DEVELOPMENT OF INTEGRATED PROCESSING LINE OF TROPICAL CYCLONE HYDRODYNAMIC FORECAST

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Basic requirements to the FERHRI automated forecasting system (AFS) for tropical cyclones are laid down. Hurricane model configuration is described. Results of quasioperational verification of HWRF and AHW models are considered. It is obtained that both approaches: movable (HWRF) and immovable (AHW) (nested grids) gives approximately similar errors in forecasting of tropical cyclone location for the period of 72 hours.

Estimates of the forecasts of the fields of some meteorological elements in vicinity of tropical cyclones on the basis of MET software are presented. Analysis of regular errors of hydrodynamic models of WRF family made with involvement of results of V.M. Losev's modified regional model forecasts with artificial vapor flow, ensures the possibility of further adjustment of convection blocks and boundary layer for working with tropical cyclone. It is obtained that errors in forecasting of location, speed and direction of tropical cyclone movement using HWRF model are less. It proves that HWRF model is more stable in comparison with AHW model.

On the basis of tests performed in 2011, a principal capability of AHW and HWRF models to produce the position/time characteristics of a tropical cyclone at various stages of development at the level of official forecasts has been proved. The authors suppose it would be reasonable to use WRF family models for the forecast of tropical cyclone movement and evolution in the Russian Far East.

1. INTRODUCTION

At the present time, forecasting of position and evolution of any tropical cyclones (TC) affecting the Russian Far East, and broadcasting the information to users are executed in operative divisions of the Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet), basically on the basis of forecast products of domestic and foreign global models. Since 1997 some departments and research centers of the Roshydromet perform the work for adaptation of regional non-hydrostatic hydrodynamic models of high resolution with respect to the Far East (Verbitskaya, 2010; Gonchukov, Lamash, 2010; Moiseev, 2010; Naumov, Nikolayeva, 2003).

However, hydrodynamic forecast of tropical cyclones has its own specific features. Tropical cyclones mainly develop above seas and oceans which are rather poorly covered with any meteorological data. By virtue thereof, such tropical cyclones are not deep enough, wedge or week in the context of objective analysis, or non-appearing at all (Pokhil, Zaychenko, 2005). So that, the regional hydrodynamic models should in a certain manner initialize the area of tropical vortex so that its vertical structure is adequate.

The most respected (in the context of tropical cyclone forecast) foreign forecast centers – NCEP in the USA and JMA in Japan – have their own automated forecasting complexes which adequately consider the contribution of tropical cyclones to the circulation over calculation area (Aberson, 2003; http://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline-nwp/pdf/pdf4/outline 4_2.pdf.). In Russia, there is no such forecast complex yet, though researches in the Hydrometeorological Center of Russia, using ETA и WRF (NMM) hydrodynamic models have been performed during the last ten years (Naumov, Nikolayeva, 2003; Pokhil, Zaychenko, 2005; Pokhil, Glebova, 2011). In addition, the first attempt to create a process line of tropical cyclone forecast (based on the FERHRI complex method) was taken at Meteorology and Tropical Cyclones Department under supervision of V.P. Tunegolovets (Report of Research, 2010). However, the FERHRI complex method of tropical cyclone forecast was not fully automated and requires a manual input of data on a tropical cyclone.

Therefore, creation of domestic automated forecasting system (AFS) for location and evolution of any tropical cyclone based on regional hydrodynamic models shall be an important and vital task. Various requirements to creation of AFS for tropical cyclone are presented in section 2.1.

Selection of the specific regional hydrodynamic models for application in AFS for tropical cyclones is also important issue. As to the FERHRI TC AFS, it is proposed to use two regional hydrodynamic models of WRF family – Hurricane WRF (HWRF) and Advanced Hurricane WRF (AHW) developed by NCEP/NCAR (Gopalakrishnan et al., 2011; Skamarock et al., 2010; WRF, 2010). Any possible variations of these models are presented in section 2.2.

Application of HWRF and AHW models is supported by preliminary results of quasioperative tests of such models (during typhoons in 2011). Section 3.1 presents the estimates of such quasioperative forecasts of tropical cyclone center position as well as minimum pressure and velocity of maximum wind. Estimates of forecasting fields of some meteorological elements in the vicinity of tropical cyclones based on MET (Model Evaluation Tools) software complex developed by (Developmental Testbed Center, 2011) are presented in section 3.2. Section 3.3 describes the problem of analysis of gross errors in hydrodynamic models of WRF family involving the results of control model forecast. V.M. Losev's modified regional model with artificial air flow is taken as a control one.

Conclusion section describes the general decisions taken in course of TC AFS creation, emphasizes a scientific and practical value of the results obtained with respect to problems of tropical cyclone forecasting.

2. DATA AND METHODS

2.1. Principles of operation of the FERHRI's automated forecasting system for tropical cyclone

In this Article, an attempt to develop the basic principles of operation of the FERHRI's automated forecasting system for tropical cyclone was made. For the sake of clarity let's define the term of "process line" as a combination of stages which stage the process of automated preparation to forecast.

The main purpose of process line for forecasting of tropical cyclone location and evolution seems to be in provision of regular receiving of the calculated operative forecasting data about tropical cyclone by a forecaster. So that the principles of operation of the FERHRI's automated forecasting system for tropical cyclone will be typically arise out of the requirements to tropical cyclone forecast.

One of the basic requirements to the tropical cyclone AFS shall be the availability of sufficient computing resources. There are different estimates and approaches. For instance, (Verbitskaya, 2010) provides the figures of response rate not less than 20 teraflops with core memory of at least 10 terabytes. Opinion of specialists from the Hydrometeorological Center of Russia may be considered as more adequate: "…operative forecast restricts the permitted time for the model counting (as a rule, not more than 20 minutes of astronomical time for 24-hour forecast)…." (Tolstykh, Mizyak, 2011).

Similarly with (Tolstykh, Mizyak, 2011), but with some amendments, the first version of scientific-and-operative process line of the TC forecast by AFS as developed by Meteorology and Tropical Cyclone Department of the FERHRI, includes the following program units:

1) subsystem for preparation (downloads) of initial data in GRIB1/GRIB2 code by schedule. It may include both operational data of the Global Forecast System with resolution of 0,5-1 degree and historical NCEP Final Analysis with degree resolution;

2) software system for AHW and HWRF models including pre-processing units "WRF Preprocessing System" and integrated post-processing (WRF Unified Post Processor);

3) facilities for recording of forecast model products on the FERHRI's servers;

4) software for calculation of quality of the forecasts of tropical cyclone position and evolution (minimum pressure, maximum velocity);

5) software for calculation quality of the forecasts of hydrometeorological element fields in the vicinity of a tropical cyclone;

6) creation of forecast maps:
- meteorological element fields near the land and on isobaric surfaces;
- tropical cyclone tracks and characteristics (wind zones for instance);
- vertical cross sections (profiles), etc.

The above-mentioned operations are impossible to be performed failing to execute the second requirement to operation of AFS for tropical cyclones – providing of an automated system operation (with minimum assistance of operator). Actual operation of AFS for tropical cyclones of the first version is carried out through scenarios (scripts) for session control on bash/ksh, if required, on-time downloaded (cron).

In additions, availability of computing resources is not a sufficient condition. It is obvious that creation of AFS for tropical cyclone requires the attraction of the efficiency condition, i.e. application of parallel calculations for calculation acceleration. Complex of WRF family models as created with application of high-level library of parallel calculations - Runtime System Library – fully meets such requirements. Besides, TC AFS system shall provide a relative ease of operation in performance regime and operative and research calculations which would be clear to an end user.

2.2. Configuration of hurricane models

Forecast of position and evolution of tropical cyclone is referred to the category of specialized hydrometeorological forecast (On-Site Testing Guidelines…, 1991). Specific nature of this forecast should take the following problems into account:

1. Peculiarities of preparation of initial data for a forecast (vortex initialization), including configuration of calculation district.

2. Configuration of hurricane models and peculiarities of solving a forecasting problem, both by way of prompt and research modes.

3. Post-processing and presentation of forecast data.

In the AFS-TC the authors propose to use two hurricane modifications of WRF model – AHW and HWRF. Full description of configuration of AHW and HWRF models contains in documentation ETROV(Gopalakrishnan et al., 2011; Skamarock et al., 2010; WRF, 2010). This article will give the basic details.

