Recent Developments in NWP and Data Assimilation Activities at the Hong Kong Observatory 35th EWGLAM, Antalya, Turkey 30th Sep 2013

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The Hong Kong Observatory



- Department of the Government of the Hong Kong Special Administrative Region, People's Republic of China
- 4 Branches:
 - <u>F</u>orecasting and Warning Services
 - <u>A</u>viation Weather Services
 - <u>D</u>evelopment, Research and Administration
 - <u>R</u>adiation Monitoring and Assessment
- Founded in 1883
 - 130th Anniversary



Forecasting Challenges

- Geography
- Topography
- Size



<u>Atmospheric Integrated Rapid-cycle (AIR)</u> Forecast Model System



Boundary conditions from ECMWF IFS / JMA-GSM







Radar – Doppler Velocity, 3-D wind retrieval & Reflectivity Aircraft Reconnaissance Data (GFS)

Winds

Temperature and relative humidity



2011-09-28 12:00 UTC (Wed) Initial Time:



- Meso-NHM and RAPIDS-NHM in AIR Forecast Model System
 - Meso-NHM Short Range (0-72 h) Mesoscale Prediction
 - RAPIDS-NHM Storm-scale Prediction (0-15h), QPF input to RAPIDS to blend with SWIRLS nowcast



Operational HPC Platform at HKO

- <u>NWP Integrated Computing</u> <u>Environment (NICE)</u>
- Linux clusters with total peak performance at 7.7 TFLOPS
 - Operation and R&D clusters
 - AIR/NHM Forecast Model System
 - Pre-processing
 - Post-processing and product generation
 - Environment for R&D on NWP and its application development



Meso-NHM 2013-09-22 00 UTC



Meso-NHM 2013-09-22 00 UTC





Meso-NHM 2013-09-22 00 UTC



Meso-NHM 2013-09-22 00 UTC



SSMI 17100

No. of obs = 14770

RAPIDS-NHM 2013-09-22 00 UTC



RAPIDS-NHM 2013-09-22 00 UTC



RAPIDS-NHM 2013-09-22 00 UTC



ECMWF as Meso-NHM Boundary Conditions

- Since commencement of operation, JMA-GSM forecast/analysis used as boundary conditions for Meso-NHM
- Sensitivity studies conducted regarding B.C.
 - TC Season of 2011 and 2012 ~ 30 TCs
 - General improvements observed in F/C track errors
- Meso-NHM (ECMWF-boundary) version in operation since 2 April 2013
 - JMA-GSM version run twice daily (00 / 12 UTC) and provides "alternative scenarios"

Comparison of Forecast Track Errors

All 00 and 12 UTC runs for TCs Aere to Nalgae in 2011



Comparison of Forecast Track Errors



Forecast Hour

Assimilation of Radar Reflectivity Data

Retrieval of RH profiles from radar reflectivity using Bayesian Inversion

- Retrieved RH profiles assimilated into 3DVAR
 - humidity adjustment
 - » "create" moisture profiles at model "dry" points where non-zero reflectivity exists



Case of Severe Convection on 2013-04-05





RAPIDS-NHM 5th Apr 06 HKT Run



Case of Severe Convection on 2013-04-25



Tropical Cyclone Reconnaissance Flights

- Collaboration between HKO and the Hong Kong Government Flying Service (GFS)
- More than 10 operations conducted in 2012 2013
- Data collection by high-res. probe installed on fixed-wing aircraft of GFS









128-km Radar Reflectivity (3-km CAPPI) and Doppler Velocity (1.8-deg Elevation)

24-hourly Rainfall over Hong Kong on 23rd and 24th July 2012 (HKT)





Wea H	Weather Warnings issued by HKO on 24 th July 2012									
oooooo oooooo Amber 世	01:55 - 10:40 HKT									
中 Thunderstorm	00:15 – 05:15 HKT									
	01:55 – 12:25 HKT									
	01:10 – 15:00 HKT									

Cheung Chau Be

香港天文台 Hong Kong Observatory

a Schoo Haglan Island



GFS Reconnaissance Flight Path, 06 UTC, 22nd July 2012

GFS Reconnaissance Flight Path



Summary of collected wind data 114°E 115° 1ºN 21°N 20°N 20°N >60 knots 19°N 19°N В В 18°N 18°N ~ 750 m ~ 3000 m

Analyses before and after assimilation of GFS data



Vertical Cross-section along points A-B



NHM Forecast of Surface (10-metre) Winds Meso-NHM (Operational) Wind Vector + Isotach (ki)33 hr F/C 2012-07-23 15:00 UTC (Mon) Initial Time: a110 m Jevel Wind Vector + Isotach (kt) 33 hr F/C 2012-07-23 15:00 UTC (Mon) Initial Time: at 10 m level Wind speed Wind speed (knots) (knots) 17 Before After 7 7 114°F 115% 116°F 112°F 114°E 115°F 116°F NHM Forecast of Surface (10-metre) Winds and Gusts Meso-NHM (Operational) Wind Vector + Gust (kt) 33 hr F/C 2012-07-23 15:00 UTC (Mon) Initial Time: at 10 m level Meso-NHM (Operational) Wind Vector + Gust (kt) 33 hr F/C 2012-07-23 15:00 UTC (Mon) Initial Time: 2012-07-22 06 UTC Wind gust Wind gust (knots) (knots) 85 85 52 48 22°N 22 21°N -Before 7 After

