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Applications of Mesoscale Atmospheric Models in Short-Range Weather Predictions During Satellite Launch Campaigns in India

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1. Introduction

Knowledge of meteorology forms the basis of scientific weather forecasting, which evolves around predicting the state of the atmosphere for a given location. Weather forecasting as practiced by humans is an example of having to make judgments in the presence of uncertainty. Weather forecasts are often made by collecting quantitative data about the current state of the atmosphere and using scientific understanding of atmospheric processes to project how the atmosphere will evolve in future. Over the last few years the necessity of increasing our knowledge about the cognitive process in weather forecasting has been recognized. For its human practitioners, forecasting the weather becomes a task for which the details can be uniquely personal, although most human forecasters use approaches based on the science of meteorology in common to deal with the challenges of the task. The chaotic nature of the atmosphere, the massive computational power required to solve the equations that describe the atmosphere, error involved in measuring the initial conditions, and an incomplete understanding of atmospheric processes mean that forecasts become less accurate as the difference in current time and the time for which the forecast is being made (the range of the forecast) increases (Doswell, 2004; Ramachandran et al., 2006; Subrahamanyam et al., 2006; 2008).

In the Indian scenario where most of the agricultural industries depend on summer monsoon rainfall, several atmospheric models are run at different organizations to deliver regular forecasts to common man and media with a special emphasis on prediction of onset of monsoon and expected amount of rainfall. However, operational forecast models run by meteorological departments are not meant for prediction of local weather with the high spatial and temporal resolutions within a specific time window. Depending on the users requirements and event-based management, atmospheric models are tuned for delivering the forecast products. During satellite launch operations, accurate weather predictions and reliable information on the winds, wind-shears and thunderstorm activities over the launch site happens to be of paramount importance in the efficient management of launch time operations (Manobianco et al., 1996; Rakesh et al., 2007; Ramachandran et al., 2006;

Subrahamanyam et al., 2010; 2011). Therefore, additional procedures based on current observations (surface and upper air observations, Radar and satellite) are required to forecast imminent weather events and to warn if necessary. In this scenario, it is highly desired to develop a comprehensive, coordinated, and sustained Earth Observation System for collection and dissemination of improved data, information, and models to stakeholders and decision makers. The present chapter gives a detailed account on the utilization of two mesoscale atmospheric models in conjunction with other observational tools in providing short-range weather predictions for satellite launch campaigns in India.

2. Weather forecasting for decision making

In the present era, weather forecasting heavily relies on computer-based numerical weather prediction (NWP) models that take many atmospheric factors into account (Cox et al., 1998; Pielke, 1984). The evolution of operational NWP from larger to smaller scales partially reflects the increased computer power that has allowed global models to resolve more details of atmospheric flow fields. Using a consensus of forecast models, as well as ensemble members of the various models, can help reduce forecast error. There are a variety of end uses to NWP model-derived forecasts, many of which are directly linked to crucial decision making. Taking meaningful decisions has always been one of the demanding points of the forecasters job. Despite our dependence on NWP models, human input is anticipated to pick the best possible forecast model to base the forecast upon, which involves pattern recognition skills, teleconnections, knowledge of model performances and model biases. Because of the huge amounts of data that forecasters face, analytical decision-making processes are limited by time constrains. Therefore intuitive approaches are virtually mandatory (Doswell, 2004; Klein et al., 2006; Rasmussen et al., 2001; Stuart et al., 2007). Klein et al. 2006 describes the decision-making process of the experienced weather forecaster with a recognition primed decision model, that combines both analysis and intuition.

During satellite launch missions the human decision-making process is put under a lot of pressure and taking the right decision can become very difficult and require a lot of experience. In such situations we can maintain and reinforce the role of the human forecaster if we are able to give the forecaster the opportunity to find ways to continue to gain expertise in a rapidly changing technological environment. This is possible only if we devote more effort, time and research in order to better understand the demanding tasks of weather forecasting and - more important - if we are able to translate our knowledge into best practice. The launch weather guidelines involving the satellite launch vehicles and rockets are similar in many areas, but a distinction is made for the individual characteristics of each. The criteria are broadly conservative and assure avoidance of possibly adverse conditions. In this chapter, we attempt to give a detailed account on the forecasting requirements during satellite launch campaigns and the usage of mesoscale atmospheric models for catering to the needs of the mission team (Subrahamanyam et al., 2010; 2011).

Every satellite launch is related to several multi-disciplinary tasks which are performed in a serial as well as in parallel modes. All the activities in a way or other are related to each other and are linked with the success of the entire mission, thus none of the activities can be ignored at any point of the time. Having quite reliable and credible information on the local weather over the launch site is one of the mandatory requirements, which is gathered through all possible sources. Once the satellite payload is declared ready for its space journey, the mission team used to define a launch window extending over a few days with a specific time-slot for the launch. Definition of such a time-slot and launch window is one of the most crucial tasks and require adequate knowledge on local weather over the launch site in terms of the launch commit criteria (LCC) so as to avoid any hazardous events due to bad weather (Case et al., 2002; Manobianco et al., 1996). Each launch vehicle has a specific tolerance for wind shear, cloud cover, temperature, whereas lightening constraints are common for all types of vehicles. On occasions, the LCC requirements are confined to "go" and "no-go" kind of situations; thus the NWP model-derived forecast products play a very crucial role during each stage of the satellite launch campaigns. Thus, NWP model simulations during launch campaign are ultimately intended to provide short-range (< 48 hours) forecasts of winds, temperature, moisture, clouds and any hazardous weather event such as thunderstorm over the launch site with good accuracy, so as to help the mission team in decision making procedure.