Vortex initialization used in the first version of AFS-TC is based on bogussing method. Specific features of this approach are: separation of an area with tropical cyclone circulation, transfer of tropical cyclone to the point true coordinates, removal of initial tropical cyclone circulation and introduction of "artificial" tropical cyclone circulation. At that, "artificial" tropic cyclone may not quite match the flow surrounding it (Hsiao Ling-Feng et al., 2010).

Peculiarity of HWRF model configuration is that the model is specially intended for work with tropical cyclone (Gopalakrishnan et al., 2011). This concerns the formation of a calculated region of a certain size, grid size and physical parameterizations.

Calculated area for HWRF model consists of mother grid measuring approximately 80°x80° spacing 0,18° (approximately 22 km) and nested grid measuring approximately 6°x6° spacing 0,06°, which moves after tropical cyclone. The mother grid is positioned relative to the initial tropical cyclone position. During the calculation the simulative tropical cyclone position together with the nested grid is monitored by the maximum of relative vortex. The number of grid nodes along x and y axes is 216 and 432 points. The forecast area is schematically shown in figure 1. The inner rectangle represents the nested grid by example of one case of TALAS tropical cyclone calculation for 00 UTC, September 01, 2011.

Vortex initialization block in HWRF model provides for division of initial analysis field into background flow and tropical cyclone circulation itself (Kurihara et al., 1995). In turn, tropical cyclone circulation is further formed of two components: symmetric and asymmetric. The asymmetric part of tropical cyclone circulation is determined based on temporal dynamics of tropical cyclone field.

The principle set of parameterizations for HWRF model is as follows (Gopalakrishnan et al., 2011):

1) Parameterization of underlying surface: single-layer scheme "GFDL SLAB" with constant thermal conductivity factor;

2) Parameterization of the surface layer: a Monin-Obukhov scheme including Zilitinkevich roughness length;

3) Parameterization of the planetary boundary layer: the high resolution GFS PBL scheme with implicit representation of inclusion layer as a part of non-local-K vertical mixing;

4) Deep convection is parameterized based on the mass-flux approach according Arakawa and Schubert;

5) Ferrier scheme for microphysical process parameterization using mixed phase processes.

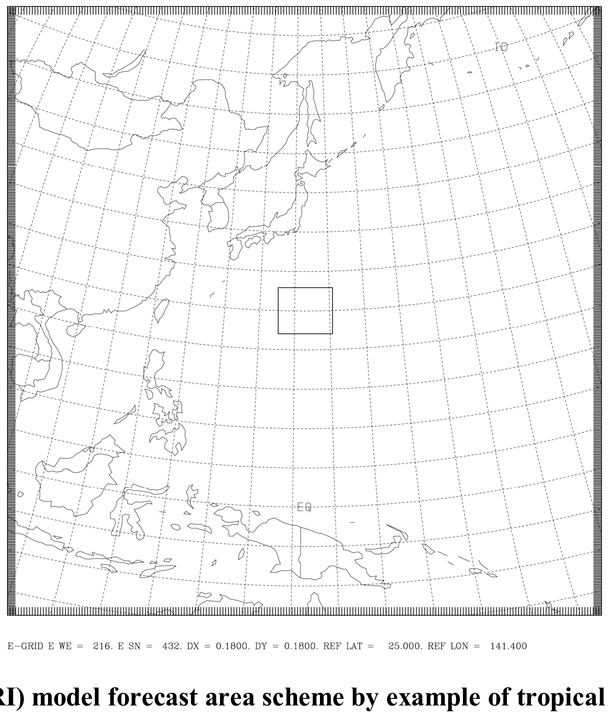

Figure 1. HWRF (FERHRI) model forecast area scheme by example of tropical cyclone TALAS (00 UTC, September 01, 2011)

Advanced Hurricane WRF (AHW) model contains ARW core, but using special parameterizations of turbulent flows of heat and humidity in the boundary layer (Charnock, 1955; Skamarock et al, 2010), as well as using a "reduced" model of quasihomogenious ocean layer. Block of vortex initialization according to NCAR method is included into ARW model data preprocessing system (Skamarock et al, 2010). Te scheme is intended for "cold start" launch. Based on the reversible balance equation solution, the tropical cyclone circulation is formed on replacement of the original vortex within 300 km radius with the "imitation" axisymmetric Rankine vortex according to data of maximum wind with the fixed radius of maximum wind (Davis and Low-Nam, 2001).

As opposed to HWRF, no particular restrictions are applied to the size of computational domain and grid spacing in ARW/AHW model. The set of two nested grids with 45 and 15 km spacing was used in the current AHW model configuration version. The grid spacing is provided to be reduced to 27 and 9 km in the future. In the current variant of grid set the (mother) area for numerical simulation is a rectangle (in Mercator projection) with approximate borders of about 0–45° N., 115–175° E. The number of points for mother and nested grids on axes x, y is 163, 121 and 367, 244 point respectively. The forecast area is schematically represented in figure 2.

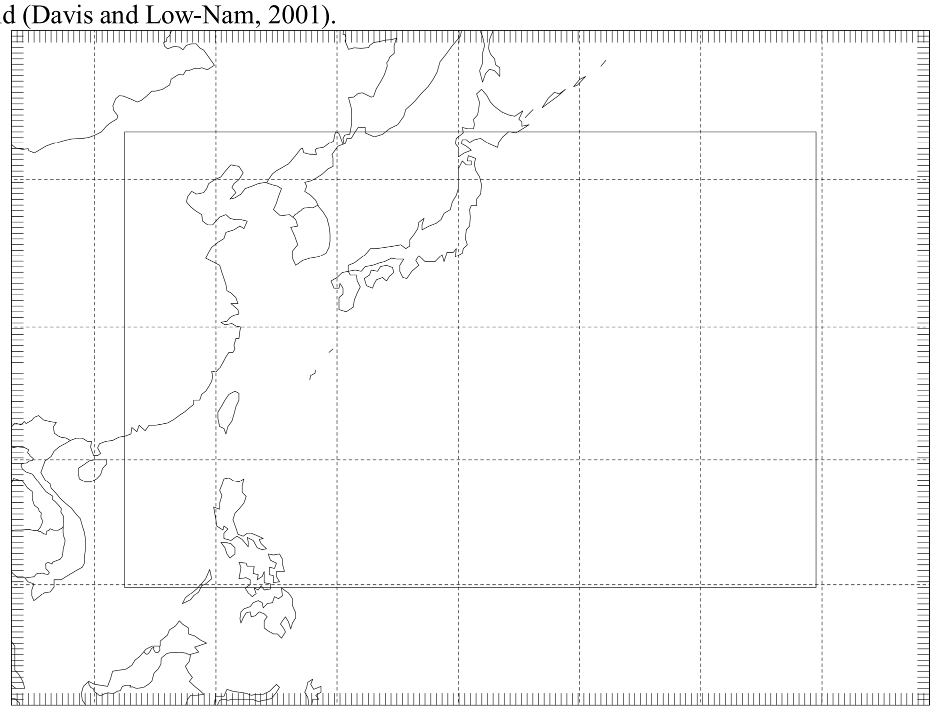

Figure 2. AHW model (FERHRI) forecast area scheme

The main set of parameterizations for AHW model (FERHRI) is as follows (Charnock, 1955):

1) Parameterization of underlying surface: Noah scheme. This is a coupled four-layer NCEP/NCAR/AFWA scheme with temperature, soil moisture, fragment snow cover, and frozen soil physics;

2) Parameterization of the surface layer: a Monin-Obukhov scheme including Zilitinkevich roughness length;

3) Parameterization of the planetary boundary layer: the high resolution Mellor-Yamada-Janjic scheme for the planetary boundary layer of the atmosphere. Otherwise it is called ETA scheme using local vertical mixing in the boundary layer;

4) The Betts-Miller-Janjic convective scheme (ETA scheme): scheme with adjustment of initial temperature and humidity profiles for a certain relaxation time to some reference profiles, which characterize the averaged state of the atmosphere after implementation of deep convection;

5) Reisner scheme for parameterization of microphysical processes (Reisner-I).