112°E

113%

Control Run

115°E

116°E

114°E

112°E

113°E

With GFS Data

115°E

116°E

114°E

Further Experiments on Vicente

Mosaic of hourly rainfall, ending on T+37, by NHM member runs



Vicente – Forecasts of Local Winds

10-minute mean wind, plotted every hour, recorded at Cheung Chau AWS (pink) and NHM forecast (box-and-whisker)



Hong Kong Time (UTC+8)



Vicente – Local Rainfall Forecasts

HKAWS Raingauges and NHM grid-points used in calculation of "Average Rainfall"



Recorded (red) and forecast (box-and-whisker) hourly average rainfall over the territory





Reconnaissance Flight for *Molave* (2009)













2009-07-19 04 HKT



CNTL

APPI



2009-07-18 12 UTC Forecast Equivalent Reflectivity T+08 h forecast from RAPIDS-NHM

GFS

2009-07-19 04 HKT





Forecast Track Error



Vertical profiles of Meso-NHM analysis and forecast RMSE in AUG 2013



Vertical profiles of Meso-NHM analysis and forecast RMSE in AUG 2013



Super Typhoon Usagi (1319)







Super Typhoon Usagi (1319)



Looking Ahead – AIR-NHM

- Expansion of computational power to support extended domain of Meso-NHM
- Assimilation of local radar data and regional composites into Meso-NHM
- Assimilation of TC reconnaissance flight data on an operational basis



Image courtesy of Guangdong Meteorological Bureau



HKO-AVM – the Aviation Model



HKO-AVM – the Aviation Model

Sig. Convection



Terrain-disrupted Airflow

Image taken from **Google Earth**

HKO-AVM – the Aviation Model

- Fine-resolution NWP system devised to:
 - Meet emerging needs of the aviation community
 - Provide enhanced aviation-specific forecast products
- Hardware:
 - Linux cluster comprising computation & pre/postprocessing nodes
 - 12 TFlop peak performance
- Software:
 - Based on WRF-ARW (v3.4.1 / v3.5)



37 x Production Compute Nodes



HK Airport (HKA) domain dx = 200 mForecast range = 6 - 9 hr



***** Hourly-updated forecasts up to 6 - 9 hours ahead

- Initial/boundary conditions: RAPIDS-NHM (2 km)
- ✤ Inner domain: 1- or 2-way nesting



LIDAR Aircraft Glide-path Scans

Laser Beams

Glide Path

LIDAR Aircraft Glide-path Scans

LIDAR-based Windshear GLYGA Detection System w/ 00 View latest RWY 07 IN USE 0 2012/12/20 02:01:00 UTC Head wind (kt) Head wind ikt) Altitude (ff) Altitude (fi 2012/12/20 01:58:58 UTC 2012/12/20 01:50:40 UTC 30 20 Last run: 1000 4000 10 2012/12/20 02:01:00 3000 2000 2000 -10 1000 1000 07LD 07RA Unavailable -20 7 τ 3 1 1 -1 -2 -2 -1 0 1 2 4 Distance from runway end (NM) Distance from runway end (NM) Head wind ikt) Altitude (ff) Head wind (kt) Altitude (fi 07LA 30 5000 30 20 4000 400 10 3000 C 2000 -10 1000 -11 D7RD -20 3 0 1 1 -1 -2 -2 -1 0 1 2 Distance from runway end (NM) 6.0 Jegree PH Distance from runway end (NM) 3.0 Jegree PH **RWY 25** Head wind (kt) Altitude (fl) Head wind (kt) Altitude (fi 2012/12/20 01:58:28 UTC 2012/12/20 01:58:47 UTC -10 -20 4000 Last run: 20 -30 3000 -31 2012/12/20 02:01:00 -40 2000 -40 -50 1000 -50 ZSRA 25RD 25RA -80 3 2 -2 -2 -1 0 1 2 7 1 1 -1 Δ Distance from runway end (NM) Distance from runway end (NM) 25RD +19K 1MD Head wind (kt) Head wind (kt) Alttude (fl) Altitude (fl 25LA -11 4000 400 25LD +19K 2MD -20 -20 -30 -30 2000 -40 -40 1000 -51 25LD -50 .3 2 1 -2 -2 0 2 1 -1-1 1 Distance from runway end (NM) Distance from runway end (NM) BU Jegree 3.0 Jeanee Ph

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Terrain-induced Windshear Event



Windshear Events due to Sea Breeze



Headwind profile simulator (HKA-AVM) - Windshear due to sea-breeze

T+4 h forecast from 01 UTC 2011-02-25



Headwind profile simulator (HKA-AVM) - Terrain-induced windshear





Looking Ahead – HKO-AVM

- Development of data assimilation system
 - Current initial & boundary conditions from RAPIDS-NHM (2 km)
 - "Dynamical Downscaling" in theory
 - Requires separate DA (based on WRF-VAR) for leveraging highresolution observations in the vicinity HKIA
- Development of aviation-specific product suite
 - Low-level windshear and turbulence
 - Guidance for sea breeze onset / retreat timing, depth, etc
 - Chance of sig. convection at key locations around HKIA
- Development of near real-time verification system





Observation Network around HKIA



Wind profiler

Meso-NHM QPF Ensemble

- Apply time-lagged ensemble approach to consecutive Meso/RAPIDS-NHM runs to generate QPF guidance
- 2 "flavours" all grid points or rainy grid only



Rainstorm on 2013-05-22











Verification of Spatial QPF Products

- Fractional Skill Score (FSS)
 - Incorporates spatial uncertainty information in model forecasts



