0m	5	7	6	6	8	10	10	12	11	11
N	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*

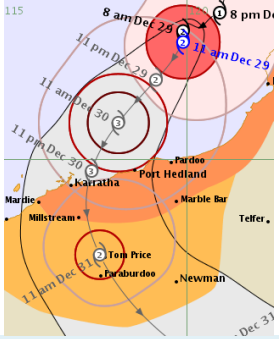
Raw

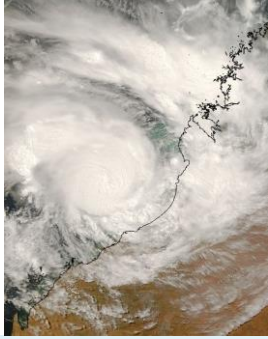
Lead time	+24	+36	+48	+60	+72	+84	+96	+108	+120	+132
> 3.0m	83	83	85	90	96	99	102	110	116	116
N	*129*	*123*	*115*	*114*	*118*	*121*	*122*	*122*	*120*	*118*
> 4.0m	24	23	25	27	27	30	31	32	32	32
N	*28*	*25*	*25*	*25*	*25*	*28*	*28*	*28*	*28*	*28*
> 5.0m	13	14	15	15	15	15	15	16	15	16
N	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*
> 6.0m	10	10	10	10	10	10	11	11	11	11
N	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*

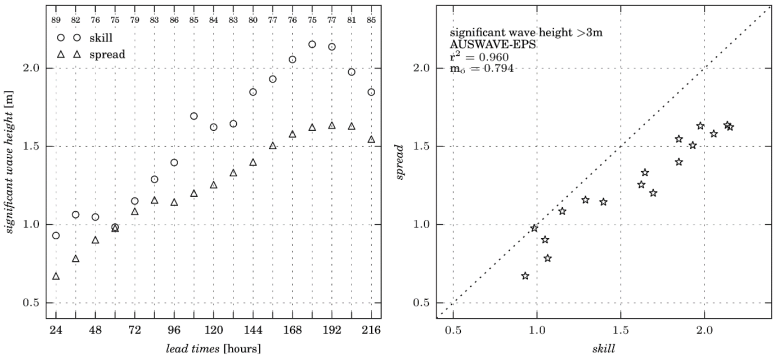
- Green = better
- Olive = equal
- Values in table are multiplied by 1000
- Range from 0 to 1
- Low values are better

Australian Government
Bureau of Meteorology

AUSWAVE-EPS







Lead time	+24	+36	+48	+60	+72	+84	+96	+108	+120	+132
> 3.0m	84	81	79	80	87	86	93	103	106	104
N	*129*	*123*	*115*	*114*	*118*	*121*	*122*	*122*	*120*	*118*
> 4.0m	18	16	15	15	19	23	27	33	32	29
N	*28*	*25*	*25*	*25*	*25*	*28*	*28*	*28*	*28*	*28*
> 5.0m	7	9	8	8	10	13	15	17	16	16
N	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*
> 6.0m	5	7	6	6	8	10	10	12	11	11
N	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*

Benefits

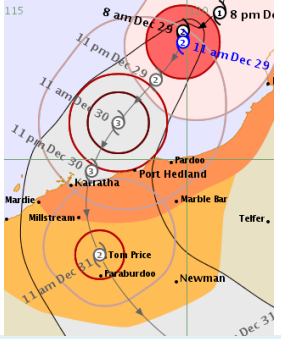
- Objective warning of risk of severe events is given sooner
- Users will be able to mitigate earlier and with greater confidence
- Wind and wave forecasts are mutually consistent

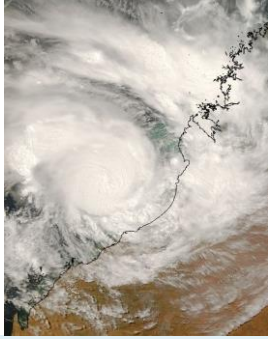
Improvements

- Forecast wave parameters are more accurate, especially in high events
- Spread-skill relationship and other probabilistic forecast skill measures are better than in raw ensemble, indicate small underspread especially on higher waves

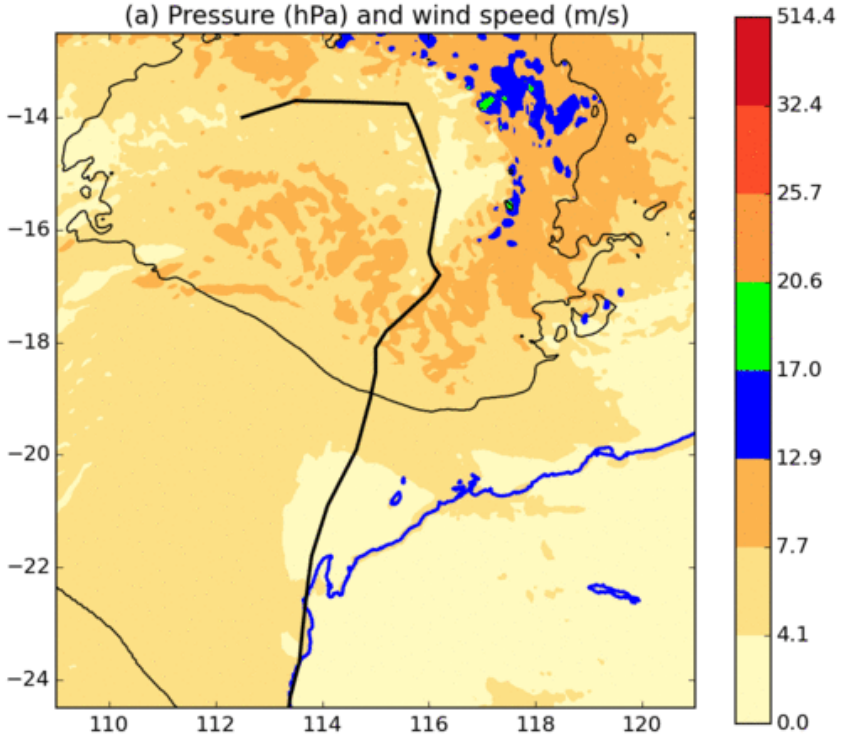
Australian Government
Bureau of Meteorology