3. Sriharikota: the Indian Satellite launch site

The Indian Satellite launch site is located at the Sriharikota High Altitude Range (also referred to as SHAR, 13.7167°N, 80.2167°E) is a barrier island off the coast of the southern state of Andhra Pradesh in India having a complex terrain with the Eastern Ghats located on its west and surrounded by the Pulicat Lake and Bay of Bengal on the east (Fig. 1). It houses India's only satellite launch centre in the Satish Dhawan Space Centre and is used by the Indian Space Research Organization to launch satellites using multi-stage rockets such as the Polar Satellite Launch Vehicle (PSLV) and the Geosynchronous Satellite Launch Vehicle (GSLV). This island was chosen in 1969 for setting up of a satellite launching station. Features like a good launch azimuth corridor for various missions, advantage of earth's rotation for eastward launchings, nearness to the equator, and large uninhabited area for the safety zone - all make SHAR an ideal spaceport. Presently, the SHAR has infrastructure for launching satellites into low earth orbit, polar orbit and geo-stationary transfer orbit. The launch complexes provide support for vehicle assembly, fuelling, checkout and launch operations. As per climatology of the Indian subcontinent, the ambient meteorological conditions are largely governed by monsoonal winds. The subcontinent experiences wet and rainy season during its summer monsoon (also referred to as south-west monsoon) in the month of June to September when the moist air from oceanic regions intrudes the continent resulting into large precipitation spells wide spread over the season. The month of March to May over the subcontinent is considered as pre-monsoon period when SHAR experiences quite hot and summer environmental conditions with very less rainfall resulting in a magnitude of about 5 to 7.5 cms (Indian Meteorological Department Website: http://www.imd.gov.in/). On the other hand, the period of October to December is considered as post-monsoon season, when SHAR experiences frequent rainfall amounting from 75 to 100 cms, almost an order larger than that observed during the pre-monsoon season. SHAR being one of the coastal stations on the eastern coastline of the Indian subcontinent very well falls in the vicinity of tropical cyclone landfall zone (Das et al., 2011; Rakesh et al., 2007; Singh et al., 2005), and therefore it is obvious that the underlying complex terrain could very well affect the local winds, resulting at times in the developments of hazardous thunderstorms. The depressions that develop over the Bay of Bengal can also affect the short-term weather of SHAR. Thus, the local weather over SHAR is highly dependent on atmospheric wind circulation prevailing over its adjoining Bay of Bengal Oceanic region and topography-induced convective activities.

Keeping the meteorological features over SHAR in background and to meet the forecasting needs for LCC, two numerical atmospheric models, namely High-resolution Regional Model

(a) Location Map of SHAR in the Indian sub-continent;

(b) Zoomed version of map showing the location of SHAR, Pulicat Lake and Bay of Bengal

Fig. 1. (a) Location Map of SHAR in the Indian sub-continent; (b) Zoomed version of map showing the location of SHAR, Pulicat Lake and Bay of Bengal (Courtesy: Google Earth Maps)

(HRM) and Advanced Regional Prediction System (ARPS) model are made operational for providing short-range weather predictions for the launch site (Ramachandran et al., 2006; Subrahamanyam et al., 2010; 2011). On one hand, the HRM simulations provide valuable information on meteorological conditions and mesoscale atmospheric circulation systems such as sea-breeze prevailing over the Indian sub-continent and its adjoining Oceanic counterpart with a special emphasis on formation of any hazardous weather event such as cyclonic storms and its movement (Ramachandran et al., 2006; Rani et al., 2010). On the other hand, ARPS is being run regularly at different time-intervals at very high horizontal and vertical resolution for alerting the mission team on probability of thunderstorm occurrence and rainfall time-slots over the launch site, if any (Subrahamanyam et al., 2010; 2011).

4. An overview of HRM and ARPS models

The basic idea of NWP models is to sample the state of the atmosphere at a given time and use the equations of fluid dynamics and thermodynamics to estimate the state of the atmosphere at some time in the future. In a broad sense, atmospheric models can be classified into two categories: (1) Hydrostatic; and (2) Non-hydrostatic. The first class of models assume hydrostatic equilibrium of atmosphere, while the second class are useful in dealing non-hydrostatic processes and their effects become more useful when the length of the feature is approximately equivalent to its height (Anthes & Warner, 1974; Bannoon, 1995; Pielke, 1984). Thus, non-hydrostatic models can be quite sensitive to small differences in atmospheric structure in vertical. Between the two models used in the present study, HRM assumes hydrostatic approximation, while ARPS is a non-hydrostatic model.

4.1 High-resolution Regional Model (HRM)

HRM is basically a hydrostatic regional model developed for shared memory computers at Deutscher Wetterdienst (DWD) of Germany that serve as one of the flexible tools for NWP for the usage in meso-α and meso-β scales and is widely used by several meteorological services, universities, and research institutes spanning a large domain of the globe (Majewski, 2010). Most of the technical features of HRM resemble with the German global model GME ((Majewski, 2010; Majewski et al., 2002)). The HRM consist of topographic data sets which can be obtained from DWD in regular or rotated latitude/longitude grid for any region of the world at mesh sizes from 30 km and 5 km. Several options exist to derive the initial state of the HRM. In the present study, however, we have used interpolation of the analysis of global model GME (grid spacing 30 km x 30 km, 60 vertical layers since 1 February 2010) to the HRM grid (Majewski et al., 2002). There is less adaptation of HRM to the fine scale topography, and local observations, not distributed on the global telecommunication system, may have a beneficial impact on the initial state of the HRM. As of now, two options are available for lateral boundary conditions of the HRM, namely (a) GME forecasts fields or (b) ECMWF forecast fields. We have made use of GME forecast fields for providing the lateral boundary conditions to the HRM. DWD provides the analyses and forecasts of GME on all 60 model layers and seven soil layers at a horizontal resolution of 30 km four times per day at 3-hourly intervals. These data are distributed by the DWD via the internet between 02:40 to 03:30 UTC for 00 UTC and between 14:40 to 15:30 UTC for 12 UTC.

Since the volume of the global data set (more than 30 GByte) is much too big for a timely transfer, DWD provides to each HRM user GME data sets tailored to the respective local HRM domain. Lateral boundary data may even be given for a frame, i.e. not covering

	High-resolution Regional Model (HRM)	Advanced Regional Prediction System (ARPS)
Dynamics	Hydrostatic	Non-hydrostatic
Usage	Different mesoscale processes	Storm model
Developed by	Deutscher Wetterdienst (DWD),Germany	Centre for Analysis and Prediction of Storms (CAPS) of Oklahoma State University, USA.
Model Domain	65°E to 95°E, 0 to 30°N	(~50 kms x 50 kms) centered around SHAR
Horizontal resolution	0.0625° (~5 kms)	~1 kms
Topography resolution	0.0625° (~5 kms) prepared by DWD	30 seconds (~1 kms), USGS
Vertical levels	60 levels with vertical stretching; Model ceiling is kept at 10 hPa (~31 kms)	35 levels with vertical stretching; Model ceiling is kept at 100 hPa (~16 kms)
Initialization and Lateral Boundary Conditions	Global Model Output for the HRM domain (horizontal resolution at 30 kms)	High-resolution GPS ascent data (maximum permissible levels = 600); symmetric initial perturbations for LBC
Prognostic variables	Surface Pressure,Cloud Ice, Temperature, Water Vapour, Cloud Water, Horizontal Wind (zonal and meridional)	Potential temperature,Horizontal wind (zonal and meridional), Water substance, subgrid scale turbulent kinetic energy
Time integration scheme	split semi implicit with Δ t = 30 seconds	Δ t = 6 seconds
Atmospheric boundary layer parameterization	Level-2 scheme vertical diffusion in the atmosphere, Similarity theory at the surface	Compute the time evolution of boundary layer depth in response to the surface heat fluxes or user specified boundary layer depth.
Turbulent Fluxes	Louis (1979) in the prandtl layer and Mellor and Yamada (1974) for the boundary layer and free atmosphere.	Modified Businger formulation (Businger et al., 1971)
Convective parameterization schemes	Tiedtke (1989)	Kuo (1965, 1974) Kain and Fritsch, (1993)
Soil Model	The Multilayer soil model (Heise and Schrodin, 2002) with seven layers.	Noilhan and Planton (1989) and Pleim and Xiu (1995)

