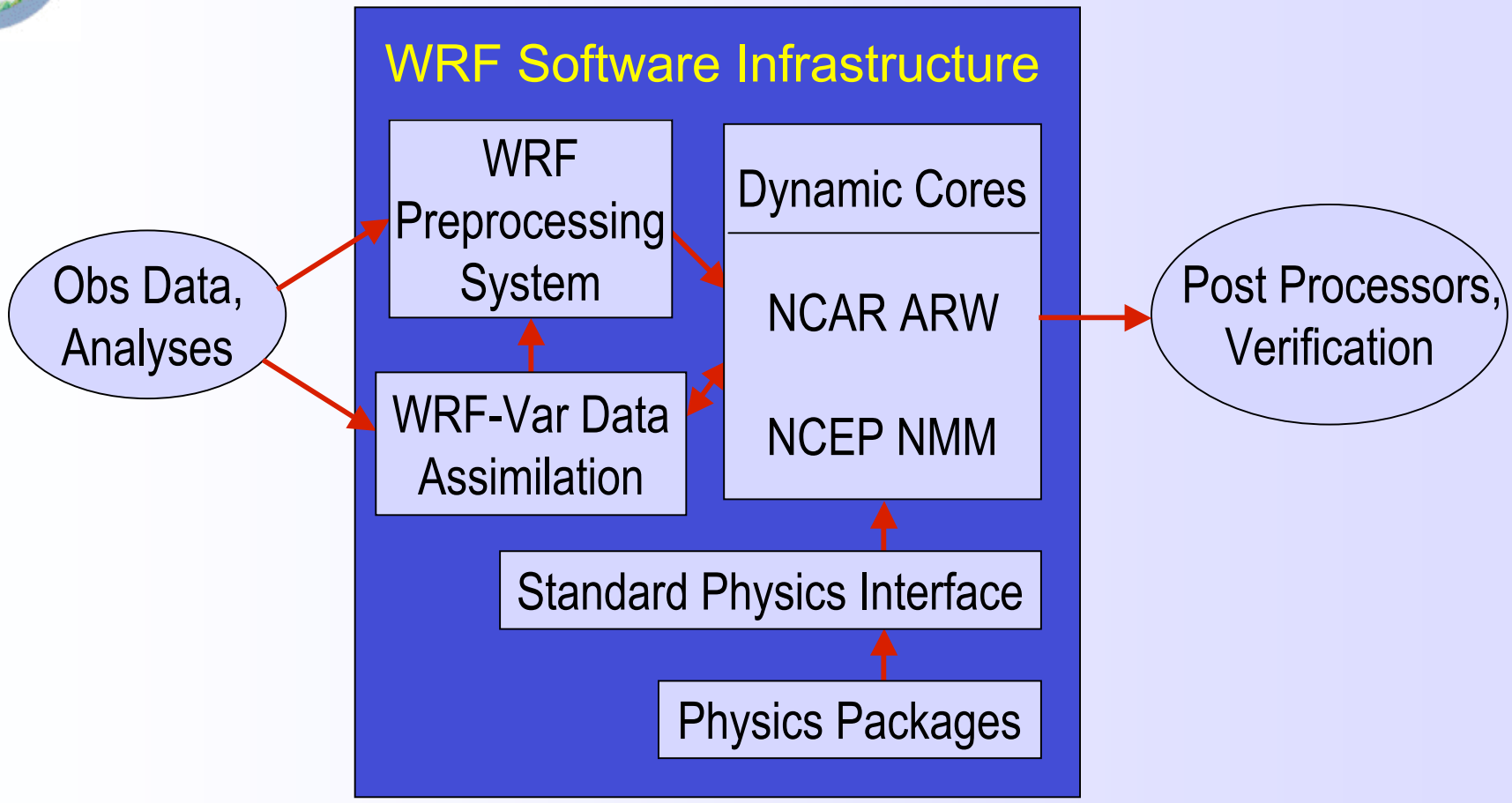
Overview Of Recent Progress In The Development And Operational Applications Of The Weather Research And Forecasting (WRF) Model.

Greg Holland, Joe Klemp, Bob Gall, Jordan Powers, Dale Barker

National Center For Atmospheric Research

ECMWF Workshop, November 15th 2007

WRF Modeling System



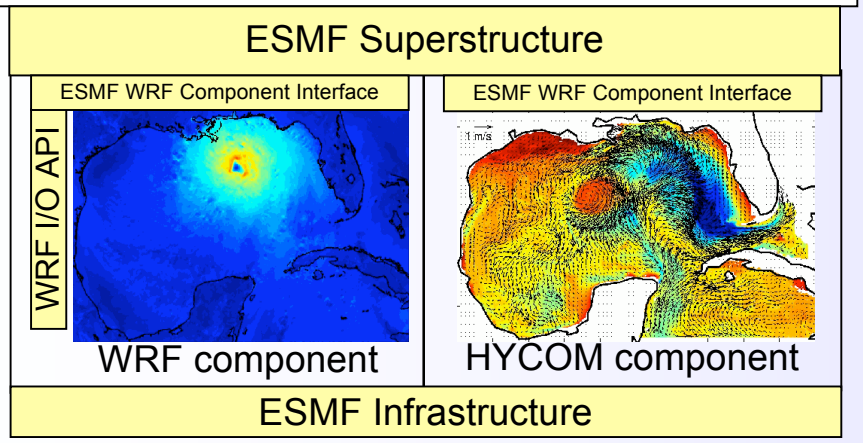
ARW = Advanced Research WRF (NCAR) Core

NMM = Nonhydrostatic Mesoscale Model (NCEP) Core

WRF Software Overview

Characteristics, Features, & Capabilities

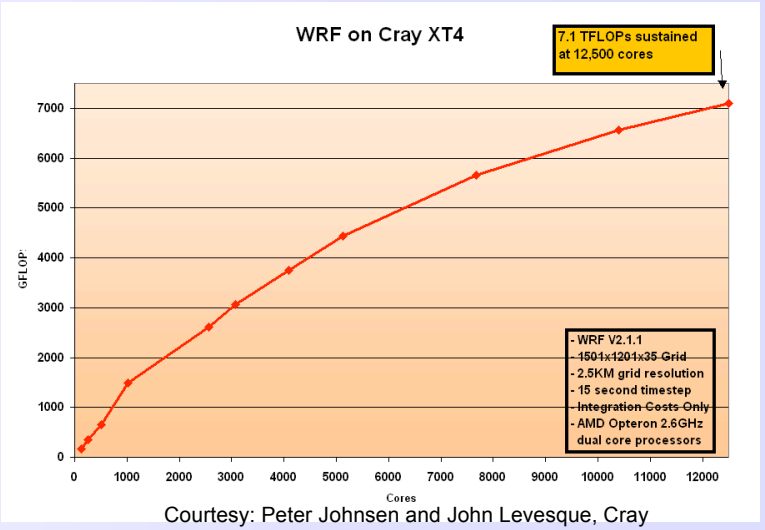
- Flexible, extensible to range of WRF applications
- Parallel, efficient on range of computers in WRF community
- Movable, feature following nested grids
- Coupling to other models



WRF/HYCOM Coupling through ESMF

Vendor	Hardware	OS	Compiler
Apple	G5	MacOS	IBM
Cray Inc.	X1, X1e	UNICOS	Cray
	XT3/XT4 (Opteron)	Linux	PGI
HP/Compaq	Alpha	Tru64	Compaq
	Itanium-2	Linux	Intel
		HPUX	HP
IBM	Power-3/4/5/5+	AIX	IBM
	Blue Gene/L	Linux	IBM
	Opteron		Pathscale, PGI
NEC	SX-series	Unix	Vendor
SGI	Itanium-2	Linux	Intel
	MIPS	IRIX	SGI
Sun	UltraSPARC	Solaris	Sun
various	Xeon and Athlon	Linux and Windows CCS	Intel, PGI
	Itanium-2 and Opteron		

Petascale precursor systems



Courtesy: Peter Johnsen and John Levesque, Cray

WRF Dynamic Cores

- ARW Core
  - Terrain-following hydrostatic pressure vertical coordinate
  - Arakawa C-grid
  - 3rd order Runge-Kutta split-explicit time differencing, 5th or 6th order differencing for advection
  - Conserves mass, momentum, dry entropy, and scalars using flux form prognostic equations
- NMM Core
  - Terrain-following hybrid sigma vertical coordinate
  - Arakawa E-grid
  - Explicit Adams-Bashforth time differencing
  - Conserves kinetic energy, enstrophy and momentum using 2nd order finite differencing

Physics Options Implemented in WRF

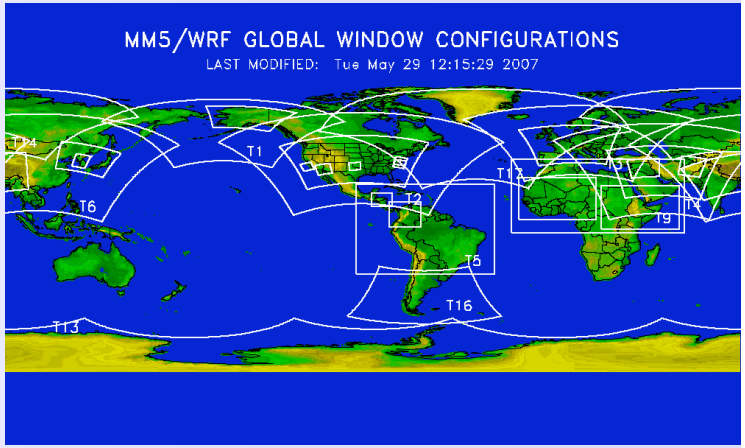
- Microphysics: Kessler-type (no-ice), WSM3/5/6 Lin et al. (graupel included), Ferrier, Thompson
- Cumulus Convection: New and Old Kain-Fritsch, GFS SAS, Betts-Miller-Janjic, Grell-Devenyi
- Shortwave Radiation: Dudhia (MM5), Goddard, GFDL, CAM3
- Longwave Radiation: RRTM, GFDL, CAM3
- Turbulence: Prognostic TKE, Smagorinsky
- PBL: MRF, MYJ, YSU, GFS
- Surface Layer: Similarity theory, MYJ
- Land-Surface: 5-layer soil model, RUC LSM Noah unified LSM with UCM

ARW Only NMM Only

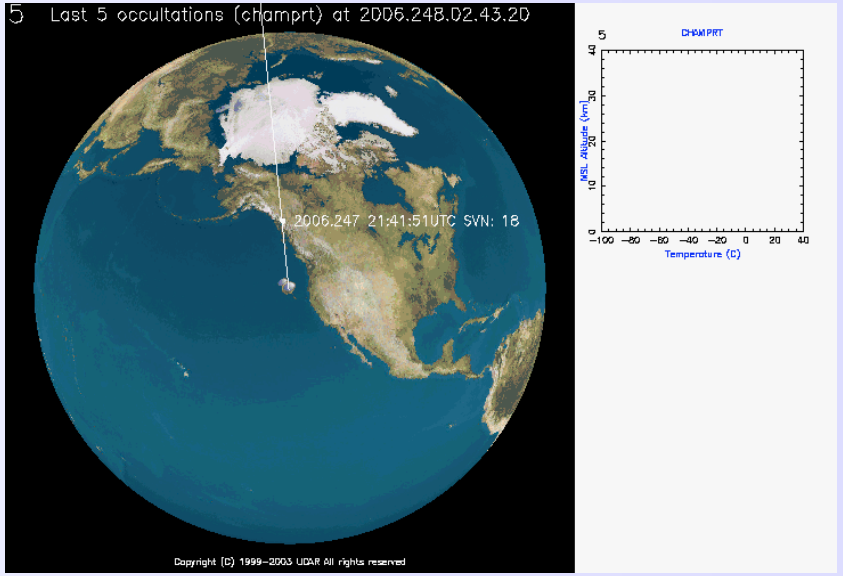
WRF-Var Data Assimilation Overview

- **Goal:** Community WRF DA system for regional/global, research/operations, and deterministic/probabilistic applications.
- **Techniques:** 3D-Var, 4D-Var (regional), Hybrid Variational/Ensemble DA.
- **Models:** WRF, MM5, KMA global.
- **Support:** MMM Division, NCAR.
- **Observations:** Conv.+Sat.+Radar

