

Observations and numerical simulation of the sea and land breeze circulations along the west coast of India

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Received 27 December 2004, revised 7 April 2006

Sea breeze circulation along the west coast of India during the Indian Ocean Experiment (1999) is investigated. Pilot balloon sounding data from Mumbai, Goa, and Trivandrum, India show a diurnal variation in wind direction caused by land and sea breeze circulations along the west coast of India. Rawinsonde wind profiles taken from R/V *Sagar Kanya* 130 km offshore from the west coast of India show the presence of sea and land breeze circulations. Infrared satellite images show the furthest extent of the sea breeze circulation over the Arabian Sea to be around 200 km. Constant level balloons released from Goa, India also showed the extent of the sea breeze over the ocean to be 200 km. A mesoscale numerical model was used to further investigate the sea breeze circulation and its horizontal extent over the ocean. Simulated cross sections along the west coast of India show the horizontal extent of the afternoon sea breeze over the ocean to vary from around 130 to 260 km. Vertical velocities of about 0.25 ms^{-1} were simulated inland as the sea breeze interacted with the mountains along India's west coast.

[**Key words:** INDOEX, sea breeze, air-se. interaction, sea breeze front, inland penetration, SST, boundary layer meteorology, Arabian Sea]

1. Introduction

The influence of anthropogenic aerosols and gases on the global radiation balance has long been a subject of debate. To study this relationship, the Indian Ocean Experiment (INDOEX) was conducted over the Arabian Sea and tropical Indian Ocean from 14 January to 31 March 1999 during the northeast monsoon. Northeast winds transport aerosols and gases from the Indian subcontinent over the ocean during this dry season. The main goal of INDOEX (1999) was to study the possible variation in the magnitude of solar absorption occurring near the surface and in the troposphere where there are high concentrations of sulfates and aerosols of continental origin^{1,2}. One interesting phenomenon observed by various data platforms during INDOEX was the sea and land breeze circulation along the west coast of India. Synoptic flow substantially influences the offshore extent of the sea breeze over the ocean^{3,4}. Opposing winds can increase the convergence associated with the sea breeze and enhance frontogenesis over land⁵. Large updrafts over a depth of 30 to 350 m along the west coast of India have

been observed with SODAR during the passage of sea breeze fronts⁶.

The horizontal extent of the sea breeze over the Arabian Sea near Mumbai⁷ is typically around 120 to 150 km while the inland penetration of the circulation is greater than 80 km. Horizontal extent of the sea breeze over the ocean in the tropics^{8,9} has been quoted at distances up to 300 km. Observations from a 10 m tower aboard R/V *Sagar Kanya* showed the existence of the sea breeze over the ocean at a distance of 80 km from the west coast of India¹⁰.

Aerosols and gases can be transported from India over the ocean in the marine boundary layer. A large increase in marine boundary layer ozone concentrations was observed close to the India coastline¹¹. Westward propagating cloud bands originating near the west coast of India were observed¹² with a geo-stationary satellite during INDOEX 1999. The presence of cloud bands appears to depend largely on the magnitude of the sea and land breeze circulation. Peaks in aerosol and carbon monoxide concentration were observed as the cloud bands passed research vessel (R/V) *Ron Brown*¹³.

Transport of pollutants in the marine boundary layer (MBL) depends on the extent and intensity of

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coastal sea-land breeze circulations. The objective of this paper is to investigate the structure of the sea and land breezes along the west coast of India using a set of multiplatform observations during the field phase of INDOEX (1999) and numerical simulations. Understanding the horizontal extent of the sea breeze and its role in pollution transport over the Arabian Sea will contribute to the core objective of INDOEX (1999), which is assessing the magnitude of radiative forcing caused by aerosols and gases.

During March, the daytime land surface temperature along the southeastern coastal region of India approaches 38°C while the sea surface temperature in the Arabian Sea is around 28°C . This contrast in surface temperatures sets up the thermally induced sea breeze circulation as shown in Fig. 1 A. Vertical depth of the sea breeze circulation is generally around 1 km. The onshore flow normally penetrates inland to around 80 km. Mountainous topography along India's west coast enhances convection associated with onshore flow. The offshore extent of the sea breeze varies depending on the magnitude and direction of synoptic flow. The land breeze circulation develops during the night when the land surface temperature drops to around $20\text{--}25^{\circ}\text{C}$ while the sea surface temperature remains the same. Offshore flow at the surface results from the horizontal temperature gradient (Fig. 1 B). Contrast in surface temperatures between ocean and land are not as great during the night as during the day. As a result, depth of the land breeze is generally less than that of the sea breeze and does not have a large horizontal extent over the ocean.

2. Materials and Methods

Several data platforms were used during INDOEX (1999) to measure parameters relevant to the magnitude and horizontal extent of the sea and land breezes along the west coast of India. These platforms include the research vessel R/V *Sagar Kanya*, Meteosat-5 infrared satellite, constant level balloons, and observations from coastal stations at Mumbai, Goa, and Trivandrum, (Fig. 2). A detailed description of the various platforms is presented below.

2.1 Coastal stations

Wind profile data were collected using pilot balloons at Mumbai (18.55°N , 72.50°E), Goa (15.25°N , 73.43°E), Trivandrum (8.5°N , 77°E) (Fig. 2), India during INDOEX (1999). The winds were measured twice daily at 00:00 UTC (0530 LT)

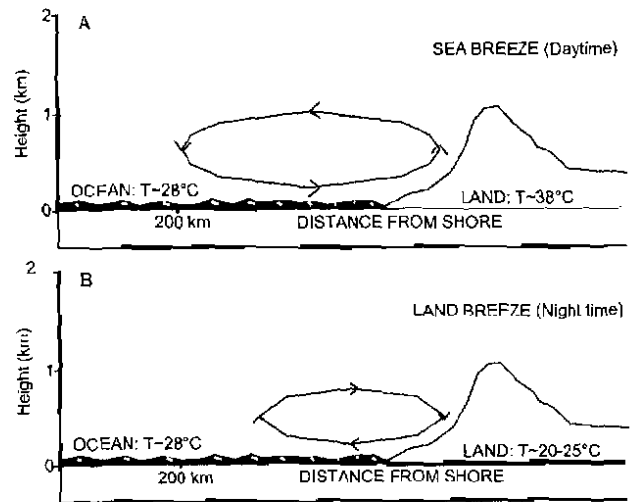


Fig. 1—Schematic diagram showing the horizontal extent of the sea breeze (A) and land breeze circulation (B) circulation along the west coast of India.

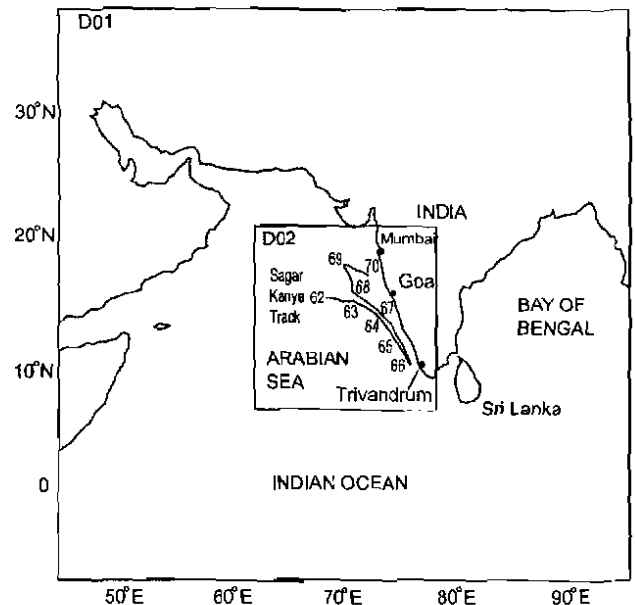


Fig. 2—Location of coastal stations and the ship track for research vessel *Sagar Kanya* during the parallel track experiment during INDOEX (1999). Location of R/V *Sagar Kanya* is denoted by Indian Day.

and 12:00 UTC (1730 LT). Data from these stations were used for this research because their locations will exhibit any latitudinal differences in the magnitudes of the sea and land breezes along the west coast of India.