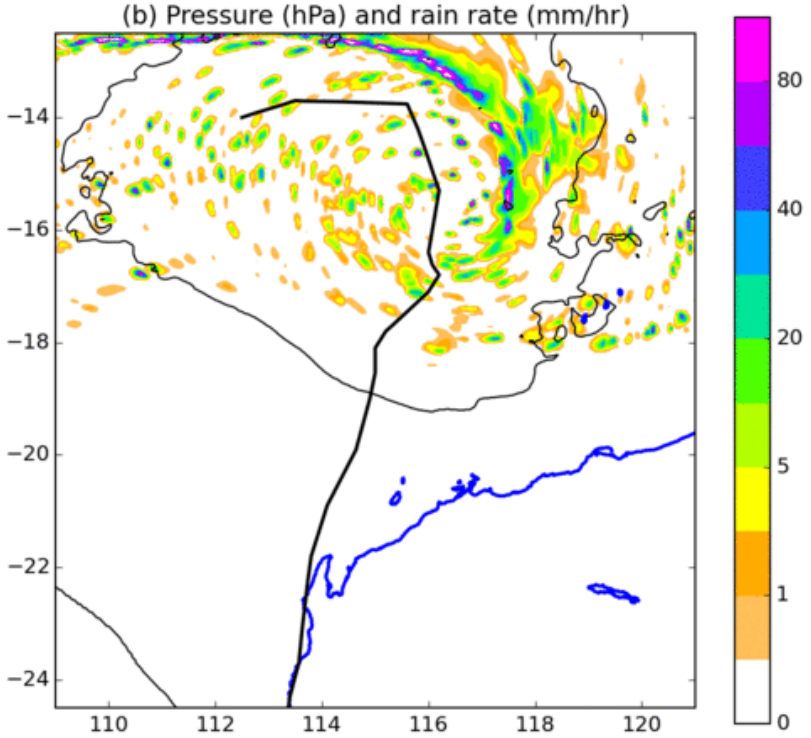
ACCESS-TCX: better intensity forecasts





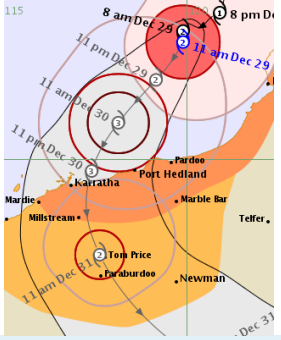
TC Olwyn. Base=20150310T00 fc=+004

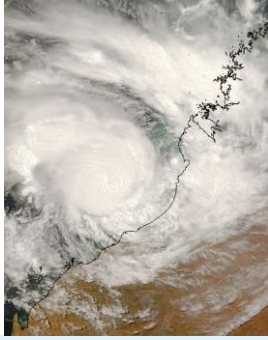




Australian Government
Bureau of Meteorology

ACCESS-TCX: improvements and benefits

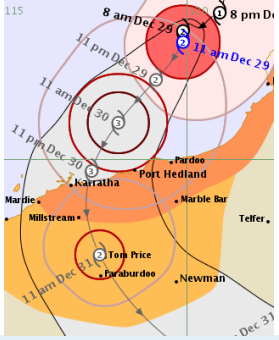


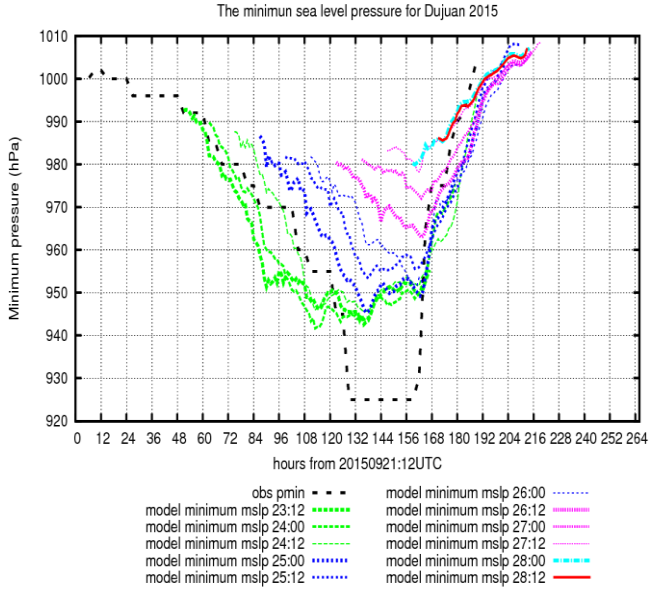


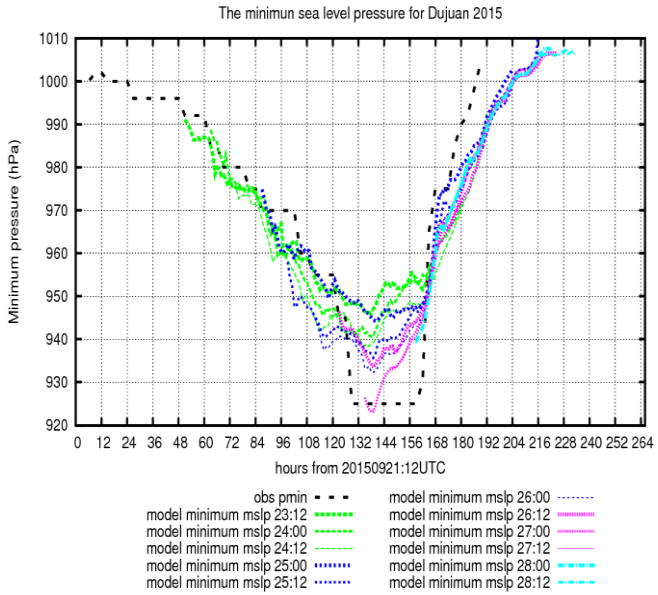
	ACCESS-TC	ACCESS-TCX	Benefits
Resolution	11 km	4 km	Excellent intensity forecasts
Domain	Small, relocatable	Large, fixed	Longer forecasts, wave model, daily running, genesis forecasts