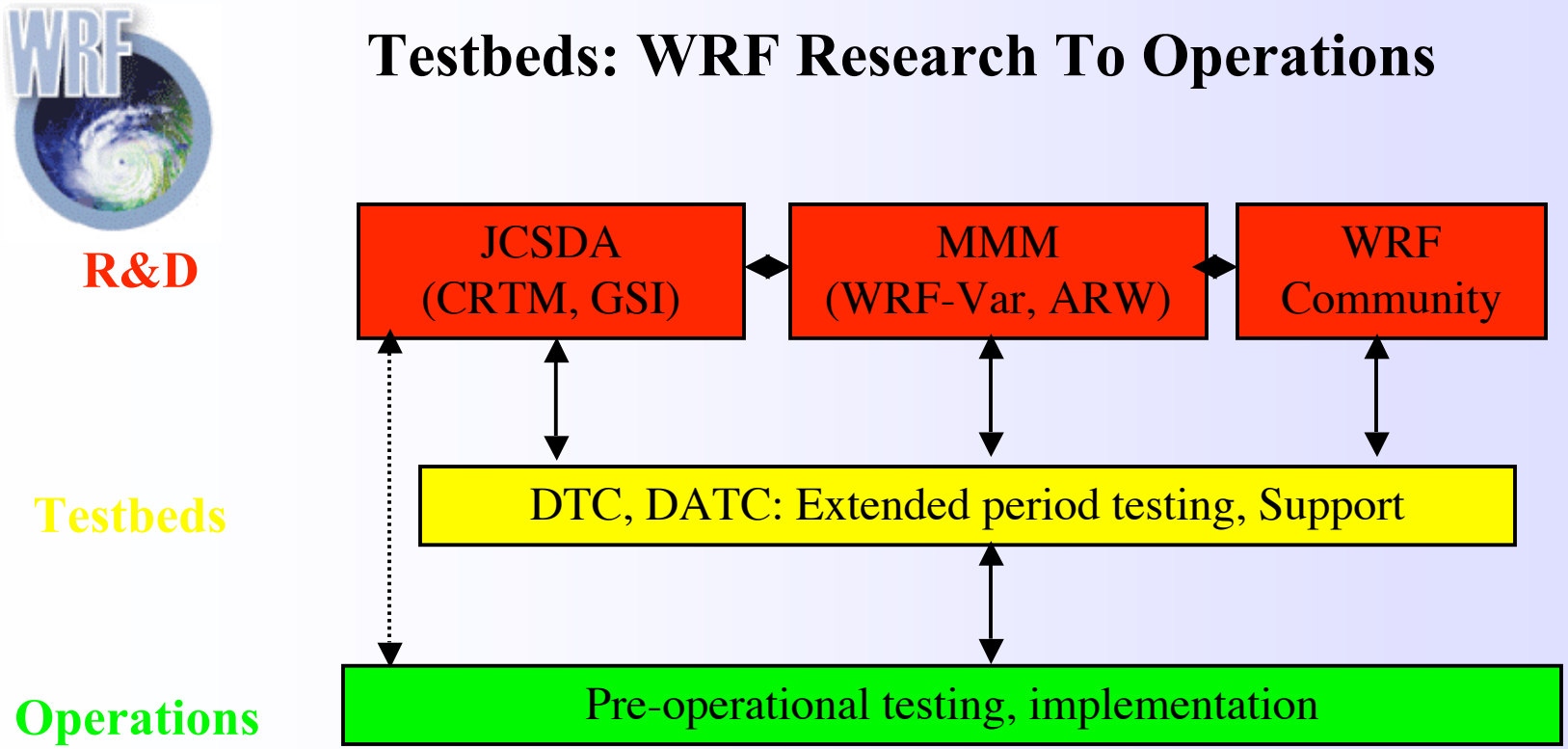
AFWA Theaters:



GPS Radio Occultation (B. Kuo):



Testbeds: WRF Research To Operations



- DTC = Developmental Testbed Center
- DATC = Data Assimilation Testbed Center.
- NCAR/MMM Division responsible for ARW/WRF-Var development and initial testing.
- NCEP responsible for NMM development and testing.
- WRF Community contributions include global WRF, radar, initial radiance assimilation.

2007-08 WRF DTC Visitor Program

Mike Baldwin	Purdue University	Establishment of a verification testbed at the DTC
Barbra Casati	Environment Canada	Scale-decomposition verification tools for the WRF model
Bill Gallus	Iowa State University	Verification of WRF ensembles using object oriented approaches
Steve Mullen	University of Arizona	Develop, test and evaluate an end-to-end limited area model ensemble forecasting system for WRF
Gert-Jan Steeneveld	Wageningen University Netherlands	Evaluation of WRF model improvements with novel boundary-layer observations: Focus on diurnal cycle and stable boundary layer
Veniamin Perov	Sweden Meteorological and Hydrological Institute Sweden	Implementation of the quasi-normal scale elimination (QNSE) model of stably stratified turbulence in WRF
Jeffrey Mirocha	Lawrence Livermore Laboratory	Testing new boundary layer turbulence models
Mariusz Pagowski	Colorado State University	Implement and evaluate an improved Mellor-Yamada level-3 turbulence closure in WRF
Laura Fowler	Colorado State University	Implementation of the two-moment RAMS cloud microphysics in ARW: comparisons against one-moment closure in WRF
Craig Epifanio	Texas A&M University	Idealized orographic flow simulations in NMM and ARW

WRF User Participation

	6/7/07 Registered Users	June 2007 8th Users Workshop Participants
Principal Partners		
NCAR	139	44
NCEP	23	3
GSD	26	15
AFWA	26	4
Navy	18	0
U.S. Universities	1006	45
U.S. Government Labs	334	30
Private Sector	524	14
Foreign	3025	65
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Total	5121	220
Foreign countries represented	91	25

2350 active subscribers to wrf-news@ucar.edu

Currently averaging 440 email inquiries per month to wrfhelp

WRF Community Real-time/Operational Forecasting Applications

National:

- WSI (ARW, CONUS, European domains)
- University of Illinois (24 km ARW, Central U. S.)
- Millersville University (25 km ARW, Eastern U. S.)
- University of Arizona (1.8 km ARW and NMM, Arizona)
- University of Utah, Utah (12.5 ARW, Western U. S.)
- University of Oklahoma (10 member 4 km ARW ensemble, Central U. S.)
- Jackson State University (27 km ARW, Southeastern U. S.)

International:

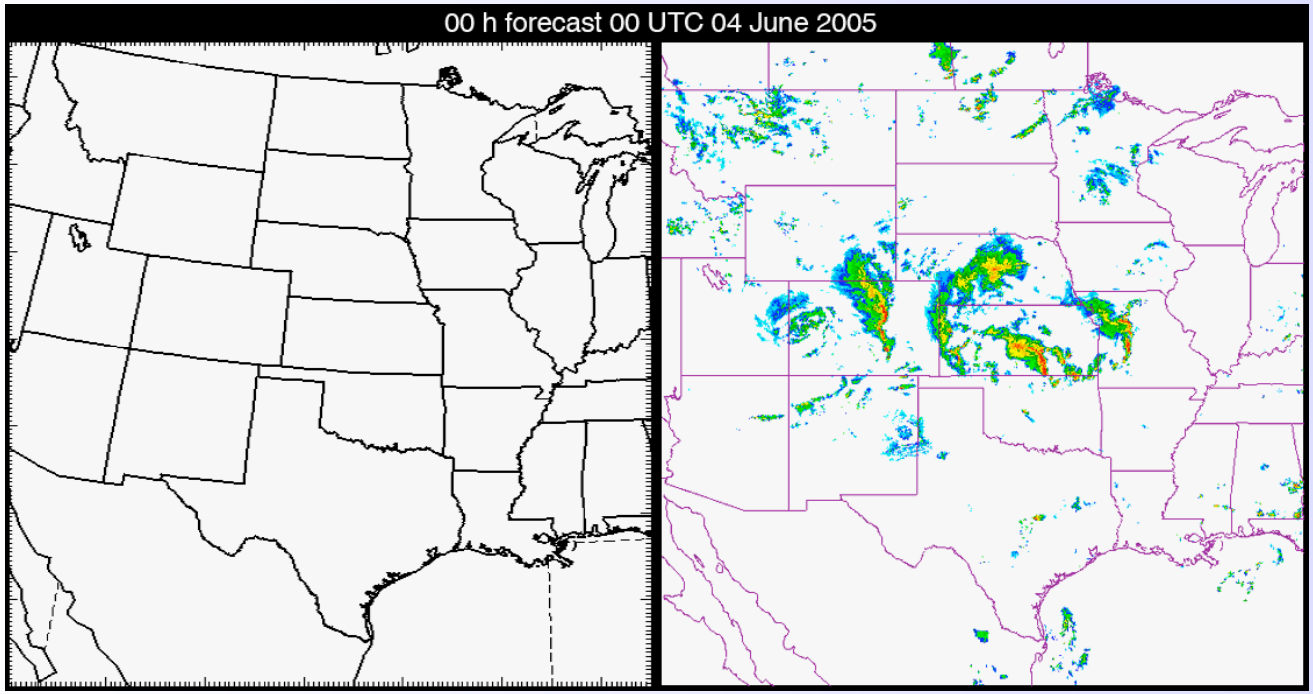
- Korean Meterological Adminsitration, **Korea** (10 km ARW, Korea region)
- NMC, China Meteorological Administration, **China** (15/5 km ARW, east-central Asia)
- Beijing Meteorological Bureau, **China** (27/9/3 km ARW, Beijing region)
- Central Weather Bureau, **Taiwan** (45/15/5 km ARW, Taiwan region)
- National Taiwan Normal University, **Taiwan** (45/15 km ARW, Southeast Asia)
- Centers for Development of Advanced Computing, **India** (36/12 km ARW, Western Ghatts)
- Meteorological Department, **India** (ARW, India Monsoon)
- AFMD, **United Arab Emirates** (20/10/3 km ARW, Arabian peninsula)
- Israel Air Force, **Israel** (ARW, Regional aviation-weather)
- Weather-It-Is, **Israel** (5 km ARW, Israel, Middle East)
- Theyr.net, London, **United Kingdom** (NMM, custom commercial forecasts)
- Swedish Armed Forces, **Sweden** (27/9/3 km ARW, Sweden, Central Africa)
- Meteo Riccone, **Italy** (5 km ARW, Central and northern Italy)
- Institute of Atmospheric Sciences and Climate, **Italy** (5 km ARW, Southern Italy)
- LaMMA - CNR IBMET, **Italy** (10 km NMM, Central Europe, Italy)
- National Observatory of Athens, **Greece** (24/6 km ARW, Europe, Greece)
- Slovenia Meteorological Research Team, **Slovenia** (4 km ARW, Slovenia)
- Hydrometeorological Service, **Serbia** (NMM, Balkan peninsula)
- Meteociel, **France** (10 km NMM, private service, France)
- Meteoblue, **Switzerland** (NMM, regional forecasts worldwide)
- Instituto de Física, Unidad de Meteorología, **Uruguay**, (ARW, Mexico & Uruguay)
- University of Guadalara, **Mexico** (10/2 km ARW, Mexico, Guadalara Province)

WRF Users Around the Globe

WRF Principal Partners		233
NCAR	139	
NCEP	23	
FSL	26	
AFWA	27	
NAVY	18	
U.S. Universities (123)		1049
U.S. Govt. Labs		334
Private Sector		545
Foreign		3138
Total		5309

36 h WRF-ARW 4 km Reflectivity Forecast

Initialized 00 UTC 4 June 05



Reflectivity forecast **Composite NEXRAD Radar**

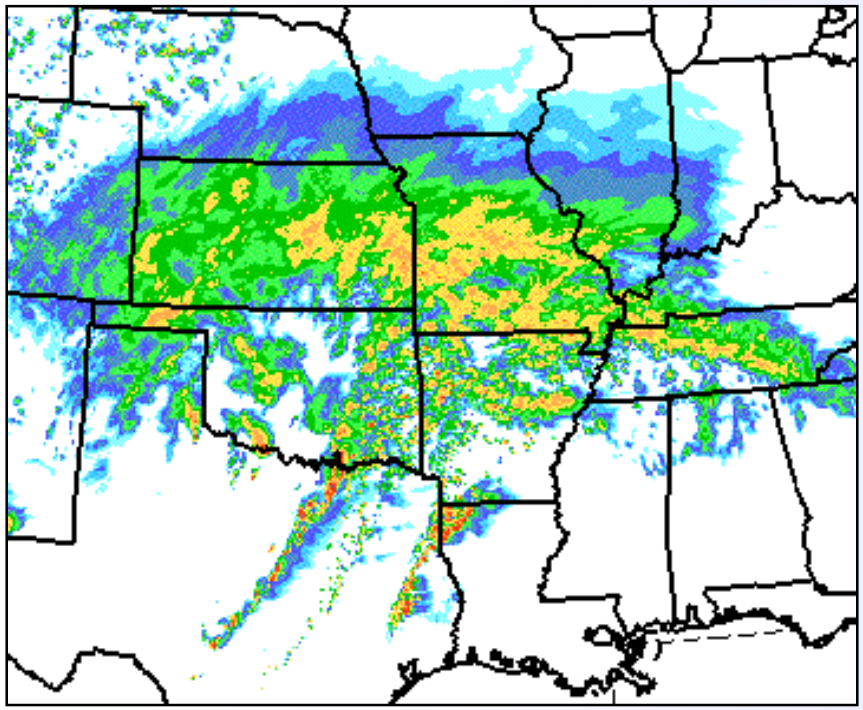
Summary Results:

- An encouraging ability to forecast mesoscale convective systems (MCS) out to 36 h
- A demonstrated skill at depicting MCS mode
- Rapid spin-up of convective systems within 3-4 h from a low-res initial condition.