In case of numerical integration HWRF and AHW models apply newly defined boundary conditions, that is all variables are defined in all points of the side boundary. The time interval is 54 seconds. Flows of short-wave and long-wave radiation in experiments is calculated every 30 minutes.

All calculations uses actual of the ocean surface in the previous 24 hours according to GFS data. Calculated data is saved to Linux file system every 3 hours. For preparation of oreography and underlying surface properties information global data sets are used – sets with 10-minute resolution (about 19 km). This data is transferred to the calculated model grid.

To interpolate the calculated data from vertical model levels to standard isobaric surfaces WRF Post-

Processor system developed in NCEP is used, which is intended to bring the WRF output data to the format suitable for use in meteorological services (Gopalakrishnan et al, 2011; Skamarock et al, 2010; WRF, 2010).

For calculation of tropical cyclone coordinates on the basis of model forecast data, GFDL Vortex Tracker program module is used in AFS-FERHRI (Gopalakrishnan et al, 2011). The result of the module work is the text ATCF-telegram, which serves as a source for generation of the forecast map of tropical cyclone track.

For visualization of calculated forecast fields of meteorological values, tropical cyclone tracks and their analysis GrADS graphic package is used.

3. RESULTS AND DISCUSSION

3.1. Results of quasi-operational tests of HWRF and AHW models

It is known that different resolution data may be used as initial and boundary conditions for WRF model. For example, historical (NCEP Final Analysis) with grid spacing 1°x1°, and operational with grid spacing 1°x1° or 0,5°x0,5°. In our case, when conducting quasi-operational tests, numerical forecasts were made on the basis of cold start principle twice a day for the time periods of 00 and 12 hours UTC according to GFS global model forecast data with resolution 1°x1° and lead time up to 72 hours. Besides, for the subsequent assessment of model performance results persistence position and evolution (first type) forecasts were calculated based on linear extrapolation in time principle (On-Site Testing Guidelines…, 1991) as well as official data of JTWC and JMA meteorological agencies for the period of 2008 - 2010.

Altogether 30 to 40 cases were calculated (depending on lead time) on two Pacific tropical cyclones for the 2011 season (MUIFA and TALAS) starting from the Tropical Storm (TS) stage, and ending with the time period before the transformation to the extratropical cyclone (L). These tropical cyclones were chosen as the most typical for the category of tropical cyclones, which directly or indirectly influence the Russian Far East.

Methods of evaluation of tropical cyclone dislocation and evolution, which is used in quasi-operational tests, is based on (On-Site Testing Guidelines…, 1991).

An absolute error of tropical cyclone position forecast was used as a principal index of tropical cyclone position forecast successfulness, the error being the distance between the actual and the forecast center positions at a forecast time accurate within 10 km.

The result analysis provided that depending on the values of the specified errors, tropical cyclone position forecasts are interpreted in the following categories:

− lead time 24 h, $\Delta r \leq 200$ km in case of good forecast, 201 km≤ $\Delta r \leq 400$ km in case of satisfactory forecast, $\Delta r > 400$ км in case of bad forecast;

− lead time 48 h, $\Delta r \leq 350$ km in case of good forecast, 350 km≤ $\Delta r \leq 550$ km in case of satisfactory forecast, $\Delta r > 550$ km in case of bad forecast;

− lead time 72 h, $\Delta r \leq 500$ km in case of good forecast, 501 km≤ $\Delta r \leq 700$ km in case of satisfactory forecast, $\Delta r > 700$ km in case of bad forecast.

Figure 3 shows comparative evaluations of forecasts of tropical cyclone location, minimum pressure and maximum wind speed calculated by models of AHW and HWRF (FERHRI) with up to 72-hour lead time, official evaluations from Regional Specialized Meteorological Center of World Weather Center Tokyo typhoon (RJTD) and from US Joint Typhoon Warning Center (JTWC) as well as persistence forecast evaluation.

Thus, mean forecast position error by HWRF (WRF-NMM) and AHW (WRF-ARW) models for the period of 24 hrs (40 events), 48 hrs (34 events), 72 hrs (30 events) was 94, 214, 357 km and 123, 243, 362 km, respectively (figure 3). According to (On-Site Testing Guidelines…, 1991), the quality of tropical cyclone position forecasts by AHW and HWRF models (FERHRI) may be considered good at official agencies level.

In addition, based on involvement of one-tailed Student's t-test according to the approach set forth in (Goerss and Jeffries, 1994), which takes into account statistical connectedness of lines of errors, successfulness of forecasts calculated by WRF models in relation to persistent forecasts of tropical cyclone position (type 1 forecast) was assessed. The calculations showed important (at 95% level) advantage of model forecast over persistent one. Errors of the later made up 184, 385, 460 km for 24, 48 and 72 hrs, respectively. This gives ground to assert that mean absolute error of tropical cyclone position forecast for both models is at the level of official methods specializing in tropical cyclone forecasts of JTWC and JMA meteorological agencies or the period 2008−2010 – 117, 226, 368 km and 131, 202, 297 km, respectively.

Minimum pressure and maximum wind forecast situation was a little worse, assessments thereof are shown in figures 4 and 5, respectively.

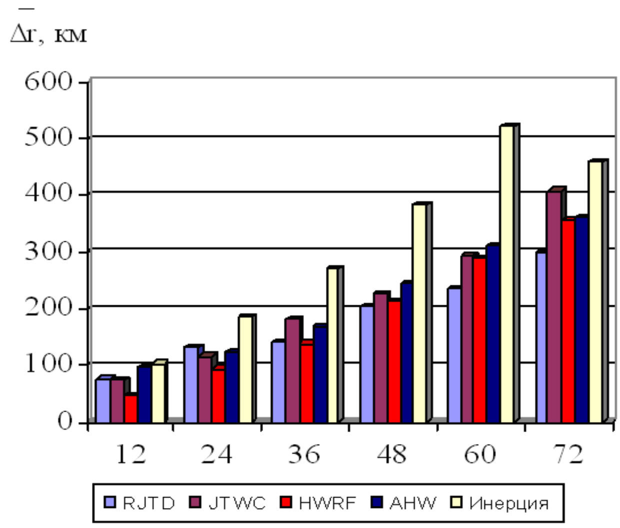

Figure 3. The mean absolute typhoon position forecast error ($\Delta \bar{r}$, км) for the various forecast lead times by RJTD and JTWC official Agencies, HWRF, AHW models (FERHRI) and persistent model

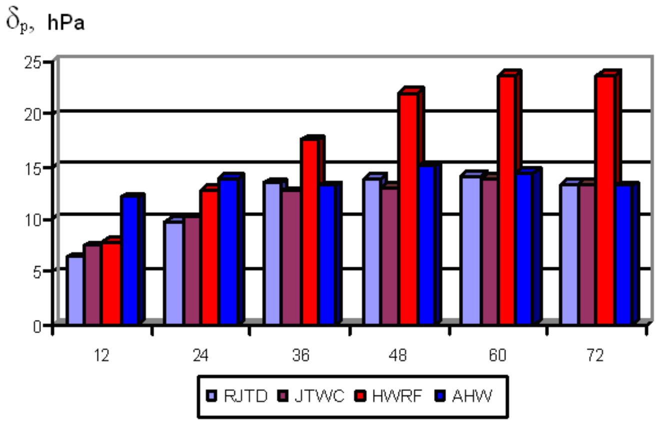

Figure 4. Mean absolute minimum pressure forecast errors (δp, hPa) for the various forecast lead times by RJTD, JTWC (2006-2010), HWRF and AHW models (FERHRI)

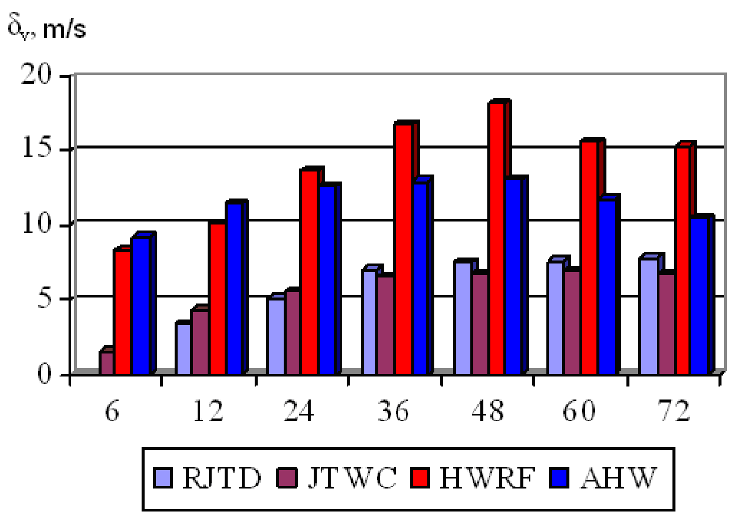

Figure 5. Mean absolute maximum wind forecast errors (δ v, m / s) for the various forecast lead times by RJTD, JTWC, HWRF and AHW models (FERHRI)

