

## INDIAN OCEAN EXPERIMENT

# Numerical study of the role of land–air–sea interactions for the northeasterly monsoon circulations over Indian Ocean during INDOEX

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One of the principal objectives of the Indian Ocean Experiment (INDOEX) was to study the aerosol transport from the Indian subcontinent to the pristine oceanic environment. The underlying hypothesis for INDOEX is that, during the northeasterly monsoon, the intruding aerosols and other anthropogenic pollutants can entrain into the Inter Tropical Convergence Zone (ITCZ) and the Equatorial Indian Ocean and finally into the clouds. The altered clouds influence the radiative transfer processes at the regional and possibly global scale. The driving mechanism for the regional transport was the boundary layer circulation. In this study, it was hypothesized that the circulation pattern, which affects the regional transport, was strongly influenced by the land–air–sea interactions. To test this, a zonally symmetric version of a primitive equation numerical weather prediction model, called the Advanced Regional Prediction System (ARPS), was used. A number of numerical experiments were performed for a 2-D domain ranging from 14°N to 16°S centered over 76°E. In the experiments, the influence of land–sea interaction (differential heating), topography (Western Ghats), and the thermal gradients (SST and land surface temperature) on the coastal circulations over Equatorial Indian Ocean were studied. Results indicated a strong land–air–sea interaction and feedback teleconnection between the local and large scale features. Interestingly, the model generated land influence to the order of 1000 km offshore in the simulation domain, consistent with different observations. Results suggest that the oceanic environment in the northeast monsoon over Arabian Sea and the Indian Ocean can display significant diurnal variability and heterogeneity due to topography and surface temperature gradients, and that the local features have interactive feedback on the large scale circulations and transport.

THE genesis of this study lies in a major multi-national field experiment: Indian Ocean Experiment (INDOEX) that was conducted during the northeasterly monsoon of

1999. INDOEX had several objectives focused towards developing a comprehensive analysis of the interactive role of radiation, clouds, and the aerosol transport leading to a better understanding of the regional scale radiative forcing for climate change. The hypothesis was, during the northeast (NE) monsoon, not-so-clean continental air parcels can be transported towards the Inter Tropical Convergence Zone (ITCZ) and alter the cloud–radiative properties. Thus, one of the pivotal components linked with this experiment was to understand, how the air parcels and aerosols could be circulated over the marine environment, and how the ITCZ dynamics related with the atmospheric chemistry and cloud formation. More details about the experimental plan can be found at <http://www-indoex.ucsd.edu> as well as from Ramanathan *et al.*<sup>1</sup>

The NE monsoon, compared to the southwest monsoon, is however traditionally a lesser studied system. This is principally because the southwest monsoon affects a large continental landmass and has climatic and economic significance. Considering this paucity of information, for INDOEX, four ship-based studies have been conducted prior to the 1999 field program. The first of these was in January 1995 (ref. 2), second in January 1996 (ref. 3), third was in January 1997 (ref. 4) and the fourth in February 1998 (ref. 5). Of these, the first two cruises collected data principally on the latitudinal variation of radiation, and aerosol and trace gas characteristics over the Indian Ocean<sup>6</sup>. The 1997 and 1998 cruises over the Indian ORV *Sagar Kanya* additionally focused on the thermodynamic structure of the marine troposphere. One consistent feature that was proposed from all the four data sets relates to the signature of a strong continental land mass influence on the marine environment to the order of hundreds of kilometers offshore. The observations of Rhoads *et al.*<sup>2</sup> suggested strong influence of continental effect till about 2°N. This influence was seen in all the trace species and aerosol characteristics. Similar land influence was observed in the western Indian Ocean region during the 1996 cruise<sup>3</sup>. These observations went beyond the realms of traditional land–sea breeze circulations and had necessitated the numerical experiment summarized in this

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paper. Consistent with the INDOEX objectives, it was important to understand these circulations and the offshore modifications of the air mass. Of particular importance was the question: 'what drives the circulation to such deep penetration offshore from the inland?'. The hypothesis to be tested was that the observed transport and circulation depends on the land-sea temperature contrast and the topography of the western peninsular India. The focus of this study hence was to understand the role of local features in modulating the circulation patterns over the west coast of India, equatorial Arabian Sea and the Indian Ocean during the north-east monsoon. A secondary objective was to complement the results obtained during the pre INDOEX observations, particularly in terms of diurnal variability of the circulation. A series of numerical experiments were conducted, principal findings from those will be presented here.

