

A numerical study of the influence of synoptic flow on coastal meso-scale circulations on the East and West Coasts of India

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सार – इस शोध-पत्र में पी.एस.यू./एन.सी.ए.आर.–एम.एम. 5 मेसोस्केल मॉडल का उपयोग करते हुए भारत के पश्चिमी और पूर्वी तटों पर तटीय परिसीमा स्तर तथा थल सागर के पवन परिसंचरण पर सिनॉप्टिक प्रवाह के प्रभाव की जाँच संख्यात्मक अनुकरण से की गई है। आरमेक्स की अवधि के दौरान 24 मई 2003 को लिए गए प्रेक्षण दोनों तटीय क्षेत्रों पर दिन के समय थल समुद्र पवन परिसंचरण और तापीय आंतरिक परिसीमा स्तर (टी.आई.बी.एल.) की घटनाओं को कुछ भिन्नताओं के साथ प्रकट करती है। पूर्वी तट की अपेक्षा पश्चिमी तट पर प्रबल दक्षिणी पश्चिमी प्रवाह के प्रभावस्वरूप समुद्री पवन परिसंचरण का शीघ्र विकास तथा त्वरित प्रसरण पाया गया है पश्चिमी तट पर बहने वाली समुद्री पवन अधिक तीव्र होती है। टी.आई.बी.एल. के बनने से तटीय क्षेत्रों में दिन के समय मिश्रण उँचाइयाँ कम हो जाती है। जटिल स्थलाकृतिक के परिणामस्वरूप पश्चिमी तट पर क्षैतिज विस्तार बहुत कम (24 कि.मी.) होता है। दक्षिणी पश्चिमी सिनॉप्टिक प्रवाह के मंद पड़ते प्रभाव से 2–4 मी./से. के क्रम के उर्ध्वार वेग के साथ पूर्वी तट पर समुद्री पवन की फ्रंटल सक्रियता अधिक तीव्र होती है।

ABSTRACT. The effect of synoptic flow on the coastal boundary layer and land sea breeze circulation on the west and east coasts has been investigated by a numerical simulation using PSU/NCAR-MM5 mesoscale model. A study on 24th May 2003 during ARMEX observation period shows occurrence of land-sea breeze circulation and formation of thermal internal boundary layer (TIBL) on both the coastal regions in the daytime but of some differences. An early development and accelerated propagation of sea breeze circulation is noticed on the west coast compared to the east coast under the influence of the prevailing southwesterly flow. The strength of the sea breeze is more on the west coast. The mixing heights during daytime in the coastal regions are reduced by the formation of TIBL. The horizontal extent of TIBL is very less (24 km) on the west coast under the complex topographic effect. The sea breeze frontal activity is more intensive on the east coast with vertical velocity of the order of 2-4 m/sec by the retarding influence of southwesterly synoptic flow.

Key words – ARMEX, Synoptic flow, Coastal boundary layer, Land-Sea breeze, TIBL, TKE.

1. Introduction

The Arabian Sea Monsoon Experiment (ARMEX) was carried out during the southwest monsoon seasons of 2002 and 2003 with the objective to investigate the Arabian Sea convection associated with intense rainfall on the west coast of India. The large-scale flow at the Arabian Sea coast in the pre-summer monsoon is northerly to northeasterly which becomes westerly/southwesterly just before the onset of the monsoon. However, within the atmospheric boundary layer the flow is modified by topography and land-sea thermal contrasts giving rise to meso-scale circulations such as land and sea breeze or mountain/valley flow, (Estoque, 1961). The characteristics of the oceanic air mass change when it

encounters a warm dry air mass over land. Internal boundary layers form in response to the change in surface roughness and thermal contrast at the coast when air flows from sea to land or *vice versa*. The Thermal Internal Boundary Layer (TIBL) is a shallow unstable layer with a rapid mixing and turbulence within it and a neutral or stable layer above it, the top of the TIBL inhibits downward mixing of the air aloft (Vughts and Businger, 1977). This has strong adverse effects on the dispersion of pollutants released at the coastal sites. The sea and land breeze circulation system causes many effects *viz.*, influencing low level clouds, precipitating convective storms, re-circulating and trapping pollutants, altering the regional mixing heights, creating strong near shore temperature and moisture gradients etc. Several theoretical

and numerical studies in the past dealt with the physics and characteristics of Sea Breeze Circulation (SBC) and the effects of topography, large-scale winds and coriolis force through latitude (Pielke, 1974; Mahrer, and Pielke, 1977). The primary features associated with the circulation are the low-level sea breeze from sea to land and the return flow aloft from land to sea, while rising and sinking air motion occurs over the land and sea respectively. Several previous studies show that the direction and strength of the synoptic flow affect the structure and evolution of sea breeze. A meso-scale model study by Venkatesan *et al.* (2002) revealed the effects of SBC of Kalpakkam coast on the dispersion of radioactive pollutants in the region.

An attempt is made in this paper to understand the influence of synoptic flow on the coastal boundary layer and the associated meso-scale circulations on the west coast at Mangalore and on the east coast at Kalpakkam during the ARMEX observation period by a numerical experiment using a high-resolution meso-scale model PSU/NCAR MM5. The study is carried out for 23-24 May, 2003 when boundary layer observations are available at Kalpakkam coast.

2. Description of the model and initialisation

A primitive equation, finite-difference non-hydrostatic meso-scale atmospheric model MM5 (Anthes and Warner, 1978) developed by National Center for Atmospheric Research (NCAR), USA is used in the study. It follows a terrain following vertical coordinate (σ) and has options to choose the region of model domain with suitable horizontal and vertical resolutions and also incorporates different schemes for physical processes of radiation, convection, atmospheric boundary layer and surface processes. The details of the model are described in Grell *et al.*, 1994.

