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Modelling of sea breeze for the Visakhapatnam region: A case study

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Abstract

The simulations are conducted in WRF mesoscale model by choosing the two-way interaction option, so that the information of outer domain of grid spacing with 18 km horizontal resolution can influence the atmospheric systems that occur in the innermost domain of grid spacing 2km horizontal resolution. The features of sea breeze circulation are discussed using air temperature, wind direction and wind speed observed at surface (about 10 m) level. The analysis was carried out considering non-rainy days in the representative months of April and May.

Key words: Modelling, Sea Breeze, Visakhapatnam

Introduction

Sea breeze is one of the most interesting mesoscale atmospheric phenomena observed in coastal regions. It is also a crucial component in the coastal weather systems. Mesoscale meteorological models are being extensively used for numerical study of land/sea breeze circulations. Because of the recent advances in computational speeds and resolutions of mesoscale models, their application in real-time forecasting has increased (Lyons *et al.*, 1995; Stauffer *et al.,* 2000; Seaman, 2000) for the study of atmospheric mesoscale systems.

The model chosen for the numerical simulation of sea breeze circulation in the present study is the non-hydrostatic, nested grid, primitive equation, high resolution mesoscale meteorological model WRF V3.1. Mesoscale models are used to provide inputs of winds, vertical temperatures, stability structure, mixing depths and other atmospheric parameters for the assessment of local circulations and other mesoscale systems in coastal/complex terrain regions. The simulations are carried out by varying the three PBL schemes YSU, MYJ and ACM2 to observe their performance in analyzing the sea breeze characteristics (onset time, cessation time, intensity and the thickness of TIBL) with the *in-situ* observations.

Numerical simulations are conducted for the Visakhapatnam region with the WRF V3.1 model for the summer months of April and May. A case study made on 03 April 2010 is presented here.

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Materials and Methods

Visakhapatnam is located on the east coast of India facing Bay Bengal. The city experiences a tropical climate. The mean annual range of temperature varies from a minimum of about 23ºC (January) to a maximum of 32ºC (May). The fluctuations in temperature are fairly uniform, except during the dry months when the rise in temperatures higher than during monsoon period. From February onwards temperature rises progressively till May which is observed as the hottest month. In recent years, it has been observed that the daytime temperatures are above 40ºC during May. December and January months are observed as the coldest period of the year. The humidity remains high (82%) throughout the year except during December and January. The average annual rain fall is 945 mm, the bulk of which occurs during south-west monsoon period.

Physicists have built mathematical models to describe a wide range of systems. A model is a substitute for a real system. Mesoscale models are numerical tools. They are a set of complicated equations which govern the motion of the atmosphere. In essence, the ultimate challenge of a model is to go near to a real atmosphere. Mesoscale models simulate atmospheric processes on a spatial scale from 20 to 2000km and resolve temporal fluctuations lasting from 1 to 12 hours. Mesoscale models are normally specialized for a particular application, such as local weather forecast or process studies. Applications of mesoscale model simulations include convective storms, heavy precipitations, and calculations for regional studies.

The Weather Research and Forecasting (WRF) model is a Numerical Weather Prediction (NWP) and atmospheric simulation system designed for both research and operational applications. WRF is supported as a common tool for the university/research and operational communities to promote closer ties between them and to address the needs of both. The development of WRF has been a multi-agency effort to build a next-generation mesoscale forecast model and data assimilation system to advance the understanding and prediction of mesoscale weather and accelerate the transfer of research advances into operations.

The initial and boundary conditions for the model have been provided from the NCEP (National Centre for Environmental Prediction) 1° ×1°horizontal resolution at every 3 hours GFS (Global Forecasting System) analysis data. This contains horizontal and vertical winds, sea level pressure, surface pressure, temperature, specific humidity potential temperature, soil moisture, soil temperature, geopotential height, perceptible water, skin temperature etc., at every 3 hours interval. The WRF Model is initialized at 0000 Indian Standard Time (IST) on each of selected days and integrated for 24 hours in simulating the sea breeze circulation. The model is run with 28 sigma levels in the vertical level from the ground to the 100 hPa top surface. The output of WRF Model has been generated at 60 minutes interval for outermost and intermediate domains and 15 minutes interval to the innermost domain. The Grid Analysis and Display System (GrADS) software is used for the purpose of drawing the visual plots of WRF model output files.

Here the land/sea breeze simulations are done by varying the ABL schemes, YSU, MYJ and ACM2 for the four cases taken for the stated summer season over Visakhapatnam region located on the east coast of India. It is also observed which scheme has given comparatively better performance among these YSU, MYJ and ACM2 schemes in simulating land/sea breeze circulations.

Results and Discussion

The synoptic wind over the Indian region varies according to the prevailing southwest(SW) monsoon(June to September), northeast (NE) monsoon (October to February) and westerlies during summer (March to May).These conditions form offshore, parallel and onshore geostropic flow situations on the east coast and influence the sea breeze development.

The simulated flow field over the Indian peninsular region under synoptic situation showed in the Figure 1 at 06:30 IST, 08:30 IST and 11:30 IST represents the morning hour of progressive increase in temperature on 03 April 2010.

During the morning, the simulated surface winds (10m level) are in an irregular manner with divergent winds on land side and southerlies and south-westerlies on Bay of Bengal from 06:30 IST to till 08:30 IST. While day is going with increase of temperature the convection process also increased and it is observed that the wind direction has changed on the sea by taking the south-westerly direction towards coast and penetrated on the land at 11:30 IST indicating the development of sea breeze.