Thus, comparative assessments of WRF minimum pressure forecast error (figure 4) showed that mean absolute pressure error for AHW model made up 13,8, 15,1, 13,2 hPa against HWRF model – 12,7, 22,0, 23,7 hPa. In addition, regular (arithmetical mean) error of AHW and HWRF models for 24, 48, 72 hours made up 9,7, 6,7, 2,6 hPa and − 1,9, -9,9, -17,1 hPa, respectively. Compared to HWRF, AHW model showed better results, at the level of official forecasts by JTWC (10,2, 13,1, 13,3 hPa) and JMA (9,7, 13,9, 13,3 hPa). Thus, we ascertained an understatement of minimum pressure by HWRF model. On the contrary, AHW model overstated the pressure, at the average by 3−7 hPa.

In the experiments of A.E. Pokhil et al. carried out in Hydrometeorological Center of Russia somewhat other results were obtained (A.E., Glebova E.S., Smirnov A.V., 2011). Minimum pressure forecasts in the center of tropical cyclone by numerical models of ETA and NMM in single-grid configuration detected that both models, on the contrary, significantly overstate atmospheric pressure, at the average by 30−40 hPa.

In this situation we can only suppose the existence of a certain dependence of forecasted minimal pressure value in the center of tropical cyclone on calculated area configuration. Comparative assessments of maximum wind forecast error showed (figure 5) that two WRF models give approximately equal assessments, which is expressed in systematic understatement of the speed of settled maximum wind approximately by 10−11 m/s for all lead times.

Though mean absolute maximum wind forecast error by WRF models is less than persistent forecast error, it is approximately 2−3-fold greater compared to the errors of official forecast of JTWC and JMA. However, one should remember that the official forecasts of JTWC and JMA are formed based on consensus forecasts methods and only for tropical zone up to 30° N., which reduces the expected forecast error even more.

Figures 6a and 6b show errors in typhoon displacement direction forecast by AHW and HWRF models (FERHRI) depending on lead time (up to 72 hours).

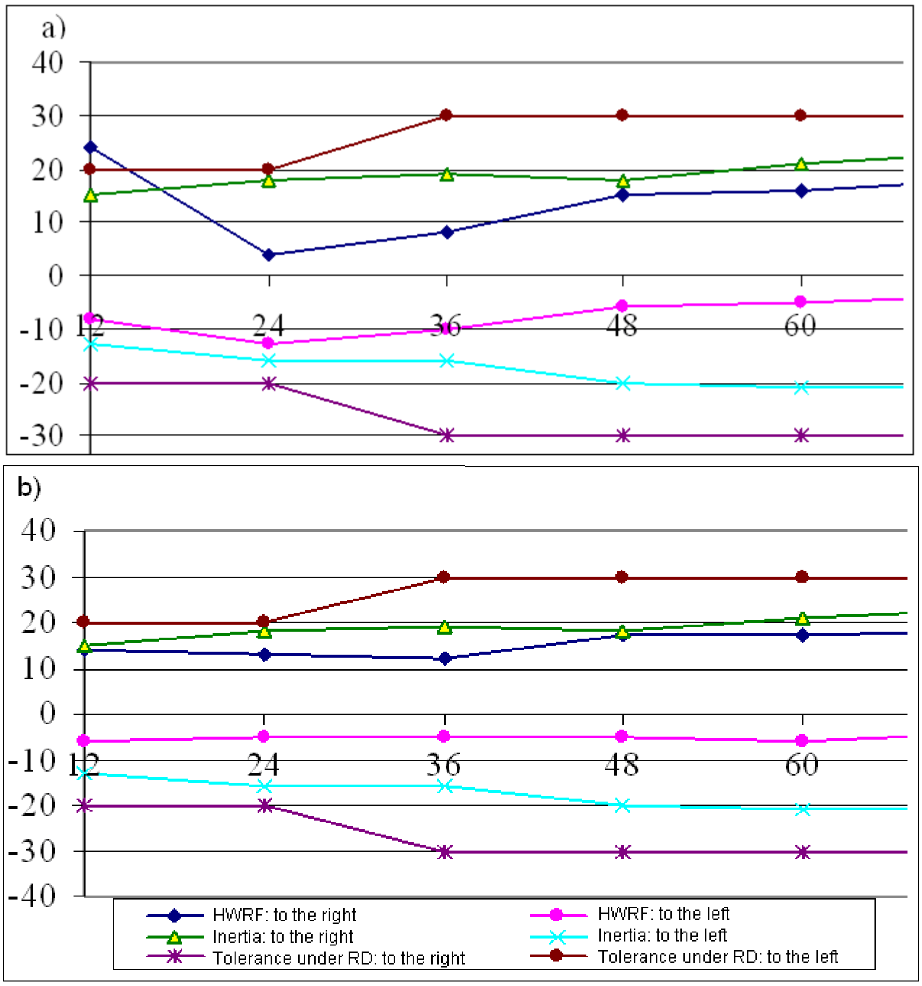

Figure 6. Errors in typhoon displacement direction forecast (Δφ,°) for various lead times by AHW and HWRF models (FERHRI) in comparison with persistent forecast and level of tolerance of good forecast (On-Site Testing Guidelines…, 1991)

In addition, for comparison, here and hereinafter, figure 7 indicates persistent forecast errors and levels of tolerance of good forecast, according to (On-Site Testing Guidelines…, 1991). Analysis of mean absolute error of tropical cyclone displacement direction by AHW and HWRF models showed that the forecast quality may be recognized as good (figures 6a and 6b). However, the above does not mean there are no gross errors of models for the period of over 24 hours. More detailed analysis of probable reasons for that will be given in section 3.3.

Figure 7 shows assessment of tropical cyclone displacement speed forecast (in km for a relevant forecast period) by AHW and HWRF models (FERHRI) depending on lead times (up to 72 hours). In spite of the fact that displacement speed error by both models is within the level of tolerance of good forecast, it can be noted that the quality of displacement speed forecast by HWRF model is better than that by AHW model by approximately 40%.

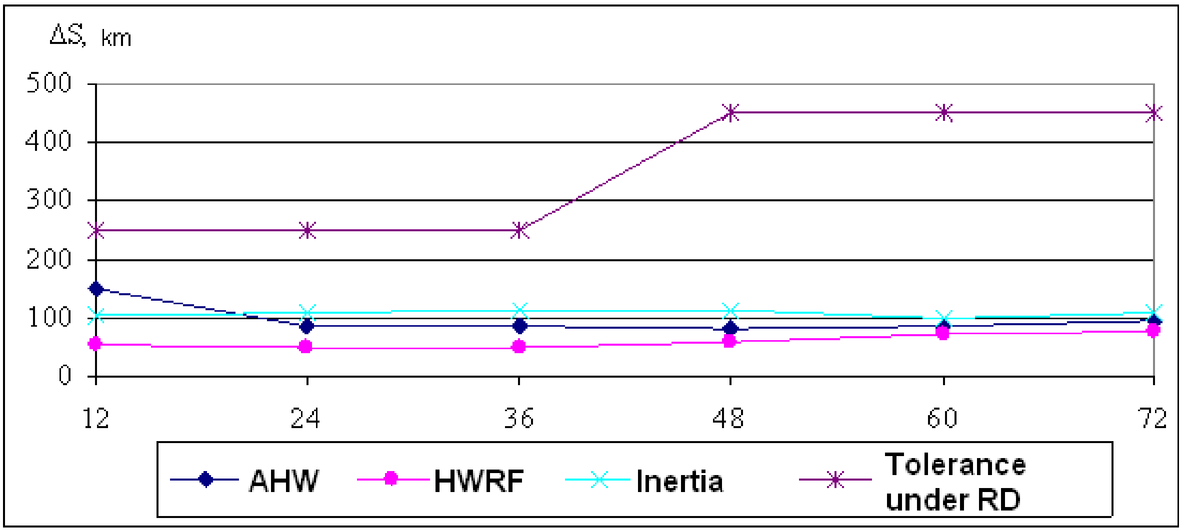

Figure 7. Typhoon displacement speed forecast errors (ΔS, km) for the various forecast lead times by AHW and HWRF models (FERHRI) in comparison with persistent forecast and level of tolerance of good forecast (On-Site Testing Guidelines…, 1991)

In general, it should be add that the greatest error values with regard to position and evolution of tropical cyclone are marked:

- at initial tropical cyclone stages when its center is not expressed good enough (Pokhil et al., 2011);

- during the first 24 hours of numerical integration due to the phenomena, so-called spin-up model, which arises out of the "shock" given rise to by introduction of the Rankine vortex to the forecast area (Leslie and Holland, 1995);

- by the end of the third 24-hour period of numerical integration due to accumulated numerical errors.