Thus the study aimed to identify the role of land-air-sea interaction processes in generating a plume-like circulation pattern over the equatorial Arabian Sea and the Indian Ocean. The following section describes the unique meteorology of the NE monsoonal process *apropos* Indian Ocean along with the numerical model, simulation domain, and the numerical experiments. The major results from the simulations along with an interpretation and discussion are presented next and the last section presents the conclusions from this study.

## Numerical experiments

For the northern Indian Ocean, the northeast or winter monsoon, causes low level winds typically coming from the tropical Indian subcontinent. The southern hemisphere has a summer with winds from SE direction. When the two air masses meet a deep convective ITCZ is formed. The ITCZ location January is around 5–7°S (ref. 7) and is known to migrate. Our aim was to address the following questions: (i) Is the 'continental effect' the driving mechanism for the NE monsoon flow over the northern Indian Ocean? That is, does the presence of land significantly affect the circulation pattern over the Indian Ocean?; (ii) What is the role of topographical features in the circulations offshore?, and (iii) what is the interaction of sea surface temperature (SST) gradients on the circulation and the transport processes over the ocean?

These questions had their genesis in the observations over the region. However, the observations alone could not answer them due to reasons such as the low resolution, and single point observations along the ship-track. To address these objectives, five numerical experiments were performed as shown in Table 1. These numerical experiments (described below) were specifically designed by adopting a primitive equation, non-hydrostatic model: Advanced Regional Prediction System (ARPS)<sup>8</sup>. In this study, we report the first set of 2-D experiments

performed. A companion study (Roswintiarti *et al.*<sup>9,10</sup>) addresses the role of interactions using a three-dimensional nested grid model. For the present study, selection of the model domain was guided by both the climatology of NE monsoon in January and also the features observed during the 1997 pre-INDOEX cruise. ORV *Sagar Kanya* started from Goa on 26 December 1996, and traveled approximately along 74°E longitude till 15°S. On the return leg, roughly the same path was followed. Figure 1 shows the cruise track and the model domain considered.

Accordingly, in the numerical experiments, the domain assigned was 14°N to 16°S centered around 1°S along 75°E. A 25-km grid resolution was adopted. The model had 33 layers in the vertical. (Note that, even though a 2-D experiment was designed, ARPS requires 4 homogeneous data points along the y-axis to account for pseudo-advection, see ref. 8 for details.) The vertical grid structure had a mean thickness of 500 m with highest resolution of 100 m in the lower layers and a hyperbolic tangent stretching. A time-step of 6 s was adopted for a complete diurnal (24 h) cycle. Additionally, for both momentum and scalar advection, fourth-order horizontal and second-order vertical advection was adopted. For all the experiments, external single profile initialization was done using an actual ship-based CLASS sounding for 0 Z on 2 January 1997, which approximately coincided with the ship location at the center of computational domain. Figure 2 shows the CLASS profile used as an initial sounding for the model. ARPS then developed its own geo-potential-based wind and thermodynamic profile for the domain based on the topography and surface parameters as discussed in Xue *et al.*<sup>8</sup>. Approximate initial geostrophic balance was imposed and a latitudinally dependent Coriolis term was adopted for both vertical and horizontal winds. Sub-grid scale turbulence was parameterized through a one and half order TKE closure using constants defined by Moeng and Wyngaard<sup>11</sup>. For the upper boundary, a spongy layer with Rayleigh damping<sup>12</sup> was adopted above 10000 m. For all the experiments, moist processes were activated with Kuo<sup>13</sup> convective cumulus parameterization and Kessler warm rain micro-

**Table 1.** Summary of the numerical experiments performed to understand the role of land-air-sea processes on the circulation pattern over the Indian Ocean. In all of the experiments, the basic wind was always from northeast as shown in Figure 2