2.2 R/V *Sagar Kanya*

The track of R/V *Sagar Kanya* with location denoted by Julian day during the parallel track experiment portion of INDOEX (1999) is shown in Fig. 2. The parallel track experiment was from March

3-11, 1999. On 7 March 1999, R/V *Sagar Kanya* was within 130 km of the west coast of India. Such close proximity to the west coast of India provided an unique opportunity to study the horizontal extent of the diurnal coastal circulation over the Arabian Sea. Soundings were made several times a day during the parallel track experiment to observe the wind profiles.

2.3 IR satellite data

The Meteosat - 5 satellite was launched on 2 March 1991 under the authority of the European Space Agency (ESA). Meteosat-5 is a meteorological satellite with a geostationary orbit operating within the worldwide network of the World Weather Watch of the World Meteorological Organization (WMO). The general mission of Meteosat - 5 is imaging in the visible, infrared, and water vapor regions of the spectrum. Meteosat -5 was positioned over the Indian Ocean in 1998 to provide remote-sensed data during INDOEX.

2.4 Constant level balloons

Constant level balloons were released from Goa, India (Fig. 2.) to visualize the wind flow in the boundary layer near the west coast of India and the eventual transport towards the Inter Tropical Convergence Zone¹⁴. Balloons were launched around 04:30 LT just before the peak of the land breeze so that the balloon would drift towards the ocean. Large scale winds during this period were also towards offshore. The balloons were filled with helium and maintained a nominal flight pressure of around 925 hPa. Balloons were equipped with a GPS receiver to measure 3D position, a pressure sensor, a thermistor mounted on the pressure sensor to control its temperature and correct for possible thermal pressure drifts, a thermistor for measuring air temperature, and a commercial hygrometer for relative humidity. Data were sampled and stored on board every 30 minutes. Stored data were transmitted daily to two satellites.

3. Observations

3.1 Coastal stations

Land breeze during the night is a common feature along the west coast of India. The u-component of the horizontal wind at Mumbai at 00:00 UTC (05:00 LT) on 2 March 1999 is shown in Fig. 3 A. Winds were easterly (offshore) at the surface with a magnitude of about 4 ms^{-1} . The easterly winds increased to a maximum of about 9 ms^{-1} at a height of 100 m. Winds remain easterly up to a height of 1200 m where they

shift to westerly. Westerly winds of about 5 ms^{-1} were observed up to 3000 m. Easterly winds near the surface were also observed further to the south at Goa at 00:00 UTC on 2 March 1999 as shown in Fig. 3 B. Winds near the surface were around 1 to 2 ms^{-1} . Winds remain weak and easterly up to 3000 m with a maximum value of 5 ms^{-1} . Westerly winds aloft were observed at Mumbai and not at Goa located further south because of the strong northeast monsoon winds present in much of the troposphere. Weak offshore flow at the surface was also observed at Trivandrum (Fig. 3 C), south of Goa, at 00:00 UTC on 2 March 1999. The easterly winds at the surface were around 0.5 ms^{-1} and increase to a maximum of 8.5 ms^{-1} at 1700 m. Easterly winds were observed from the surface up to 3000 m. No westerly winds aloft were observed at Trivandrum because of the strong northeast monsoon flow in the troposphere observed in southern India. Winds at the surface shift from easterly to westerly during the transition from land to sea breeze along the west coast of India. Westerly

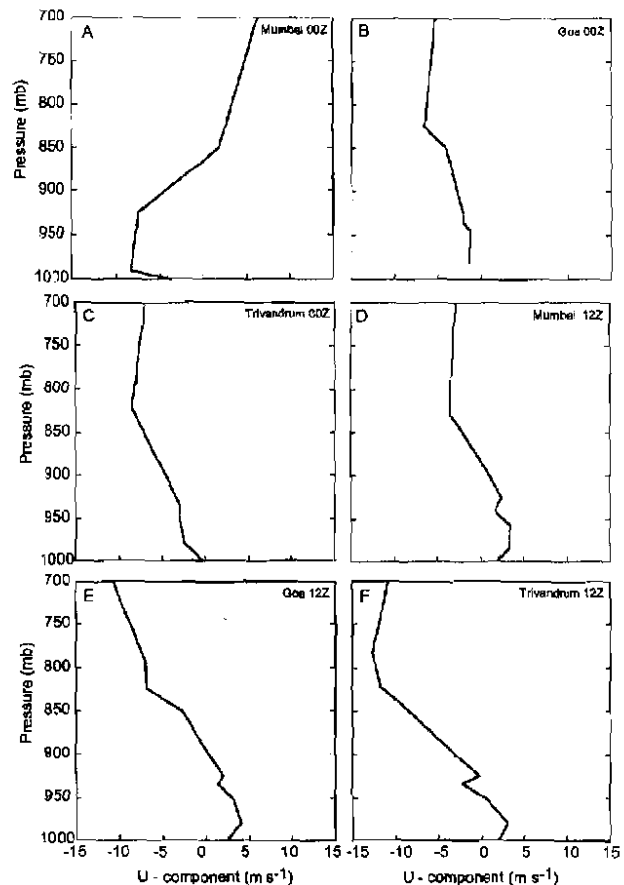


Fig. 3—The u-component of the horizontal wind at 00:00 UTC on 2 March 1999 at Mumbai (A) at Goa (B) and at Trivandrum (C). The u-component of the horizontal wind at 12:00 UTC on 2 March 1999 at Mumbai (D) at Goa (E) and at Trivandrum (F).

(onshore) winds at the surface were observed at Mumbai at 12:00 UTC (17:00 LT) on 2 March 1999 (Fig. 3 D). Winds at surface were around 2 ms^{-1} and reach a maximum of 4 ms^{-1} at 300 m. Above 1000 m, the winds shift to easterly but remain light with values of about 2 to 3 ms^{-1} . Onshore winds of around 3 ms^{-1} were observed further to the south at Goa at 12:00 UTC (Fig. 3 E). Above 1000 m, winds shifted to easterly and reached a maximum of 10 ms^{-1} at a height of 3000 m. The easterly winds aloft were much stronger at Goa than at Mumbai. The winds at the surface at Trivandrum at 12:00 UTC (17:30 LT) on 2 March 1999 were also westerly (Fig. 3 F). Westerly winds of around 3 ms^{-1} at the surface increase to 4 ms^{-1} at a height of 300 m. Above 700 m, the westerly winds shift to easterly and reach a maximum of 13 ms^{-1} at 2100 m. As was the case in Goa, the easterly winds aloft were strong because of the combined effect of the return flow aloft associated with the sea breeze and the northeast monsoon winds.

3.2 R/V Sagar Kanya

Wind profiles from R/V *Sagar Kanya* during the INDOEX Parallel Track Experiment provide an opportunity to research the horizontal extent of the sea breeze circulation over the Arabian Sea. R/V *Sagar Kanya* was approximately 130 km from the west coast of India on 7 March 1999. The observed u-component of the horizontal wind measured from R/V *Sagar Kanya* at 00:00 UTC (05:00 LT) on 7 March 1999 (Fig. 4 A) shows that winds at the surface were light but increased to 2.5 ms^{-1} at a height of 200 m. Above 200 m, the winds shifted to easterly and remained so up to 3000 m with values reaching 7 ms^{-1} . The u-component of the horizontal wind at 08:00 UTC (13:00 LT) (Fig. 4 B) shows that winds were observed to be easterly (offshore) from the ocean surface up to 3000 m. Wind speed values ranged from 1 to 8 ms^{-1} . The easterly winds throughout the depth of the lower troposphere at this time may be the result of northeast monsoon flow. Winds near the surface have shifted to westerly (onshore) by 12:00 UTC (17:00 LT) on 7 March (Fig. 4 C). Wind speeds range from 1 to 3.5 ms^{-1} up to 700 m. Above 700 m, the winds shift to easterly and remain so up to 3000 m. The maximum easterly wind speed observed at this time was around 10 ms^{-1} . The wind shift observed in the lowest 700 m of the atmosphere is believed to be due to the developing sea breeze circulation. Winds at the surface were still easterly at 18:00 UTC on 7 March (Fig. 4 D) with