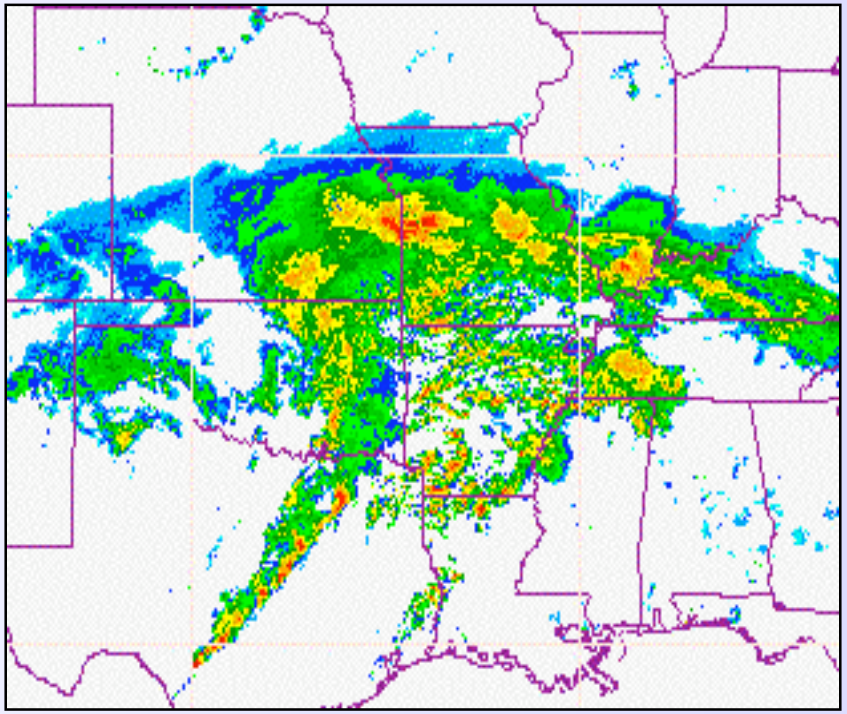
NOAA Hazardous Weather Testbed 2007 Spring Experiment

- Directed by SPC, NSSL, and the Norman WFO
- Convection allowing forecasts provided by OU/CAPS, NCAR, NCEP, and NSSL
- Daily 36 h forecasts over ~2/3 CONUS from 23 April - 8 June 2007

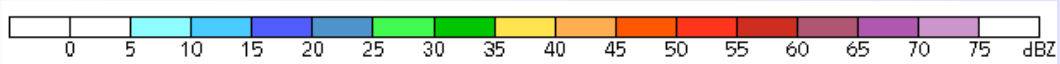
Composite radar reflectivity for tornadic squall line at 01 UTC 4/14/07



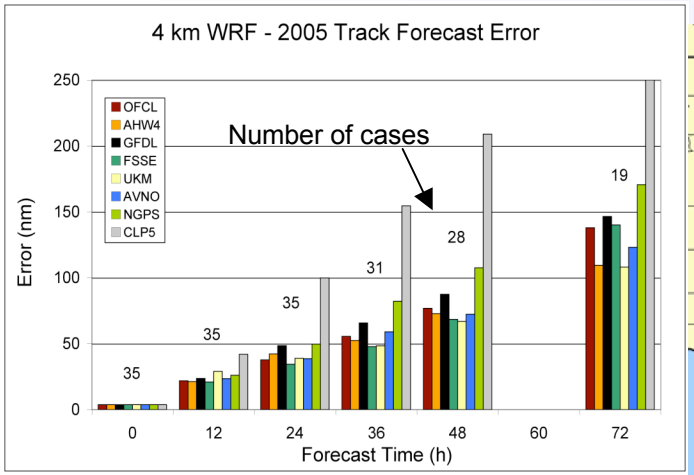
25 h WRF/ARW 3 km forecast

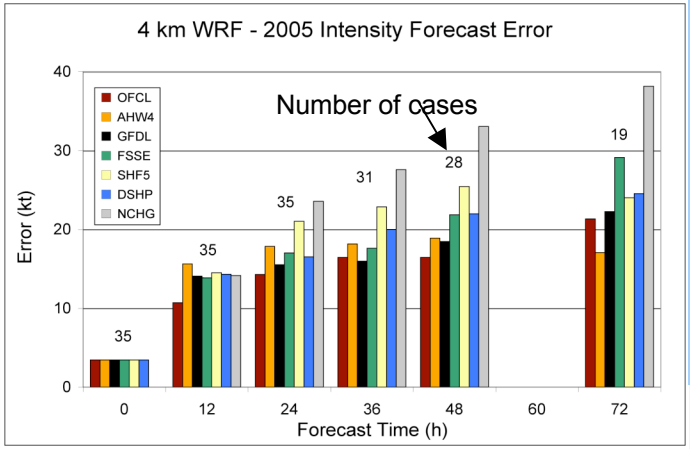


2 km NOWRAD Mosaic

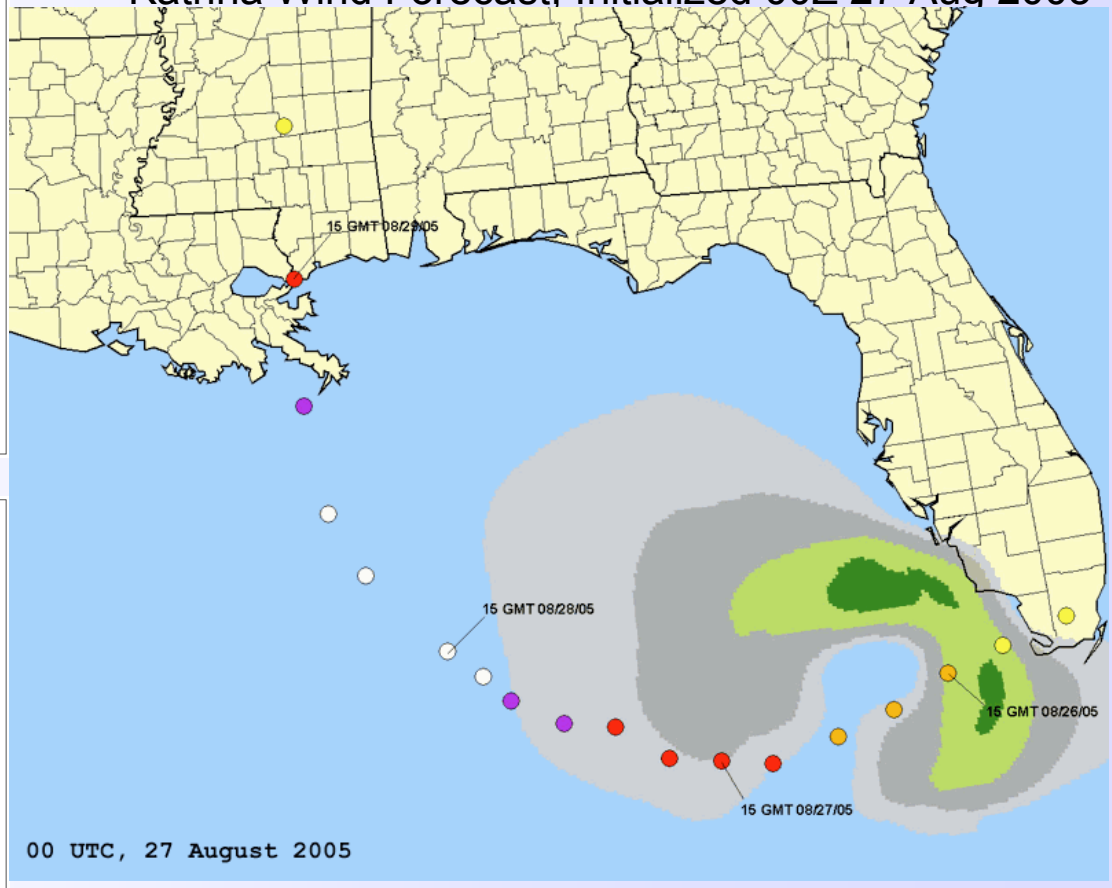


2005 Real-time 4 km ARW Moving-Grid Hurricane Forecasts





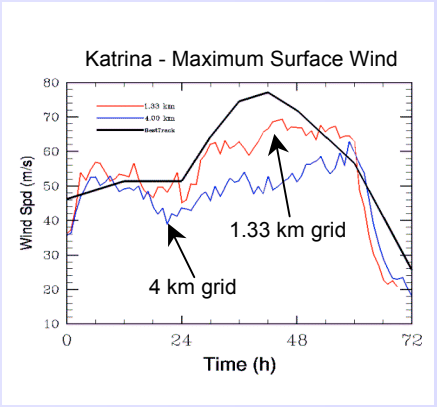
Katrina Wind Forecast, Initialized 00Z 27 Aug 2005

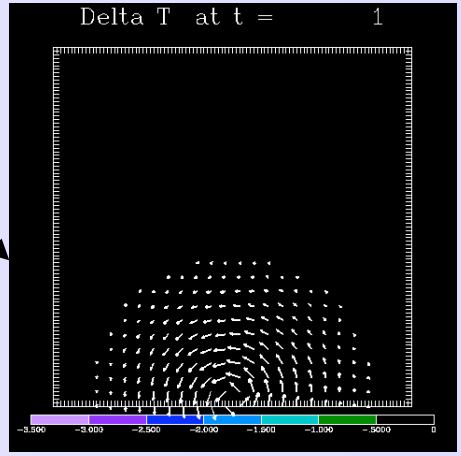


Cat 1: 33-42
Cat 2: 42-50
Cat 3: 50-59
Cat 4: 60-69
Cat 5: >69

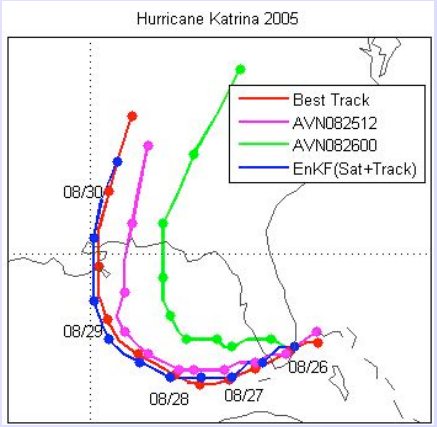
Enhancements for 2007 Real-time WRF-ARW Hurricane Forecasts

- 3 domain, 5 day forecasts - 12/4/1.33 km grids
- Include ocean mixed layer for feedback on ocean surface temperature
- Initialize from 12 h EnKF assimilation of hurricane position, intensity, and satellite winds
- Add 32 member 36/12 km ensemble forecasts
- Conduct 15 / 5 /1.67 / 0.556 / 0.185 km idealized simulations