Table 1. Comparison between HRM and ARPS Model (Subrahamanyam et al., 2011)

the full HRM domain but only a frame with a width of about 10 HRM rows and columns. Thus the amount of GME data which has to be transferred via the internet can be reduced drastically. For a typical HRM domain of 4000 x 4000 km^2 the GME data set (initial state plus 26 lateral boundary data sets at 3-hourly intervals) needed for a 78-h HRM forecast is in the order of (1 + 26)*12.6 MByte = 341 MByte for the full version and about 110 MByte for the frame version (Majewski, 2010). This particular option makes the HRM superior to other models, as we need not download the entire global data for generation of initial state and lateral boundary conditions of the regional model. Further technical details on the HRM can be found elsewhere (Majewski, 2010; Subrahamanyam et al., 2010; 2011)

4.2 Advanced Regional Prediction System (ARPS)

Since 1970s, we find mention of development of three-dimensional non-hydrostatic modeling for convection in the literature (Pielke, 1984; Xue et al., 2000). The development of non-hydrostatic models and rapid increase of computer powers have made the explicit prediction of thunderstorm into a reality. Advanced Regional Prediction System (ARPS) is a three dimensional, non-hydrostatic and fully compressible, primitive equation model designed for storm and mesoscale atmospheric simulation and real time prediction by the Center for Advanced Prediction of Storms, University of Oklahoma, USA (Xue et al., 1995). From the beginning of its development, it is serving as an effective tool for basic and applied research and as a system suitable for explicit prediction of convective storms as well as weather systems at other scales.

ARPS uses a generalized terrain following coordinate system with equal spacing in x- and y- directions and grid stretching in the vertical. The prognostic variables are Cartesian wind components, perturbation potential temperature and pressure, sub grid scale turbulent kinetic energy, mixing ratios for water vapour, cloud water, rain water, cloud ice, snow and hail. The ARPS includes its own data ingest, quality control and objective analysis packages, a data assimilation system which includes single-Doppler velocity and thermodynamic retrieval algorithms, the forward prediction component, and a self-contained post-processing, diagnostic and verification package (Xue et al., 2000; 2001; 2003). The model employs advanced numerical techniques, including monotonic advection schemes for scalar transport and variance conserving fourth-order advection for other variables. The model also includes state-of-the-art physics parameterization schemes that are important for explicit prediction of convective storms as well as the prediction of flows at larger scales (Case et al., 2002). The spatial discretization is achieved by second order quadratically conservative and fourth quadratically conservative finite differences for advection and second order differencing for other terms, while temporal discretization is treated with a second order leap-frog scheme for large time steps with Asselin time filter option. Depending on the choice of Users and availability of lateral boundary conditions, ARPS can be configured in one-, two- and three-dimensional modes (Subrahamanyam et al., 2008). This model has a salient feature that the base state of the model variables can be initialized through a single sounding profile and time dependent fields can be opted for self initialization using analytic functions.

One of the basic differences in the HRM and ARPS model simulations is that the initial and lateral boundary conditions of the HRM are derived from the analyses and forecast fields of a global model, whereas the base-state field for ARPS domain are generated through vertical column GPS ascents and potential temperature perturbations are generated through symmetric random option available within the model code (Subrahamanyam et al., 2006; 2010; 2011; 2008; Xue et al., 1995). Table 1 provides a glimpse of major differences between the two models.

5. Launch Commit Criteria (LCC) related requirements

The launch weather guidelines involving the satellite launch activities for different launch vehicles and rockets are similar in many areas, but a distinction is maintained for the individual characteristics of each. These guidelines include weather trends and their possible effects on launch day. More importantly, these guidelines, often referred to as *Launch Commit Criteria* are broadly conservative and assure avoidance of possible adverse conditions. The

LCC for a particular satellite launch activities essentially define the permissible limits of meteorological conditions prevailing over the site, and are reviewed for each individual launches.

5.1 Surface-layer meteorological conditions

During the assembly of the launch vehicle and its movement to the launch pad, surface-layer meteorological conditions are periodically reviewed. Magnitudes of horizontal wind speed measured through multi-level instruments mounted on a 100-m meteorological tower exceeding 20 m/s are not favourable. Similarly, a careful examination of wind gusts is also done during the movement of the vehicle.

5.2 Lightning and electric fields

For a perfect satellite launch, it is expected that there should neither be any precipitation or lightning (and electric fields with triggering potential) at the launch pad or within the flight path. If lightning is detected within 20 kms of the launch pad or planned flight path within 30 minutes prior to launch window, it is not advisable to go ahead for the launch. The absolute values of all electric field measurements over the launch site must be below 1000 V/m for 15 minutes during the liftoff period.

5.3 Clouds

As per the Kennedy Space Centre Press Release (2000) on LCC, it is advised that the satellite launch should be kept on hold, if any part of the planned flight path is through a layer of thick convective clouds. However, in case of the non-precipitating clouds or cirrus-like clouds which are not associated with convective events, launch can be shown green signal. In addition to this, the cloud cover over the launch site also helps in range safety operations.

A detailed description on LCC can be found online on NASA news release from Kennedy Space Centre (http://www.nasa.gov/centers/kennedy/news/facts/nasa_facts_toc.html). Keeping the criticalities involved during the launch activities, it is highly desired to have greater accuracy on local weather. For this purpose, various atmospheric and oceanic measurements are carried out on routine basis through different instruments such as Doppler Weather Radar, Field Mill, Balloon-borne GPS Sondes, Portable Automatic Weather Station and Oceanic Buoys to name a few. During the countdown, formal weather briefing occurs periodically at regular intervals with special emphasis on probability of adverse weather events on the launch site. In addition to routine measurements, different atmospheric models are run for providing short to medium-range weather predictions for the launch site. In the present chapter, we have confined our description to HRM and ARPS model simulations, which are being carried out at Space Physics Laboratory.