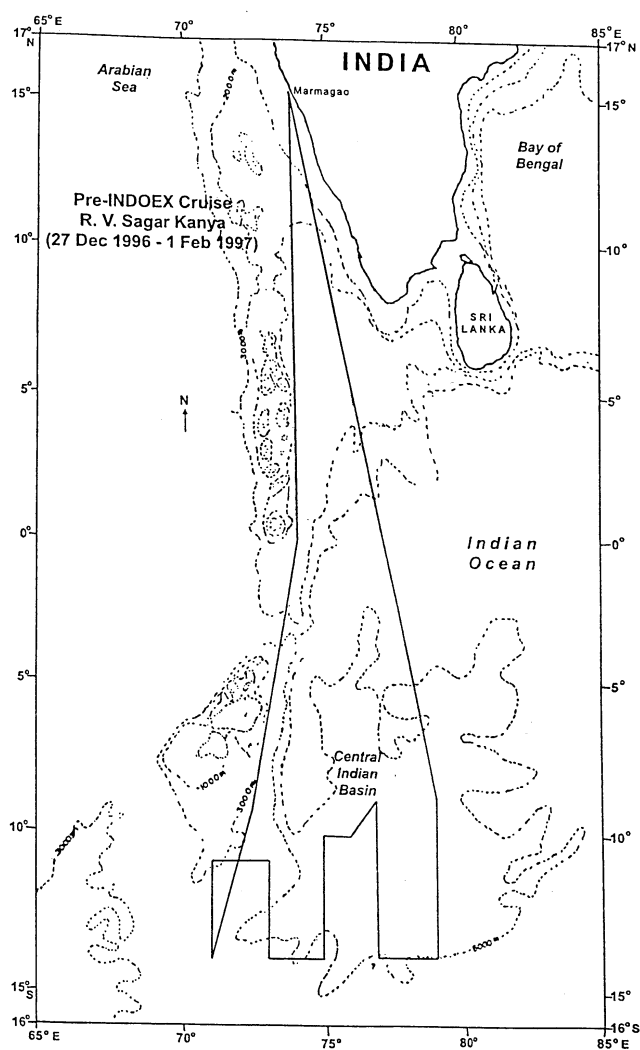
Experiment	Description
I (OCN)	Only ocean (Aqua conditions in the domain)
II (LAO)	Land and ocean, no topography (over land a constant 1 m terrain was assigned)
III (LOT)	Land and ocean with realistic topography
IV (LOTS)	LOT with realistic SST gradients
V (LOTS-L)	LOT with realistic gradient in SST and land surface temperature

## INDIAN OCEAN EXPERIMENT

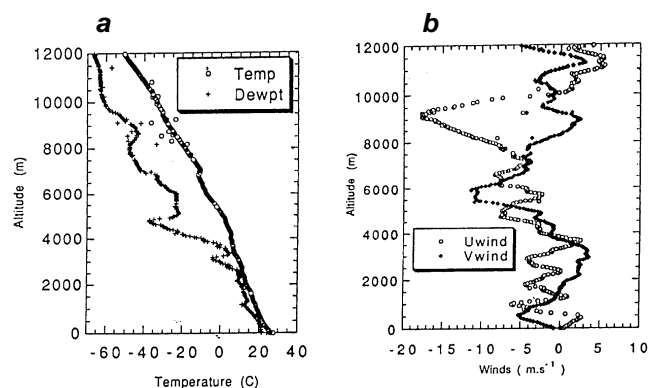
physics<sup>14</sup>. For the surface processes, land–water distinction was made for assigning the stability-dependent drag coefficients from which surface fluxes were calculated. These surface fluxes were then allowed to be linearly distributed in the boundary layer (see ref. 8 for details). When land was considered in the simulation, a sandy clayey loam soil type was assigned for domain with semi-desert vegetation. As described below, the initial experiments were performed with a spatially constant initial surface temperature (297.0 K for the land and 301.0 K for water at 0 Z). For the later experiments, gradients in the initial surface temperatures-based observation (analysis) were introduced. The assignment of land temperature was consistent with the observations available in Indian subcontinent<sup>15,16</sup>. For the SST, weekly remote sensed and surface observation data available through the NCEP at Lamont-Doherty Earth Observatory (LDEO) (<http://ingrid.ldeo.columbia.edu/>) were utilized. To introduce diurnal heating, a sinusoidal temperature variation was assigned

for the land with a peak of 7 K above the reference at 1400 LT. Of the several experiments performed, the most relevant ones are discussed in this paper (as shown in Table 1). Consistent with the objective, that is, to understand the role of land–air–sea interactions on the meso-scale circulation over Indian Ocean, a hierarchy of simulations is presented.

The first experiment (OCN) had only ocean in the entire domain. This can be treated as a reference run for the model. In the second simulation (experiment 2, LAO), land was present till 6°N in the domain. In this simulation, no topographical features were introduced. The third experiment (LOT) considered topography in the simulation. Deciding on a representative topography for the 2-D domain was a challenging task. With the winds coming from northeast, the continent north of Indian Ocean had two major topographical features. One was the Western Ghats in the Indian subcontinent and the second was the peak in Sri Lanka. Indeed to assess the impact of such topographical variation a 3-D study would be needed (Roswintiarti *et al.*, this issue). However, 2-D numerical experiments were ideal to perform sensitivity studies. Averaged topographical data were developed over land domain in a longitudinal strip of one-degree resolution. This was necessary, as the peaks were not in a single longitude but spread for the 2-D domain. However to obtain realistic scenario, the mountains in Sri Lanka and the Western Ghats were included in the analysis. Accordingly, a 2-D topographical domain was developed as shown in Figure 3. In the figure, the initial small peak (300 m high) represents the averaged mountains in Sri Lanka, while the nearly 800 m tall peak represents the Western Ghats. These topographical features were introduced in the third experiment (LOT). In the experiments LAO and LOT, the SST was maintained at a constant value of 301 K as discussed earlier. In another experiment (LOTS), the topography shown in Figure 3 was maintained and a realistic SST gradient was introduced. For this experiment, SST data from both the NCEP analysis



**Figure 1.** Cruise track for pre-INDOEX 1997 observations. The model domain was centered around 74°E from 14°N to 16°S.