For this study a two-way interactive, triple-nested domains are used to cover the peninsular region, the east coast region of Kalpakkam and west coast region of Mangalore (Fig. 1) with horizontal resolutions of 18, 6 and 2 km respectively. The Coarse Grid Mesh (CGM), Medium Grid Mesh (MGM) and Fine Grid Mesh (FGM) have 100×100 grids each. The CGM covered area between (71.16° E, 7.18° N to 86.25° E, 21.58° N, 18 km resolution). On the west coast the MGM and FGM covered areas between (72.88° E, 10.66° N to 77.62° E, 15.6° N, 6 km resolution) and (74.30° E, 12.12° N to 75.87° E, 13.77° N, 2 km resolution). On the east coast the MGM and FGM covered areas between (77.21° E, 10.11° N to 82.18° E, 14.76° N, 6 km resolution) and

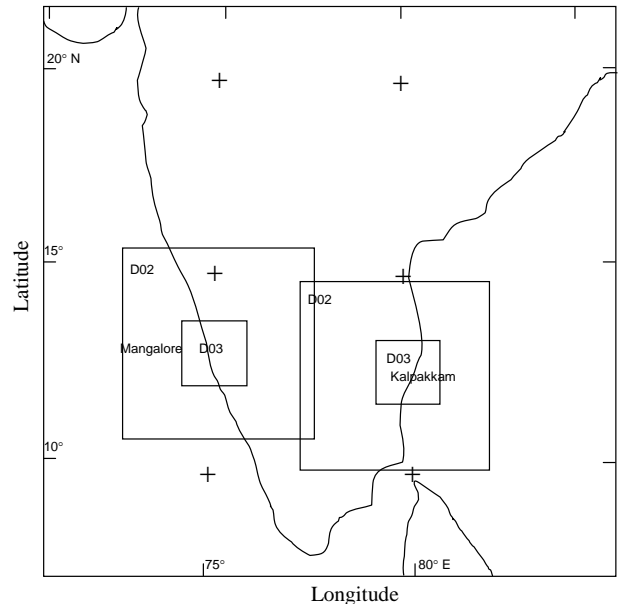


Fig. 1. Domain configuration of MM5 used for Mangalore (left) and Kalpakkam (right)

(79.15° E, 11.81° N to 80.81° E, 13.36° N, 2 km resolution) respectively. All the three domains in each case contain 23 σ levels which include 10 levels in the ABL corresponding to the pressure levels 990, 990, 985, 980, 975, 970, 960, 950, 925, 900, 875, 850 hPa.

Initial meteorological conditions for the model are provided from NCEP global analysis data (FNL) at $1^\circ \times 1^\circ$ resolution by static analysis nudging. The data contains horizontal and vertical wind, geopotential heights, pressure, temperature, mixing ratio, cloud cover, soil moisture and soil temperatures etc. Surface boundary conditions are given from USGS topography, land cover (25 category) and FAO soils types (17 category). The dependent parameters are albedo, thermal inertia, moisture availability, emissivity, roughness length etc. from land use category and soil conductivity, diffusivity, maximum reference moisture content, wilting point etc. from soil category. For the CGM, MGM and FGM these data are input at 9 km, 3.5 km and 0.9 km resolution respectively and interpolated to the model grids. Eta PBL scheme based on Mellor-Yamada formulae (Janjic, 1990) is used for atmospheric boundary layer. It predicts TKE and has local vertical mixing. It uses multi layer land surface process scheme (LSM) (Chen and Dudhia, 2001) for the prediction of surface temperature and surface fluxes. Before the LSM the scheme calculates the surface layer exchange coefficients using similarity theory and after the LSM it calculates the vertical fluxes with an implicit

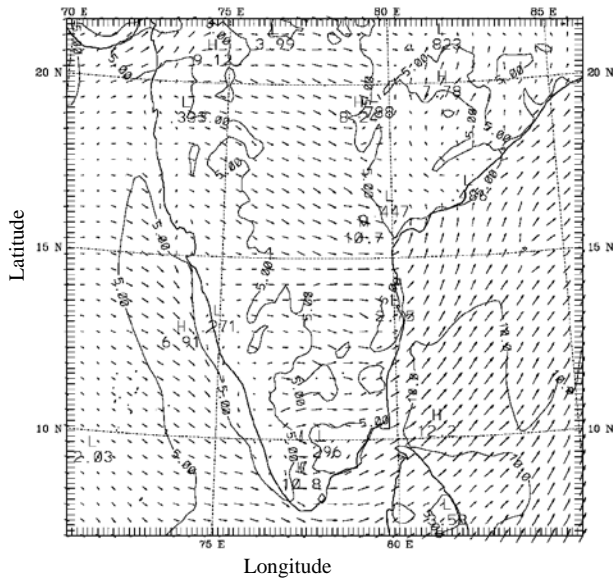
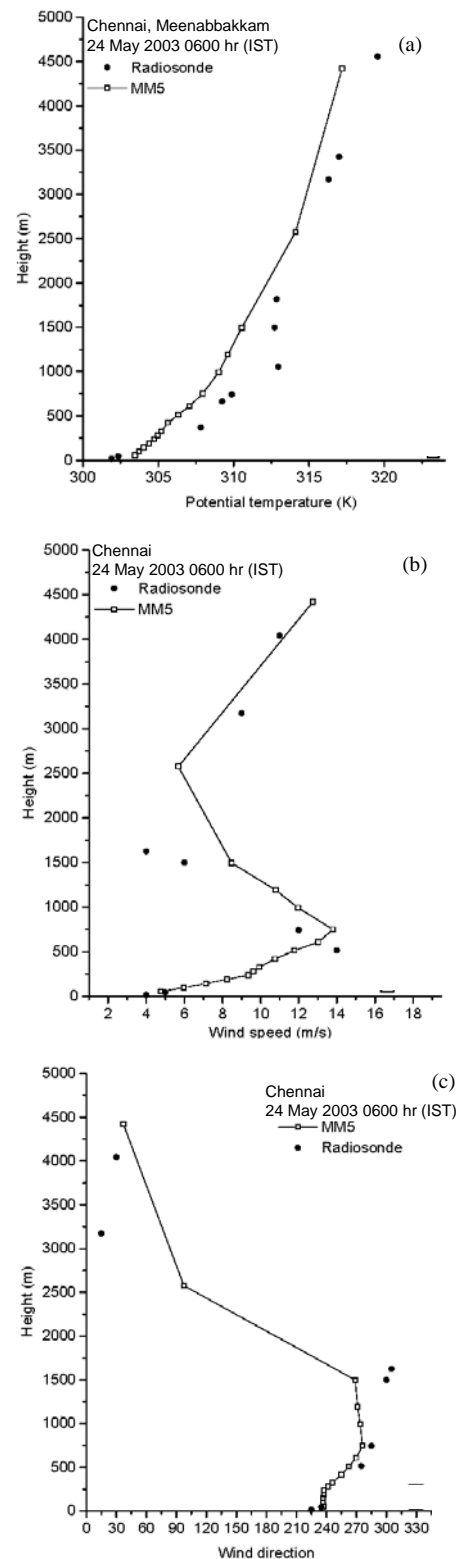