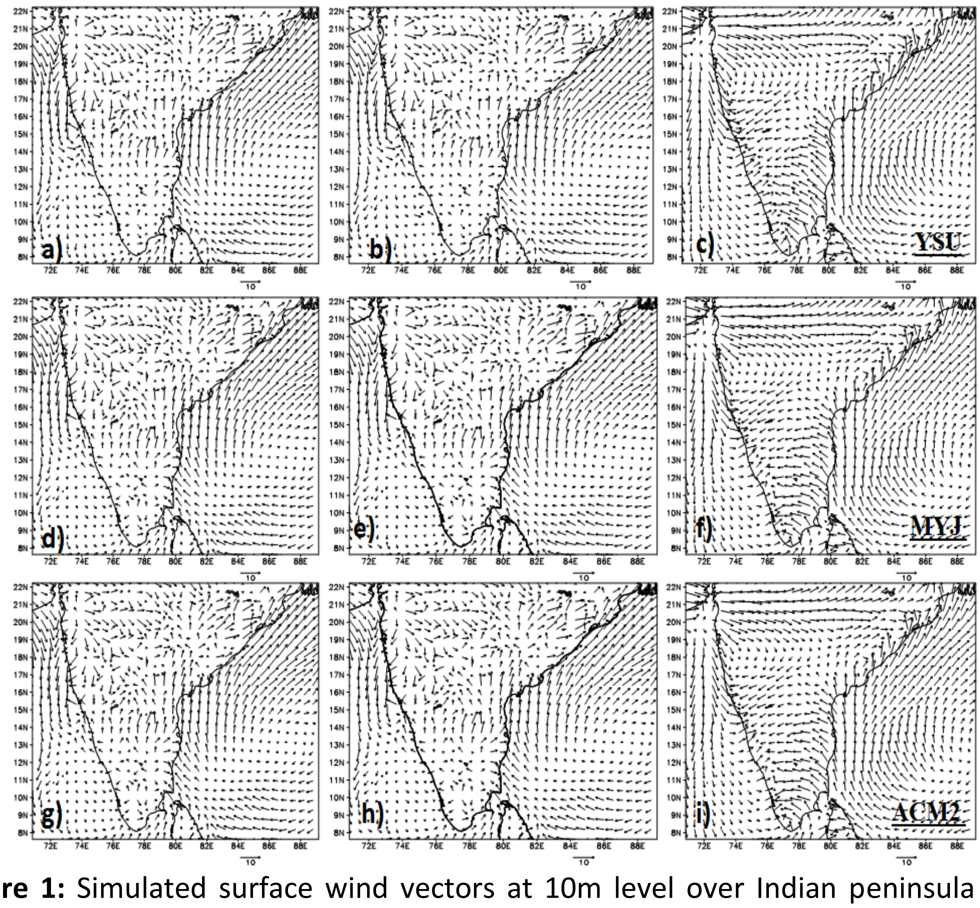

Figure 1: Simulated surface wind vectors at 10m level over Indian peninsula (Domain-1) at 06:30 IST, 08:30 IST and 11:30 IST (for YSU, MYJ and ACM2 PBL Schemes) respectively on 03 April 2010 with 18 km horizontal resolution.

In analyzing the nested model simulations, the focus is kept mainly on the innermost nest domain which covers the Visakhapatnam region to study the characteristics of sea breeze and the formation of TIBL. Here the simulations are conducted by WRFV3. 1 mesoscale model with 2 km horizontal resolution by varying three PBL schemes, YSU, MYJ, ACM2 and the output from WRF model was taken for every 15 minutes.

Horizontal flow of sea breeze circulation

The evolution of the simulated low-level (10m level) wind field over the Visakhapatnam region is shown in the Figures 2, 3 and 4 for the three PBL schemes (YSU, MYJ and ACM2 Schemes). The surface wind field is observed continuously from 08:00 IST for every 15 minutes to get a good profile of the sea breeze development, particularly the onset time, of which increase in intensity as the day progresses and with the increase in temperature. The surface winds are seen to vary diurnally and spatially on the land and this variability is also observed over the sea adjacent to the coast in the innermost domain.

The simulated surface wind field is weak with a speed of 5 ms^{-1} and flows off-shore along the coast. This westerly wind from land to sea indicates the land breeze circulation prevails till 08:30 IST. The wind takes a westerly to south-westerly turn form 08:45 IST onwards with the increase in speed to 9 ms^{-1}. As the temperature increases gradually, the differential heating occurs between the land and sea causing the pressure variation which precedes the change in wind direction. From the Figure 5e (YSU, MYJ and ACM2) that the surface wind took the shift in wind direction from south-westerly to south-easterly from 09:00 IST (ACM2) to 09:15 IST (YSU and MYJ) and crossed the coast with the speed of 9-10 ms^{-1} indicating the development of sea breeze circulation. The air temperature decreases during the time of onset of sea breeze due to the cold air advection from sea to over the land.

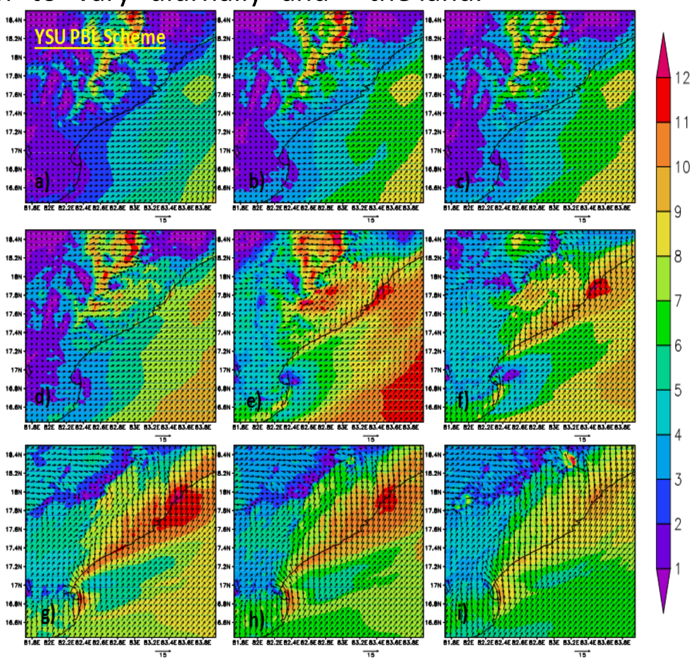

Figure 2: Simulated surface wind (onset of sea breeze regime) in Visakhapatnam region (at 10 m level) at (a)08:00 IST, (b) 08:15 IST, (c) 08:30 IST, (d) 08:45 IST, (e) 09:15 IST,(f) 10:15 IST,(g) 11:15 IST,(h) 12:00 IST, and (i) 12:45 IST respectively on 03 April 2010 with 2 km horizontal resolution.