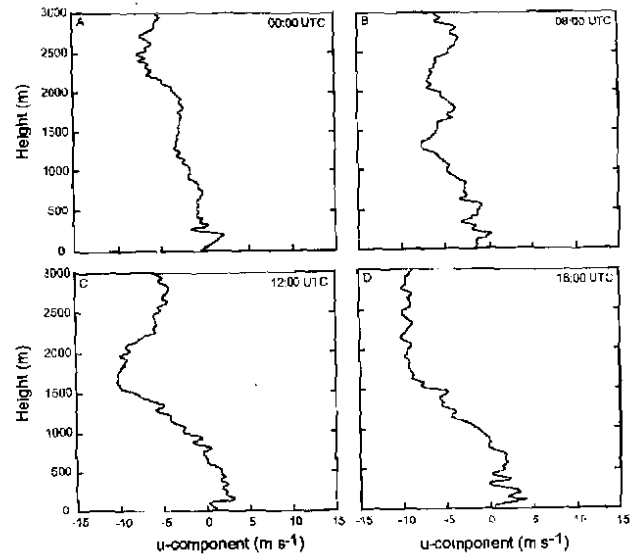


Fig. 4—A) The u-component of the horizontal wind measured 130 km from the west coast of India from R/V *Sagar Kanya* at 00:00 UTC on 7 March 1999. B) Same as A but at 08:00 UTC. C) Same as A but at 12:00 UTC. D) Same as A but at 18:00 UTC.

values ranging from 1 to 4.5 ms^{-1} up to 800 m. Above 800 m, winds shifted to easterly and remained so up to 3000 m. Maximum easterly winds were still around 10 ms^{-1} . The westerly winds in the lower portion of the atmosphere still suggest the influence of the sea breeze. The wind shift (Fig. 4) in the lowest 700 m of the atmosphere measured 130 km from the west coast of India suggests the influence of the sea breeze circulation. Wind directions at the surface changed little but a more dramatic wind shift was observed at a height of 200 to 300 m.

3.3 Constant level balloons

Horizontal extent of the sea breeze over the ocean can also be investigated using data obtained from constant level balloons released along the west coast of India during INDOEX (1999). The balloons were released around 04:30 LT just before the peak of the land breeze so that the balloons would be transported over the ocean. Balloons maintained a nominal flight level of around 600 m. Track of balloon release # 10 from 13 to 16 February 1999 is shown in Fig. 5 A. Solid line represents the nighttime track and the dashed line represents the daytime track. The balloon was released during the night and was transported over the ocean by the offshore winds near the surface associated with the land breeze. Once the balloon reached its constant height of 600 m, offshore winds associated with sea breeze circulation transported the balloon to a maximum distance of 140 km from the

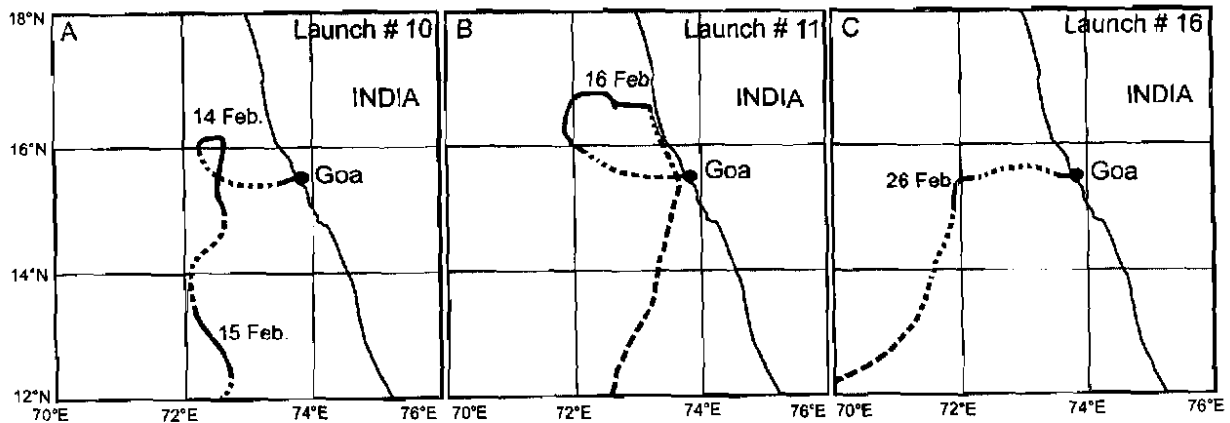


Fig. 5—A) Track of constant level balloon # 10 at an altitude of 925 hPa from 13 to 16 February 1999 during INDOEX. B) Track of constant level balloon # 11 at an altitude of 925 hPa from 14 to 16 February 1999 during INDOEX. C) Track of constant level balloon # 16 at an altitude of 925 hPa from 24 to 26 February 1999 during INDOEX.

shore. The balloon then moved back towards the coast as a result of westerly winds aloft associated with the land breeze. After briefly moving towards the coast, the balloon escapes the influence of the coastal circulation and is transported by the northeast monsoon flow towards the ITCZ. Balloon #11 was released on 14 February 1999 and was transported over the ocean because of the easterly winds at the surface associated with the land breeze (Fig. 5 B). The balloon rose to around 600 m by early morning and the influence of the easterly winds aloft associated with the developing sea breeze pushed the balloon further over the ocean. A maximum distance of 200 km from the west coast of India was observed before the balloon began to move back towards the coast at around 22:00 LT on 15 February. Onshore winds aloft associated with the land breeze transported the balloon back towards the coast. As the winds shifted to offshore aloft because of the sea breeze, the balloon became nearly stationary during the day of 15 February 1999. The balloon was then transported away from the coast by strong northeast winds aloft. Easterly winds at the surface associated with the nighttime land breeze pushed balloon #16 over the ocean during the early morning hours of 24 February 1999 (Fig. 5 C). At 700 m, the easterly winds aloft associated with the sea breeze transported the balloon further over the ocean. Once the balloon was around 200 km from the coast, it slows down and was eventually transported by the northeast monsoon winds toward the ITCZ. Since the land breeze circulation was typically weaker than the sea breeze, perhaps the northeast winds were much greater than any return circulation and prevented the balloon from moving back towards the coast on this day.

4. Numerical Simulation

A mesoscale numerical model was used along with the observations to better understand the horizontal extent of the sea and land breezes over the Arabian Sea and the magnitude of inland vertical motion caused by the sea breeze along India's west coast.

4.1 Model description

A three-dimensional, non-hydrostatic version of the fifth generation of the PSU-NCAR Mesoscale Model (MM5)¹⁵ was used in this study. MM5 is a primitive equation model that uses a non-dimensional σ -vertical coordinate system. The model uses surface layer similarity for the constant flux layer and Medium Range Forecast Model (MRF) planetary boundary layer (PBL) parameterization scheme for the mixed layer¹⁶. The Kain-Fritsch cumulus parameterization scheme was used for sub-grid scale convection¹⁷. The ground temperature was calculated using a five-layer soil model scheme¹⁸.

Initial conditions were prescribed using the operational analysis from NMC, produced by the National Center for Environmental Prediction (NCEP) in Camp Springs, Maryland, USA and archived by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, USA. Resolution of the archived data is $2.5^\circ \times 2.5^\circ$ latitude-longitude with 15 standard pressure layers. The model was run from 00:00 UTC on 27 February to 00:00 UTC on 10 March 1999. The simulation was not continuous but rather initialized at 00:00 UTC on 27 Feb., 00:00 UTC on 2 March, 00:00 UTC on 5 March, and 00:00 UTC on 8 March 1999. This particular time period was chosen to study the horizontal extent of the sea

breeze over the Arabian Sea because of the availability of wind profile data from several stations along the west coast of India and wind profiles taken from R/V *Sagar Kanya* during the Parallel Track Experiment (March 3-11).

A single nested model domain was used for the simulation. The outer domain covers an area of (38.31°N-10.61°S; 44.17°E-96.10°E) and the inner domain an area of (21.82°N-4.36°N; 61.08°E-79.01°E) (Fig. 2). The grid spacing for the outer and inner domains are 30 km and 10 km, respectively. The outer domain consists of (186 × 186) grid points while the inner domain has (178 by 178) grid points. Both domains have 36 vertical σ levels between 1000 mb

and 100 mb with 25 of the levels below 700 hPa. The inner domain is arranged to include the mountains along India's west coast.