Fig. 2. Simulated wind flow at the surface over Indian peninsula at 0600 hr (IST) on 24th May 2003

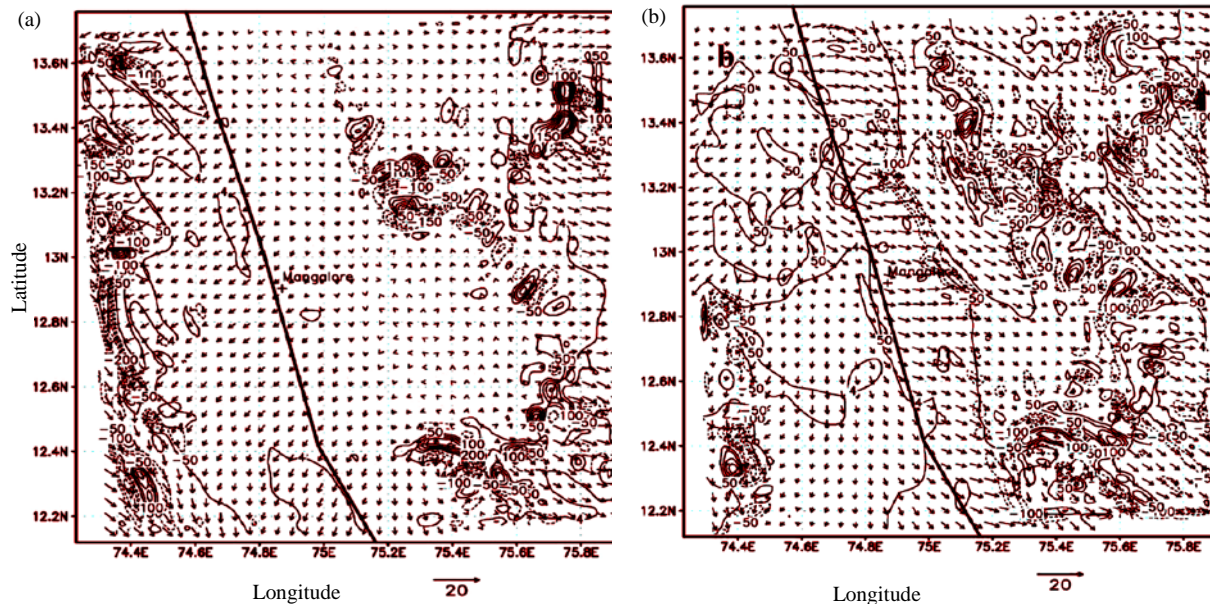
diffusion scheme. Atmospheric radiation and moisture calculations are performed using simple schemes (Dudhia, 1989). Relaxation lateral boundary condition is used for the outer domain while time-dependent lateral boundary condition is used for inner domains. The upper boundary condition is radiative for all domains. The model is initialized on 0000 hr (IST) 24th May and integrated for a numerical period equivalent to 24 hours, the lateral boundary conditions are updated every 6 hr.

3. Results

The S-W monsoon had set in over Kerala on 8th June, 2003. The low-level wind flow upto 1.5 km was southwesterly on the south east coast and westerly on the west coast a few days before the onset of the monsoon. Simulated large scale and local atmospheric structure for pressure, winds, moisture and vertical temperature distribution is in good agreement with observations. Detailed study of this comparison is available in Srinivas *et al.* (2003). Simulated wind field over the southern peninsular region is westerly to southwesterly at low-level (950 hPa) (Fig. 2) and northerly to northwesterly at high level (850 hPa). From a qualitative comparison of the observed data with the simulation Figs. 3(a-c) a fair level of agreement can be noticed. Results from fine nests (3rd domain) for winds, spatial temperature distribution, turbulence kinetic energy (TKE), and horizontal convergence/divergence are analysed to characterise the boundary layer flow. For Kalpakkam region the simulation is compared with on site experimental data



Figs. 3(a-c). Simulated and observed vertical profiles of (a) potential temperature, (b) wind speed and (c) wind direction at 0600 hr (IST) on 24 May 2003