6. Results and discussion

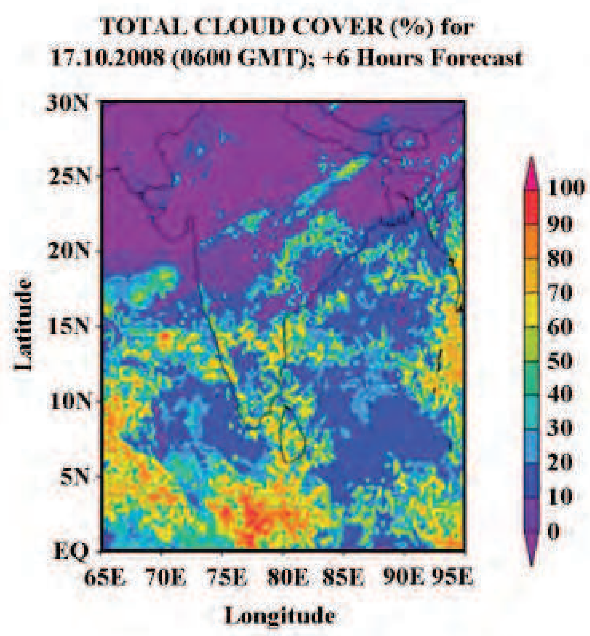
With reference to the LCC conditions summarized in Section 5, the basic requirements for satellite launch missions from SHAR (India) can be summarized under the following classes:

- **Low Pressure Systems:** Since SHAR is a coastal station located on the eastern coastline of the Indian subcontinent, the local weather is severely affected by *low pressure systems* formed in the Bay of Bengal. Thus an adequate information on the probability of formation of any *low pressure system* over Bay of Bengal with sufficient lead time remain one of the basic requirements from the mission team.

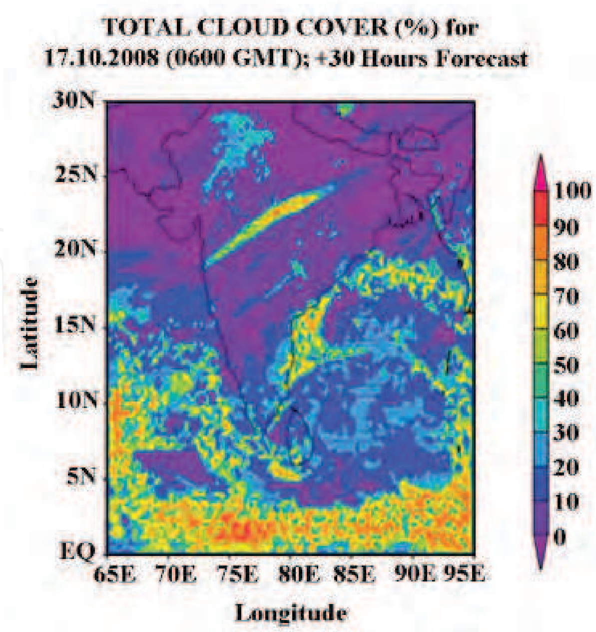
- **Thunderstorm/Lightning:** Mesoscale convective systems formed over SHAR are hazardous to the launch activities, thus reliable information on the location and timings of thunderstorms and lightning are anticipated. In-situ measurements of electric field through a network of field mill systems provide quite valuable information to address these aspects.
- **Clouds and Precipitation:** During the period of liftoff, adequate information on the cloud fraction over SHAR as well as along the trajectory of launch vehicle in the lower altitudes is crucial. Two Doppler Weather Radars (DWR, one at SHAR and another at Chennai) provide very valuable information on the passing showers and precipitating clouds. DWR products are also being assimilated in ARPS model simulations.
- **Visibility:** Periodical observations on the visibility are required for range safety operations. Ideally, direct visual observation of the launch vehicle is required through the lower troposphere (≈ 5000 m). In the case of overcast sky conditions, range safety measures depend on other remote sensing techniques.
- **Surface and Upper Winds:** During the movement of launch vehicle from assembly building to the launch pad, the surface wind speeds should not exceed a pre-designated threshold ($\approx 20m/s$). Thus, in-situ measurements of wind speed through 100-m tall meteorological tower in conjunction with balloon-borne GPS Sonde provide exact information on the surface and upper winds.

6.1 HRM simulations

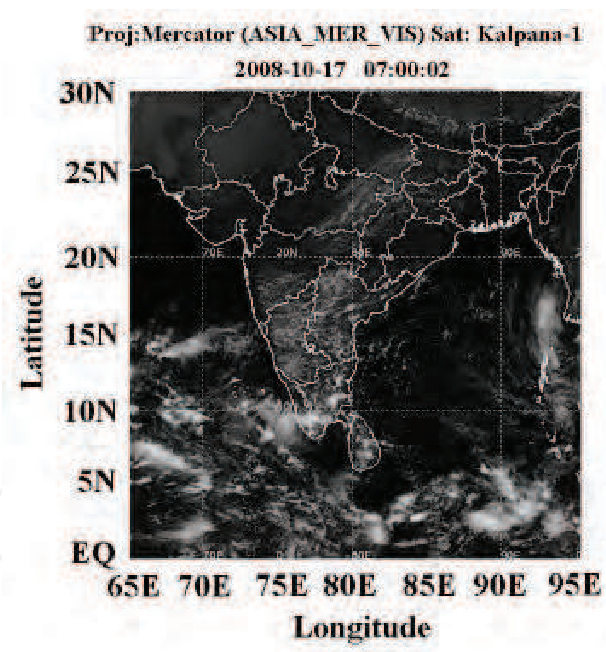
With a view to catering to the needs of LCC related requirements of PSLV and GSLV missions, HRM forecast products are customized and are disseminated to mission team members during the launch campaigns. HRM-simulated total cloud cover information is very important for forecasting the circulation and dynamics of the atmosphere. In most cases, it has been seen that HRM simulations of total cloud cover for +6 to +30 hours forecast over the Indian subcontinent showed a good agreement with the Kalpana-1 satellite cloud observations in visible range with errors of about 20% to 25%. Fig. 2 shows a typical example of HRM-simulated +6 and +30 hours forecast of total cloud cover fraction valid for 17^{th} October 2008, 0600 GMT with the Kalpana satellite imagery for the concurrent timings. It could be noticed that - while HRM is able to capture the broad features of cloud cover, there are some areas where the simulations suggest moderate to dense clouds not supported by the observations. This kind of ambiguities in forecast fields are attributed to the uncertainties in the variables like specific cloud liquid water and ice contents, relative humidity, convective activity and atmospheric stability which are the basis for defining cloudiness in HRM. A combination of these parameters provides threshold values for the probability of cloud formation. Nevertheless there was a good qualitative resemblance between the model-simulated cloud fractions and satellite observations. Accumulated rainfall is also one of the important parameters, which need to be simulated with high precision and less quantitative errors. Similar to total cloud fraction, HRM could simulate rainfall pattern also to a good extent. During PSLV-C12 launch campaign, the Bay of Bengal (BoB) underwent severe cyclonic storm named - BIJLI between 14 - 16 April 2009 and it was one of the prime concerns for launch related activities. In this regard, HRM simulated meteorological fields were found to be quite useful in inference of wind circulation prevailing over the launch site