4.2 Diurnal variation of sea and land breezes

Comparisons between the model output and observations need to be made to insure the model is able to simulate the timing and magnitude of the sea and land breeze. The model output was compared with observations of the land and sea breezes on 2 March 1999. Model output (dashed line) and observations (solid line) from Mumbai at 00:00 UTC (05:00 LT) on 2 March 1999 (Fig. 6 A) show that winds were easterly (offshore) in the lowest 1 km of

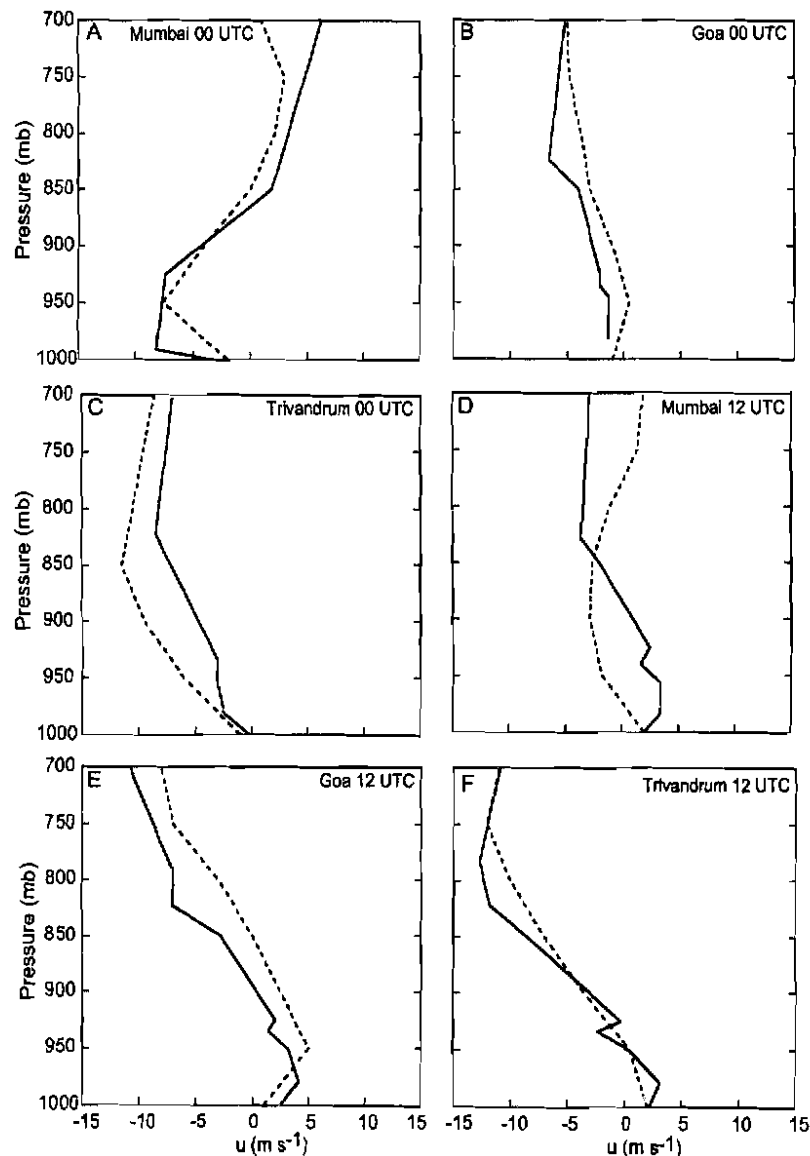


Fig. 6—Comparison of model simulated (dashed line) u-component with observed (solid line) u-component measured at 00:00 UTC on 2 March 1999 at Mumbai (A) at Goa, (B) and at Trivandrum (C). Comparison of model simulated (dashed line) u-component with observed (solid line) u-component measured at 12:00 UTC on 2 March 1999 at Mumbai (D) at Goa (E) and at Trivandrum (F).

the atmosphere indicating the presence of a land breeze. Above 1 km, the winds shifted to westerly (onshore) with a maximum value of 5 ms^{-1} . Weak easterly flow was observed at Goa ranging from 1 to 5 ms^{-1} throughout the lowest 3 km of the atmosphere (Fig. 6B). The model simulated the weak winds at Goa with values ranging from 1 to 5 ms^{-1} . Observed winds at Trivandrum were easterly throughout the lowest 3 km of the atmosphere with values ranging from 0 to 8 ms^{-1} (Fig. 6C). Simulated winds were also easterly in the lowest 3 km with a maximum value of 11 ms^{-1} .

Examining the simulated winds at 12:00 UTC (17:00 LT) on 2 March 1999 will test the model's ability to simulate the diurnal change in flow as well as the latitudinal difference in northeast winds aloft. The model simulated the observed onshore winds at the surface at Mumbai at 12:00 UTC on 2 March 1999 (Fig. 6D). Westerly winds of around 2 ms^{-1} were simulated at the surface. Simulated winds became easterly at a height of 300 m while the observed winds did not shift to easterly until about 1300 m. The model was unable to simulate the depth of the onshore flow but did simulate the diurnal wind shift at the surface from 00:00 UTC. Onshore flow was also simulated at Goa (Fig. 6 E) with westerly winds simulated to increase to 5 ms^{-1} at 600 m and then shifted to easterly. The simulated winds were within 2 to 3 ms^{-1} of the observed values for most part of the lower atmosphere. Westerly winds of around 2 to 3 ms^{-1} were simulated at Trivandrum at the surface (Fig. 6 F). The simulated winds shift to easterly at around 800 m and reach a maximum value of 12 ms^{-1} at 2100 m. The model was able to simulate the increasing northeast winds towards the equator.

Cross sections are plotted to test the model's ability to simulate the diurnal shifts in wind direction caused by the sea and land breeze circulations. A cross section was taken from $10^{\circ}\text{N}, 72^{\circ}\text{E}$ (labeled X) to $10^{\circ}\text{N}, 76^{\circ}\text{E}$ (Y) as shown in Fig. 7 A. The cross section covers a portion of the Arabian Sea and the mountains along the west coast of India. Weak westerly (onshore) winds were simulated along the coast at 06:00 UTC (11:00 LT) on 6 March 1999 (Fig. 7 B). Onshore winds were simulated up to a distance of 50 km over the ocean and represented the developing sea breeze circulation. Winds were light around 1 ms^{-1} and in the lowest 1.5 km of the atmosphere. Positive vertical motion of approximately 0.21 ms^{-1} was produced as the onshore winds converge in the vicinity of the mountains. By 12:00 UTC (17:00 LT), westerly winds have extended to

150 km over the ocean (Fig. 7C). Winds were simulated to increase towards the coast and reach a maximum value of 5 ms^{-1} along the coast. Depth of the onshore flow was about 700 m over the ocean. Simulated westerly winds at the surface shifted to easterly by 18:00 UTC (23:00 LT) on 6 March (Fig. 7D). The shift in the winds at the surface represents the developing nighttime land breeze. Easterly winds at the surface were light with magnitudes varying from 2 to 3 ms^{-1} . Westerly winds were observed at a height of 500 to 1200 m and represent the return flow aloft associated with the land breeze. The return flow wind speed was around 1 ms^{-1} . Since the atmospheric flow at the surface shifted to offshore, it is not surprising that the simulated vertical velocity along the coast decreased to 0.07 ms^{-1} . Easterly winds were simulated to increase with distance from the coast at 00:00 UTC (05:00 LT) on 7 March (Fig. 7 E). The easterly flow reached a maximum value of 5 ms^{-1} around 150 km from the coast. Increasing winds over the coastal ocean could be a result of katabatic flow caused by air cooling and rushing down the mountains along the west coast of India. No return flow typical of the land breeze was simulated at this time. Westerly (onshore) winds were again simulated in the lower atmosphere along the coast at 06:00 UTC (11:00 LT) on 7 March as shown in Fig. 7 F. The daytime sea breeze was again developing and the corresponding onshore flow was simulated to extend to about 40 km over the ocean. Depth of the onshore flow over the ocean was around 200 m and reaches a maximum value of 2 ms^{-1} inland. The onshore flow resulted in the return of convection along India's west coast. Vertical velocities around 0.16 ms^{-1} were simulated as the onshore flow interacts with the mountainous terrain.