Verification of Spatial QPF Products

- JAXA Global Rainfall Watch Data (GSMaP)
- Near-real-time hourly rainfall rate based on MW-IR algorithm
 - Incorporating TRMM TMI, Aqua AMSR-E, DMSP SSM/I and SSMIS, NOAA-19 AMSU, MetOp-A AMSU and GEO IR data
- Data available at 0.1-deg resolution
 - Similar to Meso-NHM (at 10 km x 10 km)



Verification of Spatial QPF Products

- Data period: 1 April 30 Nov 2012
- Meso-NHM QPF ensemble (3-hr rainfall)
 - 6 choices:
 - ensemble mean (all and rain-grid)
 - 75 percentile (all and rain-grid)
 - median
 - max
- "Ground Truth": JAXA GSMaP
- Metric: FSS



Sample FSS Scores for Meso-NHM

0.6

0.58

0.53

0.49

0.46

0.4

1

0.5

0.51 0.49

0.57 0.54

0.55 0.53 0.48

0.51

0.46

0.43

2

1.0

0.6

0.59 0.54

0.57 0.53

0.56 0.51

0.49

0.46

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FSS (mean)

	0.58	0.59	0.56	0.43	0.26	0.12	0.04
	0.57	0.58	0.55	0.41	0.25	0.12	0.04
	0.56	0.56	0.53	0.4	0.24	0.11	0.04
_	0.55	0.55	0.52	0.39	0.23	0.11	0.03
	0.54	0.54	0.5	0.37	0.22	0.1	0.03
_	0.53	0.52	0.48	0.35	0.21	0.1	0.03
	0.51	0.5	0.46	0.33	0.2	0.09	0.02
_	0.49	0.48	0.44	0.31	0.19	0.08	0.02
	0.47	0.46	0.42	0.29	0.17	0.07	0.02
	0.45	0.43	0.39	0.27	0.16	0.06	0.02
	0.4	0.39	0.34	0.23	0.13	0.05	0.01
	1	2	3	4	5	6	7
	0.5	1.0	2.0	5.0	10.0	20.0	30.0

FSS (mean r/g)

0.39

0.38

0.36

0.33

0.29

0.26

0.23

4

5.0

0.35 0.21

0.31 0.19

0.2

0.16

0.13

5

10.0

0.42 0.26 0.12

0.41 0.25 0.12 0.04

0.24 0.11

0.23 0.11

0.22 0.1

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		1

						1		
10		0.58	0.52	0.42	0.25	0.14	0.05	
6	10 -	0.57	0.51	0.41	0.24	0.13	0.04	
œ		0.56	0.49	0.39	0.23	0.13	0.04	
7	8 -	0.54	0.48	0.38	0.23	0.12	0.04	0.01
9		0.52	0.46	0.37	0.22	0.12	0.04	
5	6 -	0.51	0.45	0.35	0.21	0.11	0.04	
4		0.49	0.43	0.34	0.2	0.11	0.03	
ო	4 -	0.47	0.41	0.32	0.19	0.1	0.03	
N		0.44	0.38	0.3	0.17	0.09	0.03	
-	2 -	0.41	0.36	0.28	0.16	0.08	0.03	
0		0.36	0.31	0.24	0.14	0.07	0.02	
		1	2	3	4	5	6	7
		0.5	1.0	2.0	5.0	10.0	20.0	, 30.0

Mean

Mean (rain-grid)

Median

Sample FSS Scores for Meso-NHM

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FSS (75-th percentile)

					1	
0.6	0.59	0.57	0.5	0.39	0.22	0.12
0.59	0.58	0.55	0.48	0.38	0.21	0.11
0.58	0.56	0.54	0.47	0.36	0.2	0.1
0.57	0.55	0.53	0.45	0.35	0.19	0.09
0.55	0.54	0.51	0.43	0.33	0.17	0.08
 0.54	0.52	0.49	0.42	0.31	0.16	0.07
0.52	0.51	0.48	0.4	0.3	0.15	0.07
0.51	0.49	0.46	0.37	0.28	0.14	0.06
0.49	0.46	0.43	0.35	0.26	0.12	0.05
0.46	0.44	0.4	0.32	0.23	0.11	0.04
0.41	0.38	0.35	0.27	0.2	0.09	0.03
1	2	3	4	5	6	7
0.5	1.0	2.0	5.0	10.0	20.0	30.0

FSS (75-th percentile r/g)

									 - 08
	0.62	0.6	0.56	0.49	0.38	0.22	0.12		0.0
10 -	0.61	0.58	0.55	0.47	0.37	0.21	0.11	-	- 0.7
	0.6	0.57	0.54	0.46	0.36	0.2	0.1		- 0.6
8 -	0.58	0.56	0.52	0.44	0.34	0.18	0.09	-	
	0.57	0.54	0.51	0.43	0.33	0.17	0.08		- 0.5
6 -	0.55	0.52	0.49	0.41	0.31	0.16	0.07	-	- 0.4
	0.53	0.5	0.47	0.39	0.29	0.15	0.07		- 0.3
4 -	0.51	0.48	0.45	0.37	0.27	0.13	0.06	-	
	0.49	0.46	0.43	0.35	0.25	0.12	0.05		- 0.2
2 -	0.46	0.43	0.4	0.32	0.23	0.11	0.04	-	- 0.1
	0.4	0.38	0.35	0.27	0.19	0.09	0.03		
	1	2	3	4	5	6	7		- 0.0
	0.5	1.0	2.0	5.0	10.0	20.0	30.0		