**Figure 2.** CLASS profiles used in initializing the model for 0 LT for 2 January 1997. *a*, Dry bulb temperature (C) and dew point temperature (C) profile; *b*, Zonal and meridional components of wind ( $\text{m s}^{-1}$ ).

and from actual ship-borne observations made during the January 1997 cruise were utilized. Figure 4 shows the SST variation adopted for this experiment (LOTS). For the 2-D domain, the initial temperatures were relatively colder in the Northern Hemisphere (winter) with values around 301.6 K. Near the equator there was a small rise to about 301.8 K which then steadily rose to about 302.3 K around 10°S (where an organized, intense convective cloud band, representative of the ITCZ was seen in the satellite imagery (not shown)). Beyond 10°S, once again the SST reduced sharply to 301.15 K around 15°S. The next experiment (LOTS-L) considered gradients in the land surface temperature along with SST gradients over the seas and was considered to be the most realistic scenario for the model integration. This temperature data was adopted from the analysed fields obtained from the National Center for Medium Range Weather Forecasting, New Delhi. Table 1 gives a summary of the numerical experiments.

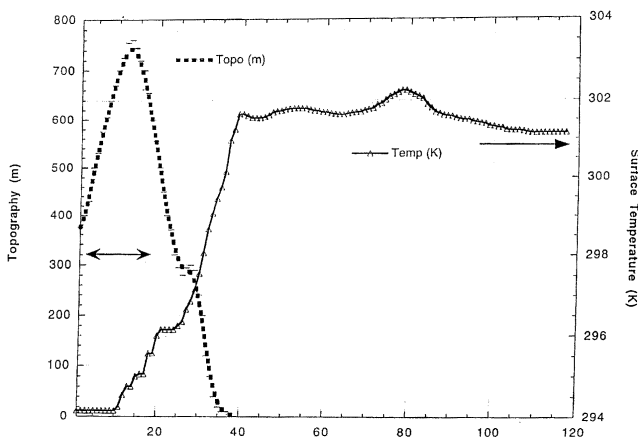
**Discussion of different experiments**

The role of the land-ocean interaction in controlling the deep off-shore penetration and related atmospheric circulation patterns is addressed in this section. The basic pattern for the homogeneous ocean case is discussed first, followed by the role of land heating, and then the impact of surface features such as topography, and temperature gradients.

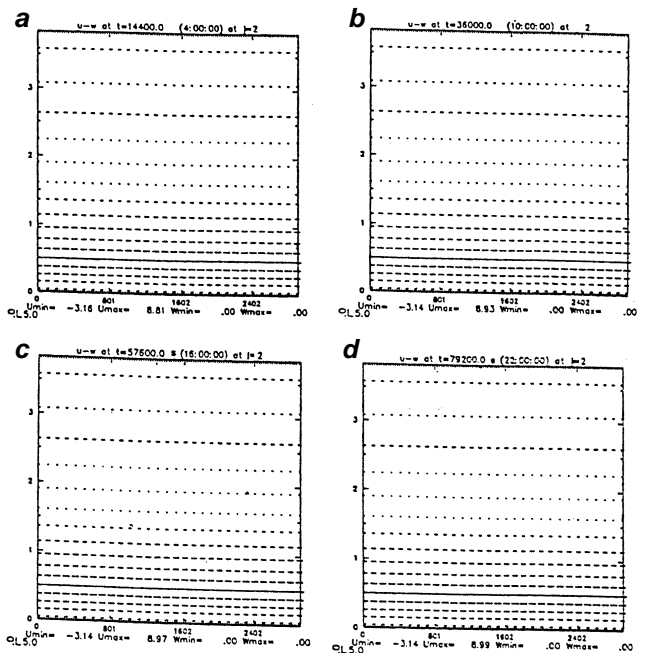
*The ocean case*

Of the various experiments detailed in the previous section, the results from the OCN case (no land, all