A comparison of model output and observations has shown that the model was capable of simulating the atmospheric flow along the west coast of India. Simulated cross sections along the west coast of India will provide further insight into the horizontal extent of the sea breeze. The location of a cross section taken along the west coast of India at Goa is shown in Fig. 8A. The cross section was designed to investigate the horizontal extent of the sea breeze and the influence of the coastal circulation on vertical velocity along the west coast of India. Circulation vectors at 17:00 LT on 5 March 1999 along the west coast of India at Goa are shown in Fig. 8B. Westerly flow at the surface was simulated to a distance of 150 km from the coastline of India. Depth of the sea breeze

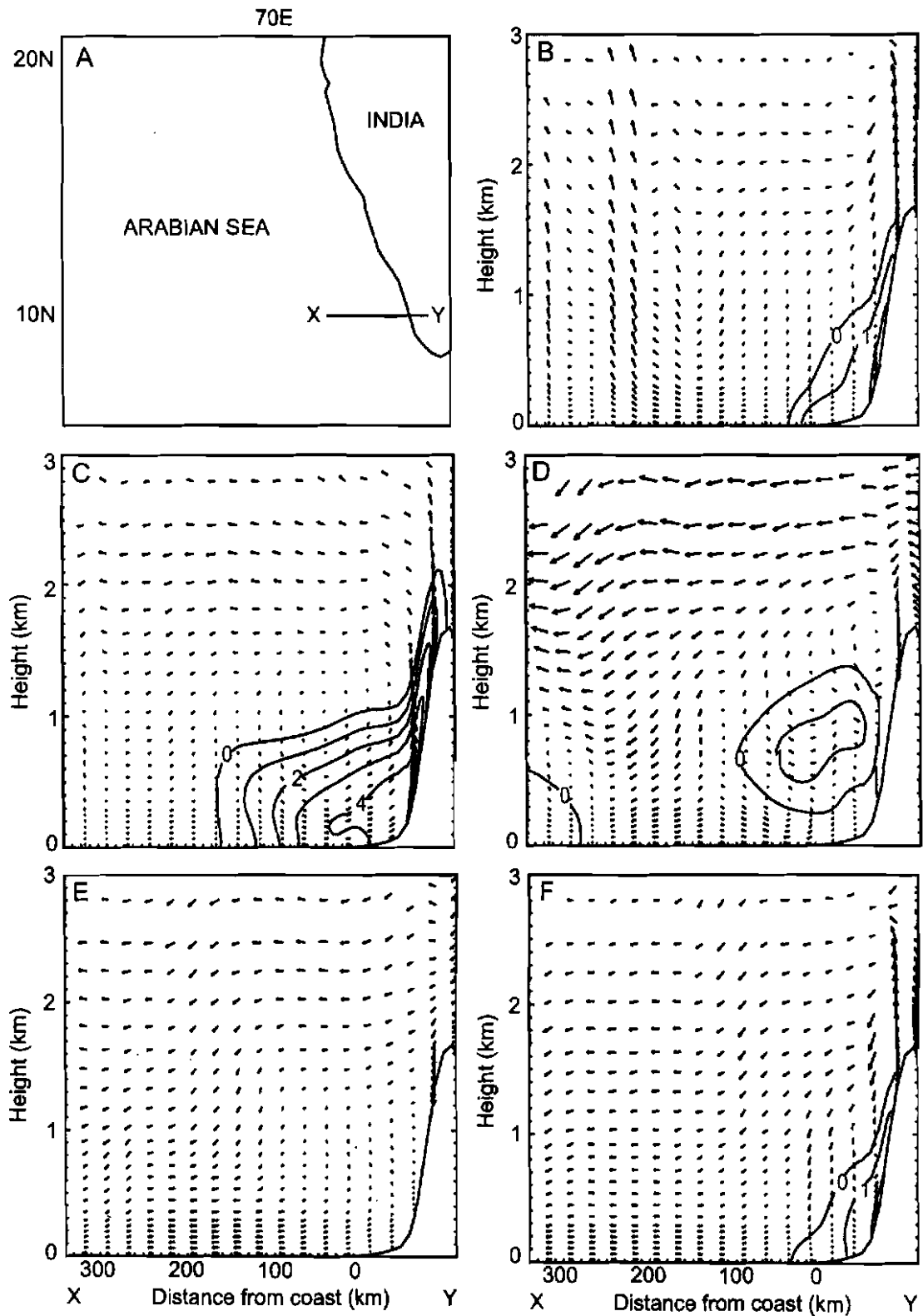


Fig. 7—A) Location of cross section taken along the west coast of India. B) Model simulated u-component of horizontal wind in contours at 06:00 UTC on 6 March 1999. C) same as B but at 12:00 UTC on 6 March. D) same as B but at 18:00 UTC on 6 March. (E) same as B but at 00:00 UTC on 7 March. (F) same as B but at 06:00 UTC on 7 March.

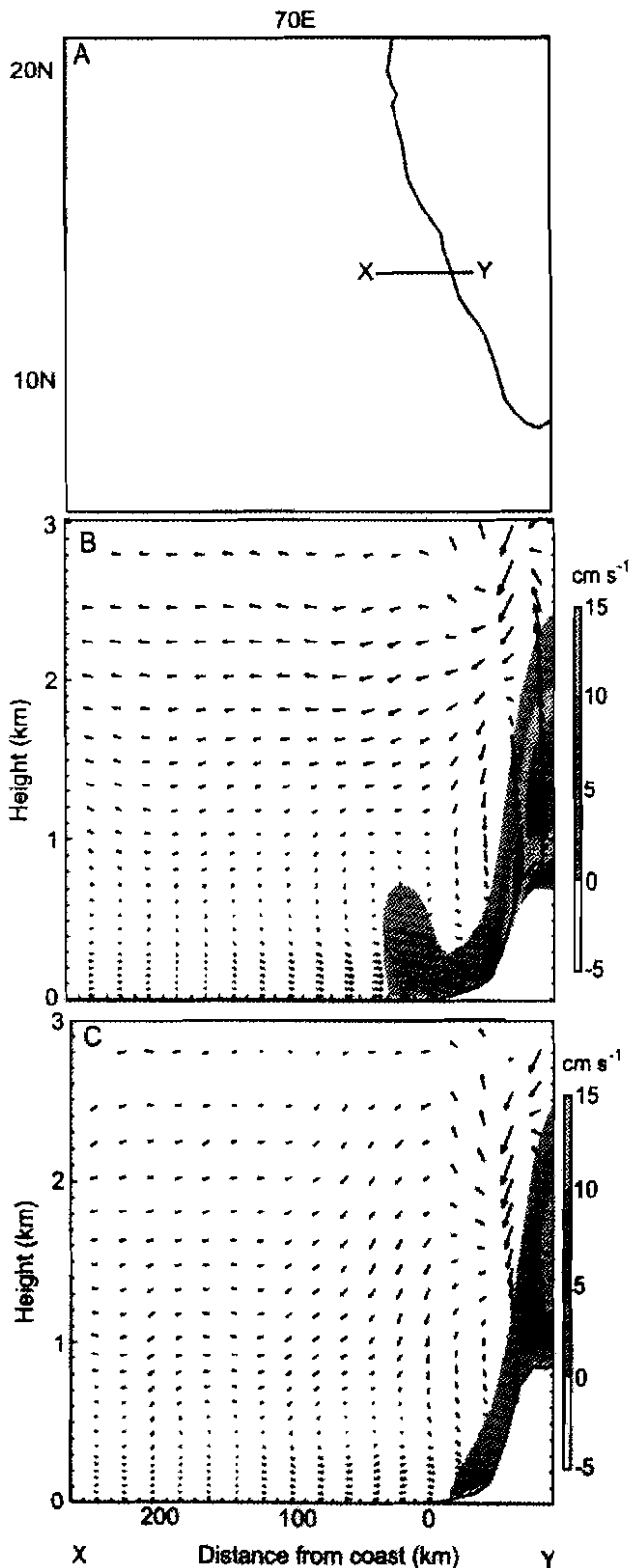


Fig. 8—A) Location of cross section taken along the west coast of India at Goa. B) Cross section of simulated circulation vectors and vertical velocity at 12:00 UTC on 5 March 1999. C) Same as B but at 12:00 UTC on 7 March 1999.

circulation was simulated to be around 900 to 1000 m. Maximum positive vertical velocities of around 0.22 ms^{-1} were produced by the onshore flow along the west coast of India. Simulated circulation vectors at 17:00 LT on 7 March 1999 are shown in Fig. 8C. The horizontal extent of the onshore flow was simulated to be around 150 km over the ocean, which has changed little since 5 March. Depth of the sea breeze circulation over the ocean was from 600 to 700 m. Maximum positive velocity resulting from the sea breeze at this time was 0.17 ms^{-1} .