Forecast length	3 days	5 days	Better match industry needs
When run	Only for TCs	All season	Genesis forecasts
Data assimilation	Cold start, 24h spinup	Hybrid cold/warm start	Initialise intense TCs
Wave model	No	Yes	Forecasts of major impact mechanism

Australian Government
Bureau of Meteorology

ACCESS-TCX: data assimilation



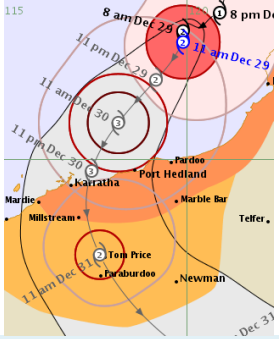


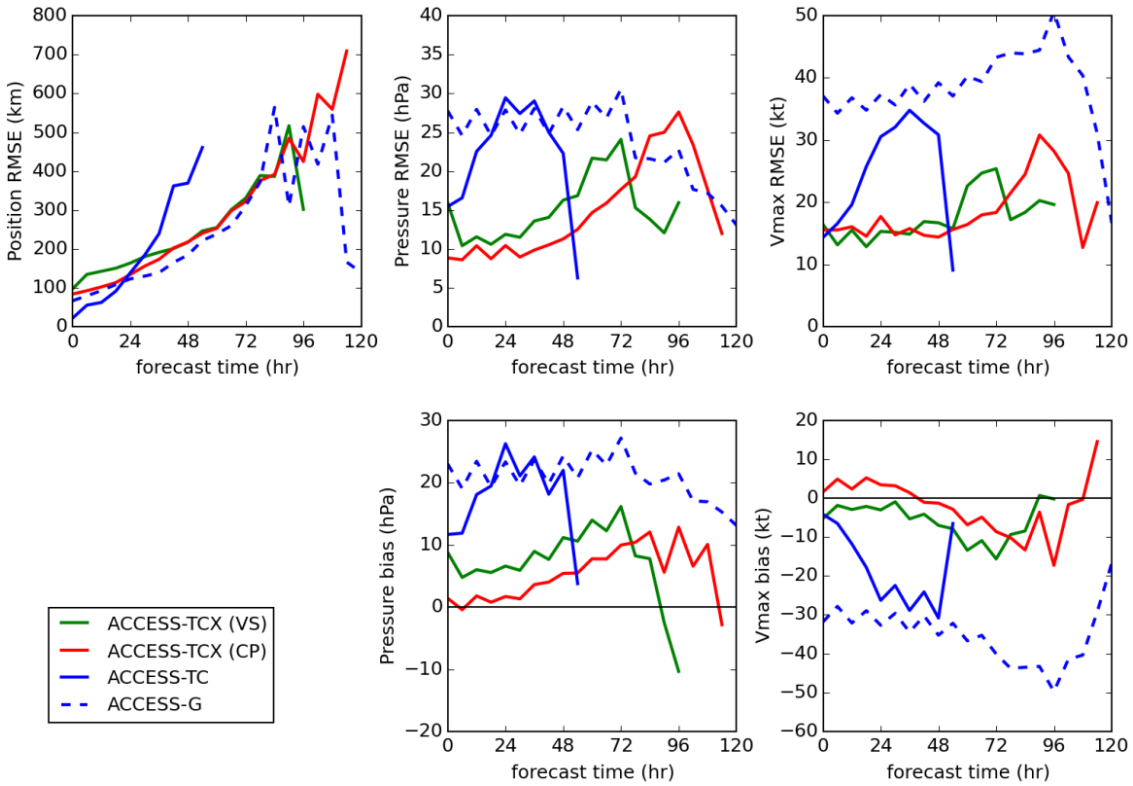


Typhoon Dujuan, series of forecasts every 12 hours

- Left: no data assimilation
- Right: with data assimilation and TC bogus
- Data assimilation gives better initial intensity and better intensity forecasts