(a) HRM-simulated total cloud cover +6 Hrs in advance;

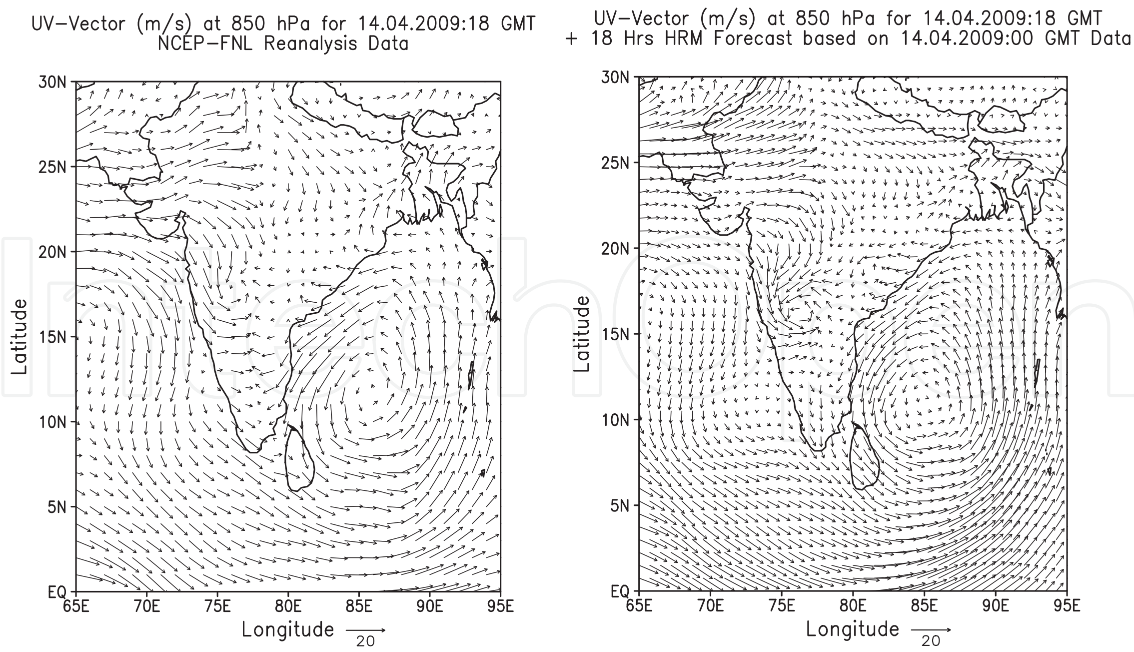


(b) HRM-simulated total cloud cover +30 Hrs in advance;



(c) Kalpana satellite imagery of cloud coverage in the visible range over the Indian sub-continent for 17th October 2008: 0700 GMT during Chandrayaan campaign;

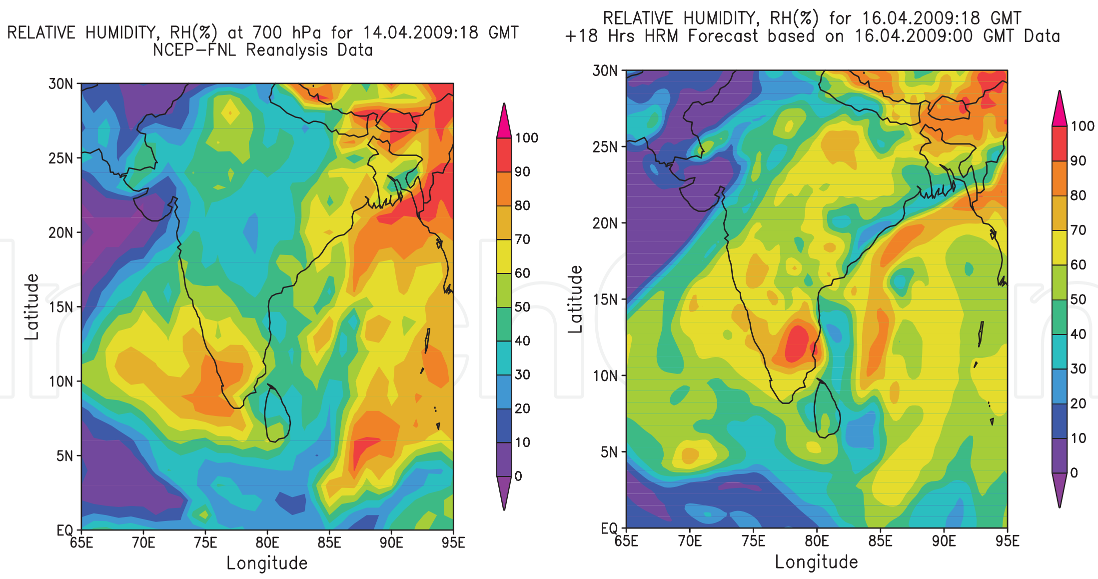
Fig. 2. (a) and (b) HRM-simulated total cloud cover +6 Hrs and + 30 Hrs in advance respectively; (c) Kalpana satellite imagery of cloud coverage in the visible range over the Indian sub-continent for 17th October 2008: 0700 GMT during Chandrayaan campaign