The best forecast quality is achieved for the period of 24-48 hours of numerical integration.

3.2. Assessments of forecasts of some meteorological element fields near tropical cyclone based on MET software system

Assessment of tropical cyclone position and evolution forecasts are not the only characteristics of the quality of performance of hurricane models adapted at FERHRI Meteorology and Tropical Cyclone Department. This section considers the attempt to evaluate the ability of AHW and HWRF models to forecast fields of basic meteorological elements, by example of surface height and air temperature at the level of 1000 hPa.

MET (Model Evaluation Tools) software system was developed by NOAA (USA) for making calculations on evaluation of quality of meteorological element numerical forecasts. The latest release of MET v3.1. version was issued in February 2012. To learn more of MET visit the manufacturer's site [http://www.dtcenter.org/met/users/index.php].

To assess the meteorological element field forecast quality in the specified grid area GRID_STAT module is used. FERHRI Meteorology and Tropical Cyclone Department carried out its adaptation and setting of AHW and HWRF hurricane models (FERHRI) to output data. MET output data – ASCII files – contain different forecast quality assessments by all specified lead times in the form of specifically structured tables. More detailed description of the assessment software system is given in documentation of FERHRI Meteorology and Tropical Cyclone Department.

Assessment calculation area was limited by 0–45° N., 110–150° E. Grid spacing equaled 0,25°x0,25°. Data of AHW and HWRF numerical models (FERHRI) as well as source data of GFS model, which serve as initial and boundary conditions for WRF forecast, were used in the calculation of assessments.

Figures 8 and 9 show time variation (depending on forecast lead time from 0 to 72 hours) of mean absolute error value (MAE) of geopotential and temperature field forecast at the levels of 1000 and 500 hPa. Forecast assessments were carried out according to On-Site Testing Guidelines… (1991). The data is averaged for all cases.

Diagram analysis shows similar (simultaneous) MAE variation for HWRF and GFS model forecast – gradual increase of MAE with the lapse of time caused by defect of computing circuit, approximation errors etc.

MAE time variation for AHW model should be mentioned particularly. As at the stage of vortex initialization tropical cyclone center pressure is overstated in the model (see previous section), the model requires about 24 hours to adapt the Rankine vortex to the surrounding tropical cyclone largescale thermobaric field.

Summarizing the section we should add that adoption of data by both models (HWRF and AHW) is somewhat worse at the lower levels. This is especially noticeable during the first 24 hours, at the average in 12–24 hours after introduction of the artificial tropical cyclone. As the introduction of the artificial tropical cyclone takes place in the lower troposphere, absolute errors of geopotential height on the isobaric surface of 1000 hPa for the first 24 hours are the most various and make up approximately 26–12 gpm, 5–12 gpm for AHW and HWRF respectively (figure 8a).

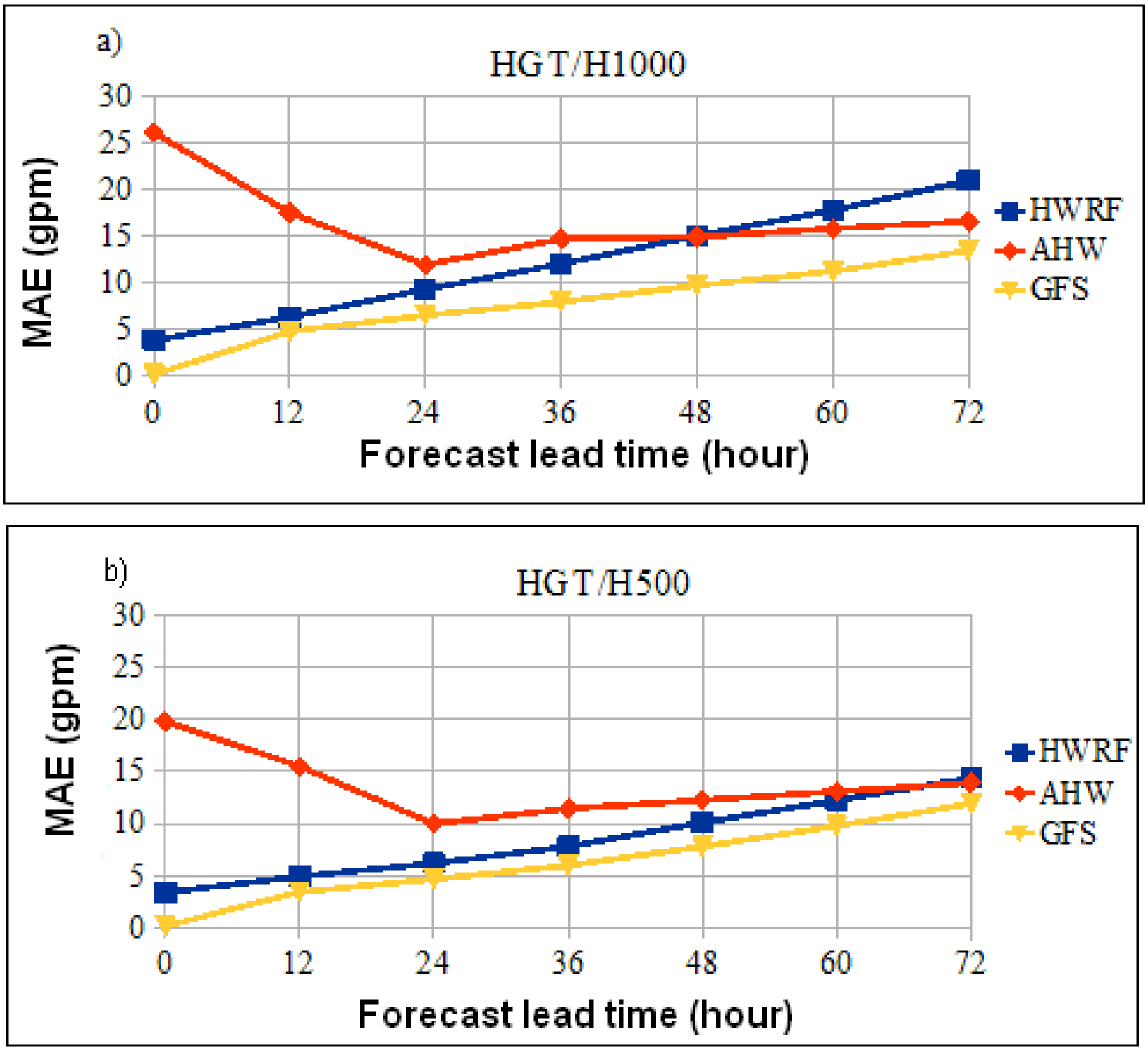

Figure 8. Mean absolute error of 1000 hPa (a) and 500 hPa (b) isobaric surface geopotential height field of in the vicinity of the tropical cyclone

By temperature absolute errors on the isobaric surface of 1000 hPa change within 0,4–1,1° for AHW and 0,4–0,6° for HWRF (figure 9a). Though originally HWRF model adopts data of artificial tropical cyclone better than AHW model, subsequent two days show slight degradation of values of mean absolute error of H1000 and H500 surface temperature field of HWRF models relative to values of mean absolute error of GFS model.