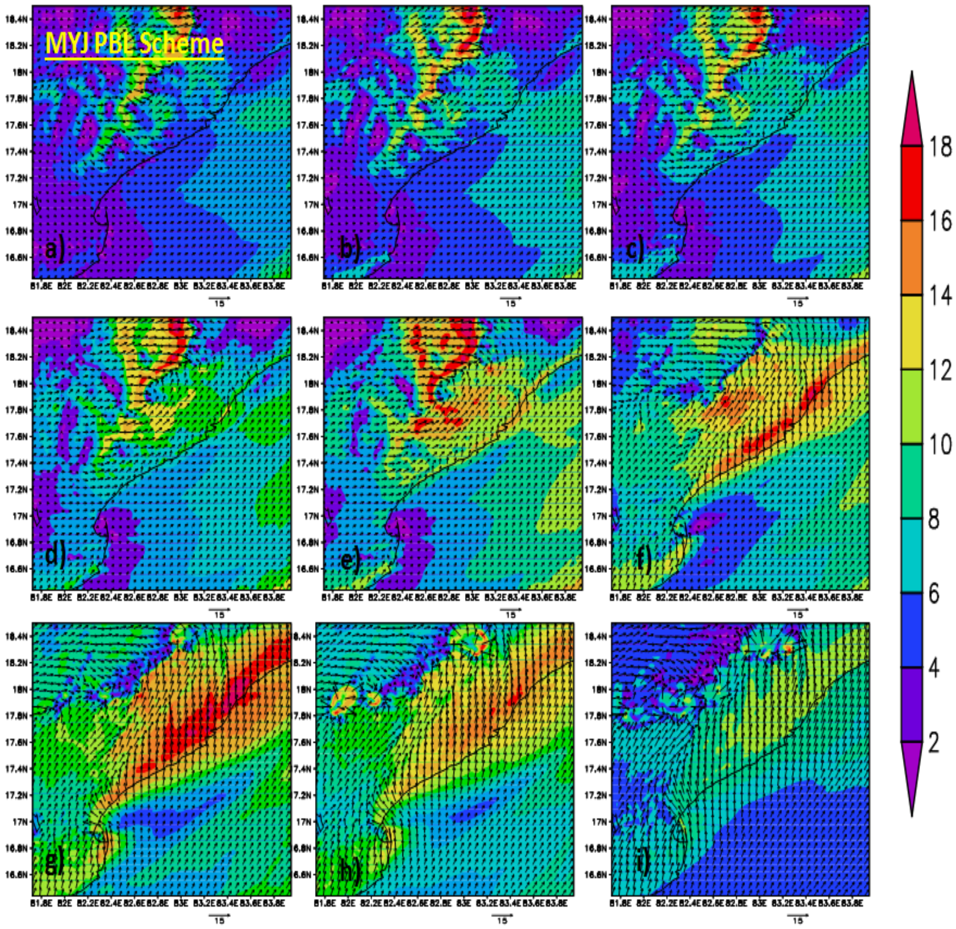

Figure 3: Simulated surface wind (onset of sea breeze regime) in Visakhapatnam region (at 10m level) at (a)08:00 IST,(b) 08:15 IST,(c)08:30 IST, (d) 08:45 IST, (e) 09:00IST, (f)10:15 IST, (g) 11:30IST, (h) 12:00 IST, and (i) 12:45 IST respectively on 03 April 2010 with 2km horizontal resolution.

It is noticed that the simulated wind speed decreases for a short period during the setting time of sea breeze due to the combined effect of land breeze and sea breeze in opposite direction. Further it is also observed that an intensified sea breeze blows with a speed of 9-11 ms^{-1} (Figure 5f, 5g and 5i of YSU, MYJ and ACM2). The horizontal extent of sea breeze over Visakhapatnam region is observed up to 40 km from the coast.

Here it is also observed that the onset time of sea breeze is at 09:15 IST in both YSU and ACM2 PBL Schemes but in MYJ PBL scheme it is ahead of time by 15 minutes. The transition of surface wind field during the onset time of simulated sea breeze is shown at 11:00 IST in the Domain-1 where as in Domain-3 shown at 09:15 IST.

The simulated spatial distribution of vertical cross-section of potential temperature profiles are shown in Figure 5 (YSU, MYJ and ACM2 PBL Schemes) for the study region at 08:00 IST, 09:15 IST and 12:00 IST representing morning time, onset time of sea breeze and intensified sea breeze time respectively to understand the stability structure of atmosphere during the time of evolution of sea breeze near the coast.