Figs. 4(a&b). Surface wind (m sec^{-1}), convergence/divergence (10^{-5} sec) fields at the surface ($\sigma = 0.995$) at Mangalore (a) 0800 hr (IST) and (b) 1200 hr (IST)

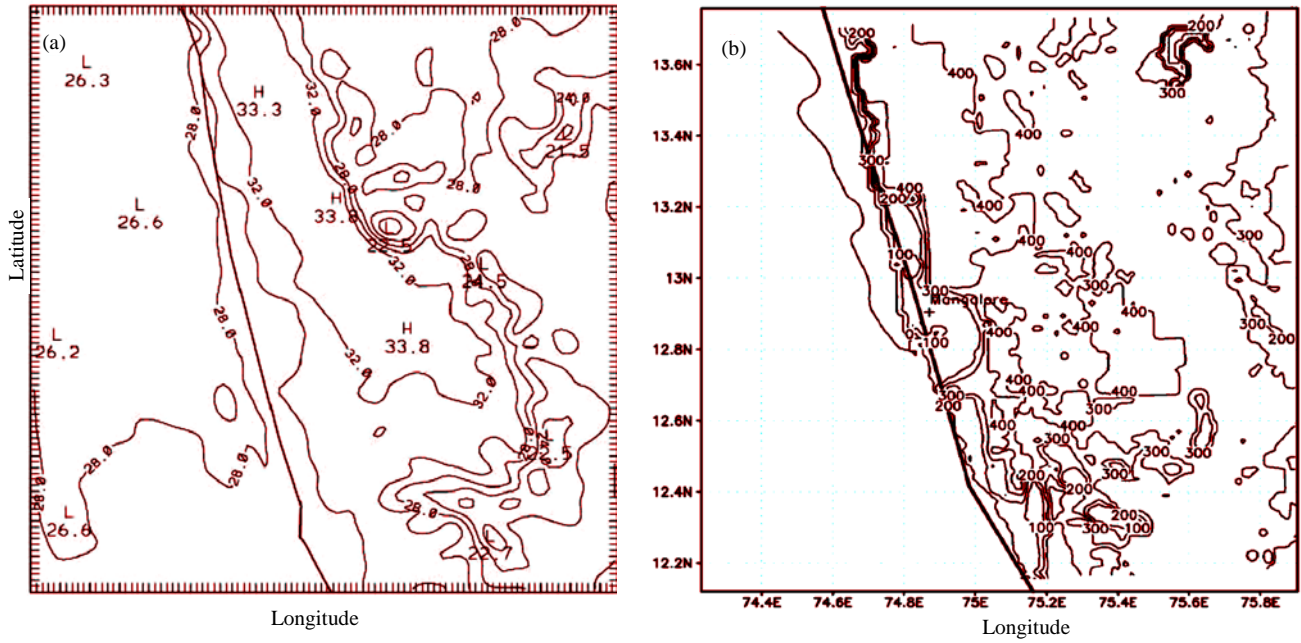
from meteorological tower, Doppler mini-Sodar and Sonic Anemometer gathered during the Coastal Atmospheric Boundary Layer Experiment (CABLE) field measurements at Kalpakkam.

3.1. Boundary layer Structure at Mangalore

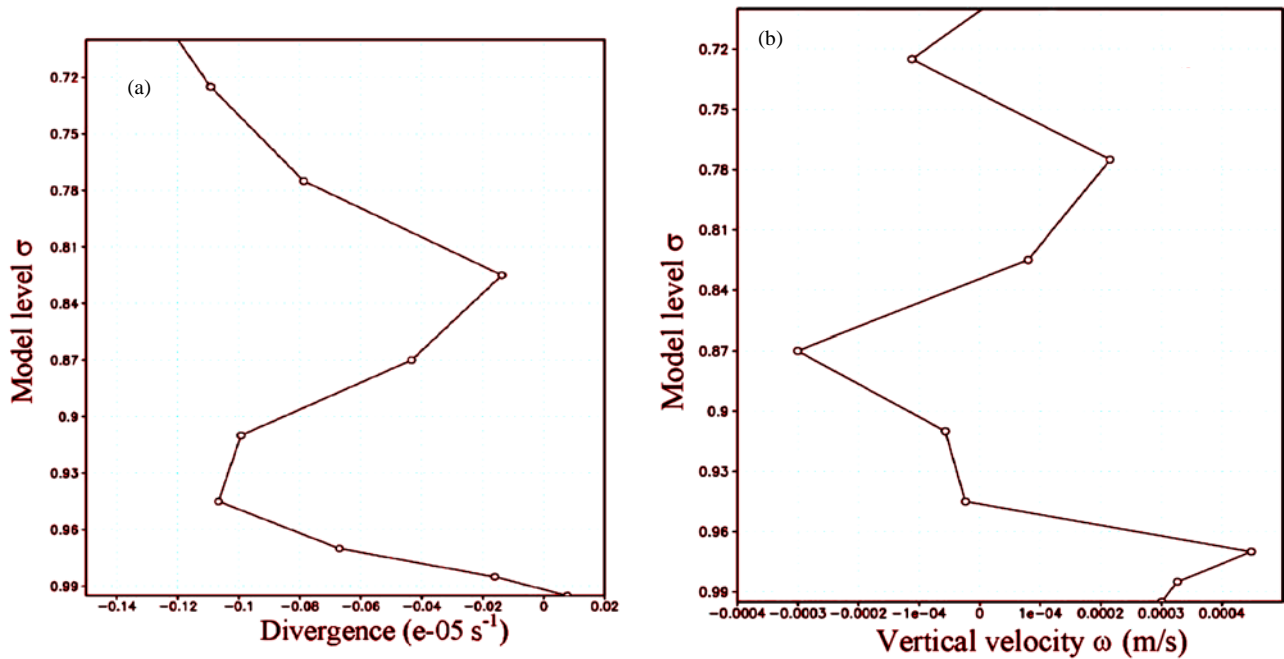
The topography of Mangalore is plain land (elevation 0-50 m) upto 30 km inside the coast and changes to undulating hilly terrain sharply towards the east in Western Ghats, the elevation of the hills is about 1000 m. The results of simulation from the innermost domain for West coast shows that the surface wind (at lowest model level $\sigma = 0.995$) at 0400 hr (IST) is north-westerly over the sea, calm/northerly over the coastal plain and westerly in the hilly region. An east/northeasterly surface wind (land breeze) develops at 0800 hr (IST) at the coast, which becomes strong over the sea [Fig. 4(a)]. The wind during the land breeze time is opposite to the synoptic flow; its strength is less due to this reason. Its direction sense indicates it is land breeze. The surface wind blows in two different directions on either side of the hills, it is northwesterly on the eastern side of the hills and easterly on the western side over the plain land, the strength of the land breeze is about 2 to 3 ms^{-1} . A zone of horizontal divergence ($10 \times 10^{-6} \text{ s}^{-1}$) is noticed over the hilly boundaries while convergence is seen over the sea much away from coast [Fig. 4(a)]. The temperature over land has increased in the daytime