(a) NCEP-FNL Reanalysis (b) +18 Hrs HRM simulations

Fig. 3. (a) Horizontal (uv) wind vector field at 850 hPa observed on 14 April 2009: 1800 GMT through NCEP reanalysis; (b) HRM simulated uv wind vector field +18 hours in advance.

and adjoining BoB oceanic region. Fig. 3 depicts wind vector field at 850 hPa seen through NCEP reanalysis during formation of BIJLI cyclonic storm in the month of April 2009. HRM simulated wind vector field for the same time +18 hours in advance shown in Fig. 3 is well in tune with the NCEP reanalysis. A cyclonic circulation with low pressure over the BoB at 850 hPa levels are clearly captured in simulations almost 18 hours in advance; however there is a mismatch in the exact location of low pressure of the system and it can be attributed to lack of observational data in HRM model runs. The steering wind circulation at 200 hPa for the concurrent timings also showed a very good comparison between the simulations and Reanalysis (not shown here). From Fig. 3, it is very interesting to note that - almost 18 hours in advance HRM simulations clearly indicated formation of a cyclonic storm over the head BoB, and the wind circulation was regularly updated to the MET team at SHAR during the campaign. During the passage of cyclonic storm, the amount of moisture at about 3 kms (roughly 700 hPa) is often treated as one of the crucial parameters by the meteorologists to categorize the cyclone in terms of its intensity. Therefore, we show HRM simulation of relative humidity at 700 hPa on 16 April 2009 (1800 GMT) when BIJLI cyclonic storm had advanced towards north-east part of the Indian sub-continent in Fig. 4. Simulated field is also compared with the NCEP-FNL Reanalysis and results are quite encouraging, as almost all the gross features in relative humidity field with realistic magnitudes are nicely captured in +18 hours simulations, thereby providing a strong justification of usage of HRM simulated meteorological fields for LCC during launch activities. With special reference to the spatial heterogeneity in rainfall events around Sriharikota, a proper parameterization of convection is very crucial for improvements in the accuracy of short-range weather predictions. In order to test the impact of different convective parameterization schemes in HRM simulations, Tiedtke and Bechtold schemes were installed and their performance on rainfall forecasts and other



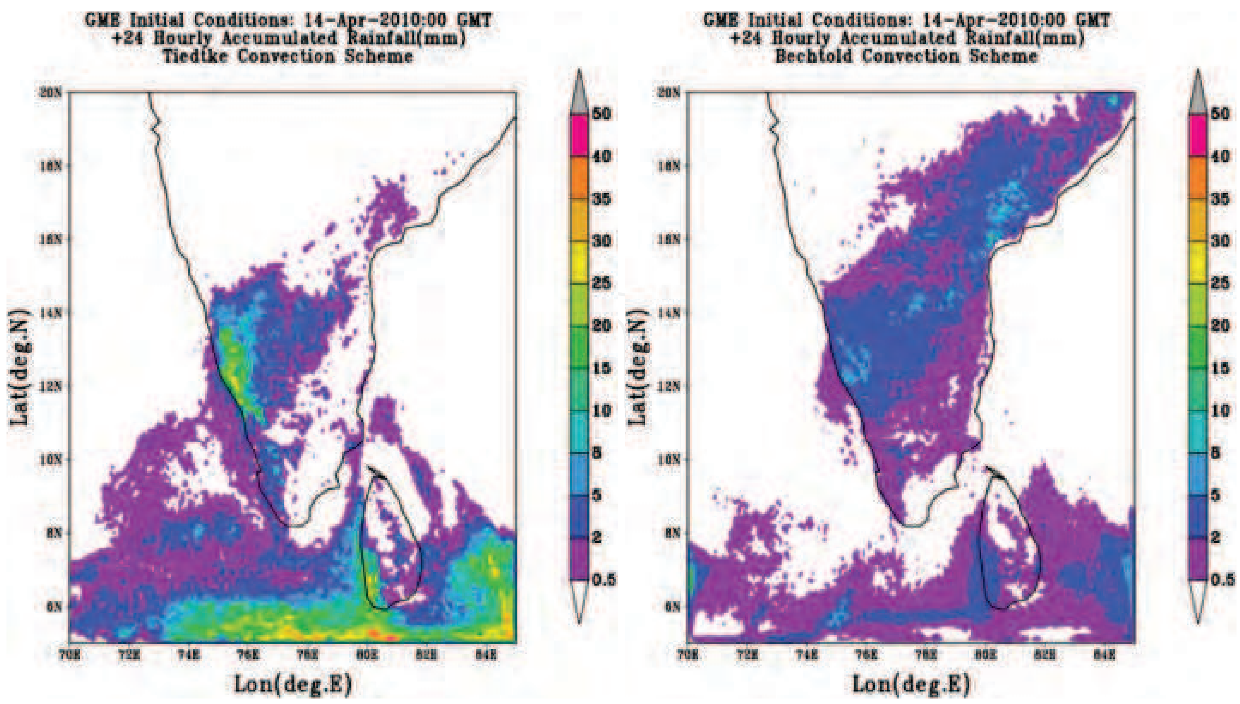
(a) NCEP-FNL Reanalysis; (b) +18 Hrs HRM simulations

Fig. 4. (a) Relative humidity at 700 hPa observed on 16 April 2009: 1800 GMT through NCEP reanalysis; (b) HRM simulated relative humidity at 700 hPa +18 hours in advance.

convective products were investigated. Fig. 5(a-b) shows daily accumulated rainfall forecast during GSLV-D3 campaign (April 2010) using Tiedtke and Bechtold convective schemes respectively. It can be seen that Bechtold convective scheme enhances the quantity of rainfall over cloudy regions. Both convection schemes are mass flux schemes and the main difference between them is that the closure assumption is based on moisture convergence in the Tiedtke scheme and CAPE used in the Bechtold scheme. Since Tiedtke convective scheme was originally developed for applications to the global scale for simulations with much smaller grid sizes, a convection closure based on convective available potential energy (CAPE) would be more suitable. In the Tiedtke scheme convection is triggered if the parcel's temperature exceeds the environment temperature by a fixed temperature threshold of 0.50 K, whereas in the Bechtold scheme, the onset of convection is decided by the large-scale vertical velocity. Both the Tiedtke and the Bechtold schemes distinguish penetrative and shallow convection. It is concluded that - Tiedtke scheme performs well with 0.25 deg. grid resolution, whereas Bechtold scheme is more suitable for smaller scale observations at 0.10 deg. grid resolution.