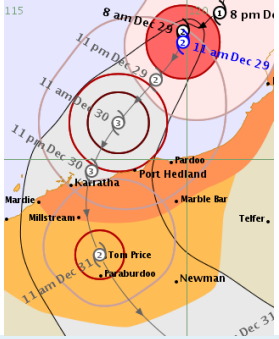
ACCESS-TCX: Australian region

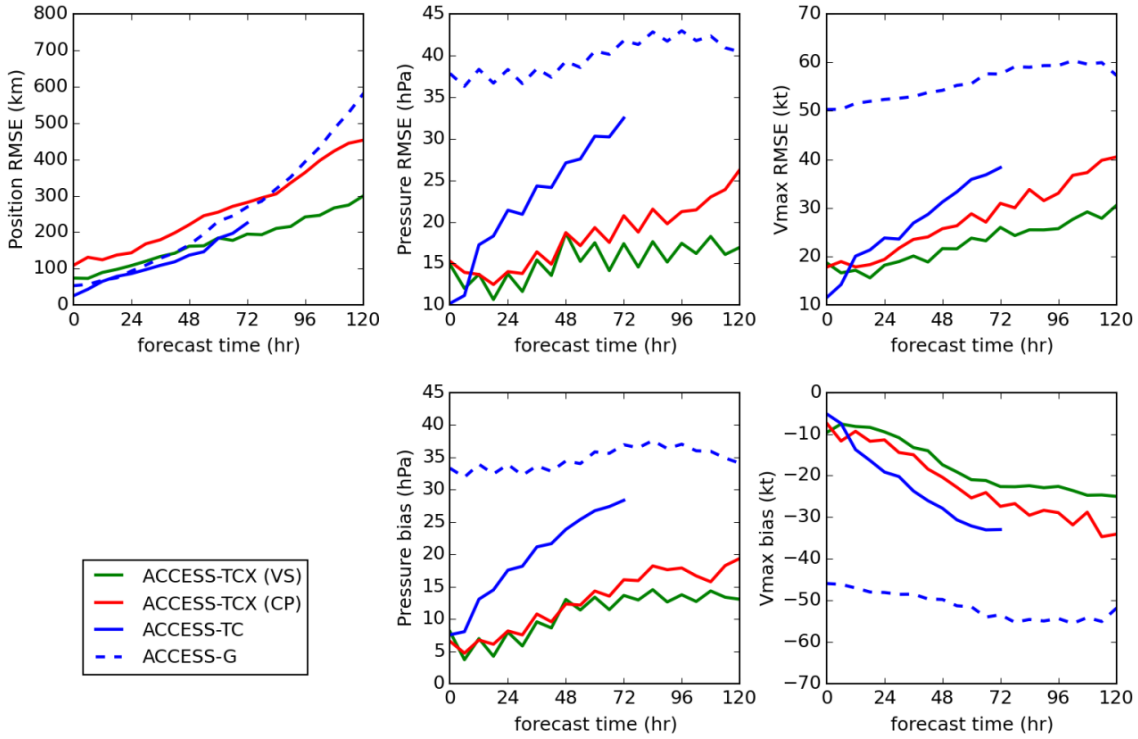




- Australian region
- Top: RMSE position and intensity (central pressure and maximum wind)
- Bottom: intensity bias
- ACCESS-TCX predicts intensity more accurately with less bias
- ACCESS-TCX track forecast accuracy is worse in short term, but small influence on forecast outcome