To investigate any possible latitudinal variation in the horizontal extent of the sea breeze, a cross section was also taken along the west coast of India at Trivandrum. The location of the cross section is shown in Fig. 9 A. Simulated horizontal extent of the onshore flow at 17:00 LT on 5 March 1999 was 200 km from the west coast of India (Fig. 9 B). This was around 50 km further offshore than was simulated at Goa for the same time. Depth of the sea breeze circulation was simulated to be 1.5 km above the ocean surface. Maximum inland vertical velocity resulting from the onshore flow was around 0.19 ms^{-1} . Horizontal extent of the onshore flow decreased to around 130 km at 17:00 LT on 7 March 1999 (Fig. 9 C), considerably less than what was simulated for 5 March at the same location. Simulated depth of the sea breeze circulation was around 800 m. The maximum positive vertical velocity inland was 0.24 ms^{-1} .

4.3 Simulated trajectories

An analysis of model simulated trajectories is expected to show the influence of the coastal circulations on air parcels along the west coast of India. Model trajectories released at a height of 10 m and simulated from 15:00 UTC on 5 March to 00:00 UTC on 8 March 1999 are shown in Fig. 10 A. Trajectory 1 was released from 15.8°N , 73.5°E and was observed to move along the coast for several hours and then eventually over the ocean due to strong northerly winds. At 00 UTC, the trajectory was 200 km off the west coast of India and did not get caught up in the coastal circulations. Further to the south at 14.2°N , 74.5°E , trajectory 2 was released and did not travel far initially due to a weaker land breeze further south. As the sea breeze develops and strengthens on 6 March, the parcel moved around 50 km inland. The parcel was lifted to around 1.5 km by interaction with the mountains and is transported out to sea by the northeast winds aloft. Onshore flow

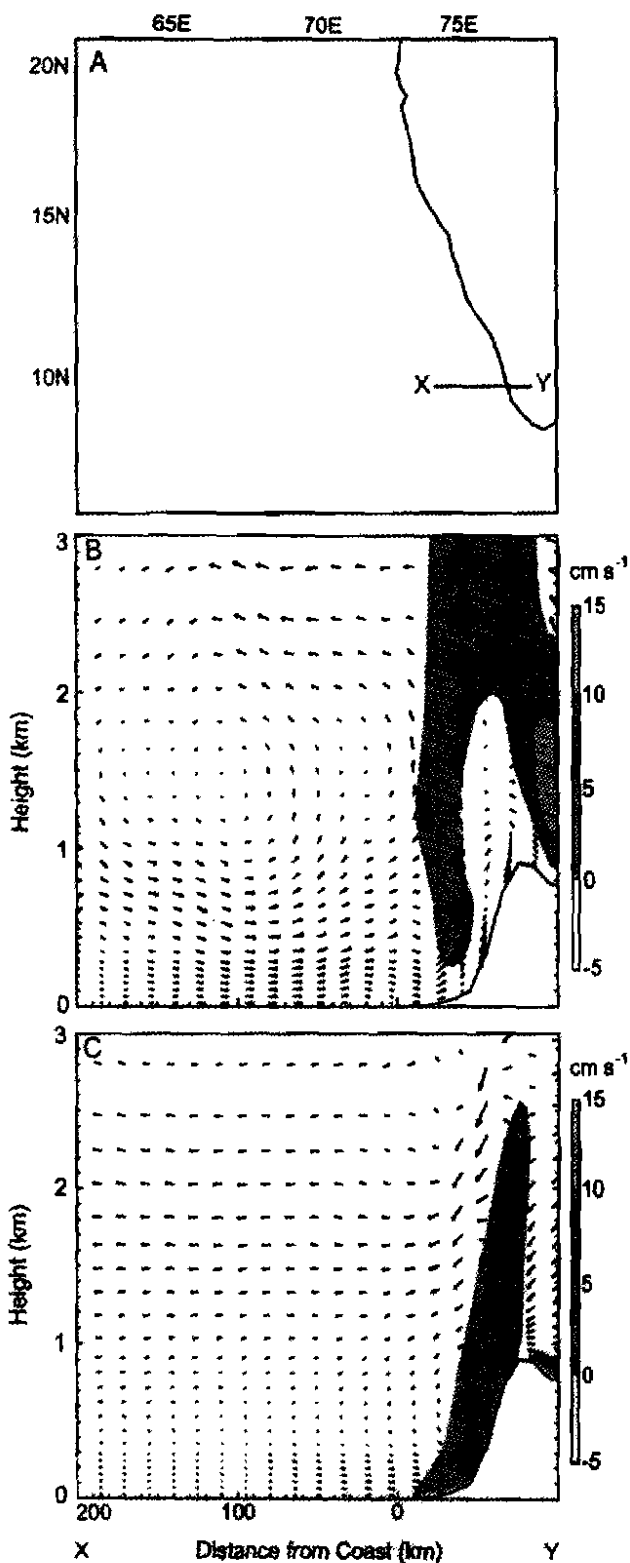


Fig. 9—A) Location of cross section taken along the west coast of India at Trivandrum. B) Cross section of simulated circulation vectors and vertical velocity at 12:00 UTC on 5 March 1999. C) Same as B but at 12:00 UTC on 7 March 1999.

associated with the sea breeze transported trajectory 3 ($11.5^{\circ}\text{N}, 75.7^{\circ}\text{E}$) around 50 km inland. Vertical motion along the mountains raised the parcel to around 2 km. Northeast winds then transported the parcel over the ocean. By 00:00 UTC on 8 March, the parcel was around 500 km from the west coast of India. Onshore flow on 5 March transported parcel 4 approximately 100 km inland. The parcel was raised to about 1 km height by the vertical motion associated with the mountainous terrain. Strong northeast winds aloft transported parcel 4 over the ocean. By 00:00 UTC on 8 March, the parcel was around 75 km offshore from the west coast of India.

Simulated trajectories released at a height of 1 km at 15:00 UTC (20:00 LT) on 5 March 1999 and ending at 00:00 UTC (05:00) on 8 March 1999 are shown in Fig. 10 B. Trajectory 1 moved along the coast for about 15 hours at a constant height of 1 km. Once offshore, the trajectory rose to a height of 2.5 km. The strong northeast winds at this height transported the parcel over the Arabian Sea and by 00:00 UTC on 8 March the trajectory was around 900 km from the west coast of India. Trajectory 2 also does not get influenced by a coastal circulation. The trajectory was observed to move offshore at a height of approximately 1 to 1.5 km. Strong northeast winds transported the parcel over the Arabian Sea. The parcel was around 400 km from the west coast of India by 00:00 UTC on 8 March. Trajectory 3 moved little during the night because of the weak winds associated with the land breeze. The parcel began to move offshore at a height of 1 km because of the return flow associated with the sea breeze. The trajectory was observed to travel to about 150 km over the Arabian Sea before it started to return to the coast. Return flow aloft associated with the land breeze probably transported the parcel back towards the shore and comes within 50 km of the coast before the influence of the sea breeze transports the parcel back over the ocean. By 00:00 UTC on 8 March, the parcel was around 250 km from the west coast of India. Trajectory 4 traveled parallel with the coast during the night when the winds were light. As the daytime sea breeze developed, the trajectory was observed to move offshore because of the return flow aloft. The trajectory was around 100 km from the coast when it began to move back towards the shore because of the land breeze. Onshore flow aloft associated with the land breeze transported the parcel inland where it interacts with the mountains along India's west coast. The trajectory was raised to a

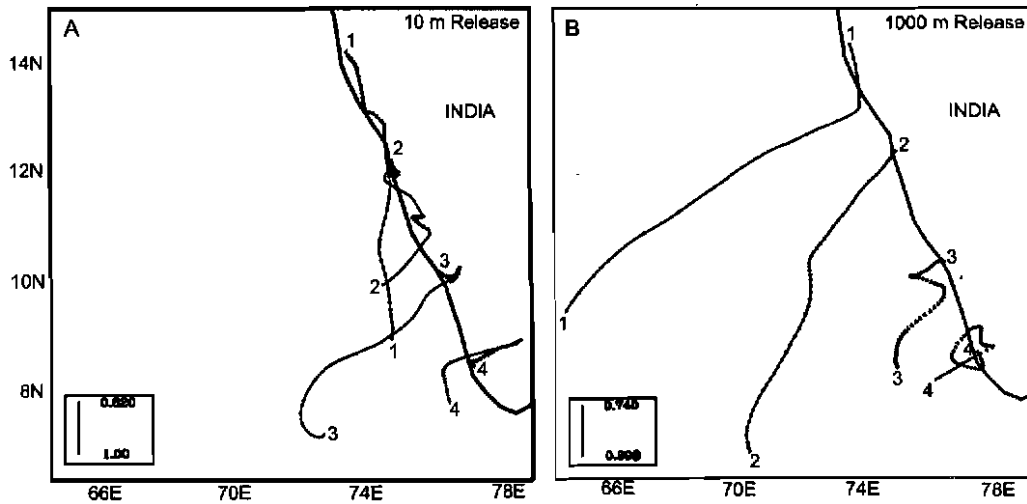


Fig. 10—A) Model simulated forward trajectories released at a height of 10 m and simulated from 15:00 UTC on 5 March to 00:00 UTC on 8 March 1999. B) Model simulated forward trajectories released at a height of 1 km and simulated from 15:00 UTC on 5 March to 00:00 UTC on 8 March 1999.