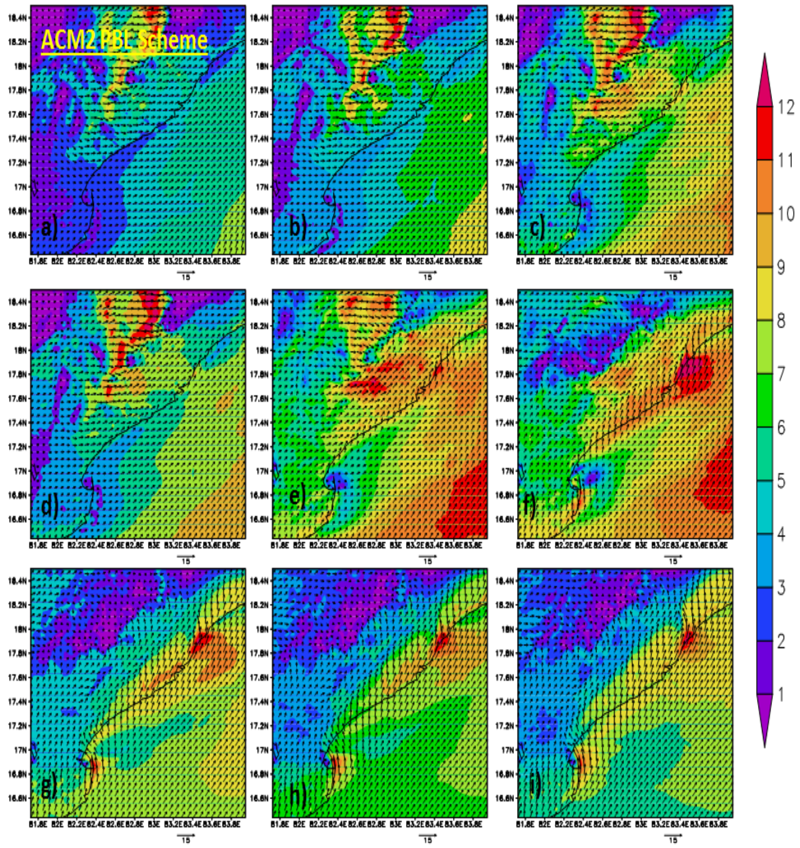

Figure 4 Simulated surface wind (onset of sea breeze regime) in Visakhapatnam region (at 10m level) at (a)08:00 IST, (b) 08:15 IST,(c)08:30 IST,(d) 08:45 IST, (e) 09:15 IST,(f)10:15 IST,(g)11: 30IST, (h) 12:00 IST, and (i) 12:45 IST respectively on 03 April 2010 with 2km horizontal resolution.

At 08:00 IST, all the contours are almost parallel which represents a stable atmosphere. While the day progresses with increase of temperature, it is observed that the value of potential temperature increases with spatial interval between the contours and with sharp peaks (Figure 5b) representing a strong convection over land resulting in instability at the time of onset of sea breeze. It is also seen that the shifting of simulated potential temperature profiles from land to seaward in the Figures 5b and 5c at 09:15 IST and 12:00 IST indicate the advection of warm air towards sea and the maritime air (sea breeze) towards land. The WRF model results in the Visakhapatnam region are validated with the radiosonde observations. The plots in the Figure 6 are drawn to compare between the WRF model to radiosonde observations for wind speed, wind direction, potential temperature and relative humidity.

The profiles of wind speed in Figure 6 as hows relatively low speeds at the lower atmosphere and high speeds at the higher levels up to 3000 m (WRF observations) of atmosphere. The wind speeds with the model is lesser in intensity than the observed. The wind speed decreased from above 8 ms^{-1} speed to a minimum value of 2 ms^{-1} which is realized at 3km height. Figure 6b shows both the model and radiosonde observations of the wind direction at different levels of height in the atmosphere.

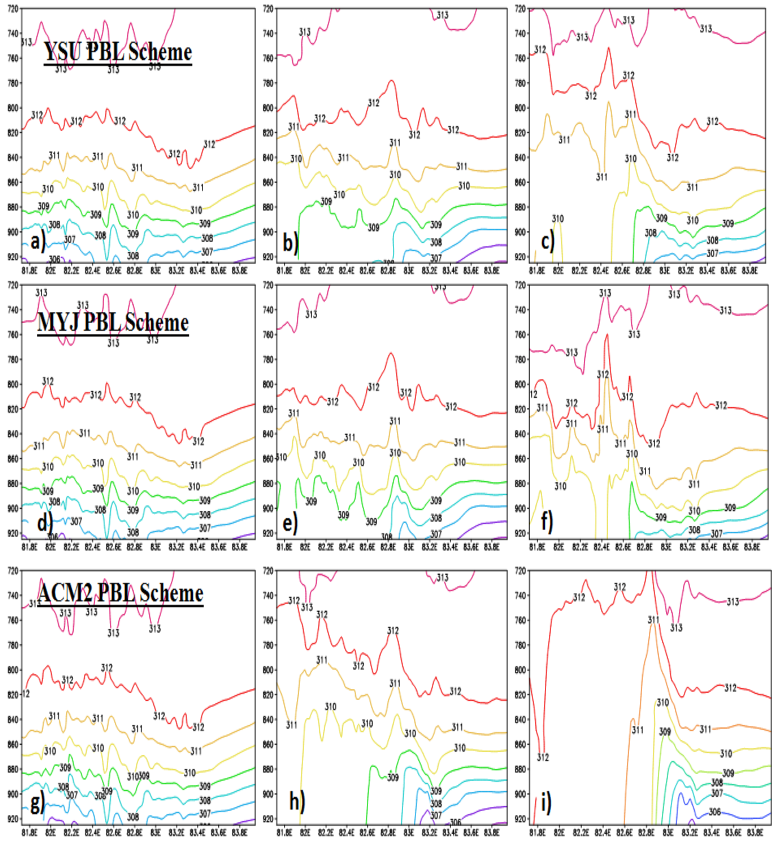

Figure 5: Simulated spatial distribution of potential temperature in a vertical cross-section across the Visakhapatnam coast at 08:00 IST, 09:15 IST, and 12:00 IST respectively on 03 April 2010.

The simulated wind is very close to the observed one in the morning at a direction of 230°(S-W) at lower level of 800m. It is observed that the direction of simulated wind is deviated from the observed but both the values show the change in direction by taking a turn up to140° (S-E), signifying the development of the sea breeze circulation. Both the model and observed almost agreed well till 3000m and afterwards the model has over-estimated the direction of simulated wind at higher levels in atmosphere.