6.2 ARPS simulations

As part of PSLV and GSLV missions, various atmospheric models ranging from global scale, regional scale to mesoscale are made operational at SHAR for providing regional weather forecast during the period of launch campaign. With a view to in digesting the local in-situ information in an atmospheric model, ARPS is customized for SHAR domain and made operational for providing the probability of thunderstorm for +6 to +12 hours and forecast products were updated regularly in time during the launch window. The initial conditions to the ARPS model are provided by the vertical profiles of thermodynamic parameters obtained from balloon-borne GPS sondes, whereas the DWR products are assimilated for improvements in the initial conditions (Ramachandran, 2008). The DWR is perhaps one of the rare instruments that can sniff inside severe weather systems like tornado, tropical cyclone



(a) Tiedtke convective scheme (b) Bechtold convective scheme

Fig. 5. HRM simulated 24 hours accumulated rainfall using (a) Tiedtke and (b) Bechtold convective schemes during GSLV-D3 launch campaign.

and other convective systems such as severe thunderstorms. With the advent of operationally available Doppler radial wind data interest has increased in assimilating these data into NWP models. The limited area models require observations with high spatial-temporal resolutions for determining the initial conditions. Doppler radar wind measurements are one possible source of information, albeit over limited areas within about 100 km of each radar site. The resolution of raw data is however much higher than the resolution of the numerical models. Therefore these data must be preprocessed, to be representative of the characteristic scale of the model, before the analysis. When several observations are too close together then they will be more corrected and as a result the forecast error correlations at the observation points will be large. In contrast, the individual observations are less dependent and they will be given more weight in the analysis than observations that are close together. To reduce the representativeness error, as well as the computational cost, one may use (i) the vertical profiles of horizontally averaged wind in the form of Velocity Azimuth Display (VAD) technique, (ii) the observations of sparse resolution, or (iii) calculate spatial averages from the raw data to generate the so-called super-observations. The generated data correspond more closely to the horizontal model resolutions than do the raw observations. The 3D-Var has been used operationally to assimilate radar wind information in the form of VAD wind profiles (Ramachandran, 2008). The radar wind observations operator in this technique produces the model counterpart of observed quantity that is presented to the variational assimilation.

The radar reflectivity depends upon the size and density of the water droplet, whereas the radial velocities are one of the ways of measuring the horizontal and vertical wind pattern. While the DWR provides useful information on the reflectivity and radial winds over the region of interest within the radar-sight, it is equally important to make use of this information in the numerical weather prediction, so as to improve the prediction of severe weather events,

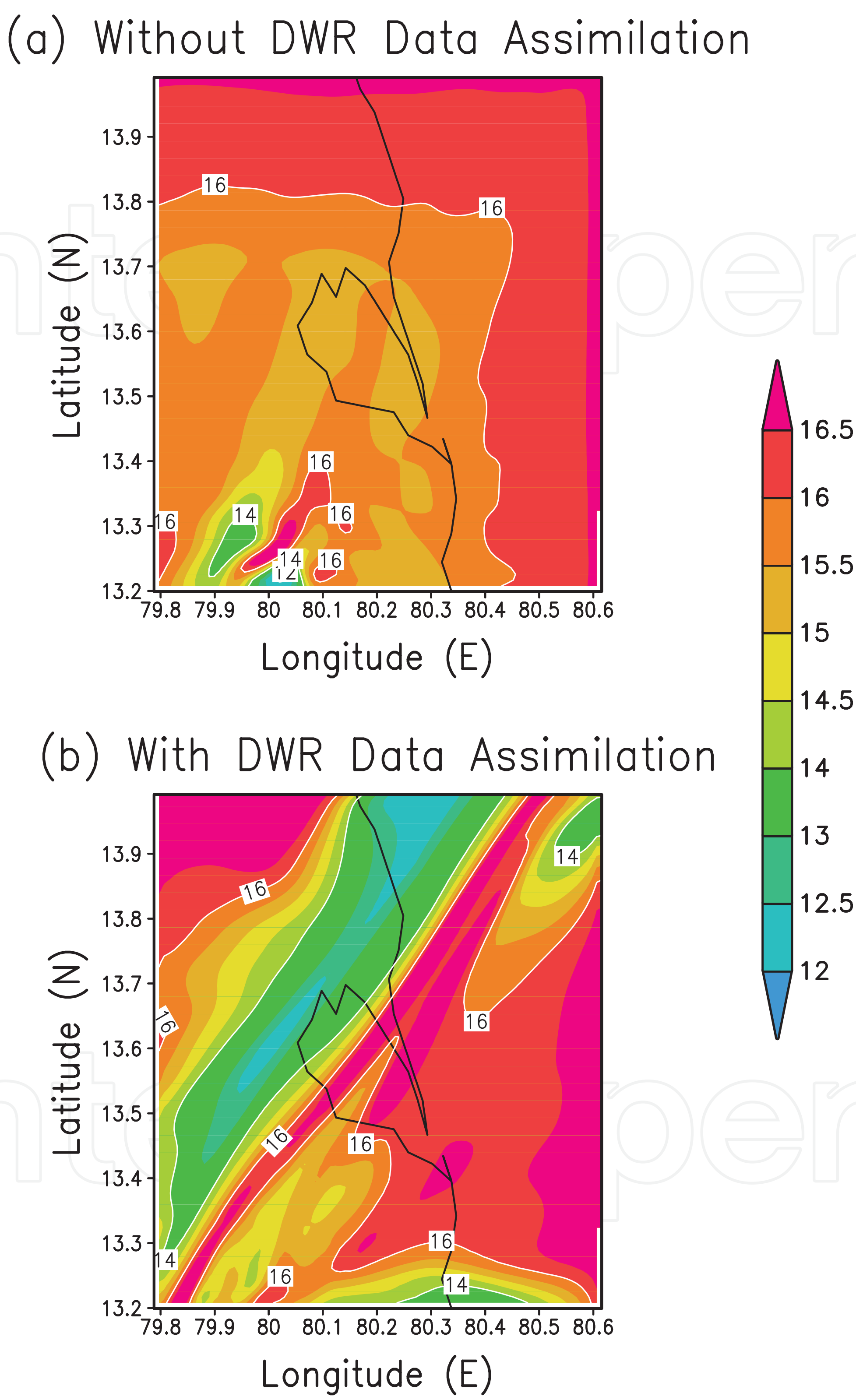


Fig. 6. Impact of DWR data assimilation on surface layer water vapour mixing ratio (g/kg) field over the SHAR, showing the refinement in magnitudes of mixing ratio in accordance with the DWR derived reflectivity.

such as the thunderstorms. The radial winds and reflectivity pattern obtained from the DWR of SHAR are assimilated in the ARPS for improvements in the initial conditions. The assimilation package consists of three codes: (1) in the very first step, the DWR products which are available on radar coordinates are converted to the model grids and a re-mapping package is activated so that the actual time of the observations and the concerned meteorological parameters (water vapour and wind patterns) are converted to the model grid coordinates; (2) after obtaining the radial velocity and reflectivity information from DWR in the model coordinates, the initial conditions are altered in accordance with the observational data and (3) finally the re-mapped data is used by activation of 3-D VAR assimilation package in the ARPS model. After incorporation of DWR derived radial velocities and reflectivity in the ARPS model, surface layer water vapour mixing ratio fields over the model domain are considerably changed in accordance with the DWR observations thereby improving the initial conditions of the model (Fig. 6).