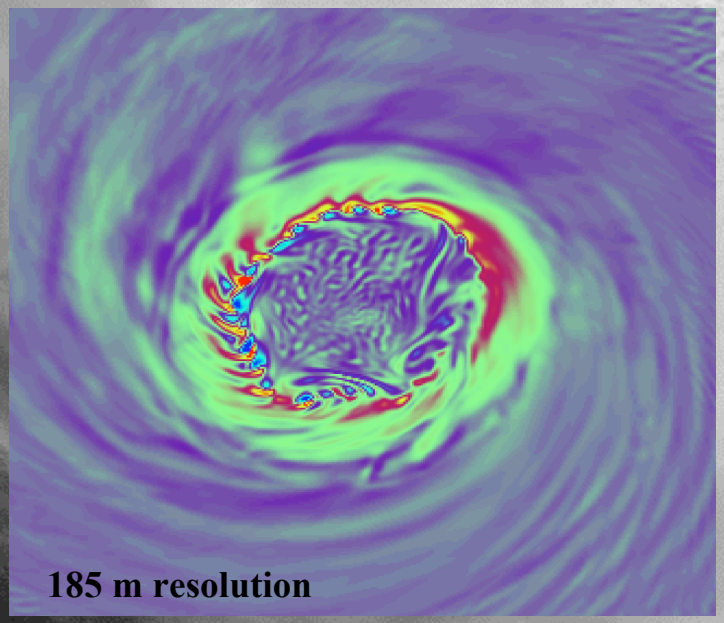
1-D Ocean Mixed Layer with Idealized Hurricane Vortex



12 h ENKF - 26 Ensemble Members, 36 km

Forecasts posted at: http://www.wrf-model.org/plots/realtime_main.php

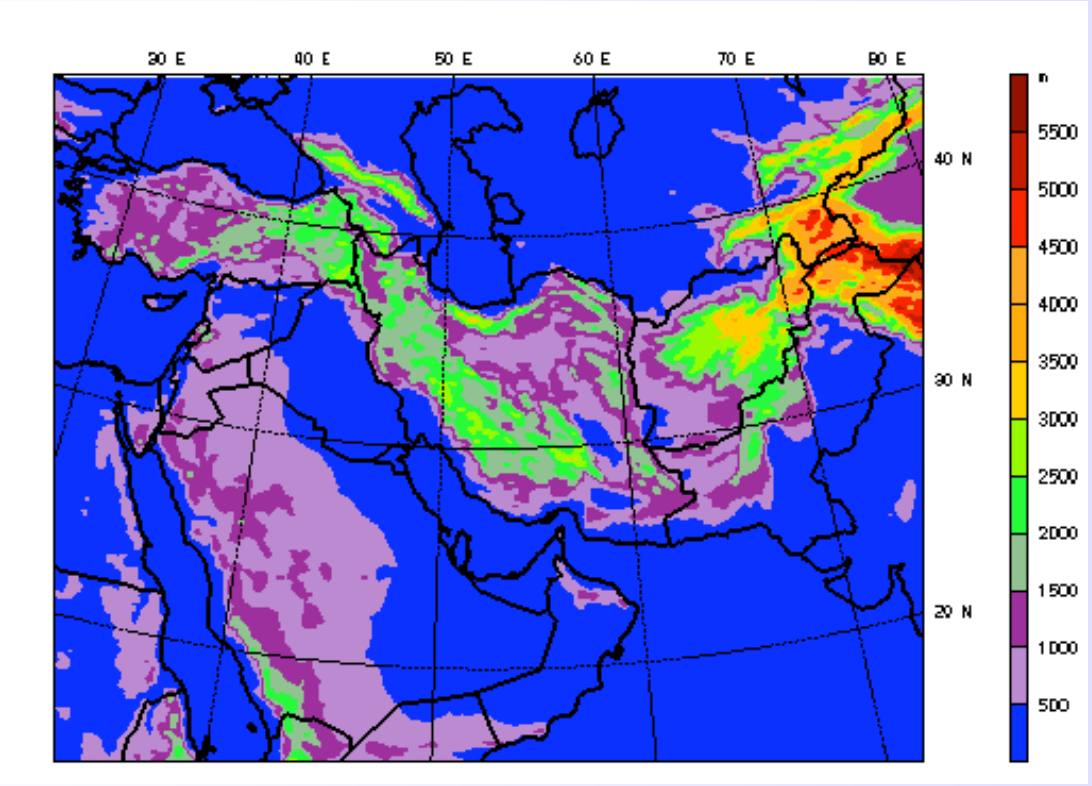
Note the simulation of the vertical striations on the eye wall together with the vortices that develop off the high-shear region inside the eye wall.



W at z = 500m, Day 9

Very-High-Resolution Simulations being used to provide input to Reinsurance industry cost-loss models.

DATC AFWA S. W. Asia Testbed

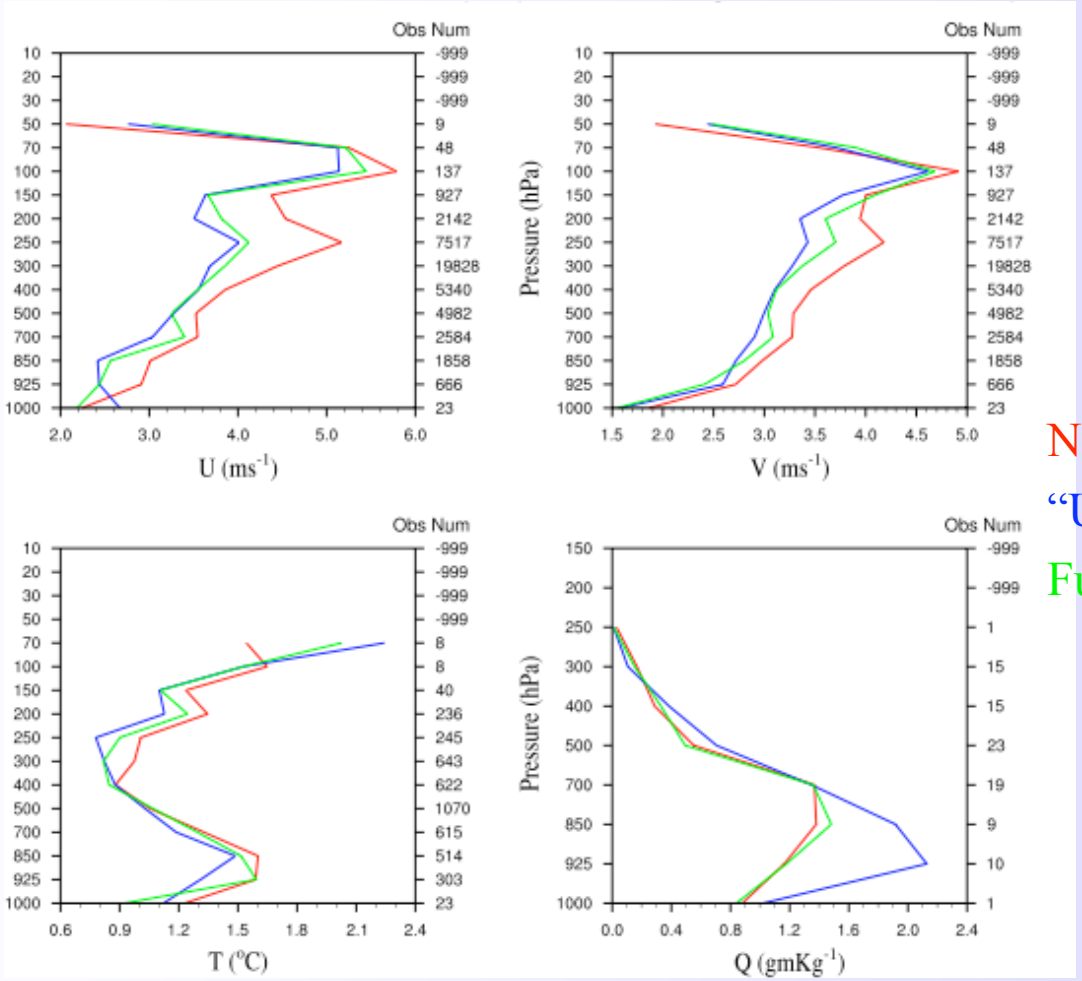


Testbed Configuration (from AFWA):

- **Model:** WRF-ARW, WRF-Var (version 2.2).
- **Namelists:** 15km (301x238), 42 vertical levels, 90s timestep.
- **Period:** October 2006.
- **Suite:** NoDA, 3D-Var (6-hourly full-and “update” cycling).

24hr Forecast Verification Vs. Obs for AFWA Testbed

Meral Demirtas, DATC



No Data Assimilation

"Update" Cycling

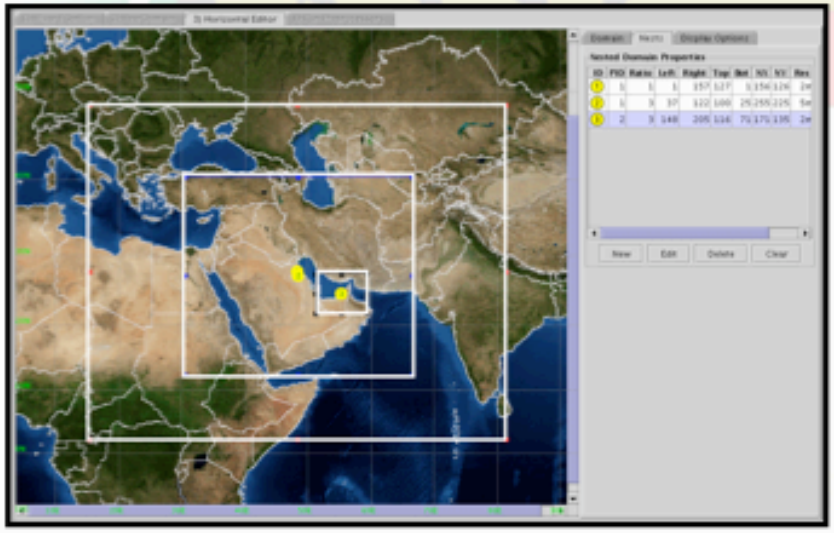
Full-cycling

Conclusions:

1. Regional DA adds significant value (cycling compared to NoDA).
2. Update-cycling superior to full-cycling (note: no radiances used).

UAE Air Force and Air Defence: Operational WRF

WRF 2.2	Domain 'd01'	Domain 'd02'	Domain 'd03'		Domain 'd01'	Domain 'd02'	Domain 'd03'
Grid dimensions	40 km 156 x 126 x 38	13.33 km 256 x 226 x 38	4.44 km 172 x 136 x 38	Radiation	RRTM/Dudhia scheme	RRTM/Dudhia scheme	RRTM/Dudhia scheme
Time step	225 s	75 s	25 s	PBL	YSU scheme	YSU scheme	YSU scheme
Micro-physics	Ferrier*	Ferrier*	Ferrier*	Surface physics	Noah LSM	Noah LSM	Noah LSM
Cumulus scheme	Kain-Fritsch scheme	Kain-Fritsch scheme	Explicit.	Initial and Boundary Conditions.	NCEP GFS/GSI analyses	Two-way nest	Two-way nest

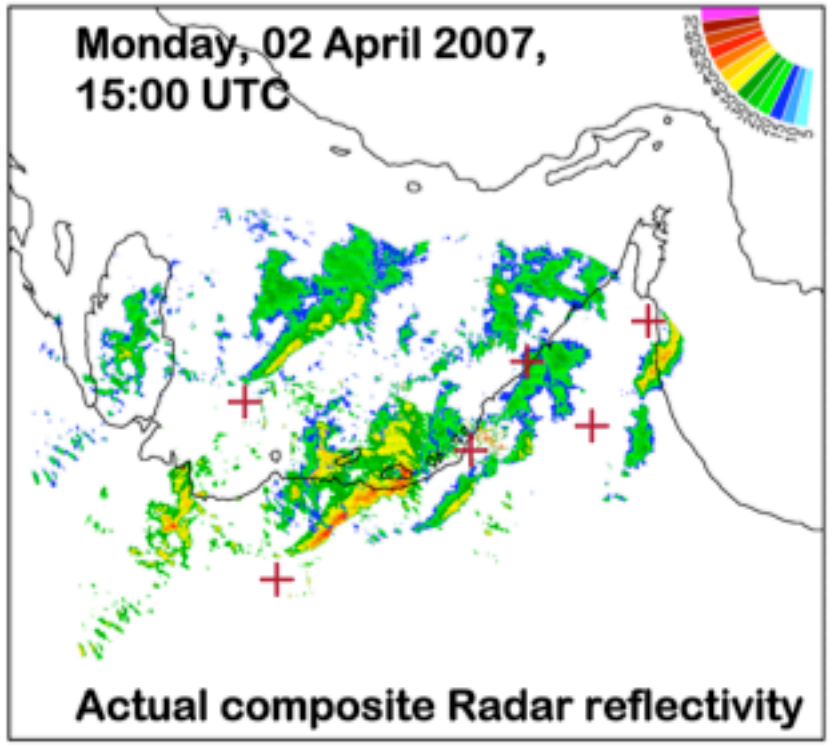


- d01: Middle-East
- d02: Arabian Peninsula
- d03: United Arab Emirates
- WPS is used for LBC interpolation.
- WRF-VAR is still in parallel suite (for d01, d02 and d03)
- UAE/WRF outputs on the net:
- http://www.afmet.ae/main.html