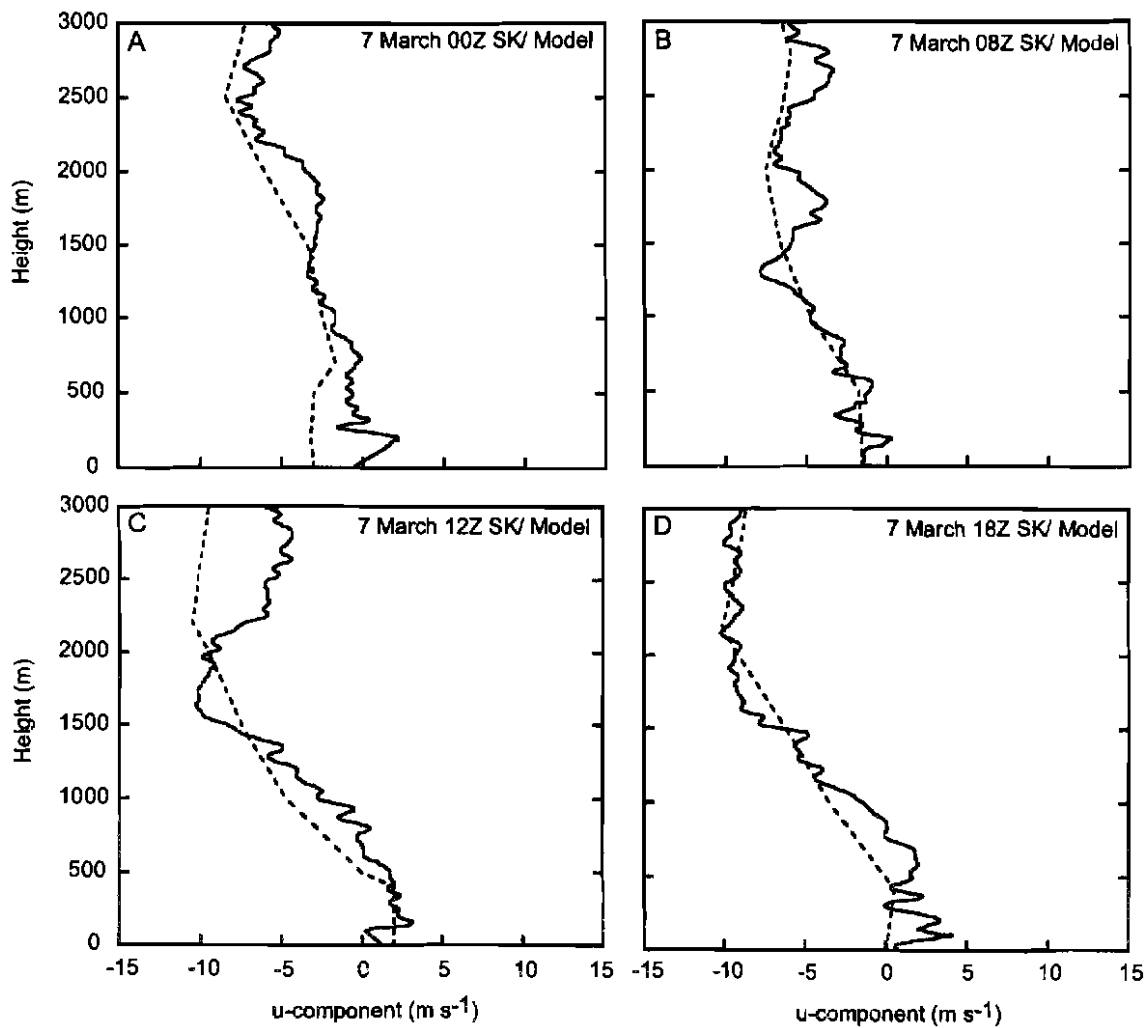


Fig. 11—A) Comparison of model simulated (dashed line) u-component with observed (solid line) u-component measured at 00:00 UTC on 7 March 1999 from R/V *Sagar Kanya*. B) Same as A but at 08:00 UTC. C) Same as A but at 12:00 UTC. D) Same as A but at 18:00 UTC.

height of around 2.5 km by convection near the mountains. Strong northeast winds at 2.5 km transported the parcel offshore and by 00:00 UTC on 8 March the trajectory was observed around 200 km from the coast.

4.4 Horizontal extent of the sea breeze over the ocean

Data collected by *R/V Sagar Kanya* provides an excellent opportunity to research the model's ability

to simulate the timing and the horizontal extent of the sea and land breeze circulations along the west coast of India. The observed (solid line) u-components of the horizontal wind measured from *R/V Sagar Kanya* and model simulated (dashed line) at 00:00 UTC on 7 March 1999 are shown in Fig. 11 A. The model simulated the easterly flow throughout most of the lowest 3000 m of the atmosphere reasonably well. Light westerly winds were present at 200 m that the