FSS (maximum)

	1					
1	0.39	0.38	0.36	0.33	0.24	0.15
ŀ	0.39	0.38	0.35	0.32	0.23	0.14
ŀ	0.39	0.37	0.35	0.31	0.22	0.13
ŀ	0.38	0.37	0.34	0.3	0.22	0.12
9	0.37	0.36	0.33	0.29	0.21	0.11
9	0.37	0.35	0.32	0.29	0.2	0.11
8	0.36	0.34	0.31	0.27	0.19	0.1
7	0.35	0.33	0.3	0.26	0.17	0.09
6	0.34	0.32	0.29	0.25	0.16	0.08
5	0.33	0.31	0.27	0.23	0.14	0.07
2	0.3	0.28	0.24	0.19	0.11	0.05
	2	3	4	5	6	7
;	1.0	2.0	5.0	10.0	20.0	30.0

75th Percentile

75th Percentile (rain-grid)

Maximum

RAPIDS-NHM

Verification area confined to within TMS 256 km range; radar based QPE using static Z-R relationship: verification period: Apr - Nov 2012

) +/- 4	0 km	FSS ((75–th pe	ercentile))					H4_comp PA_comp R_cc_030_p2 R_sc_030_p2 PAF:57644 H4:eq:h:13, Nav Range 200 200 1500 1500 150 150 150 150 150 150 150	56 60** 32 12:35 km 6:17 2013 HKT 3000 support 100 users 100 support 100 support 10	FSS (7	5-th per	centile r/	'g)		
S	0.51	0.48	0.43	0.31	0.14	0.05	0.03		0.8	20	0.51	0.49	0.43	0.3	0.14	0.05	0.03	0.8
<u>ଜ</u> 20 -	0.51	0.47	0.42	0.31	0.15	0.05	0.03	_		<u>ଜ</u> 20 –	0.5	0.48	0.43	0.3	0.15	0.05	0.03	-
8	0.5	0.47	0.42	0.3	0.16	0.06	0.03		- 0.7	8	0.5	0.48	0.42	0.3	0.15	0.06	0.03	- 0.7
1	0.5	0.46	0.41	0.3	0.16	0.06	0.03			17	0.49	0.47	0.42	0.3	0.16	0.06	0.02	
16	0.49	0.45	0.41	0.3	0.16	0.06	0.02			16	0.49	0.46	0.41	0.29	0.16	0.06	0.02	
15	0.48	0.45	0.4	0.29	0.16	0.06	0.02		- 0.6	15	0.48	0.45	0.4	0.29	0.16	0.06	0.02	- 0.6
7 15 -	0.47	0.44	0.39	0.28	0.16	0.05	0.02	-		7 15 -	0.47	0.45	0.39	0.28	0.16	0.05	0.02	-
13	0.47	0.43	0.38	0.27	0.15	0.05			- 0.5	13	0.46	0.44	0.38	0.27	0.15	0.05		- 0.5
12	0.46	0.42	0.37	0.26	0.15	0.05			0.0	12	0.45	0.43	0.38	0.26	0.14	0.05		
÷	0.45	0.42	0.36	0.26	0.14	0.04				÷	0.44	0.42	0.37	0.25	0.14	0.04		
9	0.44	0.41	0.35	0.25	0.13	0.04			- 0.4	10	0.43	0.41	0.36	0.24	0.13	0.04		- 0.4
თ 10 -	0.44	0.4	0.34	0.24	0.13	0.04	0.01	-		თ 10 –	0.42	0.4	0.35	0.23	0.12	0.04	0.01	
8	0.43	0.39	0.34	0.23	0.12	0.03	0.01		- 0.3	8	0.41	0.39	0.34	0.22	0.12	0.03	0.01	- 0.3
~	0.42	0.38	0.32	0.22	0.11	0.03	0.01		0.0	~	0.4	0.38	0.32	0.21	0.11	0.03	0.01	0.0
9	0.41	0.37	0.31	0.21	0.1	0.03				9	0.39	0.36	0.31	0.2	0.1	0.03		
Ω	0.4	0.36	0.3	0.19	0.09	0.03			- 0.2	5	0.37	0.35	0.3	0.19	0.09	0.03		- 0.2
4 5-	0.39	0.35	0.29	0.18	0.09	0.02		-		4 5 -	0.36	0.34	0.29	0.18	0.09	0.02		
e S	0.37	0.33	0.27	0.17	0.08	0.02	0.01		- 0.1	e e	0.34	0.32	0.27	0.17	0.08	0.02	0.01	
N	0.36	0.31	0.26	0.15	0.07	0.02			- 0.1	N	0.32	0.3	0.25	0.15	0.07	0.02		0.1
-	0.33	0.29	0.24	0.14	0.06	0.01				-	0.3	0.28	0.23	0.14	0.06	0.01		
0	0.29	0.25	0.19	0.1	0.04	0.01			0.0	0	0.25	0.23	0.19	0.1	0.04	0.01		0.0
	1	2	3	4	5	6	7				1	2	3	4	5	6	7	
	0.5	1.0	2.0	5.0	10.0	20.0	30.0				0.5	1.0	2.0	5.0	10.0	20.0	30.0	

raction Skill Score as function of lead time (Meso-NHM)