ACCESS-TCX: NW Pacific

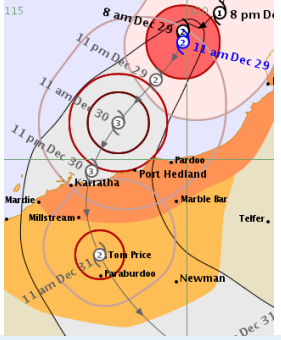


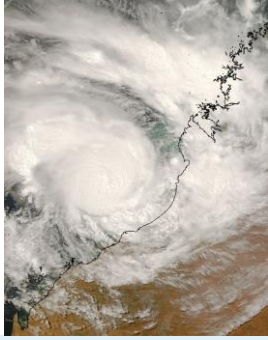


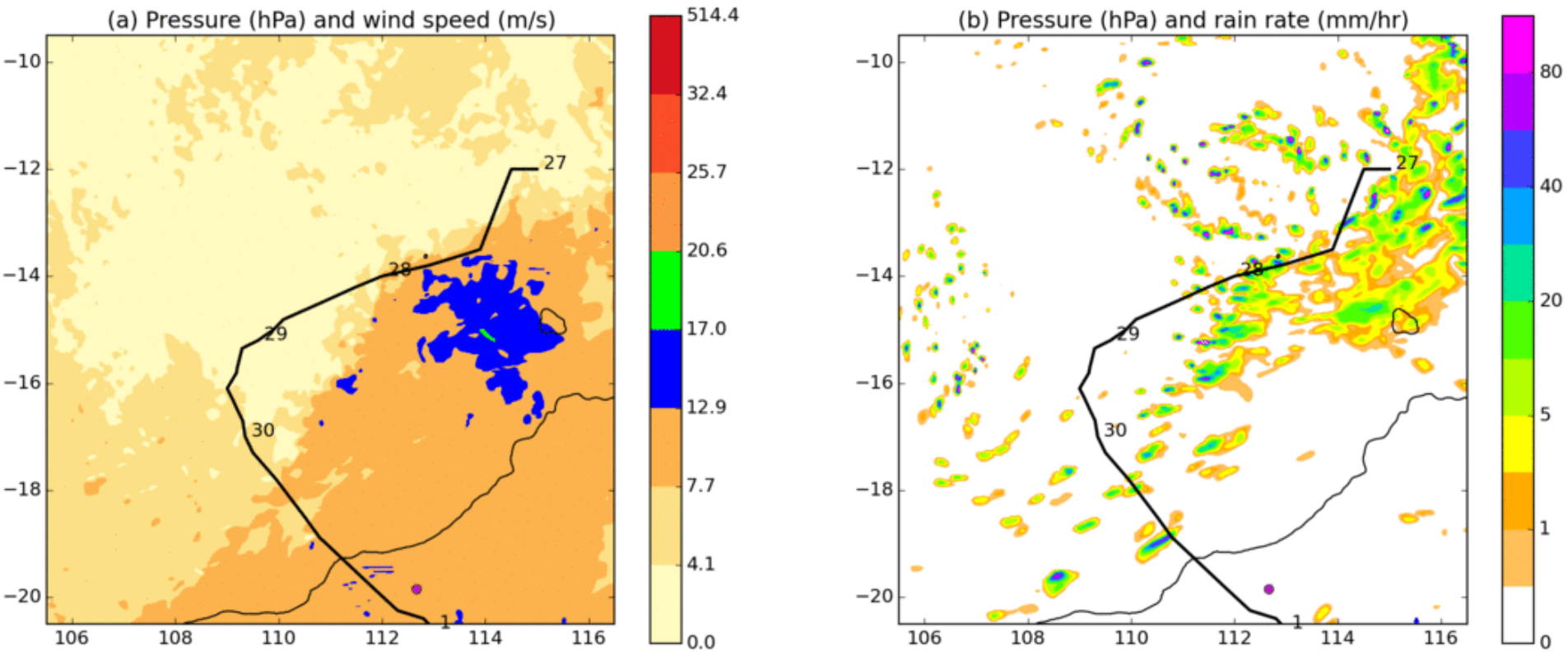
- North West Pacific
- Top: RMSE position and intensity (central pressure and maximum wind)
- Bottom: intensity bias
- ACCESS-TCX predicts intensity more accurately with less bias
- ACCESS-TCX track forecast accuracy is worse in short term, but small influence on forecast outcome

Australian Government
Bureau of Meteorology

ACCESS-TCX: better genesis forecasts

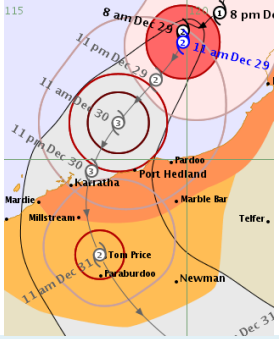


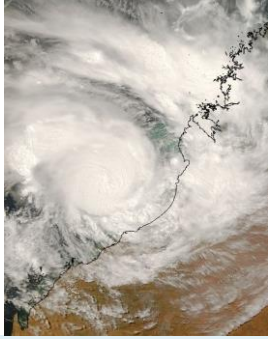




Australian Government
Bureau of Meteorology

Tropical cyclone definition

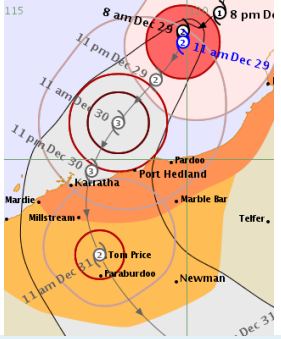


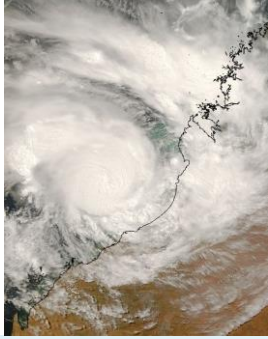


- “A tropical cyclone is defined as a non-frontal low pressure system of synoptic scale developing over warm waters having organised convection and a maximum mean wind speed of 34 knots or greater extending more than half-way around near the centre and persisting for at least six hours.” (http://www.bom.gov.au/cyclone/faq/index.shtml#definitions)
- Many models have an intensity bias, so customarily, use detector/tracker software that looks for somewhat different thresholds.
- It turns out that ACCESS-TCX genesis verifies best with the unmodified definition.