leading to a land sea temperature contrast of 4° C and a corresponding horizontal variation in sensible heat flux (100 to 400 Wm^{-2}) at 1200 hr (IST) Figs. 5(a&b). A horizontal temperature gradient of about 0.16° C/km exists over the plain land area while the temperature decreases to the east further away over the hilly region. The land breeze became weak by 1000 hr (IST); there is a surface wind shift at 1100 hr (IST) over the coastal plain in SE direction giving rise to development of sea breeze with NW surface wind. The sea breeze circulation has intensified after 1200 hr (IST) [Fig. 4(b)] intercepting the topographic flow and is modified at the topographic boundaries leading to channel flow. The circulation after 1800 hr (IST) is an inertial flow. The peak horizontal wind speed during sea breeze regime is 8 ms^{-1} . A low level divergence and high level convergence ($\sigma = 0.87$) is associated with land breeze at 0800 hr (IST) while a low level convergence and high level divergence is associated with sea breeze circulation at 1200 hr (IST) Figs. 6(a&b).

Simulated vertical temperature structure agrees with radiosonde profile at Mangalore coast, a neutral layer up to 250 m height and a stable/inversion layer aloft are observed at 0600 hr (IST) (not shown). The surface wind up to 250 m height is southerly and above 300 m it is northwesterly. Potential temperature distribution in a vertical cross section across the Mangalore coast at 0400 hr (IST) suggests that a stable boundary layer exists over



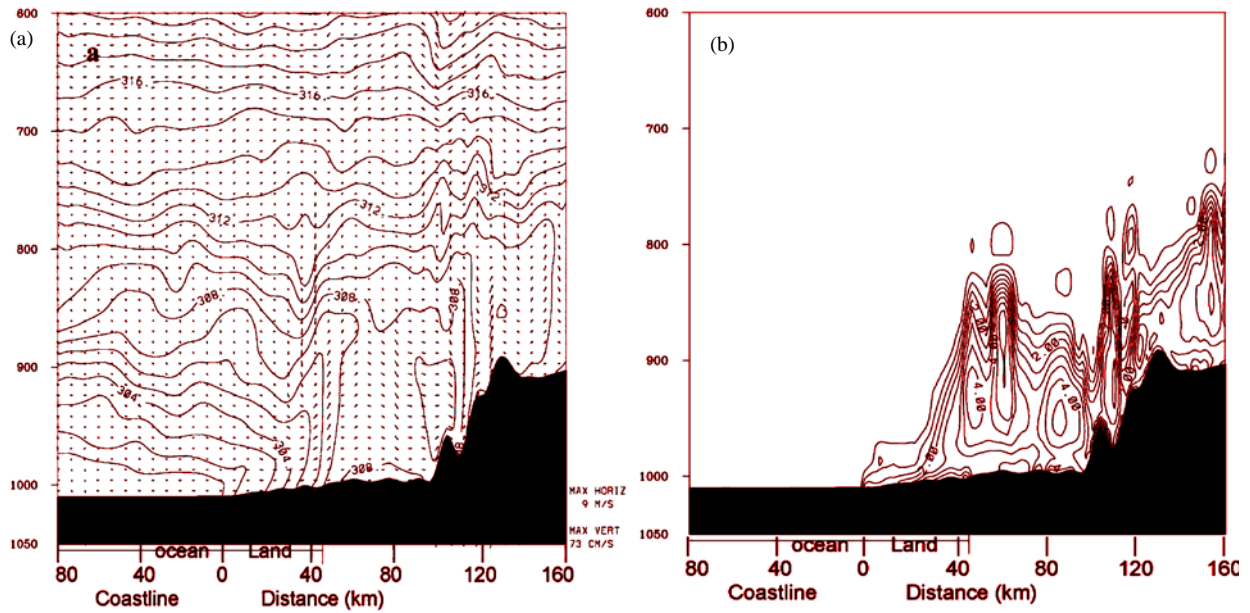
Figs. 5(a&b). (a) Temperature ($^{\circ}C$) and (b) Sensible Heat flux ($W m^{-2}$) distribution over Mangalore coast at 1200 hr (IST)