It is observed that the ACM2 PBL Scheme is more sensitive than the other two YSU and MYJ PBL Schemes. Figure 6c shows the relative humidity profile as depicted against the radiosonde observations. The intensities were simulated up to 1.5km and the model is moister between 1.5 and 4.5 km. The potential temperature profiles in Figure 6d shows the depth of the TIBL as 200m and it can be seen that the both the observations (radiosonde and WRF model) are almost in good agreement with each other. The WRF model derived parameters such as wind speed, wind direction, relative humidity and potential temperature are in good agreement with radiosonde observations. The percentage of agreement is 56 (Robinson, 1957).

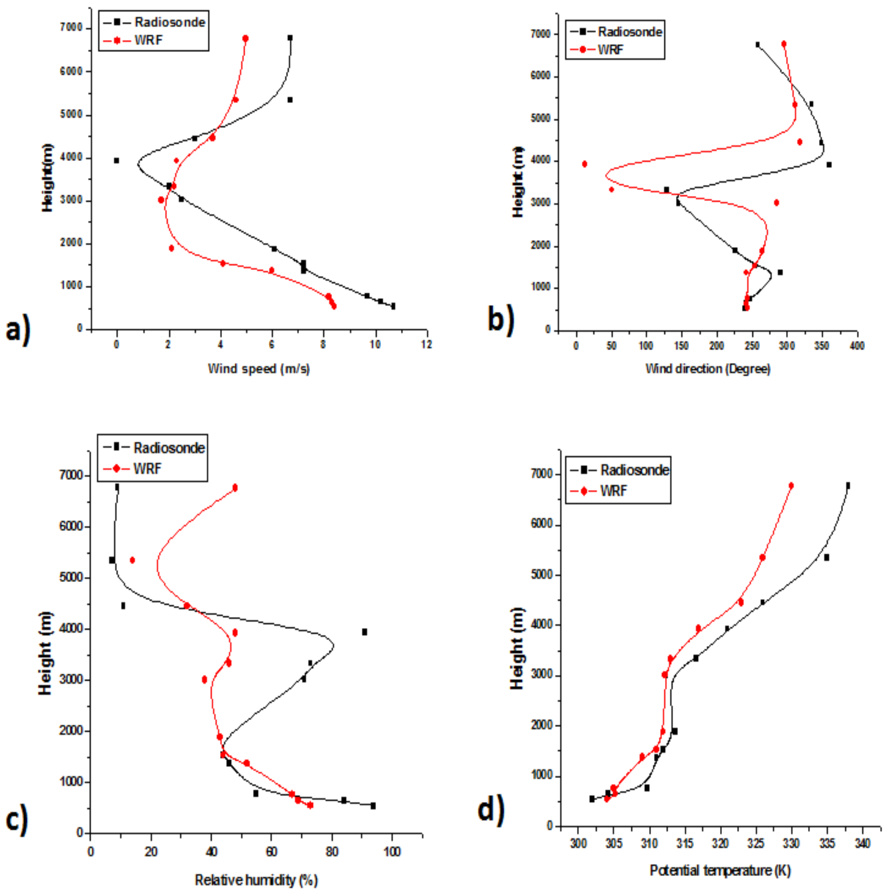

Figure 6: Comparison of simulated and observed (a) wind speed, (b) wind direction, (c) potential temperature, and (d) relative humidity to Visakhapatnam on 03 April 2010.

The diurnal variation of simulated surface heat fluxes are shown in Figure 7 (for three YSU. MYJ and ACM2 PBL Schemes) for the purpose of understanding the heat budget during sea breeze (Kuo*et al.*, 1991). Here in Figure 7a, the sensible heat response in YSU PBL Scheme is more sensitive and, in the Figure, 7b, the latent heat response in ACM2 PBL Scheme is less sensitive to the model simulation when compared tothe rest of the PBL Schemes for 03 April 2010.

Vertical extent of sea breeze circulation

The simulated vertical extent of sea breeze circulation can be estimated at the time of intensified sea breeze. The Figure 8 (with the YSU, MYJ and ACM2 PBL Schemes) at 12:00 IST represents the maximum strength of sea breeze that formed over Visakhapatnam on 03 April 2010. It is observed from above Figure 8 that the sea breeze vertical extent is about 0.76 km on average of three schemes(YSU, MYJ and ACM2) with 8-9 ms^{-1} speed. It corresponds to the pressure level of 924 mb.

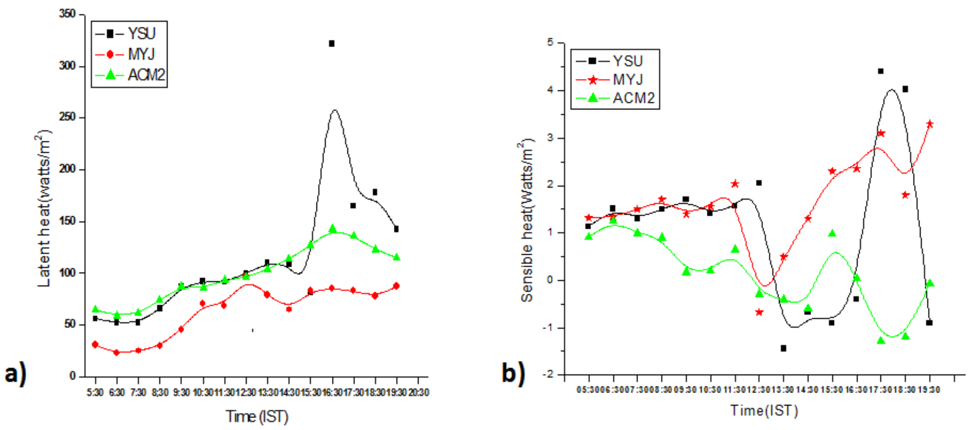

Figure 7: Simulated surface energy fluxes (a) latent heat and (b) sensible heat at the model grid for Visakhapatnam on03 April 2010.