T+3	FSS (fore $T+6$	FSS (for $T+9$	FSS T+12	FSS (forecast hr = 15)	FSS (forecast hr = 18)	FSS (forecast hr = 21)	FSS (forecast hr = 24)	
0.67 0.64 0.56 0.49 0.41 0.29 20.21 0.66 0.62 0.57 0.47 0.39 0.28 0.19 0.64 0.6 0.55 0.46 0.38 0.27 00.18	0.66 0.63 0.58 0.5 0.42 0.32 20.24 0.66 - 0.65 0.61 0.56 0.48 0.41 0.3 0.22 0.65 0.63 0.59 0.55 0.47 0.39 0.29 0.21 0.63	0.63 0.58 0.5 0.42 0.32 >0.25 0.61 0.56 0.48 0.41 0.3 0029 0.59 0.55 0.47 0.39 0.29 0021	0.66 0.63 0.5 0.41 0.3 30.23 0.64 0.61 0.56 0.46 0.39 0.29 0.29 0.63 0.6 0.55 0.46 0.38 0.27 ∞0.29	0.65 0.62 0.57 0.46 0.39 0.28 50.2 0.64 0.66 0.56 0.47 0.38 0.27 0.19 ¹ - 0.62 0.59 0.54 0.45 0.36 0.26 9.17	0.66 0.67 0.38 0.27 50.18 0.63 0.55 0.45 0.37 0.25 0.18 0.61 0.56 0.55 0.44 0.35 0.24 0.16	0.64 0.55 0.46 0.37 0.25 50.16 0.62 0.58 0.53 0.44 0.35 0.24 00.10 0.66 0.57 0.52 0.43 0.34 0.32 =0.13	0.63 0.6 0.54 0.44 0.35 0.22 0.13 0.62 0.56 0.52 0.43 0.33 0.21 0.12 0.6 0.56 0.51 0.41 0.32 0.2 0.1	0.8
0.52 0.58 0.53 0.44 0.36 0.25 0.14 0.6 0.56 0.51 0.42 0.35 0.24 #0.16 0.57 0.54 0.49 0.4 0.33 0.23 #0.16	0.61 0.58 0.53 0.45 0.38 0.27 ►0.19 0.61 0.59 0.56 0.51 0.43 0.36 0.26 ₽0.16 0.59 - 0.57 0.53 0.49 0.41 0.34 0.24 ₽0.16 0.57	0.58 0.53 0.45 0.37 0.27 ►0.28 - 0.56 0.51 0.43 0.36 0.25 ¢0.18 0.53 0.49 0.41 0.34 0.23 ¢0.16	0.61 0.58 0.53 0.44 0.36 0.25 0.18 - 0.56 0.51 0.42 0.34 0.24 0.16 - - -	0.6 0.57 0.52 0.43 0.35 0.24 0.16 ¹ 0.58 0.55 0.5 0.41 0.33 0.23 0.14 0.58 0.52 0.48 0.39 0.31 0.21 0.13	0.6 0.56 0.51 0.42 0.34 0.23 0.14 0.58 0.54 0.49 0.4 0.32 0.21 0.33 0.56 0.52 0.47 0.36 0.3 0.2 0.14	0.58 0.55 0.41 0.32 0.21 0.12 0.56 0.53 0.48 0.39 0.31 0.2 0.11 0.54 0.51 0.46 0.37 0.29 0.11 0.15	0.58 0.54 0.48 0.39 0.38 0.18 0.09 0.56 0.52 0.47 0.38 0.29 0.17 0.38 - 0.54 0.55 0.45 0.46 0.27 0.18 0.07	
0.55 0.51 0.46 0.38 0.31 0.21 ±0.13 0.52 0.48 0.43 0.36 0.29 0.19 ±0.12 0.49 0.45 0.4 0.33 0.26 0.17 ±0.11	0.54 0.51 0.46 0.39 0.32 0.22 +0.15 0.54 - 0.52 0.48 0.43 0.36 0.3 0.22 +0.15 0.51 0.48 0.45 0.4 0.33 0.28 0.18 +0.12 0.48	0.51 0.46 0.38 0.32 0.22 *0.14 0.48 0.43 0.36 0.29 0.2 *0.13 - 0.45 0.4 0.33 0.27 0.17 <0.11	0.54 0.51 0.46 0.38 0.31 0.2 0.13 0.51 0.48 0.43 0.35 0.28 0.18 0.11 - 0.48 0.45 0.4 0.33 0.26 0.16 •0.09	0.55 0.5 0.45 0.37 0.29 0.19 0.11 0.51 0.47 0.42 0.34 0.27 0.17 *0.14 * 0.47 0.44 0.39 0.32 0.25 0.16 *0.06	0.55 0.49 0.45 0.36 0.28 0.18 -0.11 0.5 0.47 0.42 0.33 0.26 0.16 -0.09 0.47 0.43 0.39 0.31 0.24 0.14 -0.07	0.52 0.48 0.43 0.35 0.27 0.17 -0.08 0.49 0.45 0.41 0.32 0.25 0.15 •0.07 0.46 0.42 0.37 0.33 0.23 0.14 •0.08	0.51 0.48 0.42 0.33 0.25 0.14 0.06 0.49 0.45 0.4 0.31 0.23 0.13 0.05 0.45 0.42 0.37 0.28 0.21 0.11 0.04	- 0.7