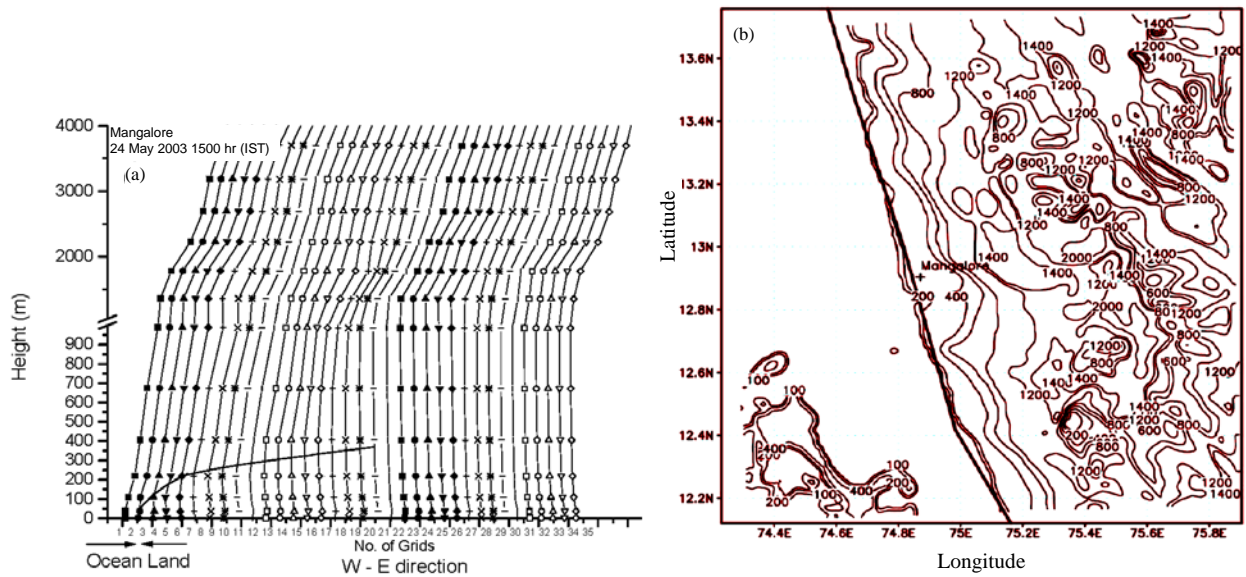
Figs. 6(a&b). (a) Divergence and (b) vertical velocity profiles at Mangalore coast at sea breeze onset at 1200 hr (IST)

both land and sea. It has changed to an unstable stratification by 1100 hr (IST) in the afternoon due to

daytime heating; it grows further at 1500 hr (IST) [Fig. 7(a)]. A sea breeze frontal convergence zone is also



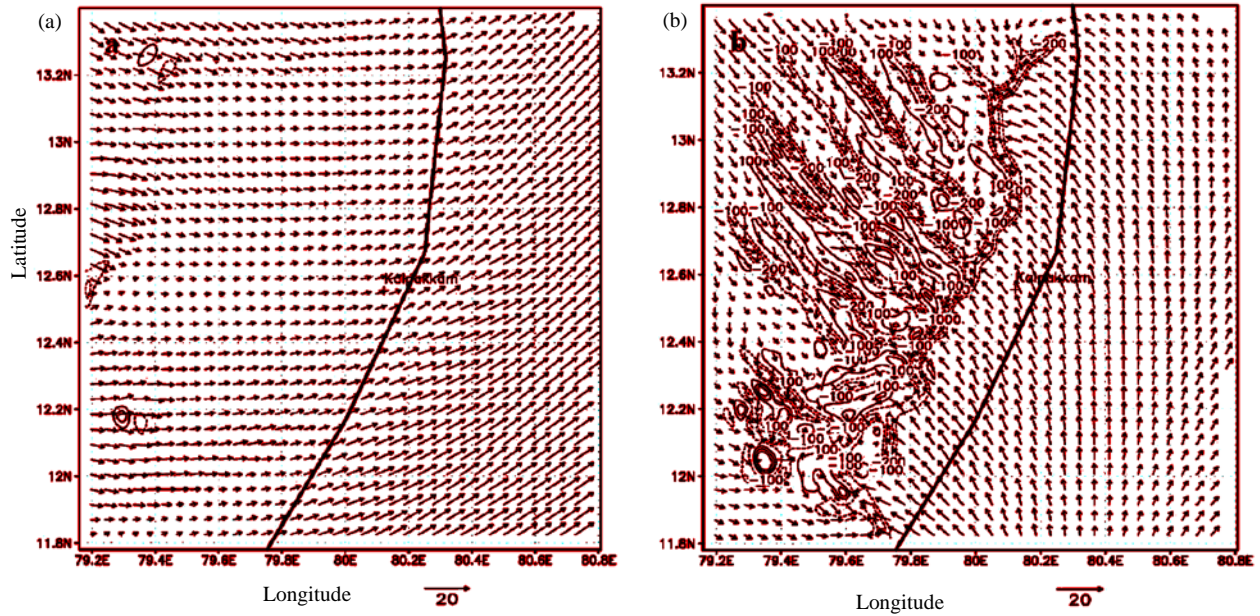
Figs. 7(a&b). (a) Potential temperature (K) and (b) Turbulence Kinetic Energy (J/kg) distribution across Mangalore coast at 1500 hr (IST)