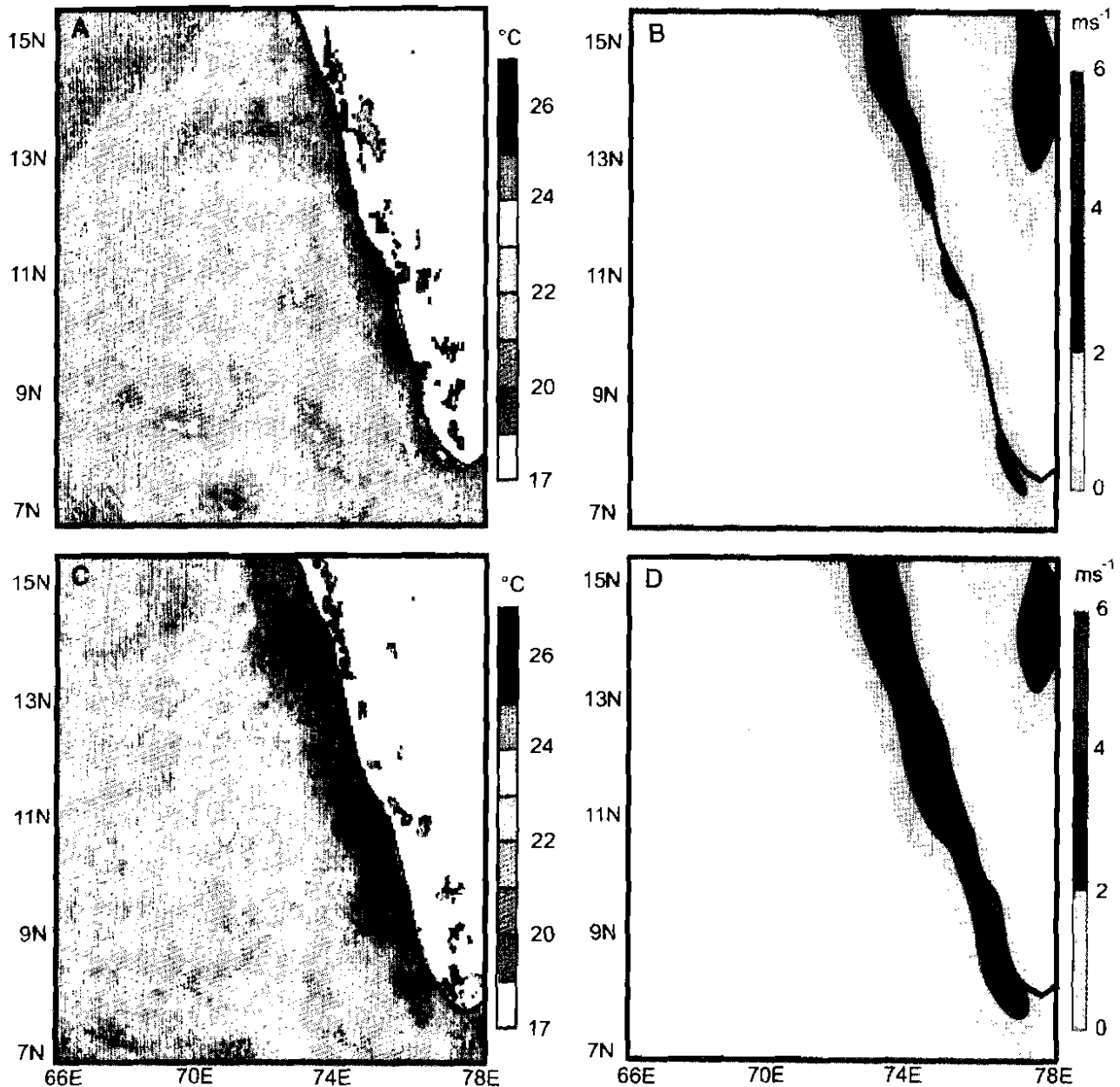


Fig. 12? A) Meteosat 5 IR satellite image at 11:30 LT on 7 March 1999 showing the horizontal extent of the sea breeze over the ocean to be around 100 km. B) Model simulated u-component of the horizontal wind at 12:00 LT on 7 March 1999 showing onshore flow extending for 100 km over the ocean. C) Meteosat 5 IR satellite image at 14:30 LT on 7 March 1999 showing the horizontal extent of the sea breeze over the ocean to be around 200 km. D) Model simulated u-component of the horizontal wind at 15:00 LT on 7 March 1999 showing onshore flow extending for around 200 km over the ocean.

model does not simulate but for the rest of the lower troposphere the model was within 1 to 3 ms^{-1} of the observed winds. The model simulated easterly flow throughout the lowest portion of the atmosphere (at 08:00 UTC on 7 March Fig. 11 B). The model was again within 1 to 3 ms^{-1} of the observed wind speeds at all heights. Simulated winds at the surface shift to westerly at 12:00 UTC on 7 March because of the developing sea breeze circulation (Fig. 11 C). Winds have shifted from easterly in the lowest 700 m of the atmosphere at 08:00 UTC to westerly at 12:00 UTC on 7 March. The model simulated the timing of the wind shift and the magnitude of winds in the lowest atmosphere. Above 700 m, the model simulated the observed change to easterly winds aloft. Westerly winds were weakening in the lower atmosphere by 18:00 UTC on 7 March (Fig. 11 D). The observed westerly winds in the lowest 200 m of the atmosphere have strengthened slightly from 12:00 UTC, but the model has simulated weakening. However, above 700m, the model simulated the shift to easterly winds and was within 1 to 3 ms^{-1} of the observed winds up to a height of 3000 m.

Now that a comparison of model and observed vertical wind profiles has been made, a regional comparison is needed as well. An infrared satellite image taken on 7 March 1999 at 11:30 LT over the Arabian Sea is shown in Fig. 12 A. A region of warm temperatures (red) around 26°C was observed along the west coast of India extending up to 100 km offshore. This region represents an unpolluted air mass being advected onshore by the sea breeze. As described by Simpson & Raman¹², the unpolluted marine air mass has fewer aerosols than the

continental air mass that was transported over the ocean during the land breeze. As a result, there was less attenuation of the infrared signal in the marine air mass and thus warmer temperatures were measured. The horizontal extent of the sea breeze can therefore be determined from the near coast region of warm temperatures in infrared satellite imagery. Model simulated u-component of the horizontal wind at 10 m at 11:00 LT on 7 March 1999 is shown in Fig. 12 B. Westerly (onshore) flow was simulated along the west coast of India at this time representing the sea breeze. The simulated horizontal extent of the onshore flow over the ocean was around 100 km, which agrees well with observations. An infrared satellite image taken on 7 March 1999 at 14:30 LT is shown in Fig. 12 C. The region of warm temperatures along the west coast of India has extended further offshore due to the developing sea breeze circulation. Horizontal extent of the sea breeze over the ocean derived from the IR satellite was observed to be around 150 to 200 km. Simulated u-component of the horizontal wind at 10 m at 14:00 LT on 7 March 1999 is shown in Fig. 12 D. The region of westerly (onshore) flow along the west coast of India has extended further offshore since 11:00 LT and was around 200 km over the ocean. This simulation agrees with the infrared satellite images showing the increase in horizontal extent of the sea breeze.

Maximum horizontal extent of the sea breeze over the ocean appears to occur along the southern portion of India's west coast because of weaker synoptic influence. Increasing land surface temperatures towards the equator also cause stronger sea breeze circulations in southern India. A cross section taken

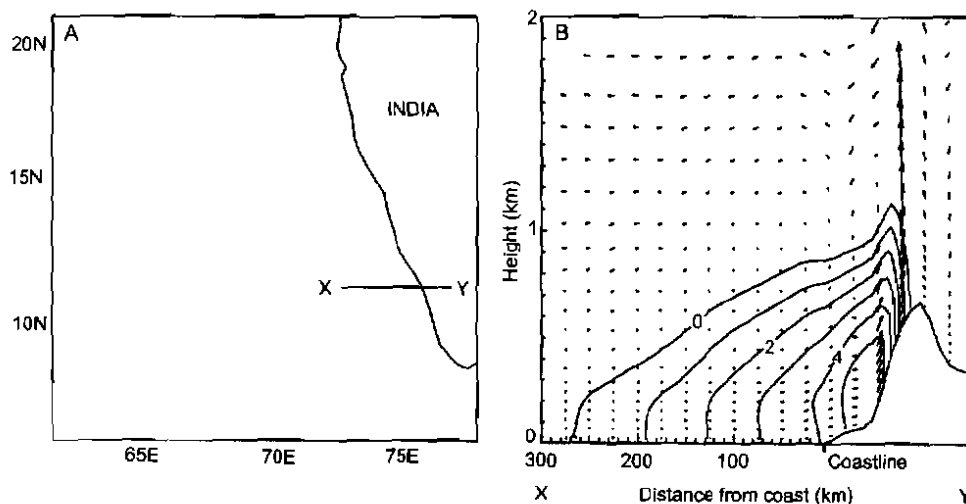


Fig. 13—A) Location of cross section taken along the west coast of India B) u-component of horizontal winds (ms^{-1}) in contours showing the horizontal extent of the sea breeze over the ocean to be around 260 km at 12:00 UTC (1700 LT) on 6 March 1999.

from 11°N, 73°E (labeled X) to 11°N, 77°E (Y) is shown in Fig. 13 A. The cross section extends for 450 km from the Arabian Sea to the mountains along the west coast of India. Westerly (onshore) winds were simulated to extend 260 km over the ocean on 6 March 1999 at 12:00 UTC (1700 LT) (Fig. 13 B). The westerly component (in contours) of the horizontal wind shows onshore wind speeds were simulated to increase towards the coast. A maximum value of 6.0 ms⁻¹ was simulated around 30 km inland. Positive vertical motion was produced as the onshore flow interacts with the mountains along India's west coast. A maximum vertical velocity of 0.25 ms⁻¹ was simulated at a height of 1.5 km. The positive vertical velocity produced by the sea breeze was responsible for convection and stratocumulus cloud formation along India's west coast during the northeast monsoon.

In conclusion, the MM5 numerical model was able to simulate the land and sea breeze circulations observed along the west coast of India during INDOEX (1999). Simulated wind directions were in good agreement with observations from several different data platforms showing wind shifts due to the land and sea breeze. Cross sections of simulated wind vectors show the offshore horizontal extent of the afternoon sea breeze along the west coast of India to vary from 130 to 260 km. A latitudinal variation in the offshore extent of the sea breeze was simulated due to the influence of the northeast monsoon large scale flow. Maximum vertical velocities of 0.25 ms⁻¹ were simulated inland as onshore winds associated with the sea breeze interacted with the mountains along the west coast of India.

Acknowledgement

This research was supported by the Atmospheric Sciences Division of the National Science Foundation (USA) under Grant ATM-0080088 and ATM-0233780. Computer resources were provided by the North Carolina Supercomputing Center, RTP, the Scientific Computing Division (SCD) of NCAR, and the State Climate Office of North Carolina, USA.

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