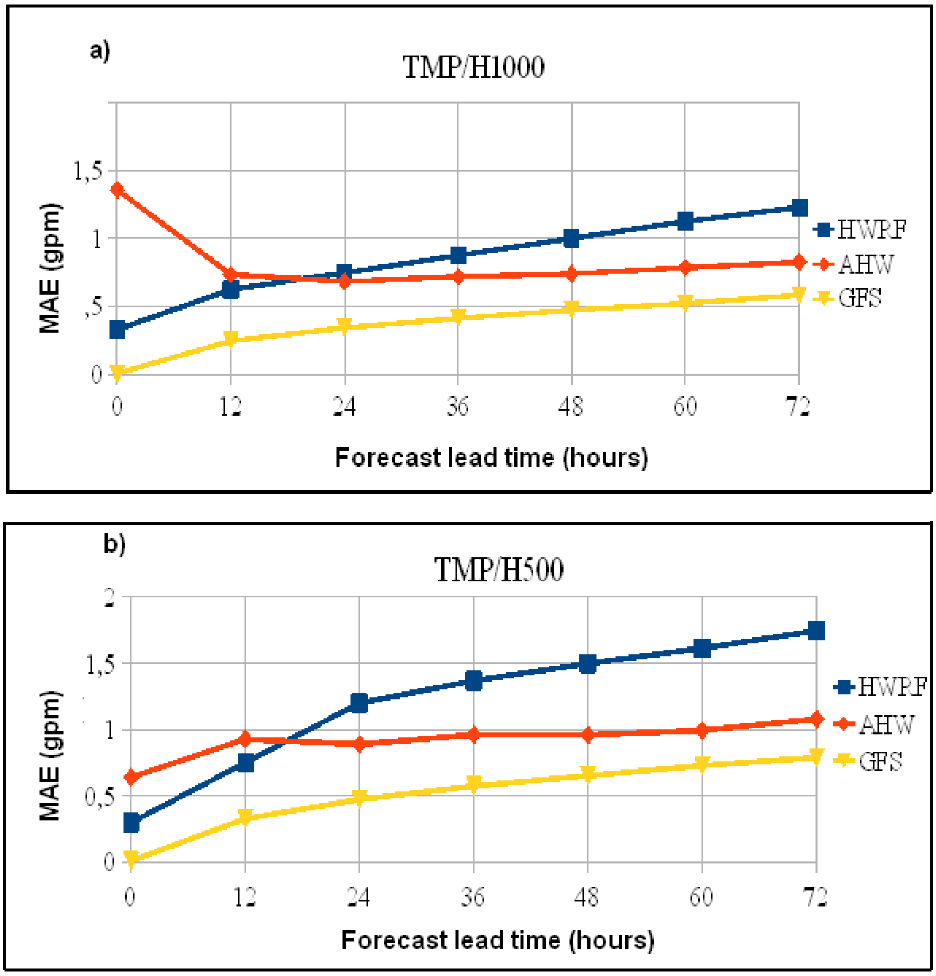

Figure 9. Mean absolute error of the temperature field at 1000 hPa (a) and 500 hPa (b) pressure surfaces in the vicinity of the tropical cyclone.

Difference between the fields of geopotential of HWRF and GFS models is reduced in proportion to the height increase. In case of 72-hour forecast, mean absolute error figures at 1000 and 500 hPa are 8 and 3 gpm correspondingly.

3.3. Analysis of regular errors of WRF family hydrodynamic models with attraction of the results of a control model forecast

Despite that both models in general showed the results which may be considered as good (position forecast) and satisfactory (evolution forecast) according to the On-Site Testing Guidelines… (1991), in some cases the regular errors in tropical cyclone track forecast took place. This may be shown by an example of MUIFA tropical cyclone forecast by AHW and HWRF models (FERHRI) dated August 05, 2011 at 12 UTC. Forecast date is referred to the case when tropical cyclone has not passed a turning point and still moves along the straight line.

On August 05 at 12 UTC, MUIFA tropical cyclone was in area of 26,1°N, 127,8°E and moved northwestward with a speed of 5 knots. Minimum pressure in MUIFA tropical cyclone was 950 hPa, maximum wind was 80 knots. Figures 10 and 11 show the fields of surface pressure and pressure surface heights of 500 hPa.

The tropical cyclone moved along south-east peripherals of subtropical anticyclone extension that is clearly shown in the field of lower troposphere geopotential. About 30 degrees from MUIFA tropical cyclone eastward there was the other tropical cyclone – TS MERBOK that also slowly moved to the northwest along the straight line of track.

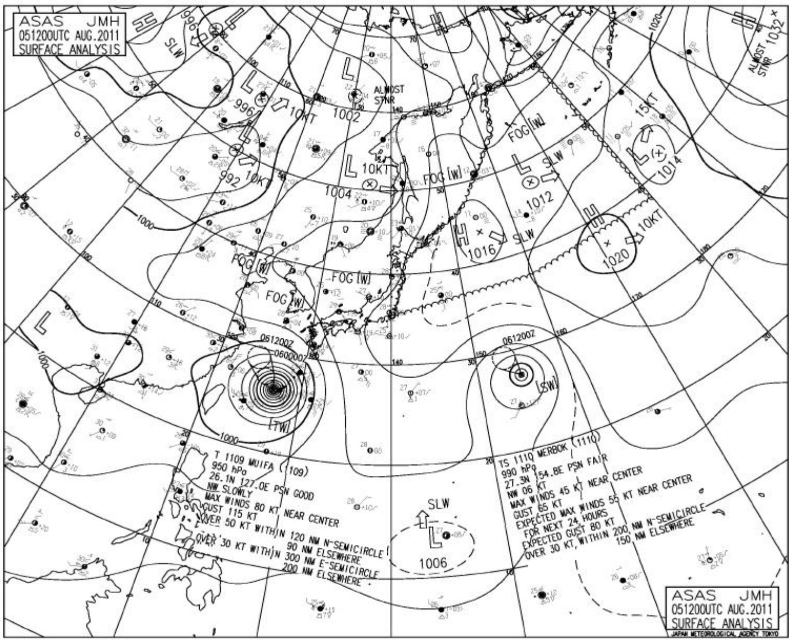

Figure 10. JMA surface analysis chart at 12 UTC on August, 05, 2011

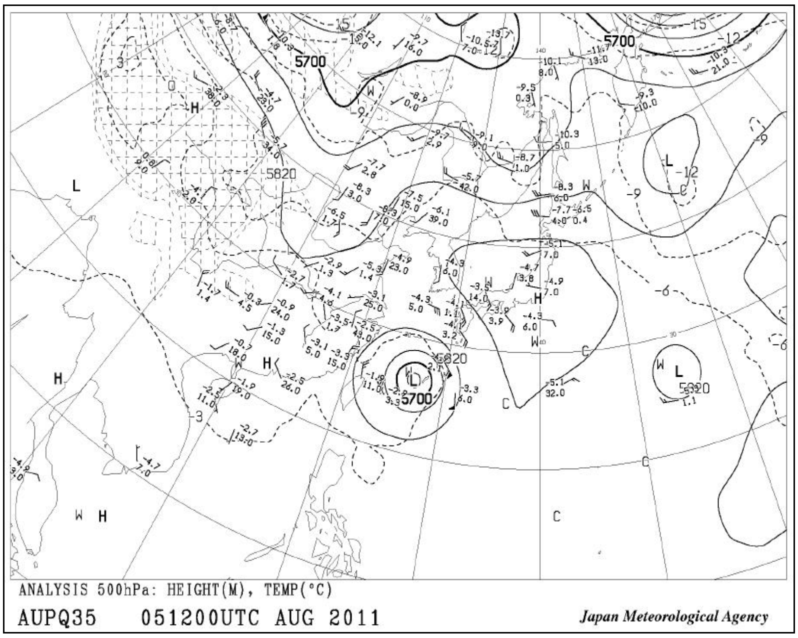

Figure 11. JMA constant pressure map for 500 hPa at 12 UTC on August 05, 2011

In the mid and upper troposphere, in place of the anticyclone extension, on JMA charts there was an isolated anticyclone the center of which was situated above Tokyo. A trough with line of 110°E was located above the northeast China (Figure 11).