From Ajjaji et al, 2007 WRF Workshop

Assimilation of Radar Data

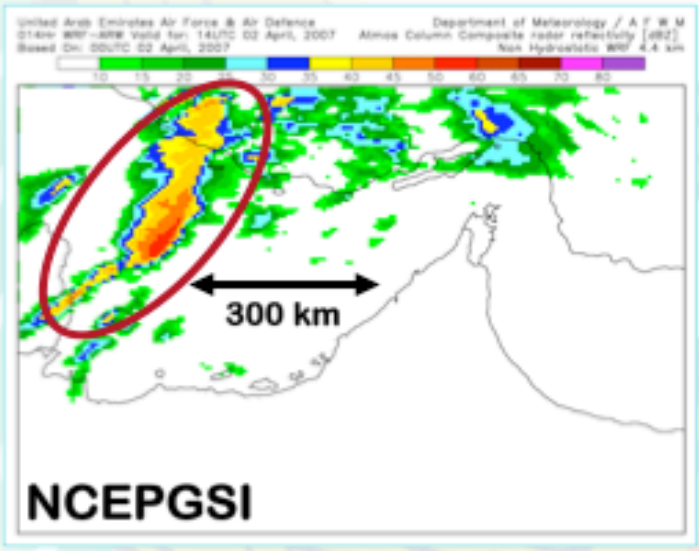
- 6 Doppler Radars (Abu Dhabi, Dubai, Al Ain, Liwa, Delma)
- 1 km horizontal resolution, 11 different elevation angles and 15 minutes frequency.
- Normal/Anomalous Propagation ground clutter corrected by Radar software (Radar Echo Classifier software)
- Mosaic radial velocities, refletivities, precipitation rates in BUFR format.
- BUFR to GRIB/ASCII (super-obbing)
- Raw observations are thinned (1 super obs. / 3 km), then a rejection threshold of 20 dBZ is applied.
- Three dimensional coherence control
- Time distribution coherent with FGAT.
- Multi-radar redundancy check.
- Observations errors depend on the distance to the Radar center.

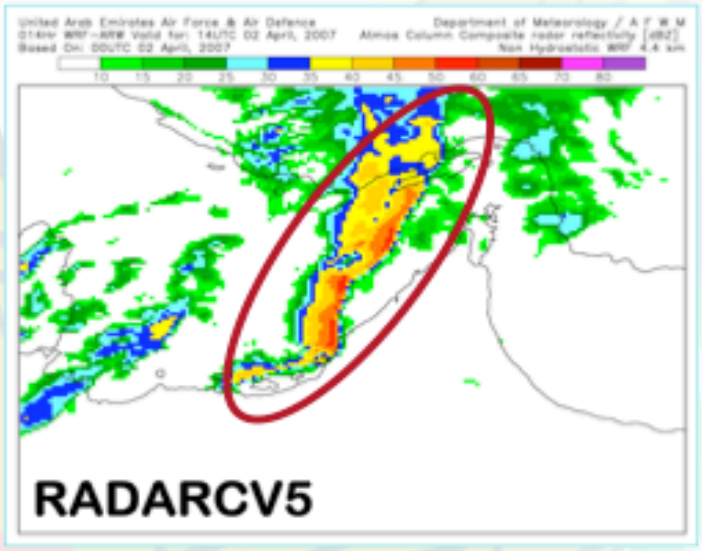


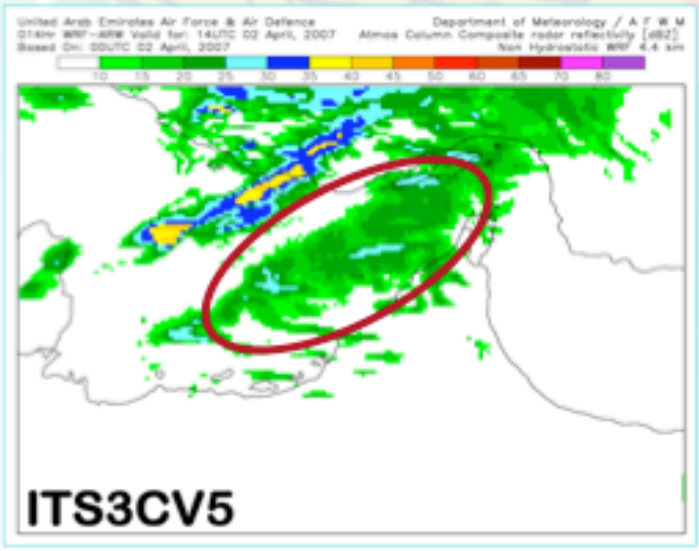
DWSR-88C, 240 km horizontal range

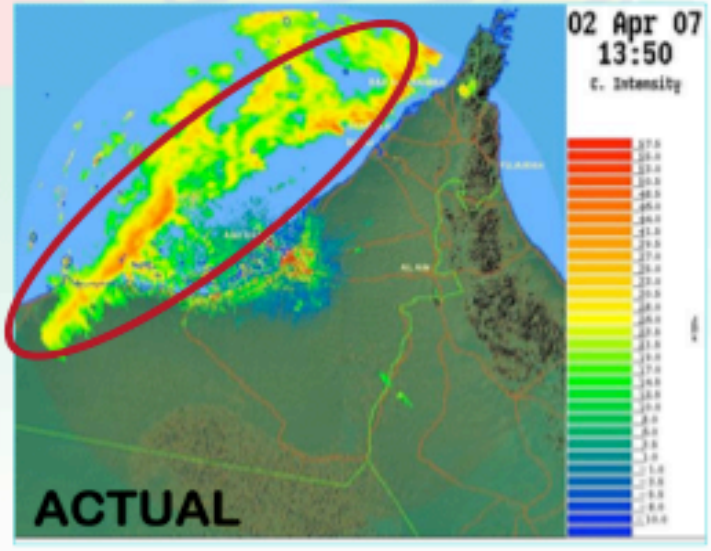
From Ajjaji et al, 2007 WRF Workshop

Radar reflectivities impact





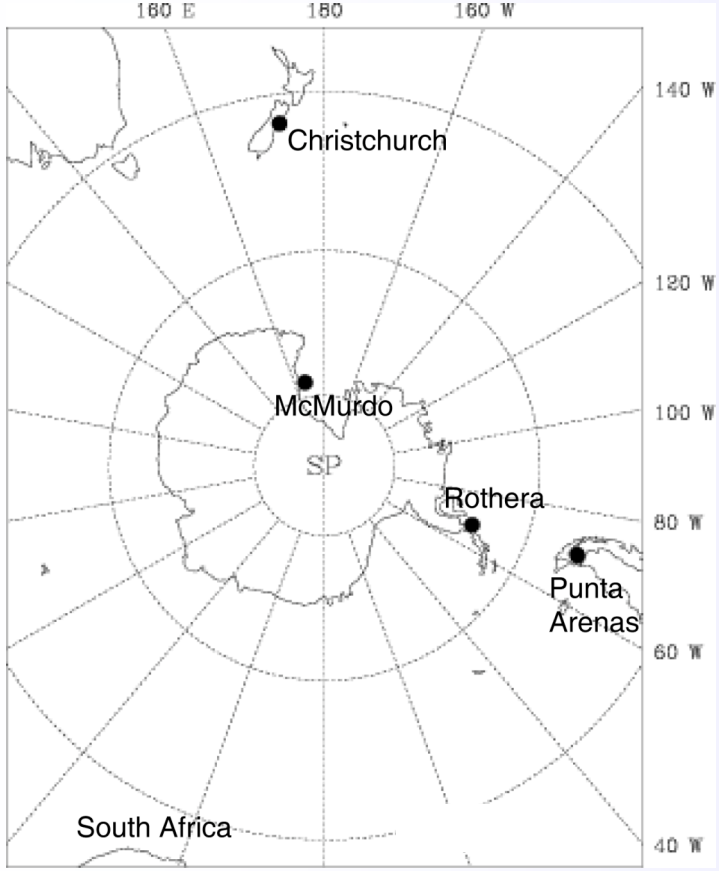




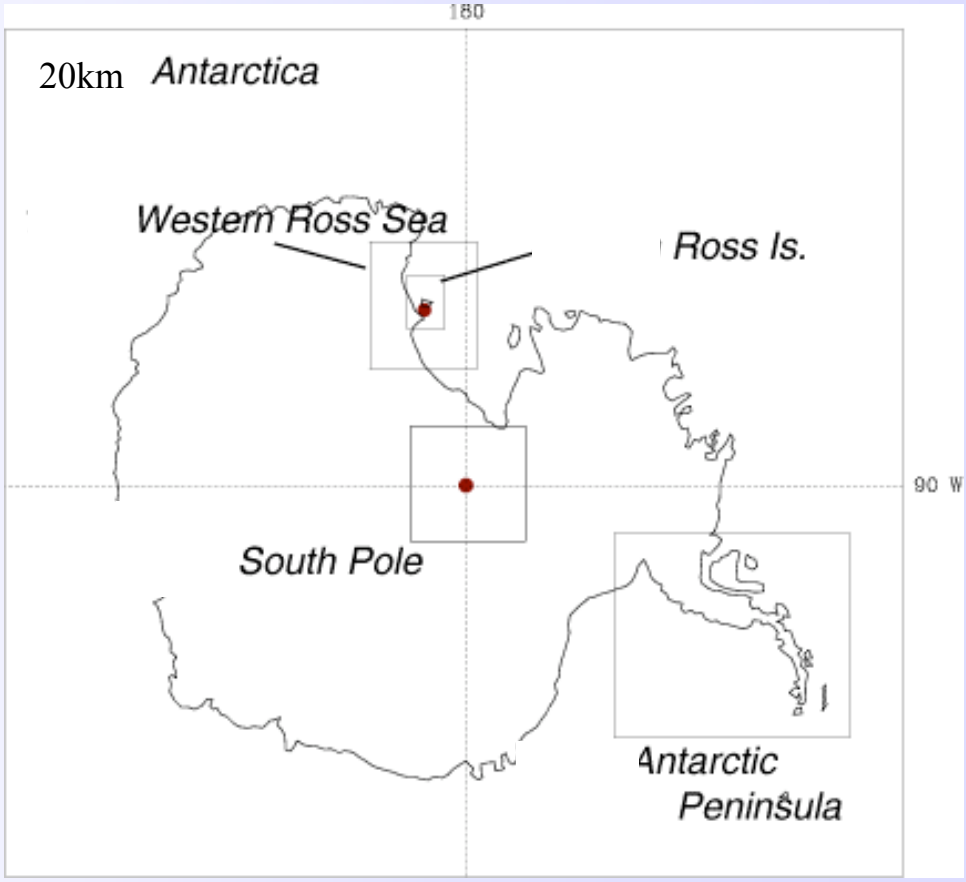
From Ajjaji et al, 2007 WRF Workshop

Antarctic Mesoscale Prediction System (AMPS)