During Chandrayaan mission, Subrahamanyam et al. (2011) made use of five different parameters obtained from ARPS simulations namely (1) hourly accumulated rainfall; (2) cloud and rain water mixing ratio; (3) vertical velocities; (4) low level wind shear and (5) magnitude of surface layer specific humidity as the probable indicators of thunderstorm occurrence, and ARPS model simulations were found to be of great importance, as a careful examination of model derived products could help in providing a logistic forecast on probability of thunderstorms. Through these products, ARPS could capture more than 70% of rainfall slots successfully; however, there were a few localized events, where model did not capture the rainfall properly. This model has also got very good potential in simulation of vertical profiles of winds. Fig. 7 shows one of the typical comparisons between ARPS model-simulated vertical profiles of zonal and meridional winds on 28 May 2008 with concurrent measurements through balloon-borne GPS sonde. Within the permissible constraints of the model, it was noticed that these parameters required hyper-tuning with greater accuracy and quantification. For nowcasting purpose, ARPS model- simulated forecast products are vastly used and are considered to be reasonably accurate up to +6 hours (Subrahamanyam et al., 2008).

7. Advantages of HRM and ARPS

There are various NWP models available for providing short-range weather predictions over a specific site, however in the present study we have confined our description to HRM and ARPS for the following reasons:

1. Very first, the initial and lateral boundary conditions for HRM are derived from the analysis and forecast fields of the German Global Model - GME which are made available to us very fast compared to other global models, thereby providing sufficient lead time for generation of forecast products.
2. Secondly, the required meteorological fields for running the HRM are tailored at DWD for our specific region. Thus, we need not download the entire global data which would obviously require relatively large number crunching.
3. ARPS model is probably one of the rare atmospheric models, which has got the potential of using highly localized observations such as upper-air meteorological data obtained through balloon-borne GPS Sondes. Also it assimilates the DWR-derived winds and reflectivity fields.

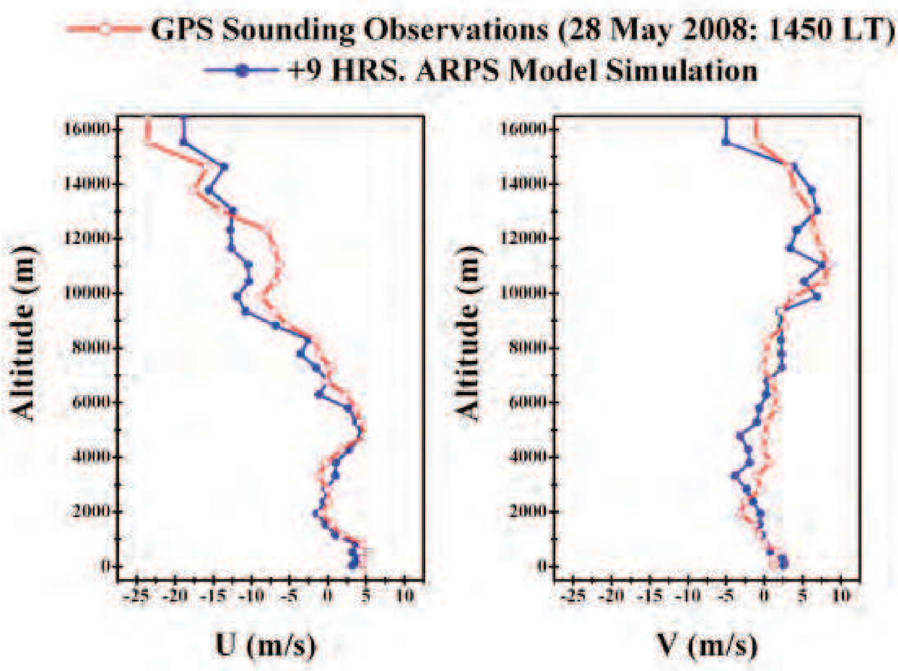


Fig. 7. A typical comparison of ARPS model-simulated zonal and meridional winds in vertical with balloon-borne GPS Sonde measurements.

4. By choosing HRM and ARPS, we take care of the possible differences in forecasting due to hydrostatic and non-hydrostatic approach. Thus, we make use of both the models simultaneously to provide short-range weather predictions over SHAR.

8. Scope for future work

In the present chapter, we described the potential of two atmospheric models, namely HRM and ARPS in providing valuable information with respect to *launch commit criteria* for satellite launch missions. Among various regional atmospheric models, HRM has got a definite advantage as the initial conditions and lateral boundary conditions are derived through a tailored dataset of the GME global model, or else, one need to depend on the whole global sets, thereby spending excessive time. Thus, the HRM simulations can be made available to PSLV and GSLV mission teams with a reasonable lead time. The HRM has also got a good potential to capture low pressure systems over the Bay of Bengal well in advance ($\approx$ 18 hours), thus severe weather threats can be provided at right time. Similarly, the potential of ARPS model is vastly exploited in simulations of mesoscale convective events, such as thunderstorms. It was also very useful in capturing the fine features in the vertical profiles of zonal and meridional winds to +9 hrs.

Having exploited the potential of these two models, one need to explore the possibility of assimilating the routine meteorological observations on a regular basis for continuous improvements in the initial and lateral boundary conditions of the model. Also there is need of generation of very good quality climatology of mesoscale convective events which are hazardous to the launch activities. In future, there may also be enough scope of validating a combination of different NWP models, which can lead to development of a statistical ensemble model. In a broad perspective, it may be indeed a difficult task to achieve 100% accurate model, but intelligent human intervention to the model-derived forecast products would lead to generation of error statistics of individual models, which can help the mission team in decision making tasks.

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