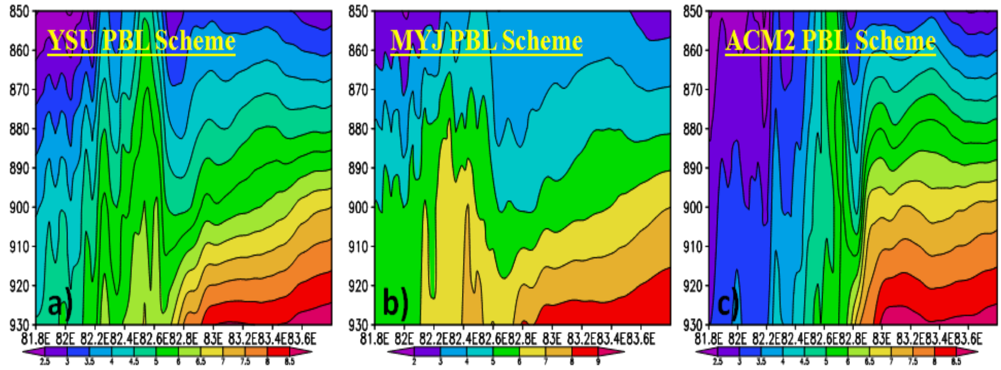

Figure 8: Simulated vertical extent of sea breeze (for YSU, MYJ and ACM2) over Visakhapatnam coast at 12:00 IST on 03 April 2010.

Decay of sea breeze

In the wee hours, the convection becomes less due to the decrease of temperature leading to the decrease in the strength of the sea breeze circulation. The simulated surface wind flow at the time of decay or cessation of sea breeze circulation is clearly shown in the below Figures 9, 10 and 11 (for YSU, MYJ and ACM2 PBL Schemes) which represents the progressive timings to show the decrease in strength and change of wind direction pattern on 03 April 2010 over the Visakhapatnam region.

In Figure 9, a strong divergent system is observed on south side of landward and moves towards coast and pushed the sea breeze away from land. Under this condition the sea breeze struggled to cross the coast and decayed by the time 18:15 IST itself. The sea breeze totally decayed and changed to south-east direction at 19:30 IST. The YSU PBL Scheme is comparatively more sensitive in this case which clearly indicates the decay of sea breeze.

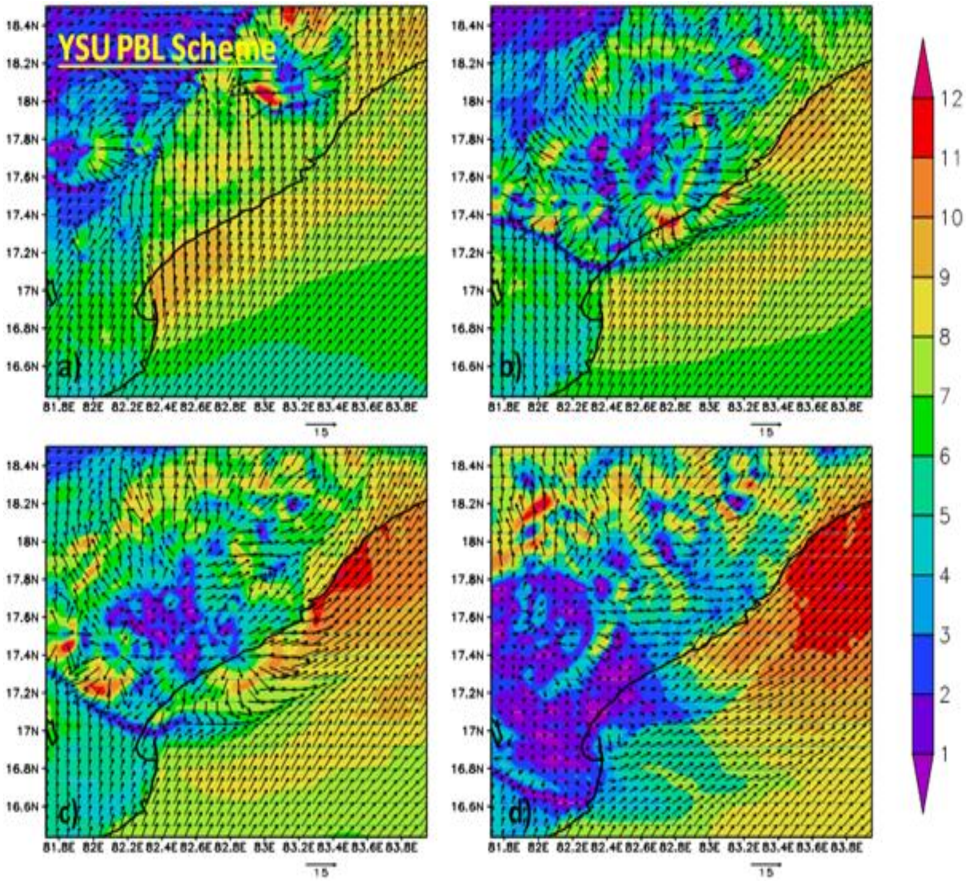

Figure 9: Simulated surface wind (decay of sea breeze regime) in Visakhapatnam region (at 10m level) at (a)15:00 IST, (b) 17:45 IST, (c) 18:15 IST, and (d) 19:30 IST respectively on 03 April 2010 with 2 km horizontal resolution.

From the simulation of MYJ PBL Scheme(Figure 10) over Visakhapatnam region, a divergent system is seen moving along the coast by pushing sea breeze away from land.But this mchanism is observed one hour late and the decay of sea breeze is observed much later, after two hours, as compared to theYSU PBL Scheme. It is found that the decay of sea breeze at Visakhapatnam coast occurred in this MYJ PBL Scheme at 20:15 IST.