0.44 0.41 0.37 0.3 0.24 0.15 = 0.08 0.38 0.35 0.31 0.25 0.2 0.12 = 0.07 1 2 3 4 5 6 7 0.55 1.0	- 0.44 0.41 0.37 0.3 0.25 0.16 - 0.17 - 0.44 0.37 0.35 0.31 0.25 0.21 0.13 - 0.08 0.37 1 2 3 4 5 6 7 1 0.5 1.0 2.0 5.0 10.0 20.0 30.0 0.5	0.41 0.37 0.3 0.24 0.15 -0.09 - 0.34 0.31 0.25 0.2 0.12 -0.07 2 3 4 5 6 7 1.0 2.0 5.0 10.0 20.0 30.0	0.44 0.41 0.36 0.29 0.23 0.14 0.09 - 0.37 0.34 0.31 0.25 0.19 0.11 90.06 - <th>0.43 0.4 0.36 0.28 0.22 0.14 0.078 0.37 0.34 0.3 0.24 0.18 0.11 90.05 1 2 3 4 5 6 7 0.5 1.0 2.0 5.0 10.0 20.0 30.0</th> <th>0.43 0.4 0.35 0.28 0.21 0.12 -0.02 0.36 0.33 0.29 0.23 0.18 0.1 -0.02 1 2 3 4 5 6 7 0.5 1.0 2.0 5.0 100 200 30.0</th> <th>0.42 0.39 0.34 0.27 0.2 0.12 -0.02 0.35 0.32 0.28 0.22 0.17 0.1 -0.02 1 2 3 4 5 6 7 0.55 1.0 2.0 5.0 100 200 300</th> <th>0.42 0.38 0.33 0.25 0.19 0.1 0.04 0.35 0.32 0.28 0.21 0.15 0.08 0.03 1 2 3 4 1 1 7 0.5 1.0 2.0 5.0 10.0 20.0 30.0</th> <th>- 0.6</th>	0.43 0.4 0.36 0.28 0.22 0.14 0.078 0.37 0.34 0.3 0.24 0.18 0.11 90.05 1 2 3 4 5 6 7 0.5 1.0 2.0 5.0 10.0 20.0 30.0	0.43 0.4 0.35 0.28 0.21 0.12 -0.02 0.36 0.33 0.29 0.23 0.18 0.1 -0.02 1 2 3 4 5 6 7 0.5 1.0 2.0 5.0 100 200 30.0	0.42 0.39 0.34 0.27 0.2 0.12 -0.02 0.35 0.32 0.28 0.22 0.17 0.1 -0.02 1 2 3 4 5 6 7 0.55 1.0 2.0 5.0 100 200 300	0.42 0.38 0.33 0.25 0.19 0.1 0.04 0.35 0.32 0.28 0.21 0.15 0.08 0.03 1 2 3 4 1 1 7 0.5 1.0 2.0 5.0 10.0 20.0 30.0	- 0.6
0.52 0.58 0.54 0.45 0.37 0.25 °0.1	FSS (forecast hr = 30) 5 0.82 0.59 0.54 0.48 0.37 0.28 0.15 0.61 4 0.6 0.57 0.53 0.44 0.36 0.25 0.14 0.6	FSS (forecast hr = 33) 0.56 0.54 0.45 0.36 0.24 €0.13 0.57 0.52 0.44 0.34 0.22 ∞0.12 -	FSS (forecast hr = 36) 0.6 0.56 0.53 0.44 0.34 0.23 20.13 0.59 0.56 0.52 0.43 0.32 0.22 00.12 -	FSS (forecast hr = 39) 0.50 0.57 0.52 0.43 0.32 0.2 20.12 0.58 0.55 0.51 0.41 0.31 0.19 00.110 -	FSS (forecast hr = 42) 0.50 0.55 0.51 0.41 0.3 0.17 20.1 0.57 0.53 0.49 0.4 0.29 0.16 00.09	FSS (forecast hr = 45) 0.56 0.53 0.49 0.4 0.3 0.17 206 0.55 0.52 0.47 0.39 0.29 0.16 0.070	FSS (forecast hr = 48) 0.55 0.52 0.48 0.39 0.29 0.16 0.08 - 0.54 0.51 0.46 0.37 0.27 0.15 0.07	- 0.5
0.6 0.57 0.52 0.44 0.35 0.24 ±0.11 0.58 0.55 0.5 0.42 0.34 0.22 ±0.11 0.58 0.53 0.48 0.4 0.32 0.22 ±0.11	2 0.59 0.55 0.51 0.43 0.34 0.23* 0.12 0.54 - 0.57 0.54 0.49 0.41 0.32 0.22* 0.11 0.59 - 0.55 0.51 0.47 0.39 0.31 0.22* 0.11 0.59	0.55 0.51 0.42 0.33 0.21 ∞0.11 0.53 0.49 0.4 0.31 0.19 ►0.18 0.51 0.47 0.38 0.29 0.18 ±0.09	0.57 0.54 0.5 0.41 0.31 0.22 0.01 0.55 0.52 0.48 0.39 0.29 0.19 >0.09 - 0.58 0.52 0.46 0.37 0.27 0.17 40.08	0.55 0.43 0.39 0.29 0.17 \$\$0.11\$ 0.55 0.51 0.47 0.38 0.27 0.16 \$\$0.09\$ - 0.58 0.49 0.45 0.38 0.27 0.16 \$\$0.09\$ -	0.55 0.52 0.47 0.38 0.27 0.15 *0.08 0.53 0.5 0.45 0.36 0.26 0.13 *0.08 0.51 0.48 0.44 0.34 0.24 0.12 *0.07	0.53 0.5 0.45 0.37 0.27 0.15 0.06 0.51 0.48 0.44 0.35 0.26 0.14 9008 0.5 0.46 0.42 0.33 0.24 0.12 9008	0.52 0.49 0.44 0.36 0.26 0.14 0.07 - 0.51 0.47 0.43 0.34 0.25 0.13 0.06 0.49 0.45 0.41 0.32 0.23 0.12 0.05	