Australian Government
Bureau of Meteorology

ACCESS-TCX: verify genesis *occurrence*

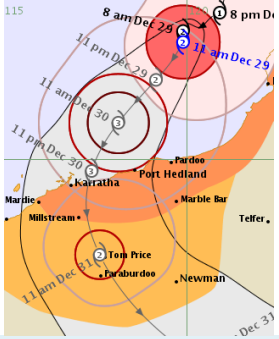


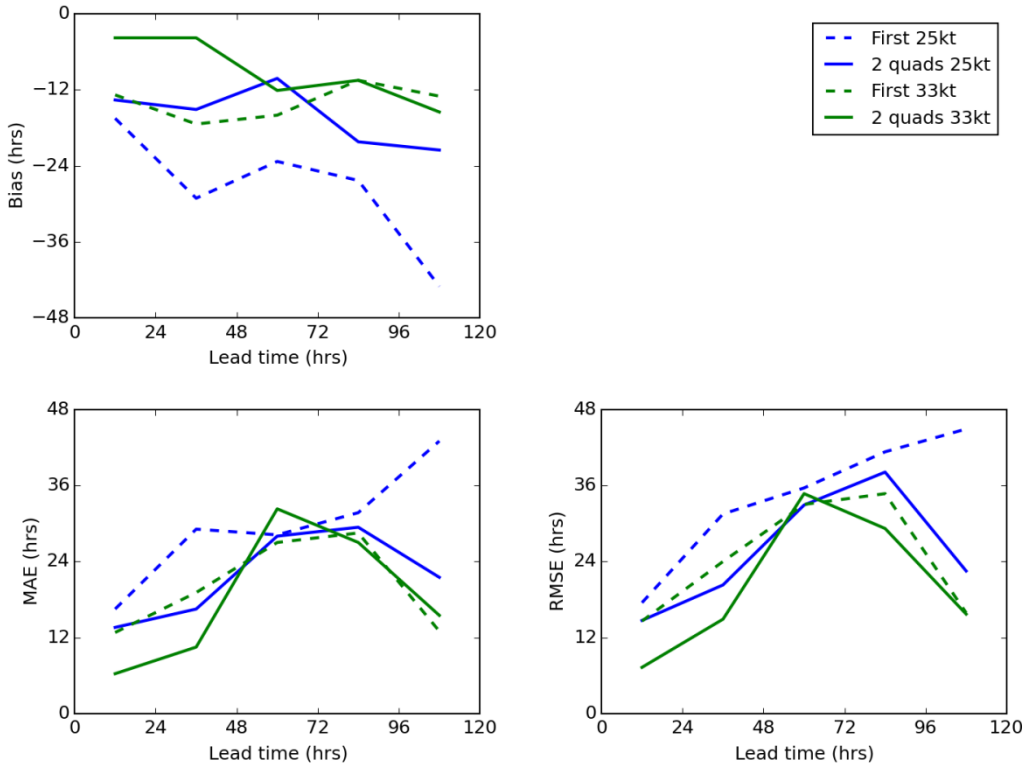


		No (percentage) of detections			
Time to genesis (hrs)	**No of cases**	**First 25 kt**	**2 quads 25 kt**	**First 33 kt**	**2 quads 33 kt**
6-24	8	8 (100%)	8 (100%)	8 (100%)	8 (100%)
30-48	13	13 (100%)	13 (100%)	13 (100%)	12 (92%)
54-72	11	11 (100%)	10 (91%)	10 (91%)	10 (91%)
78-96	7	6 (86%)	5 (71%)	6 (86%)	4 (57%)
102-120	7	6 (86%)	6 (86%)	5 (71%)	3 (43%)

- POD > 90% up to day 3 on all criteria for genesis *occurrence* (not timing)
- Green shading indicates POD > 80%
- POD declines at longer lead time, particularly with more stringent criteria
- FAR stats not available on final system but 2015-16 trial on preliminary system suggests low FAR (i.e. few false alarms)

ACCESS-TCX: verify genesis *timing*

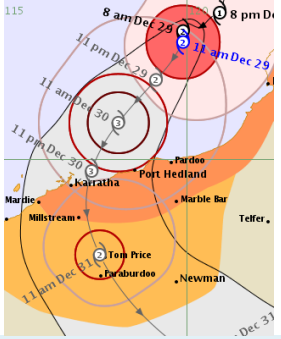


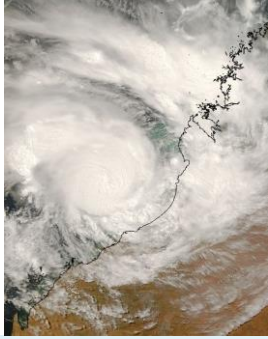


- Most realistic criterion (2 quads 33 kt) generally best performer.
- Caution: small number of cases, especially at long lead time.
- Stats suggest genesis is forecast early (i.e. model is “too fast”).
- Decline in RMSE at longer lead times probably not real, due to smaller sample.
- Calculated from forecasts where genesis occurred.

Australian Government
Bureau of Meteorology

Benefits of better genesis forecasts





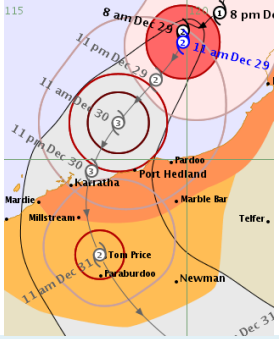
- WA has unusual number of storms that form close to the coast – unique problem to area
  - Longer-range TC forecasts are very often genesis forecasts

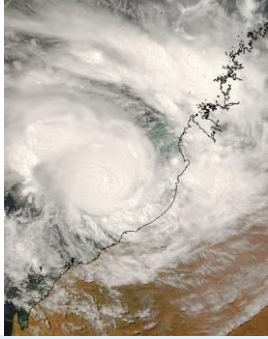
		No (percentage) of detections			
Time to genesis (hrs)	**No of cases**	**First 25 kt**	**2 quads 25 kt**	**First 33 kt**	**2 quads 33 kt**
6-24	8	8 (100%)	8 (100%)	8 (100%)	8 (100%)
30-48	13	13 (100%)	13 (100%)	13 (100%)	12 (92%)
54-72	11	11 (100%)	10 (91%)	10 (91%)	10 (91%)
78-96	7	6 (86%)	5 (71%)	6 (86%)	4 (57%)
102-120	7	6 (86%)	6 (86%)	5 (71%)	3 (43%)