Figure 11 shows the results of the ACM2 Scheme. It could not clearly capture the divergent system and its movement on the land at north-east side which is observed in the other two YSU and MYJ PBL Schemes. This divergent system moved down towards the coast and dissipated at 18:45 IST by pushing the sea breeze towards sea. The decay of the sea breeze event happened at that time only. So,the decay of sea breeze is observed at 19:30 IST. Among the three PBL schmes YSU, MYJ and ACM2, YSU is comparitively more sensitive.

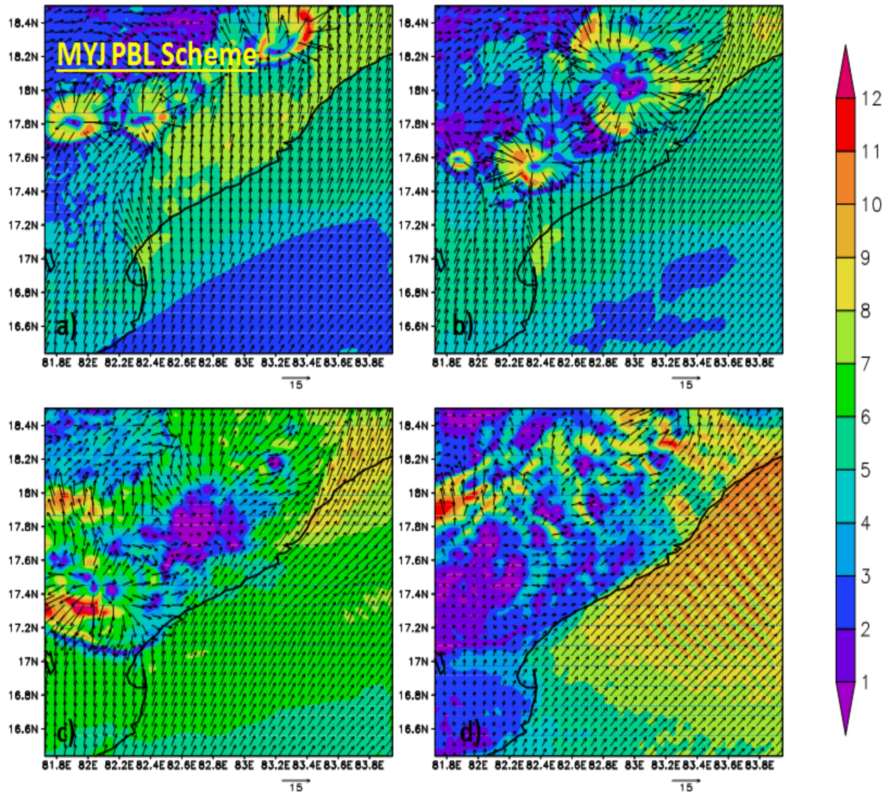

Figure 10: Simulated surface wind (decay of sea breeze regime) in Visakhapatnam region (at 10m level) at (a)16:00 IST, (b) 19:00 IST, (c) 20:15 IST, and(d) 21:30 IST respectively on 03 April 2010 with 2km horizontal resolution.

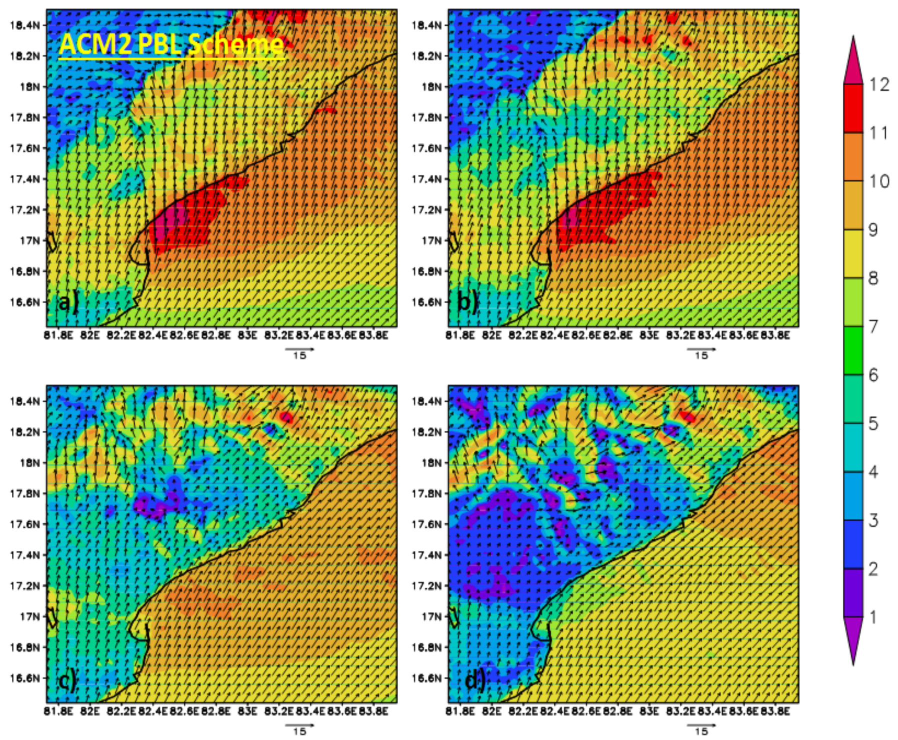

Figure 11: Simulated surface wind (decay of sea breeze regime) in Visakhapatnam region (at 10m level) at (a)17:15 IST, (b) 18:45 IST, (c) 19:30 IST, and (d) 21:30 IST respectively on 03 April 2010 with 2 km horizontal resolution.

Formation of TIBL

The present study also concentrated on another important characteristic of sea breeze, namely, the formation of TIBL during sea breeze.

The simulated boundary layer height over Visakhapatnam in the morning sea breeze time is shown in Figure 12 drawn for YSU, MYJ and ACM2 PBL Schemes representing the morning time and sea breeze time.