Moving along the anticyclone extension, on August 07 at 00 UTC, MUIFA tropical cyclone reached the southwest trough currents, in the result of which its circulation in mid and upper troposphere combined with circulation of the southern part of the trough. It resulted in the formation of cutoff high-level double-center cyclone that has existed for 12 hours. Then, when a high pressure bridge was destructed the cutoff cyclone became a two-line trough. Eastern line of the trough corresponded to MUIFA tropical cyclone, and western line corresponded to the western high-level On August 08, STS MUIFA (1109) moved to the north-eastern China. By 12 UTC, it was transformed into a tropical storm and after 12 hours – into a tropical depression. Cloud mass of MUIFA tropical cyclone covered the significant part of the southern Far East: northeastern provinces of China, Primorye, southern Khabarovsk region and Amur region. By

August 09, the tropical cyclone changed its moving direction to the northeast and in the night on August 10 it was in the south of Khabarovsk region. On August 11, it moved to Sakhalin Island and then moved to the Sea of Okhotsk. Transformation of MUIFA tropical cyclone into an extratropical cyclone was completed on August 09 at 12 UTC within 47,3°N, 129,9°E.

Distinction of forecasts of the most models (and meteorological centers) for approximate period from August 04 to 06 was a regular deviation of forecast tracks westward from the actual track of MUIFA tropical cyclone. In warning message dated August 04 at 18 UTC, JTWC's forecasters noted that in each new calculation the model forecast tracks of the tropical cyclone diverge eastward with respect to the previous forecasts, i.e. the forecast tracks over the course of time turned to the actual track of the tropical cyclone. So that, the JTWC-forecasted tracks which from 18 UTC August 03 moved tangentially to Chinese shore and then to Beijing also diverged with each new forecast eastward until on August 07 at 18 UTC they began to direct the tropical cyclone exactly to the north – to the West Korea Bay.

Figure 12 presents the forecast track of MUIFA tropical cyclone dated August at 12 UTC according to JTWC's data. The forecast tracks of MUIFA tropical cyclone dated August 05 at 12 UTC, as calculated by JTWC and KMA, crossed Shandong and Liadong peninsulas and then to Manchuria and turning of MUIFA tropical cyclone to the reverse line of its track must have been happened exactly in three days above Liaodong Peninsula (i.e. on August 08 at 12 UTC). In fact, MUIFA tropical cyclone in the next three days moved eastward of the forecast track and crossed the West Korea Bay in the area of 124°E.

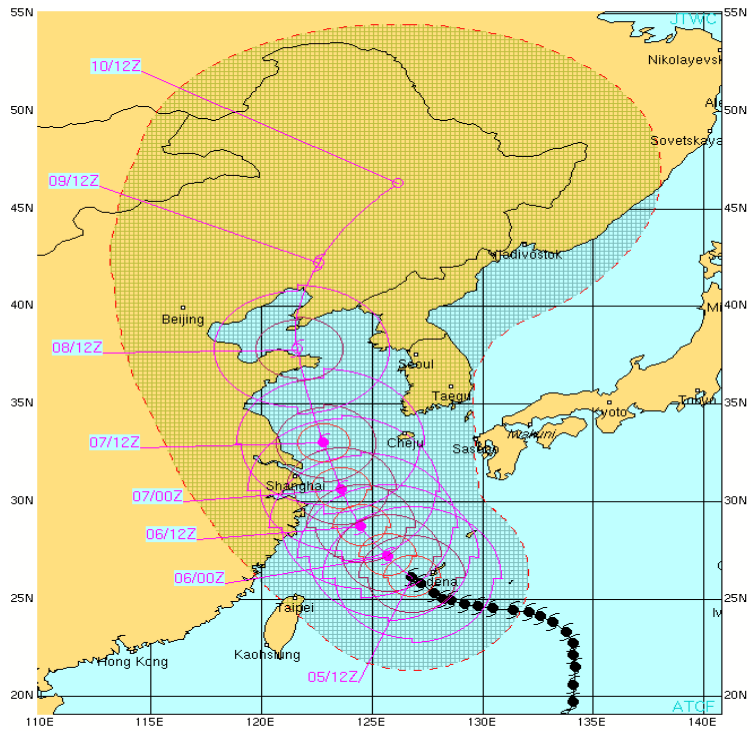

Figure 12. Forecast track of MUIFA tropical cyclone as of 12 UTC on August 05 (JTWC)

Figures 13a and 13b show the forecast tracks of MUIFA tropical cyclone by AHW and HWRF models (FERHRI) at 12 UTC on August 05, 2011, for three days (72 hours). It is obvious that the forecast track of MUIFA tropical cyclone according to the both models turned eastward, meanwhile in fact MUIFA tropical cyclone in the next three days passed the East China Sea and Yellow Sea, i.e. its track had a significant north component.

To clarify possible reasons of such deviations in the forecast track eastward, a numerical control experiment with a regional hydrodynamic model (RHM) of the Russian Hydrometeorological (author − V.M. Losev) as adapted for forecast purposes with respect to the tropical cyclone was performed at the FERHRI Meteorology and Tropical Cyclone Department. More detailed description of the model is presented in the records of the Meteorology and Tropical Cyclone Department and in (Report of Research, 2010).

The sense of the experiment was in the fact that intensity of the tropical cyclone is connected with its forecast track, so, if amending the parameters connected with the tropical cyclone intensity, it is possible to assess their influence on the tropical cyclone track, and secondly, use the same for making the appropriate corrections to the forecast track in order to reduce errors in forecasting.

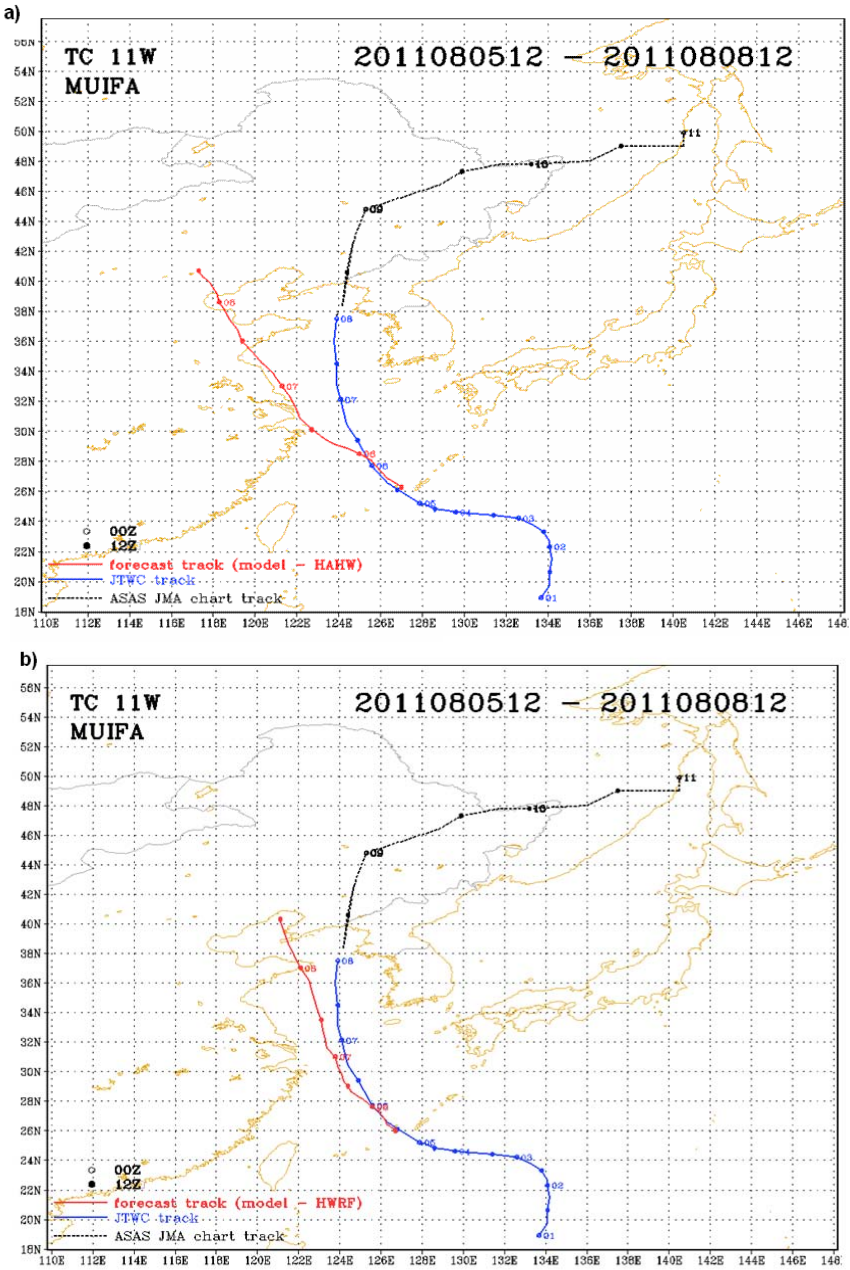

Figure 13. Example of MUIFA tropical cyclone track forecast by AHW (a) and HWRW (b) models (FERHRI) as of 12 UTC on August 05, 2011