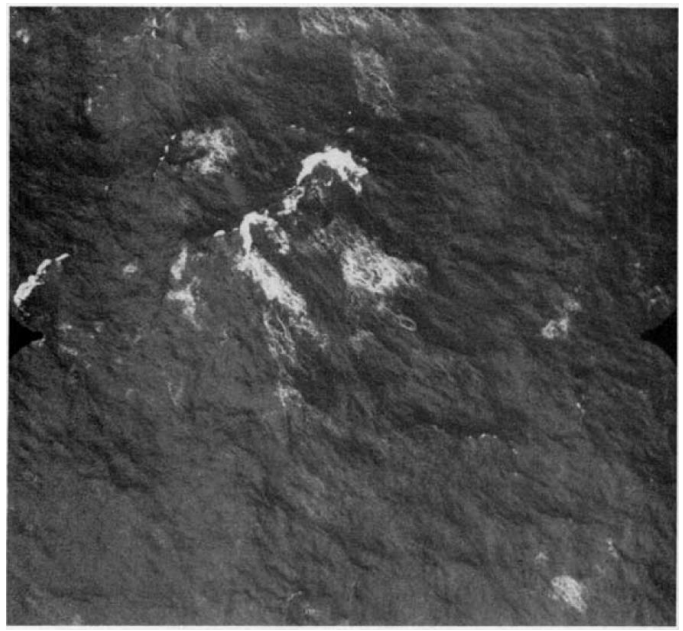
- ACCESS-TCX is providing excellent guidance on *occurrence* and *timing* of genesis out to 3 days, useful guidance in 3 – 5 day range
- Industry will be able to make better decisions, with greater confidence, out to 5 days, even when the cyclone has not yet formed

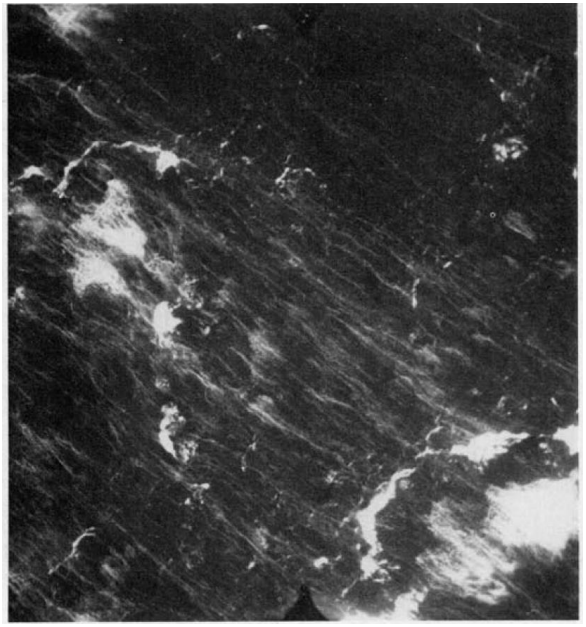
Australian Government
Bureau of Meteorology

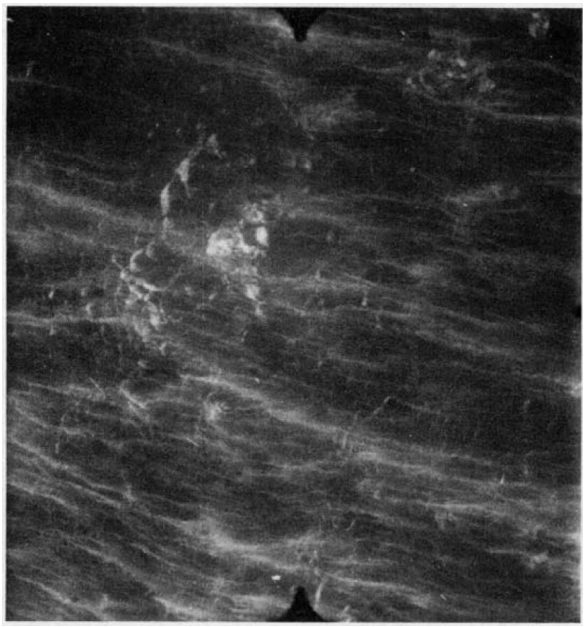
AUSWAVE-TCX: Better TC Wave Forecasts







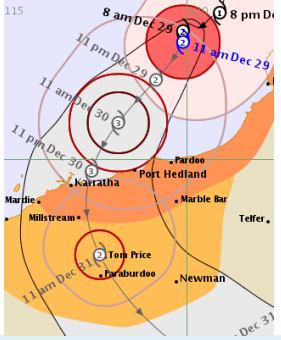


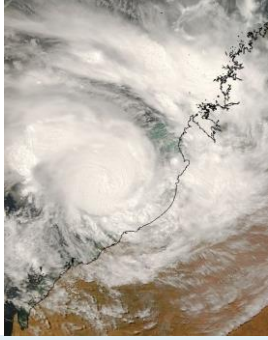


Sea state at 30, 53 and 74 kt (Black et al 1986)