MM5 / WRF Grids



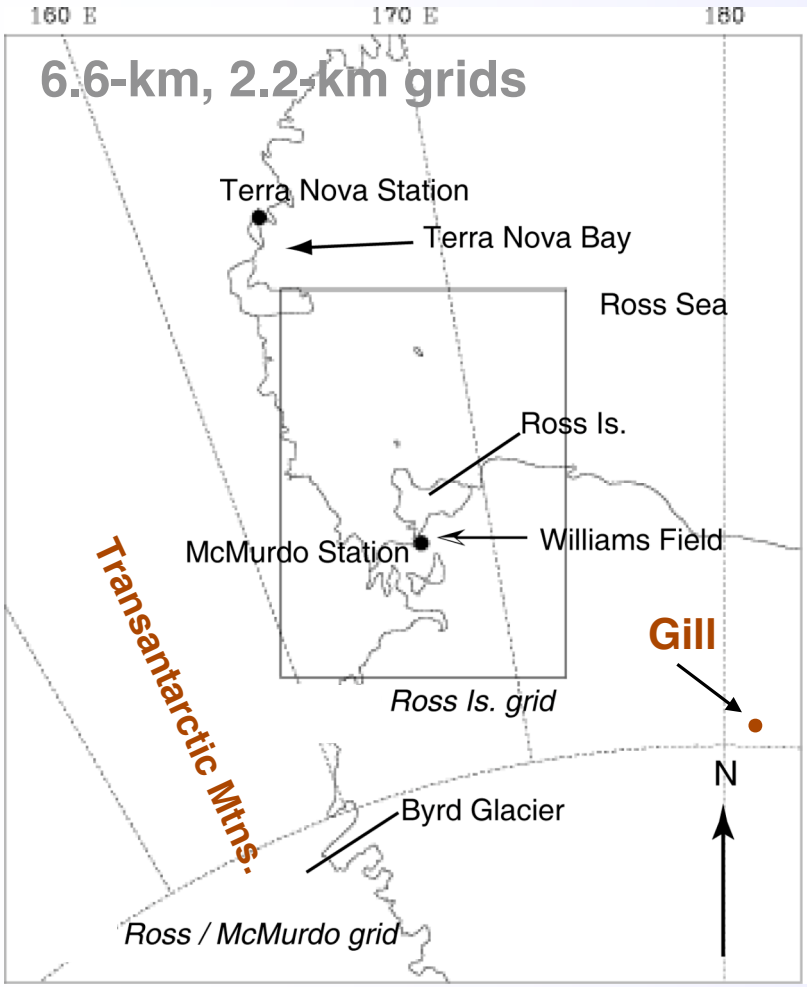
60-km

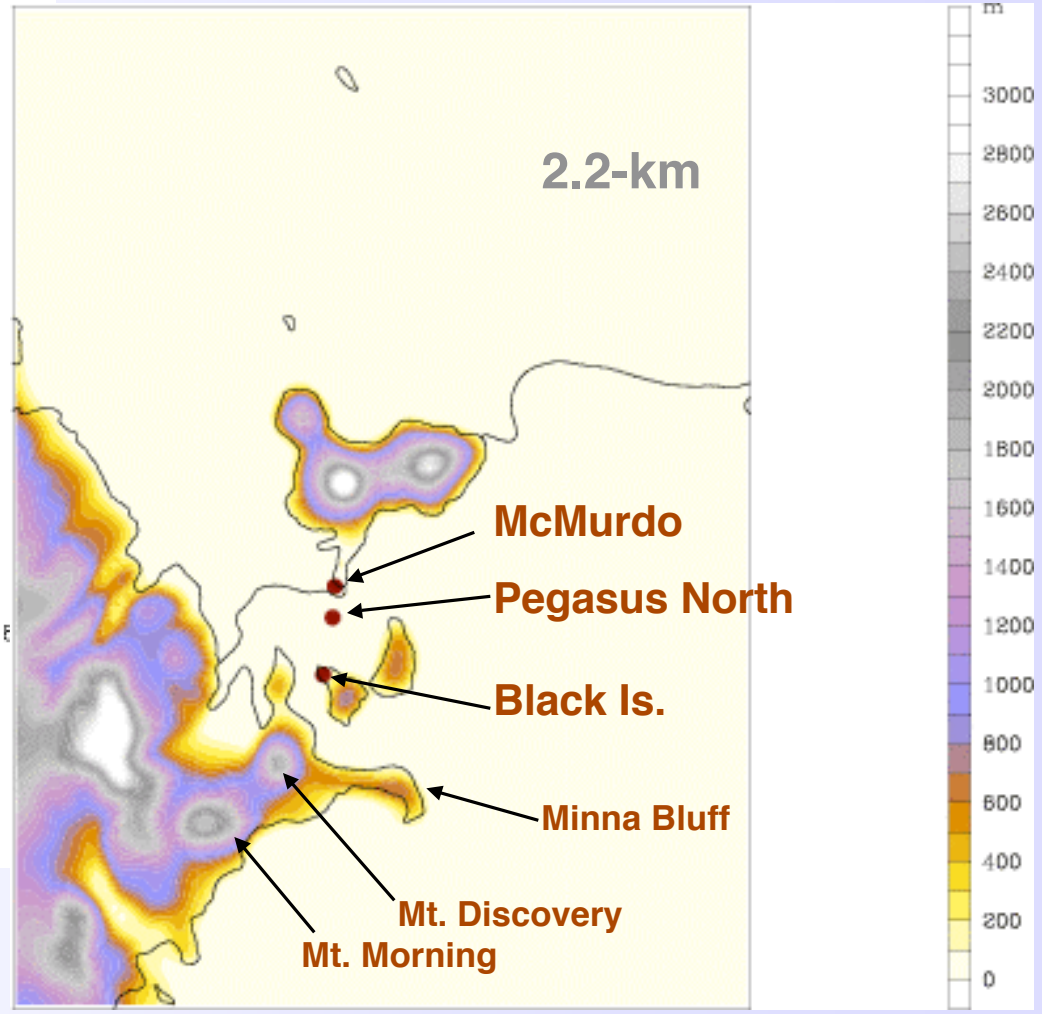


20-km, 6.6-km, 2.2-km

NB: WRF— No Peninsula or Pole grids for May 2004 simulations

Western Ross Sea / Ross Is. grids



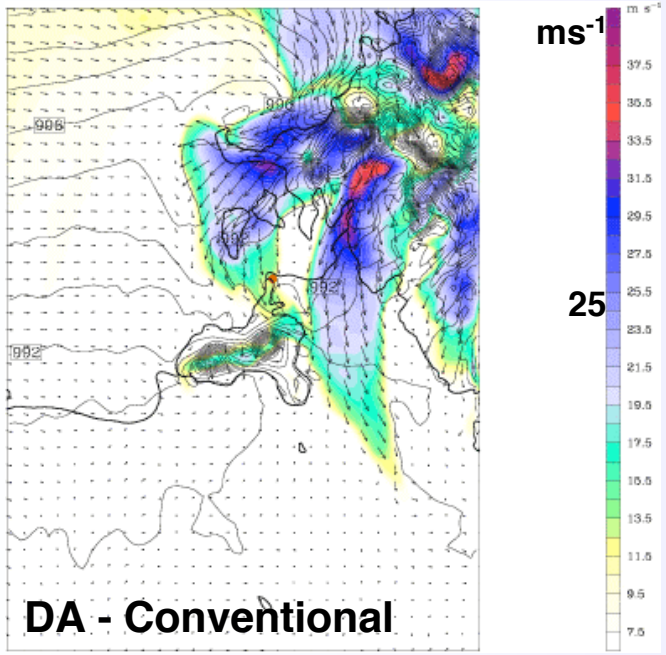


McMurdo Region & AWS sites

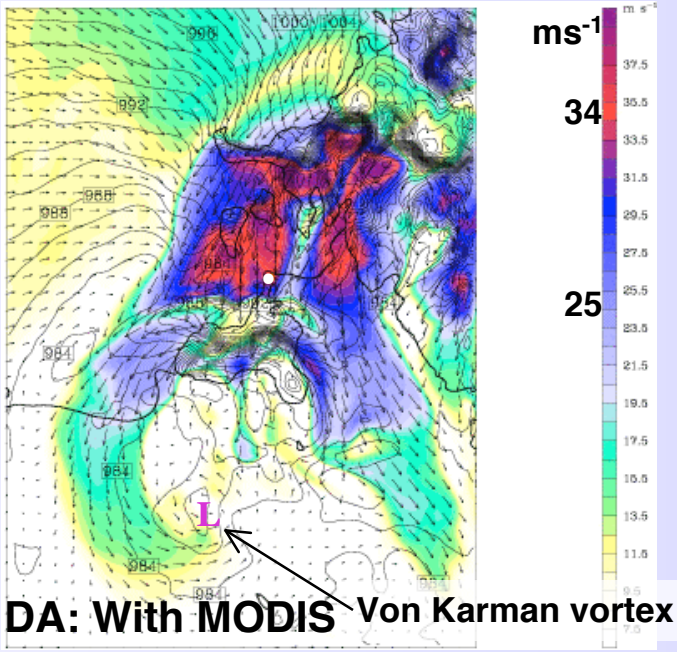
Impact Of High-Resolution Cycling

2300 UTC 15 May— Hr 23

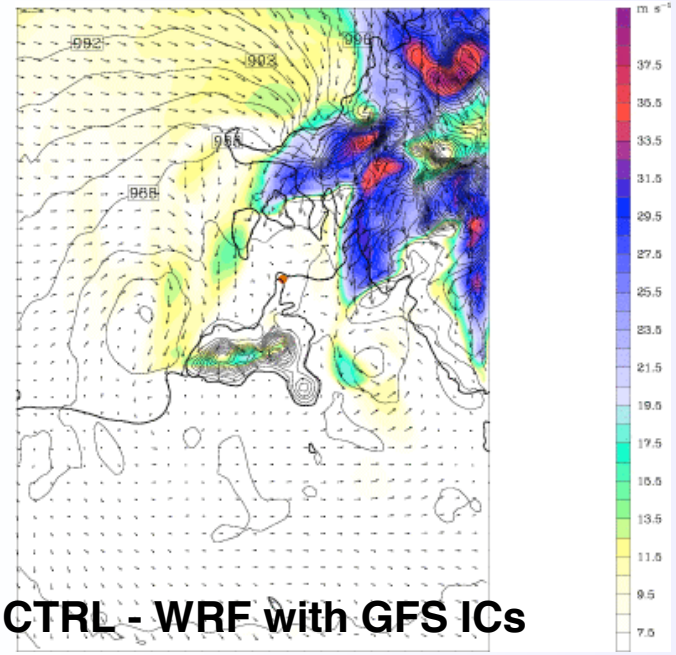
Sfc Winds (ms^{-1})
SLP (hPa)