Among the factors affecting the tropical cyclone intensity, JTWC's forecasters in particular at all times pay attention to 4 factors: vertical wind shear on forecast track of tropical cyclone, air flow intensity in the upper layer of tropical cyclone (flow channel), water temperature and probability of landfall point during the period of forecast lead time. In this case, regular errors in forecast tracks of the tropical cyclone actually could result in a wrong recording of the following two factors – vertical wind shear and (or) record of intensity of air flow from the tropical cyclone.

It is difficult to assess the direct influence of these two factors in intensity and track of the tropical cyclone. So that, an attempt to assess the connection of intensity and track of the tropical cyclone was made by the way of varying a latent heat flow in the sphere of tropical cyclone using V.M. Losev's model. Data of Japanese re-analysis with space resolution of 1,25x1,25 degrees were taken as a benchmark for RHM.

Previously, as (Report of Research, 2010) shows, RHM in general properly describes the advective processes in middle latitudes, movement of extratropical cyclones and precipitation but in order to adapt the sa+me to the tropical cyclone, an artificial latent heat flow is required to be introduced.

So that, a theory similar to the approach by Rosenthal (Rosenthal, 1978) was taken as a basis for experiment: track of a tropical cyclone is mainly formed with advective factors plus influence of intensive moist convection (keeping or enforcing of tropical cyclone intensity by generation of condensation heat). In the result, a clear method of the introduction of artificial latent heat to the RHM was chosen – introduction of artificial moist sources to moist equations. Numerical experiments are presented in Figure 14.

Forecast track of tropical cyclone is highlighted in red, and actual track – in blue.

In the absence of vapor flow, the track of MUIFA tropical cyclone resembles the forecast tracks from AHW and HWRF models very much (especially AHW). However, when introducing a vapor flow to the RHM which is close to the deadline, the forecast track from the RHM approaches to the actual track with a reasonable degree of accuracy.

The result of numerical experiment shows that in this "by default" configuration AHW and HWRF models describe track and evolution of a tropical cyclone adequately not at all times. To be fair, we should note that the track of MUIFA tropical cyclone as estimated by GFS's forecasts dated August 05, 2011 at 12 UTC, also provides an error in displacement, but a little bit less than HWRF model error.

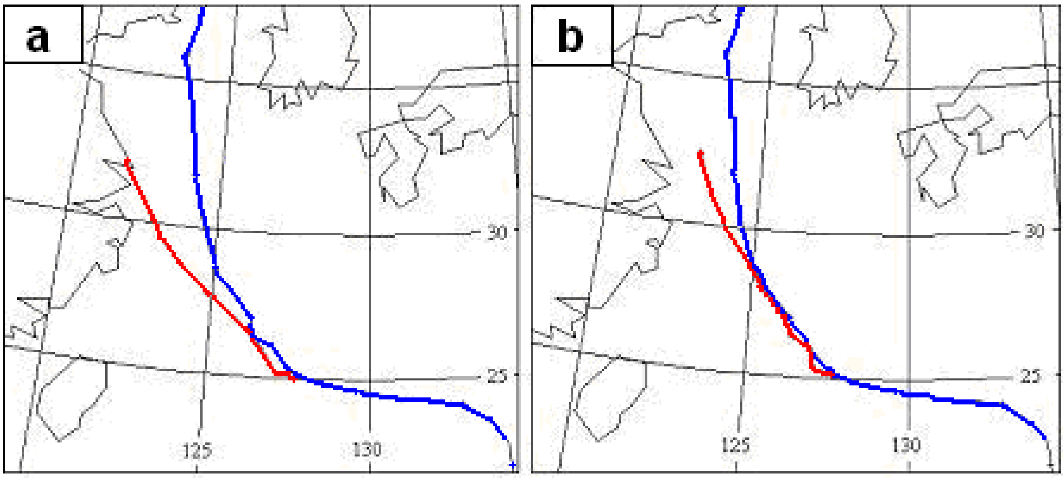

Figure 14. Comparison of forecasts by regional hydrodynamic model without vapor flow (a) and with introduction of artificial vapor flow from the ocean (b) by the example of MUIFA tropical cyclone as of 12 UTC on August 05, 2011

Therefore, it may be assumed that there is an opportunity to adjust finely the convection blocks and process parameterization in a boundary layer that would enable to increase the quality of forecasts for position and evolution of tropical cyclones by WRF family models.

Visual analysis of general meteorological situation shows that variation of parameters influencing the intensity of tropical cyclone, may result in improvement of not forecast of tropical cyclone position only but improvement of forecast of the whole field (meteorological position) as well, except for vicinity of tropical cyclone where "overdeeping" of geopotential fields is happened.

The authors recognize that, along with the simultaneous improvement of forecasts for tropical cyclone position, this approach deteriorates the forecasts of its intensity (tropical cyclone becomes deeper), therefore it shall be applied only for the purpose of improving in forecasting the position of any tropical cyclone but not for its evolution.

4. CONCLUSION

On the basis of review of domestic and foreign papers, some demands to performance of the FERHRI automated forecasting system for tropical cyclone are made:

- availability of sufficient computational resource;

- automation of system operation (with minimum assistance of operator);

- efficiency including application of parallel evolution for calculation acceleration;

- availability of a stable and high-speed communication channel (Internet);

- competitive serviceability for on-line operation and performance of operative and research calculations which would be clear for an end user (forecaster or researcher).

Results of quasioperational testing of AHW and HWRF storm models showed the following:

1. It was obtained that both approaches -movable (HWRF) and immovable (AHW) (nested grids) – provide practically equal forecast error in the position of a tropical cyclone for period up to 72 hours. This conclusion is agreed with the results by (Fiorino and Harrison, 1982).

2. Errors in forecast of position, speed and direction of tropical cyclone movement is less than the same of HWRF model and that proves its robustness, i.e. its capability to provide the best results of calculations (outputs), in comparison with AHW models.

3. It may be assumed that configuration of a sole mother grid with space interval of about 45–22 km in the area of tropical cyclone is significantly insufficient for a good forecast of tropical cyclone evolution, and application of nested grid of not more than 9-15 km may be recommended.

4. Due to high pressure of tropical cyclone in the initial period, tropical cyclone initialization block in AHW model requires additional researches for the Far Eastern region.

5. Experiments involving V.M. Losev's control model show a possibility of further adjustment of convection blocks and boundary layer for operation with a tropical cyclone.

6. The examples of two tropical cyclone of 2011 confirms an essential capability of AHW and HWRF models to reproduce the position/time properties of a tropical cyclone at various stages of development at the level of official forecasts.

Accuracy of estimates is supported by the usage of two models with different approaches to implementation of a dynamic core and methods of grid creation (AHW – EM dynamic core applies C class grid by Arakawa, nested grid is immovable; HWRF –NMM dynamic core applies E class grid by Arakawa, nested grid moves following the tropical cyclone). Obviously, these results are of indicative nature, however, the performed preliminary assessment of estimate dispersion with respect to methodical WRF-forecast of tropical cyclone position and evolution (errors in position, minimum pressure and maximum wind) evidences a significant privilege over persistence forecast.

Therefore, the main result of this paper is in conclusion of perspectiveness in application of WRF family models for the forecast of movement and evolution of tropical cyclone in the Russian Far East.

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