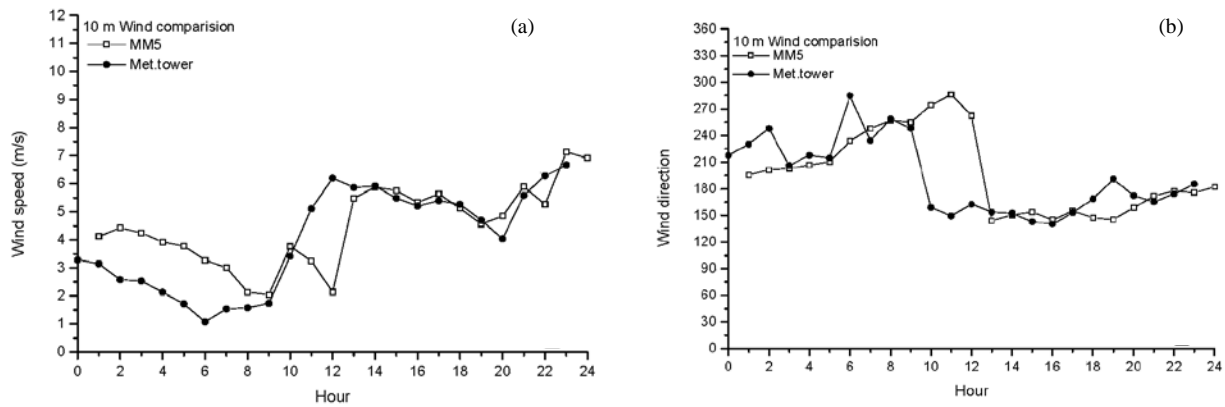
Figs. 8. (a&b). (a) Vertical profiles of Potential temperature at Mangalore coast showing TIBL, (b) Variation of mixing height over Mangalore region at 1500 hr (IST)

noticed with strong updrafts ($w \approx 0.52$ m/s) at the front and downdrafts on the rear side of the front. This once

again confirms the surface convergence, divergence fields noticed earlier. The turbulence kinetic energy (TKE),



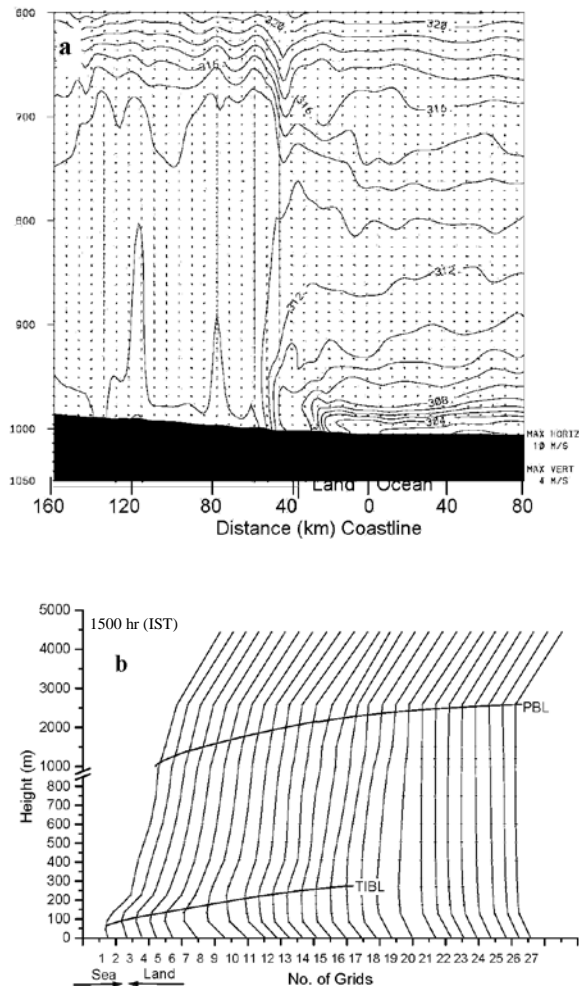
Figs. 9(a&b). Simulated horizontal surface wind (at 1001 hPa) at Kalpakkam (a) at 0800 hr (IST) and (b) 1300 hr (IST) on 24 May 2003. Contours show horizontal divergence ($1e-05 \text{ s}^{-1}$)



Figs. 10(a&b). Comparison of (a) wind speed and (b) direction at 10 m level from Met.Tower with simulation

which is a measure of the intensity of turbulence, is seen to increase during daytime due to thermal convection and shear. The TKE is modified by sea breeze flow near the coast [Fig. 7(b)] and the effects of land sea contrasts can be clearly seen. It is high over land and rapidly falls as the coastline is approached. A sea breeze inflow layer exists

by the advection of cool and moist sea breeze over land during sea breeze time. By its influence the temperature structure near the coast is modified such that a shallow unstable layer, a neutral layer and a stable/inversion layer aloft form. The shallow unstable layer is the TIBL and its vertical extent is given by the base of the lowest inversion



Figs. 11(a&b). (a) Potential temperature distribution and (b) temperature profiles showing TIBL formation across Kalpakkam coast at 1500 hr (IST)

(Arritt, 1987). This is not seen over the land much far away from coast (inland boundary layer). The rapid fall of TKE vertically near the coast is related to TIBL formation. The level at which TKE becomes minimum vertically can be considered as the TIBL vertical extent, which is about 300 m. Analysis of Temperature distribution indicates that the TIBL started developing after 1200 hr (IST) and its horizontal extent reached a maximum at 1700 hr (IST). It is about 350 m at 1500 hr (IST) and the TIBL extends to 25 km inland [Fig. 8(a)]. The mixing height over land near the coast is modified by advection of sea breeze; the internal boundary layer could be seen extending up to 30 to 40 km inland from the coast [Fig. 8(b)].