Australian Government
Bureau of Meteorology

AUSWAVE-TCX: Verification in TCs

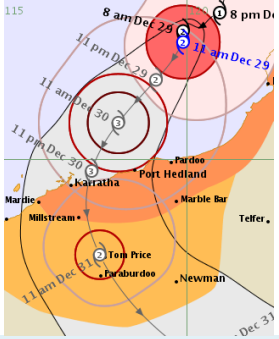


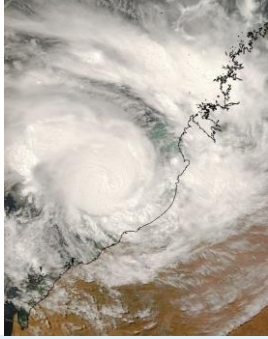


		AUSWAVE-TCX					AUSWAVE-R				
	Lead time	***+24***	***+48***	***+72***	***+96***	***+120***	***+24***	***+48***	***+72***	***+96***	***+120***
Wind Speed	Correlation	0.81	0.62	0.51	0.22	0.11	0.76	0.49	0.26	*n/a*	*n/a*
	RMSE	2.45	3.67	4.23	5.01	4.14	3.06	4.07	4.75	*n/a*	*n/a*
	Bias	-0.80	-1.04	-0.78	0.04	1.33	-1.09	-0.84	-0.32	*n/a*	*n/a*
	SI	0.22	0.36	0.48	0.62	0.58	0.29	0.42	0.51	*n/a*	*n/a*
	slope	0.91	0.83	0.78	0.79	1.02	0.83	0.80	0.80	*n/a*	*n/a*
Significant Wave Height	Correlation	0.93	0.80	0.64	0.50	0.66	0.83	0.68	0.61	*n/a*	*n/a*
	RMSE	0.45	0.71	0.94	1.08	0.72	0.65	0.85	0.95	*n/a*	*n/a*
	Bias	0.04	-0.06	-0.21	-0.26	0.03	0.03	-0.06	-0.18	*n/a*	*n/a*
	SI	0.19	0.30	0.40	0.46	0.36	0.29	0.37	0.41	*n/a*	*n/a*
	slope	0.99	0.91	0.81	0.77	0.97	0.93	0.88	0.81	*n/a*	*n/a*
Peak Period	Correlation	0.59	0.52	0.44	0.48	0.66	0.61	0.43	0.44	*n/a*	*n/a*
	RMSE	2.94	3.09	3.70	3.74	3.01	2.92	3.32	3.57	*n/a*	*n/a*
	Bias	1.11	1.24	1.98	1.63	0.98	1.14	1.00	1.19	*n/a*	*n/a*
	SI	0.30	0.32	0.34	0.34	0.27	0.31	0.36	0.38	*n/a*	*n/a*
	slope	1.08	1.10	1.16	1.10	1.05	1.09	1.07	1.09	*n/a*	*n/a*
Peak Direction	Correlation	0.67	0.59	0.48	0.42	0.58	0.60	0.49	0.38	*n/a*	*n/a*
	RMSE	80.9	90.7	93.7	78.7	49.8	86.4	99.1	105.6	*n/a*	*n/a*
	Bias	22.1	26.5	26.0	21.6	-0.2	23.1	24.3	42.9	*n/a*	*n/a*
	SI	0.53	0.53	0.50	0.37	0.22	0.54	0.57	0.52	*n/a*	*n/a*
	slope	1.00	1.00	0.98	1.00	0.98	0.98	0.97	1.04	*n/a*	*n/a*
Swell Peak Period	Correlation	0.36	0.16	0.23	0.55	0.93	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
	RMSE	2.2	2.4	2.4	1.9	0.94	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
	Bias	-0.17	0.47	0.76	0.17	-0.35	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
	SI	0.18	0.19	0.18	0.15	0.06	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
	slope	0.98	1.02	1.04	1.00	0.97	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*

Australian Government
Bureau of Meteorology

AUSWAVE-TCX





Benefits

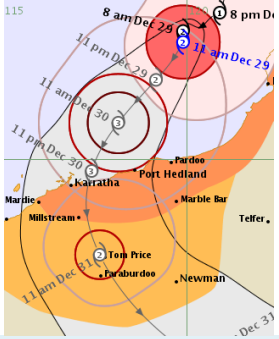
- Consistent wind and wave forecasts
- Inherits benefits of ACCESS-TCX (good intensity, good genesis, 5-day forecasts)

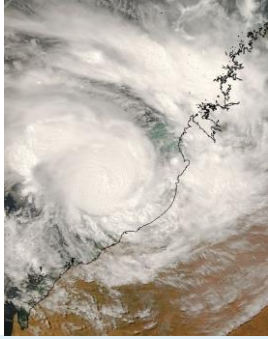
Improvements

- First operational wave model for tropical cyclones in Australia
- Up-to-date wave model, tuned and verified in TCs
- More accurate than AUSWAVE-R in and out of TCs

Australian Government
Bureau of Meteorology

Operations



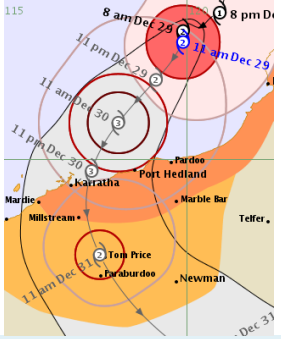


- EPS-BC and Auswave-EPS operational since last November
- ACCESS-TCX and Auswave-TCX are currently in transition

- In the Bureau, "operational" means
  - 24/7 support on our supercomputer
  - highly robust IT infrastructure
  - highly secure IT environment
  - end-to-end chain including product generation and verification
  - R&D support for ongoing maintenance and calibration

Australian Government
Bureau of Meteorology

Industry Benefits



- EPS-BC and AUSWAVE-BC
  - Better forecast use of ensemble prediction system
  - Greatly reduced bias
  - Probabilities of wind and wave exceedance are more accurate
  - Consistent wind and wave forecasts
  - Verification to improve forecaster and user confidence
- ACCESS-TCX and AUSWAVE-TCX
  - Extended forecast length to 5 days
  - Better genesis forecasts so industry can plan for storms before they form
  - Markedly better intensity forecasts
  - Wave forecasts more accurate in and out of TCs