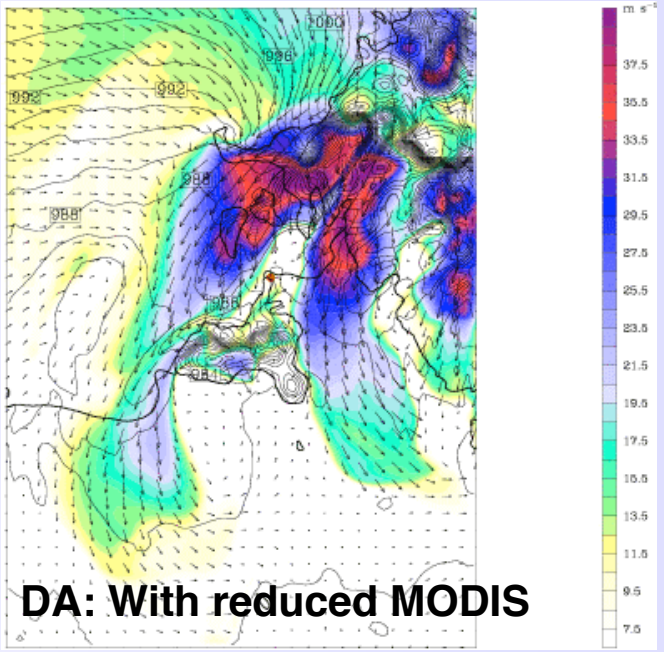
DA - Conventional



DA: With MODIS

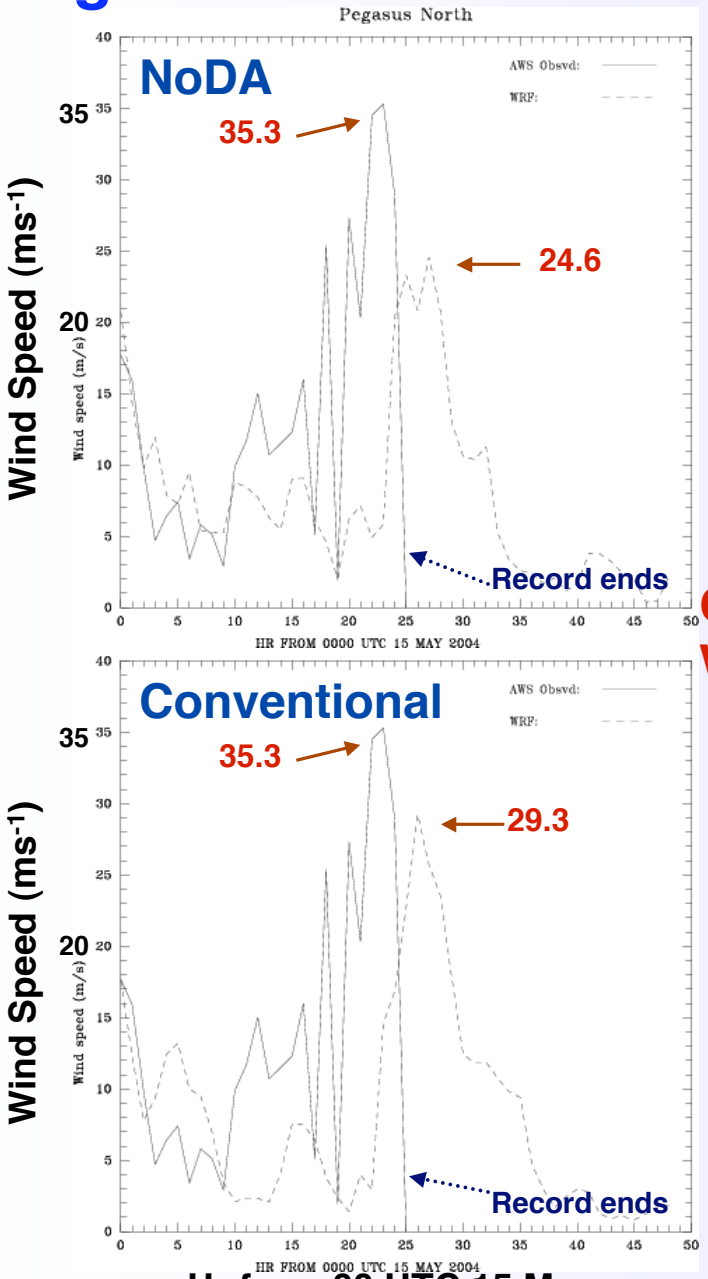


CTRL - WRF with GFS ICs



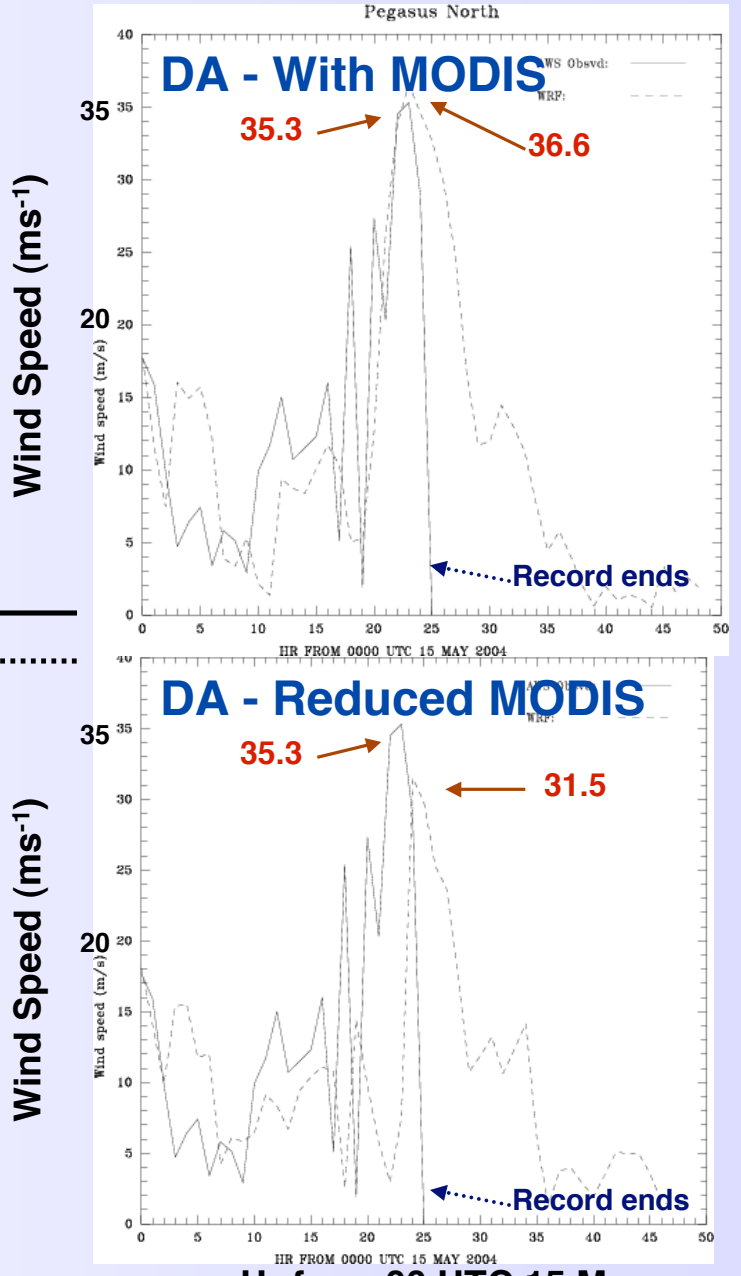
DA: With reduced MODIS

Pegasus North Winds



OBS: ——

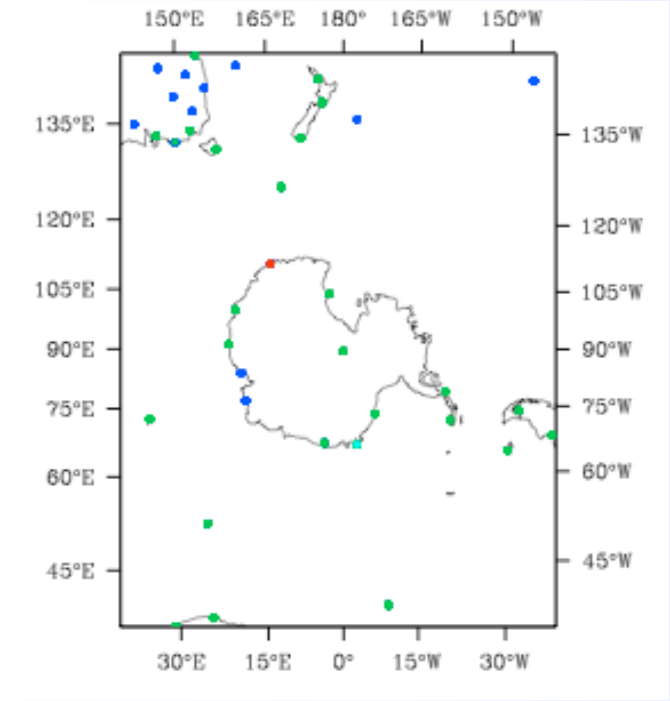
WRF: .....

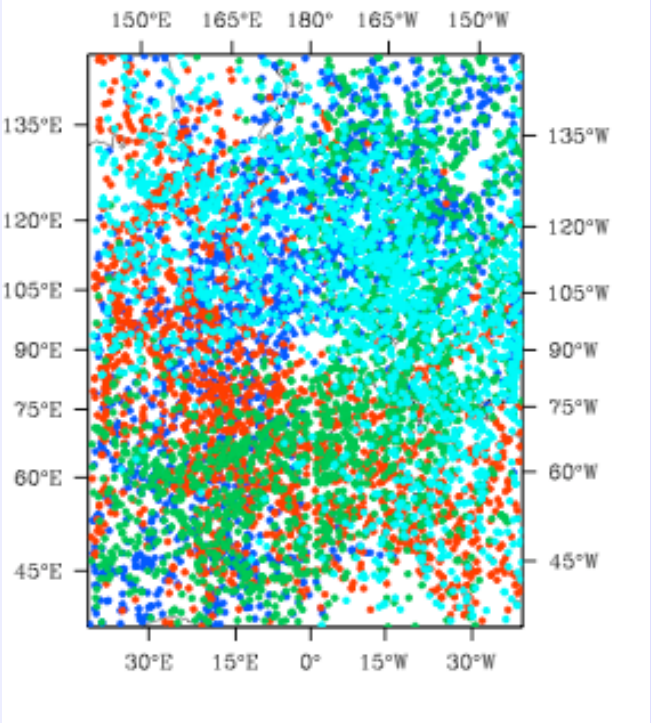


DATC Antarctica Testbed

Hui Shao, DATC

Sonde Coverage



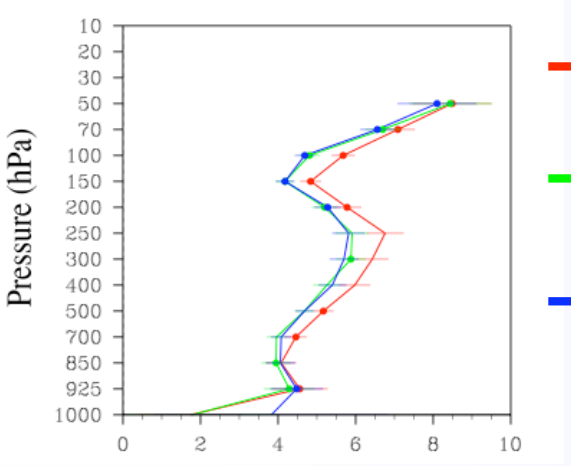


COSMIC Coverage

Testbed Configuration (from MMM/AMPS):

- **Model:** WRF-ARW, WRF-Var (version 2.2).
- **Namelists:** 60km (165x217), 31 vertical levels, 240s timestep.
- **Period:** October 2006.
- **Suite:** NoDA, 3D-Var (6-hourly full cycling).

Antarctica Testbed: 36hr Forecast Verification Against Obs

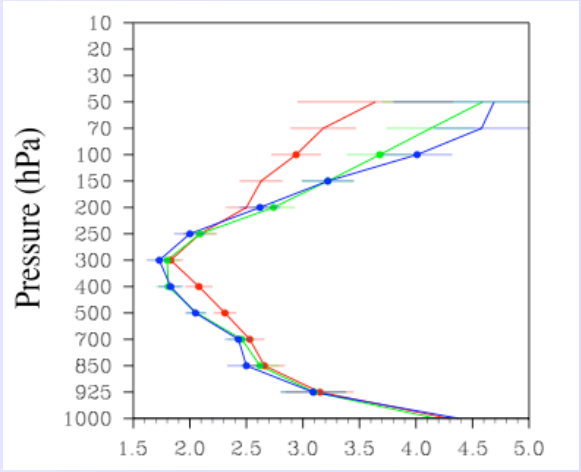


U RMSE (m/s)

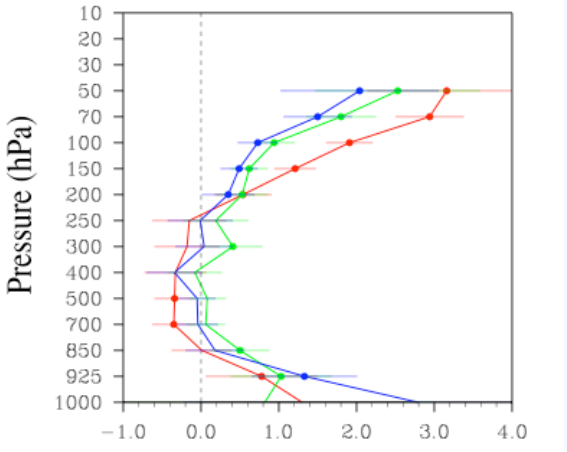
Conventional Obs

Conv. + COSMIC

Conv. + COSMIC + Tuned BE

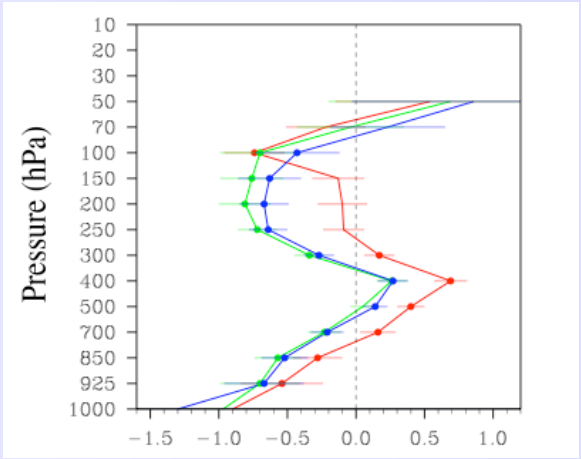


T RMSE (degK)



U Bias (m/s)

- COSMIC improves polar wind forecasts.
- COSMIC improves tropospheric temperatures.
- COSMIC degrades stratospheric temperatures.
- "2nd generation" tuned BE has small impact.