0.54 0.51 0.46 0.38 0.3 0.19 ∞0.0 0.52 0.48 0.43 0.35 0.28 0.17 ♥0.0 0.49 0.45 0.41 0.33 0.26 0.15 ♥0.0	- 0.53 0.49 0.45 0.36 0.29 0.18% 0.00 0.52 7 0.5 0.47 0.42 0.34 0.27 0.17% 0.08 0.49 8 - 0.47 0.44 0.42 0.24 0.27 0.15% 0.07 0.47	0.49 0.44 0.36 0.27 0.16 40.08 - 0.46 0.42 0.34 0.25 0.15 40.07 0.43 0.39 0.31 0.23 0.13 40.06 -	0.51 0.48 0.44 0.35 0.26 0.16 40.07 - 0.49 0.46 0.41 0.33 0.24 0.14 -0.06 0.46 0.43 0.39 0.33 0.24 0.13 =0.06	0.5 0.47 0.43 0.34 0.24 0.13 •0.07 0.48 0.45 0.4 0.31 0.22 0.12 •0.06 0.45 0.42 0.38 0.29 0.22 0.11 •0.09 -	0.49 0.46 0.41 0.32 0.22 0.11 90.06 0.47 0.44 0.39 0.3 0.21 0.1 90.06 0.44 0.41 0.37 0.28 0.19 0.09 90.04	0.47 0.44 0.4 0.31 0.23 0.11 0.04 0.45 0.42 0.38 0.29 0.21 0.1 9.04 0.43 0.39 0.35 0.27 0.19 0.09 9.03	- 0.47 0.43 0.39 0.3 0.22 0.11 0.05 0.44 0.41 0.37 0.28 0.22 0.1 0.04 - 0.42 0.38 0.34 0.26 0.16 0.09 0.03	- 0.4
0.46 0.42 0.38 0.3 0.23 0.13 0.0 0.42 0.38 0.34 0.27 0.2 0.12 0.0 0.35 0.32 0.28 0.22 0.17 0.09 0.0	0.44 0.41 0.37 0.28 0.22 0.139 0.06 0.44 a 0.4 0.37 0.38 0.26 0.2 0.12+ 0.05+ 0.4 a 0.34 0.37 0.28 0.21 0.16 0.09= 0.04 0.33 a 0.34 0.31 0.28 0.21 0.16 0.09= 0.04 0.33	0.4 0.36 0.29 0.21 0.11 00.05 0.37 0.33 0.25 0.18 0.1 -0.04 - 0.31 0.27 0.21 0.15 0.06 -0.03 -	0.43 0.4 0.36 0.27 0.2 0.11 0.04 0.39 0.36 0.32 0.25 0.17 0.1 -0.03 - 0.33 0.3 0.27 0.2 0.14 0.08 - 0.03	0.42 0.39 0.35 0.27 0.18 0.1 •0.05 0.38 0.36 0.31 0.24 0.16 0.09 -0.04 - 0.32 0.33 0.26 0.2 0.13 0.06 =0.03	0.41 0.38 0.34 0.26 0.17 0.08 0.04 0.37 0.35 0.3 0.23 0.15 0.07 -0.03 0.31 0.29 0.25 0.19 0.12 0.05 50.02	0.4 0.37 0.32 0.25 0.17 0.08 0.02 0.36 0.33 0.29 0.22 0.15 0.07 9.022 0.3 0.28 0.24 0.18 0.12 0.05 9.01	0.39 0.36 0.31 0.24 0.17 0.08 0.03 - 0.35 0.32 0.28 0.21 0.15 0.07 0.02 0.3 0.27 0.24 0.18 0.12 0.05 0.02	- 0.3
0.5 1.0 T+51	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	2 3 4 5 6 7 1.0 2.0 5.0 10.0 20.0 30.0 FSS (forecast hr = 57)	0.5 1.0 2.0 5.0 10.0 20.0 30.0 FSS (forecast hr = 60)	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	1 2 3 4 5 6 7 0.5 1.0 2.0 5.0 10.0 20.0 30.0 FSS (forecast hr = 66)	0.5 1.0 2.0 5.0 10.0 20.0 30.0 FSS (forecast hr = 69)		
0.53 0.5 0.5 0.5 0.5 0.6 0.1 0.05 0.1 0.05 0.05 0.46 0.41 0.31 0.2 0.09 0.04	0.52 0.48 0.43 0.32 0.21 0.1 20.05 0.51 - 0.51 0.47 0.41 0.31 0.2 0.09 0.09 0.05 0.51 0.49 0.45 0.4 0.29 0.19 0.09 0.04 0.44	0.47 0.42 0.31 0.2 0.1 9004 0.46 0.4 0.29 0.19 0.09 9006 3 0.44 0.39 0.28 0.18 0.06 40.03	0.51 0.47 0.41 0.3 0.19 0.09 20.03 0.49 0.45 0.4 0.29 0.18 0.08 20.09 0.47 0.44 0.38 0.27 0.17 0.07 20.03	0.51 0.47 0.41 0.29 0.18 0.08 20.03 0.49 0.45 0.39 0.28 0.17 0.07 20.09 0.47 0.43 0.38 0.27 0.16 0.07 20.03	0.5 0.46 0.4 0.29 0.17 0.07 90.03 0.49 0.45 0.39 0.27 0.17 0.06 0.00 0.47 0.43 0.38 0.26 0.16 0.06 0.02	0.49 0.45 0.39 0.28 0.16 0.05 €02 0.48 0.44 0.38 0.27 0.16 0.05 902 0.46 0.42 0.37 0.25 0.15 0.04 902	0.48 0.43 0.37 0.26 0.16 0.04 0.00 0.45 0.41 0.36 0.25 0.15 0.04 0.0	- 0.2