Figure 12 (a & b) shows the results of YSU PBL Scheme, the increase in height of the TIBL is from 250 m to 300 m. In MYJ PBL Scheme [Figure 12 (c)&(d)], it is from 500m to 600 m and in ACM2 PBL Scheme [Figure 12 (e)&(f)] from 400 m to 500 m. The increase in TIBL height can be seen as 50 m in YSU and 100 m in both the MYJ and ACM2 PBL Schemes. So, the depth of TIBL can be considered as 50-100 m. The concept of the formation and increase in the height of TIBL during sea breeze can be observed as compared to the morning time.

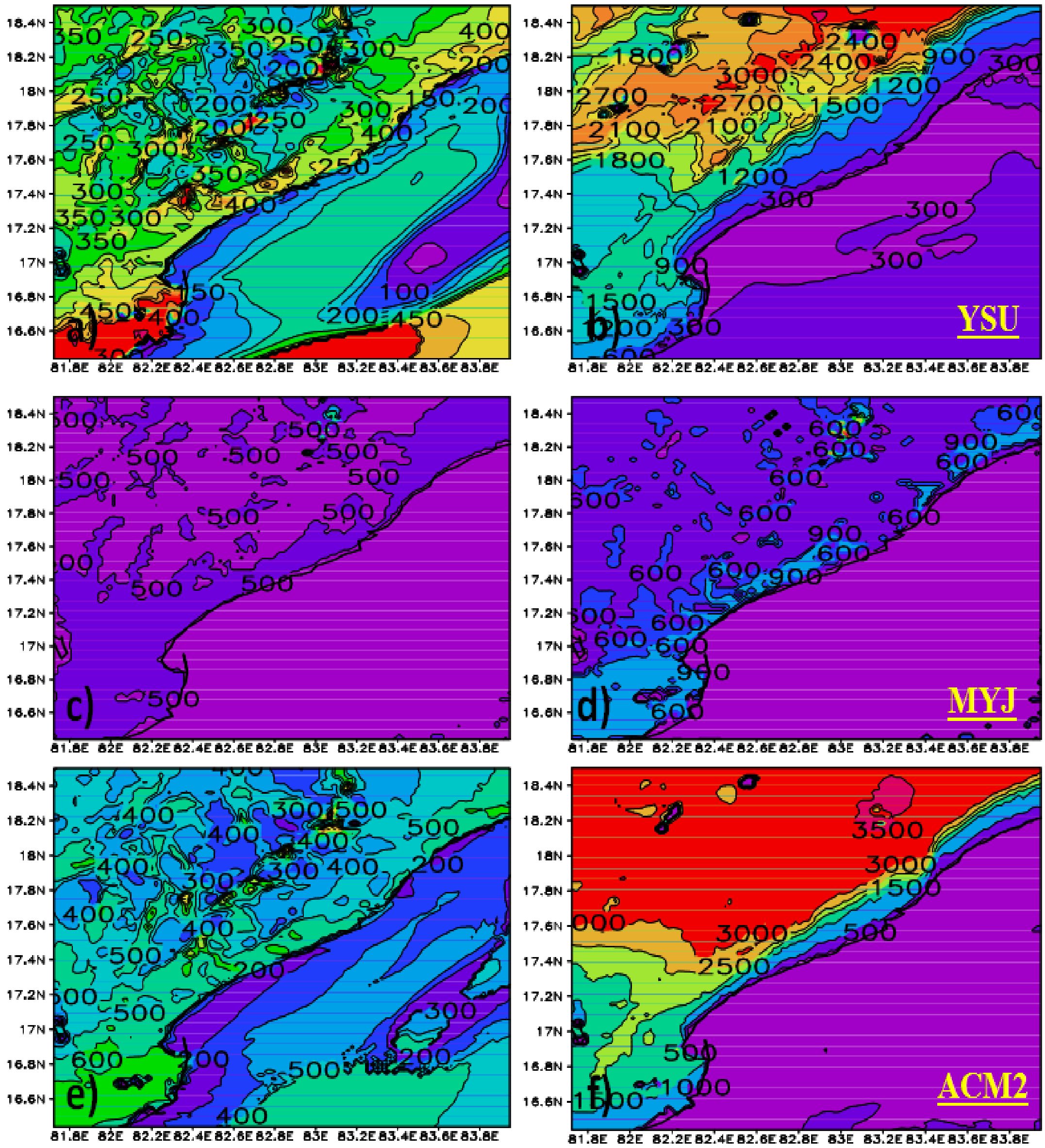

Figure 12: Simulated boundary layer height (m) over Visakhapatnam coast at 08:00 IST and 12:30 IST (with YSU, MYJ and ACM2 PBL Schemes) respectively on 03 April 2010

Conclusions

The numerical simulation of sea breeze circulation over Visakhapatnam for 03 April 2010 has been studied using WRF V 3.1 Mesoscale Model with the three PBL Schemes (YSU, MYJ and ACM2). The study is focussed on the characteristics of the sea breeze circulation and the associated height of the TIBL. The simulation study revealed that well-developed sea breeze is observed. The simulated results of YSU, MYJ and ACM2 PBL Schemes give the salient information about the characteristics of sea breeze (onset, strength, duration, decay) and the height of TIBL over the Visakhapatnam region.

In general, all the five parameters chosen to characterize the sea breeze (onset, strength, duration, decay and height) over the Visakhapatnam region are within the range of values reported earlier (Ramanadham and Subbaramayya, 1958; Rao *et al*., 1981; Rao *et al*., 1982; Kumar *et al*., 1985). The height of the sea breeze usually ranges between 300 and 1000 m. The values from the three schemes agree with these general features. However, caution must be exercised in accepting these results, as the conclusions are drawn based on a limited dataset of four days. A thorough study needs to be conducted using a dataset of 30 to 40 days to draw reasonable and firm conclusions on the characteristics of the sea breeze over Visakhapatnam region.

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