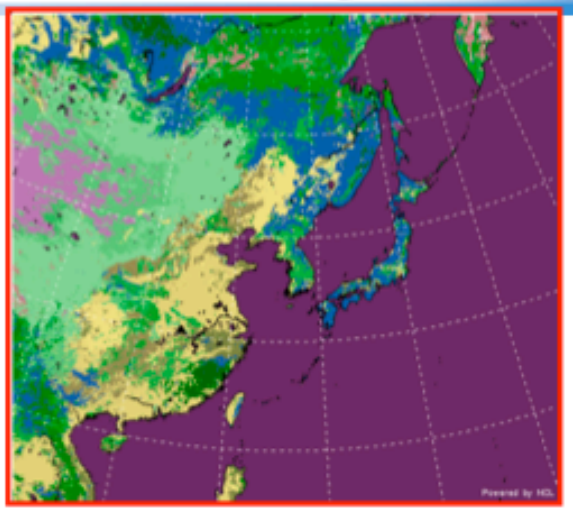
T Bias (degK)

Korean WRF (KWRF) Implementation (S. W. Joo - KMA)

KMA

WRF configuration

- WRF Version 2.1.2
- WRFSI
- KWRF 10km(574x514x31)
- 48 Hours forecast
- U3VR 6 hour cycle
- DFI



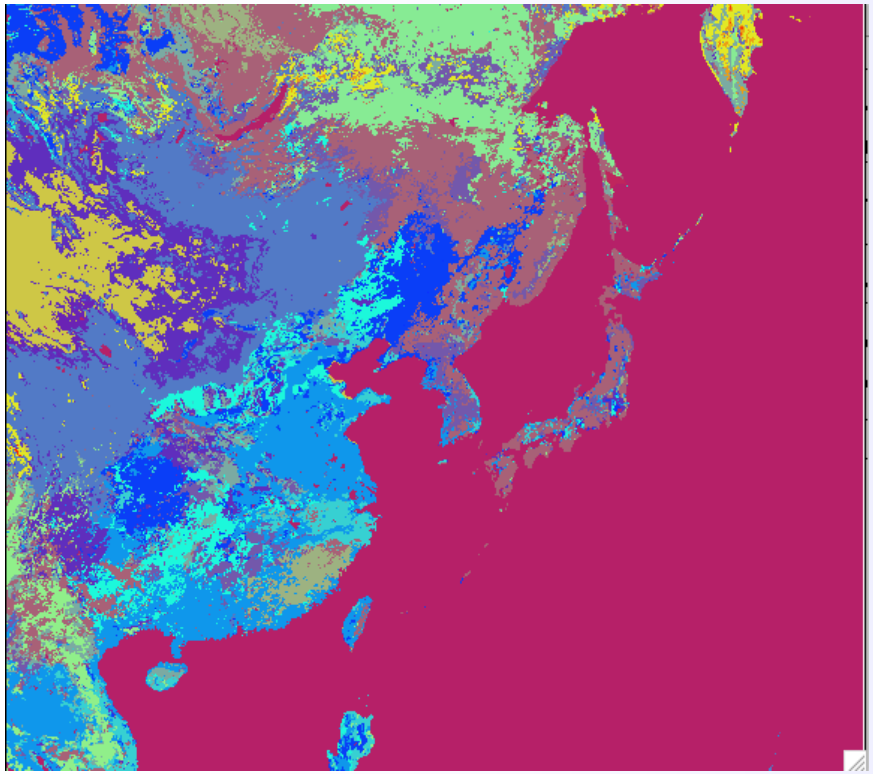
Model Physics

	RDAPS	KWRF
Microphysics Scheme	Mixed Phase	WSM6
Radiation Scheme	Cloud radiation	Dudhia/RRTM
Cumulus parameterization	New Kain-Fritsch	New Kain-Fritsch
Land-Surface model	5-layer soil	Noah LSM
PBL Scheme	MRF PBL	YSU PBL

KWRF Operational in May 2007

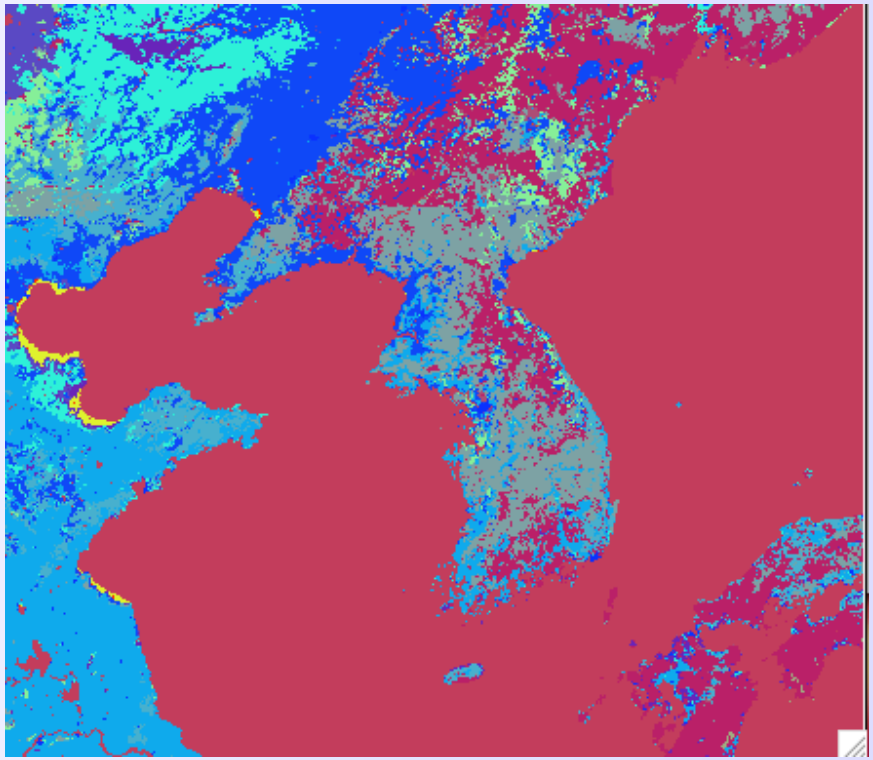
RDAPS/HiNWP KWRF Testbed

RDAPS Domain



10km, dt=60s, 574x514x33.

HiNWP Domain

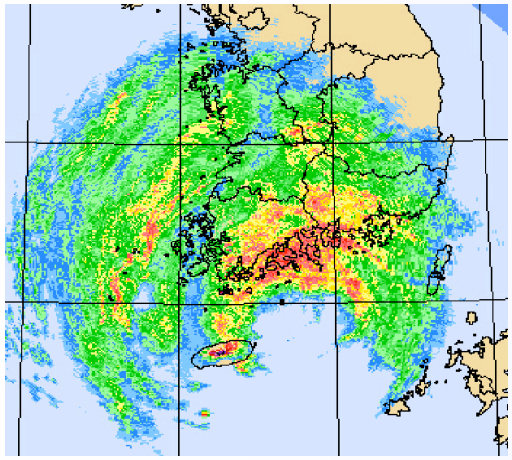


3.3km, dt=20s, 488x388x33.

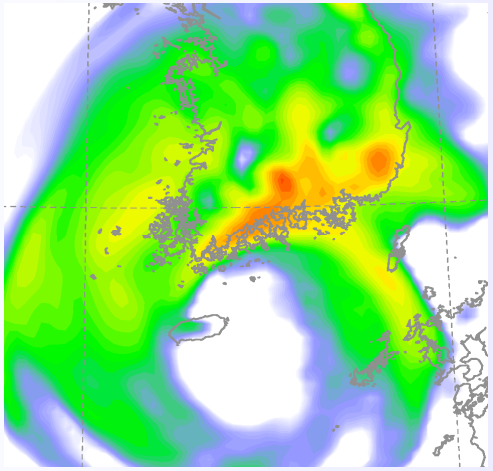
Radar Data Assimilation in KWRF

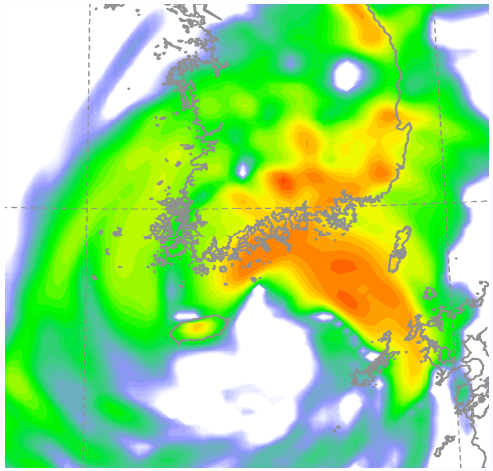
Typhoon Rusa Test Case 3hr Precip:

Obs (03Z, 31/08)

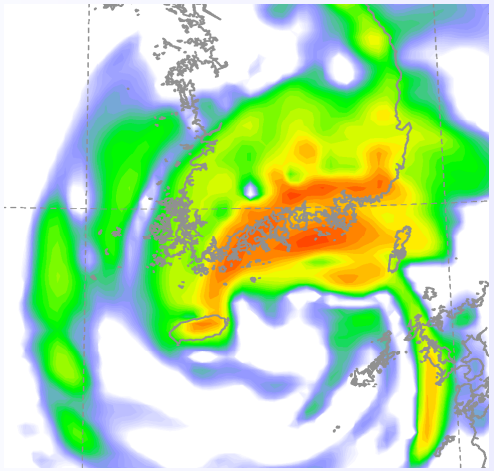


No Radar



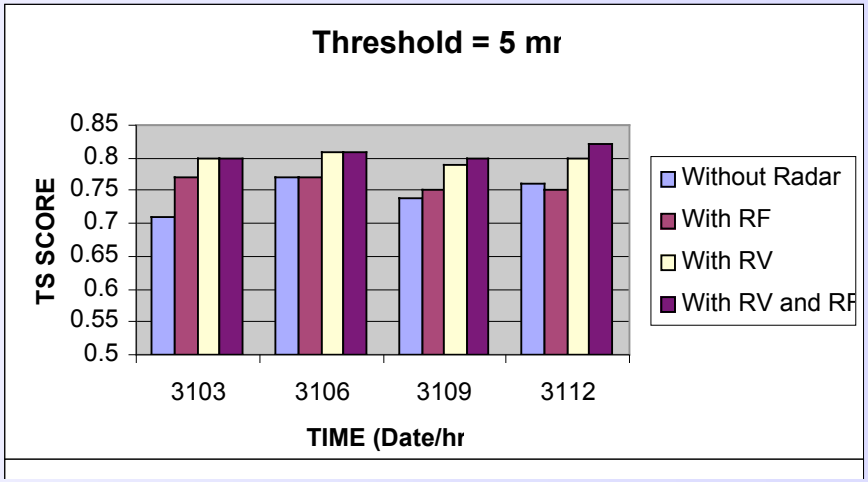


Radar RV

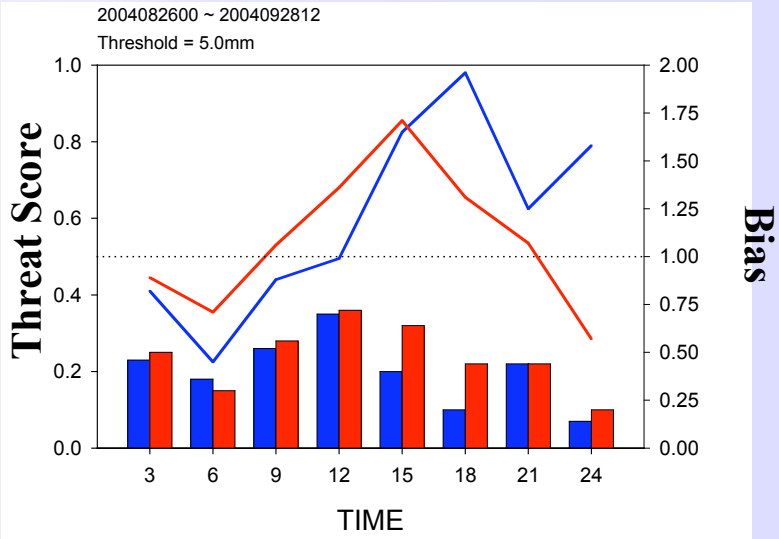


Radar RV+RF

Typhoon Rusa 3hr Precip. Verification:



KMA Pre-operational Verification:
(no radar: blue, with radar: red)



Summary

- WRF Model Maturing As A Model For Community Use.
- Strong international flavour to WRF.
- Emphasis on flexibility. high-resolution, and severe weather.
- Growing number of operational implementations (>10 countries).
- More info at http://www.wrf-model.org