0.48 0.45 0.39 0.29 0.18 0.09 0.04 0.47 0.43 0.37 0.28 0.17 0.08 40.04 0.44 0.41 0.36 0.26 0.16 0.07 40.03	- 0.47 0.43 0.38 0.28 0.18 0.08 0.04 0.44 0.45 0.42 0.36 0.27 0.17 0.08 00.03 0.44 - 0.43 0.4 0.36 0.25 0.16 0.07 0.09 0.44	0.42 0.37 0.27 0.17 0.08 •0.03 0.41 0.35 0.25 0.16 0.07 •0.03 0.39 0.33 0.24 0.15 0.07 •0.03	0.46 0.42 0.38 0.26 0.17 0.07 0.02 0.44 0.4 0.35 0.25 0.16 0.06 90.02 0.42 0.38 0.33 0.23 0.15 0.06 90.02	0.46 0.42 0.36 0.26 0.15 0.06 0.02 - 0.44 0.4 0.34 0.24 0.14 0.06 90.02 - - 0.42 0.38 0.33 0.23 0.14 0.06 90.02 -	0.45 0.41 0.36 0.25 0.15 0.05 F0.02 0.43 0.4 0.34 0.24 0.14 0.05 e0.02 0.42 0.38 0.32 0.22 0.13 0.04 e0.02	0.44 0.4 0.35 0.24 0.14 0.04 0.014 0.43 0.39 0.33 0.23 0.13 0.04 9014 - 0.41 0.37 0.32 0.22 0.13 0.04 9014	- 0.44 0.4 0.34 0.23 0.14 0.03 0.0 0.42 0.38 0.33 0.22 0.13 0.03 0.0 - 0.4 0.36 0.31 0.21 0.12 0.03 0.0	- 0.1
0.42 0.38 0.33 0.24 0.15 0.07 -0.03 0.4 0.36 0.31 0.23 0.14 0.06 -0.03 0.37 0.33 0.29 0.21 0.12 0.05 N002	0.41 0.38 0.32 0.23 0.14 0.06 70.03 0.4 - 0.39 0.35 0.3 0.22 0.13 0.06 70.03 0.34 0.36 0.33 0.28 0.2 0.12 0.05 90.02 0.33	0.36 0.31 0.22 0.14 0.06 0.02 3 0.34 0.29 0.2 0.13 0.05 00.02 5 0.32 0.27 0.19 0.12 0.05 00.02	0.4 0.36 0.31 0.22 0.14 0.05 00.22 - 0.37 0.34 0.29 0.2 0.13 0.05 r0.01 0.35 0.31 0.27 0.18 0.11 0.04 90.01	0.4 0.36 0.31 0.21 0.13 0.05 90.02 - 0.37 0.34 0.29 0.2 0.12 0.04 90.01 0.35 0.31 0.26 0.18 0.11 0.04 90.01	0.39 0.36 0.31 0.21 0.12 0.04 -0.01 0.37 0.33 0.29 0.19 0.12 0.03 -0.08 0.35 0.31 0.26 0.18 0.1 0.03 -0.01	0.39 0.35 0.3 0.2 0.12 0.03 001 0.36 0.33 0.28 0.19 0.11 0.03 0014 0.34 0.33 0.26 0.17 0.1 0.02 0014	0.38 0.34 0.29 0.19 0.11 0.02 0.0 0.36 0.32 0.27 0.18 0.1 0.02 0 0.33 0.3 0.25 0.16 0.09 0.02 0	
0.34 0.3 0.26 0.18 0.11 0.05 -0.02 0.28 0.25 0.22 0.15 0.09 0.04 0.01	- 0.33 0.3 0.25 0.18 0.11 0.04 -0.02 0.33 0.28 0.25 0.21 0.14 0.09 0.03 -0.02 0.22	2 0.29 0.24 0.17 0.1 0.04 -9.019 7 0.24 0.2 0.14 0.08 0.03 40.01	0.32 0.28 0.24 0.16 0.1 0.04 -0.01 0.27 0.24 0.2 0.13 0.08 0.03 =0.01	- 0.32 0.28 0.24 0.16 0.09 0.03 +0.01 0.27 0.24 0.2 0.13 0.08 0.03 +0.01	0.32 0.28 0.24 0.16 0.09 0.03 -0.01 0.27 0.24 0.2 0.13 0.08 0.02 e0.01	0.31 0.27 0.23 0.15 0.09 0.02 e701 0.26 0.23 0.19 0.13 0.07 0.02 90	0.3 0.27 0.23 0.15 0.08 0.02 0 0.28 0.23 0.19 0.12 0.07 0.01 0	0.0
0.5 1.0 2.0 5.0 10.0 20.0 30.0		1.0 2.0 5.0 10.0 20.0 30.0	0.5 1.0 2.0 5.0 10.0 20.0 30.0	0.5 1.0 2.0 5.0 10.0 20.0 30.0	0.5 1.0 2.0 5.0 10.0 20.0 30.0	0.5 1.0 2.0 5.0 10.0 20.0 30.0	0.5 1.0 2.0 5.0 10.0 20.0 30.0	