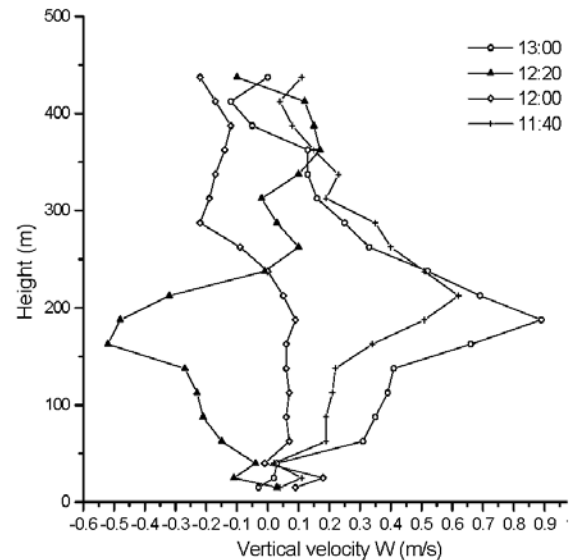


Fig. 12. Vertical velocity profile from Doppler Mini-Sodar at Kalpakkam on 24 May 2003 after the onset of sea breeze

3.2. Boundary layer flow at Kalpakkam

The terrain at Kalpakkam on the east coast is mostly plain. Simulation shows a southerly to southwesterly surface flow between 0000 & 0500 hr (IST), which changes to westerly land breeze at 0600 hr (IST) and is well established at 0800 hr (IST) [Fig. 9(a)]. Subsequently the flow becomes weak northwesterly at 1200 hr (IST) and a southeasterly wind from sea enters land at 1300 hr (IST) indicating onset of sea breeze [Fig. 9(b)]. The circulation vectors indicate the movement of a sea breeze front across the coast on to the land creating a calm condition ahead of the front; the updrafts associated with the front have a strong vertical velocity ($\approx 2 \text{ ms}^{-1}$) [Fig. 11(a)]. It can also be noticed that regions of strong horizontal convergence formed when the sea breeze meets the land breeze/synoptic wind. The sea breeze covered a distance of 70 km by 1800 hrs (IST) from coast and by 2000 hr (IST) it covered almost 90 km. The direction of the circulation changed from southeasterly to southerly at 2200 hr (IST). While the sea breeze progresses on the land the region of convergence also moves along with it. From the circulation vectors the depth of the sea breeze inflow layer is found to increase from 300 m at 1200 hr (IST) to about 450 m at 1800 hr (IST). The peak wind speed during sea breeze is about 5.5 ms^{-1} .

Simulated diurnal wind speed and direction closely agree with observations except at noon between 1100-1200 hr (IST). This deviation is because of the delay in

sea breeze simulation by the model Figs. 10(a&b). The model delay in sea breeze simulation is also confirmed by observations from Doppler Mini-SODAR and other instruments at Kalpakkam. The potential temperature distribution indicates alteration from early morning stable conditions to unstable stratification in the afternoon [Fig. 11(b)]. An unstable Thermal Internal Boundary Layer (TIBL) developed over land with height up to 300 m at 1500 hrs (IST). The horizontal extent of the TIBL over land increased towards evening with a maximum at about 1800 hrs (IST), thereafter TIBL disappeared. The vertical velocity from Mini-Sodar measurements at Kalpakkam confirms the converging (updrafts) and diverging motions (downdrafts) due to sea breeze onset and movement across the coast (Fig. 12).

4. Discussion

While it is found that the model lags behind the observations by an hour such as in the occurrence of sea breeze, there are some differences in the simulated boundary layer features on the west and east coasts. The sea breeze onset is seen to be much early (at 1100 hr IST) on the west coast and its inland penetration is also accelerated, it covered nearly 100 km inland by 1600 hr (IST). On the other hand sea breeze at Kalpakkam on the east coast is set late by 2 hours (on set time at 1300 hr IST), its progression is slow and its inland penetration is deep up to 70 km only in the late evening by 1800 hr (IST). The reason for this is the southwesterly synoptic flow, which opposes the sea breeze circulation on the east coast. Under the opposing force of the southwesterly synoptic wind on the east coast, the sea breeze onset and its propagation have been delayed. The strength of the sea breeze is noticed to be higher on the west coast. The internal boundary layer associated with sea breeze at Mangalore has a vertical extent of 350 m and horizontal extent up to 25 km only, whereas at Kalpakkam the TIBL extended up to 45 km inland with a vertical extent of 200 to 250 m. The complex topography of the Western Ghats affects the horizontal extent of sea breeze flow as well as the growth of TIBL by roughness effect at Mangalore coast.

Secondly, the low level circulation on the west and east coasts show regions of strong horizontal convergence and divergence associated with land-sea breeze flow. The vertical velocity of the sea breeze updrafts on the east coast is about 2 m s^{-1} and that on the west coast is about 0.5 m s^{-1} . Thus a more intense frontal activity is seen to exist on the east coast when the SW'ly synoptic flow opposes the sea breeze and retards its movement. On the west coast only the static topography effect on the sea breeze leads to vertical winds and hence the fronts are less intensive. The variation in the simulated features of ABL

(sea breeze and thermal internal boundary layer characteristics) at Kalpakkam and Mangalore coasts suggests that the pattern of atmospheric dispersion in these two regions would be significantly different.

5. Conclusion

The numerical study indicates that the boundary layer characteristics and the meso-scale land-sea breeze circulation along the east and west coastal regions of India have significant variations under the influence of topography and the direction of large-scale synoptic wind. Results of a simulation with a mesoscale atmospheric model for 24th May, 2003 shows development of land and sea breeze circulation and formation of thermal internal boundary layer at both the places but of different features. While the development and inland propagation of sea breeze is accentuated on the west coast under the influence of the southwesterly synoptic flow, it is delayed and retarded on the east coast by the opposing action of the synoptic flow. The sea breeze strength is more on the west coast. The vertical extent of TIBL is higher on the west coast; the TIBL has spread horizontally more on the east coast. The mixing height overland in both the coast regions is modified in the afternoon hours due to the occurrence of sea breeze.

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