ocean) were most stationary and least dramatic. This was not surprising, as the oceanic response was fairly slow for the diurnal effects being studied. Some of the typical features of the simulation are presented here. First, no cloud formation or rainfall was predicted anywhere in the domain. Second, from the potential temperature profile a fairly deep, around 500–700 m, neutral layer existed almost uniformly over the domain for the 24-h simulation (not shown). The only perceivable difference was in the specific humidity values. Within the first 1000 m, the maximum value was around 15 g kg<sup>-1</sup> initially, which then increased to about 15.5 g kg<sup>-1</sup> till 1200 LT, reducing to around 14.0 g kg<sup>-1</sup> for the rest of the simulation (not shown). This constant specific humidity layer thus fluctuated from about 200 m around 0800 LT to 600 m, 20 h after simulation (2200 LT next day). This reduced around 200 m at 24 h of simulation. The wind fields remained fairly constant and did not show any large variation. Figure 4 a–d summarizes the typical wind flow pattern for the OCN case. These plots are for 0600 LT, 1200 LT, 1800 LT, and 2400 LT. As discussed, due to lack of any differential heating, circulations or convergence bands were absent in the homogeneous domain simulation results. Thus there were no clouds or precipitation during the entire simulation period. Overall, specific humidity values were higher in the first 200 to 700 m, while the surface potential temperature had a surface value of 300 K rising gradually to 301 K at 850 m. A wind maxima of about 9 m s<sup>-1</sup> around 450 m was simulated for the entire period.



**Figure 3.** Initial surface temperature (K) at 0 LT, and the surface topography used in the model simulations. The peak in the topography was due to the Western Ghats. For the night time, land was significantly cooler than the sea. Each grid point corresponds to 25 km width.



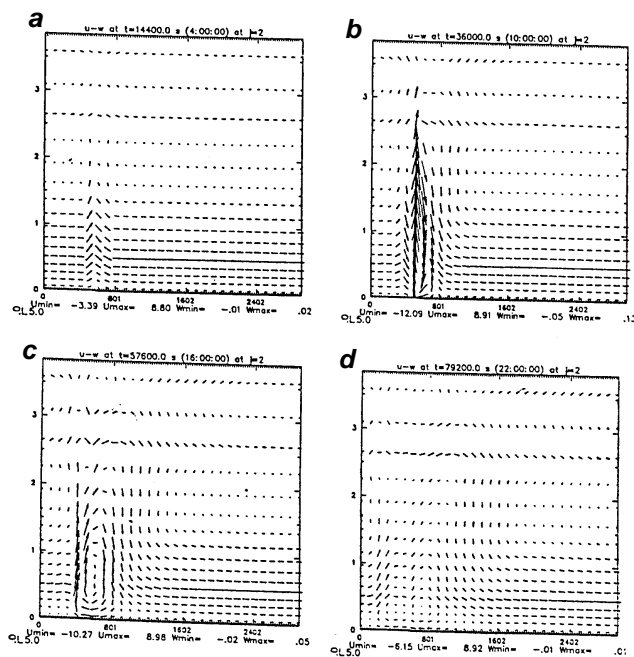
**Figure 4.** OCN case. X–Z cross section of the horizontal (*u*) and vertical (*w*) wind components for (a) 6 LT, (b) 12 LT, (c) 18 LT, and (d) 24 LT of 2 January 1997. For this control case, due to the homogeneous domain no circulation pattern was obtained.

This reference OCN experiment will act as a control against which influences of land, topography and SST gradients can be compared.

*Land-ocean circulation with diurnal variability*

The LAO (land and ocean) is the basic experiment of any monsoon-related study. The differential heating between the land and ocean surface leads to a circulation. This feature has been simulated successfully in the LAO case and is described *apropos* the diurnal evolution of land-sea breeze circulation. The model was initialized at 0600 LT and two hours later, very weak updrafts about 50 to 75 km inland and weak downdrafts (order of  $0.5 \text{ cm s}^{-1}$ ) about 100 km offshore were generated. The vertical velocity showed a distinct frontal formation at approximately 100 km inland. Around 1200 LT, the vertical wind had strengthened in intensity (about 1 to  $2 \text{ cm s}^{-1}$ ) and its influence was dominant for about 100-km inland and about 200 km offshore. At the land-sea interface particularly, a strong convective cell was formed. For this noon hour in the LAO case, the lower 1500-m had a mean flow from sea to land (sea breeze), following which till about 3500 m no mean winds were generated. Above 3500 m, a return flow from land to sea was obtained. The convective band for the updrafts on land penetrated about 2500 m. In the afternoon, this convective band strengthened further (vertical velocities around  $5 \text{ cm s}^{-1}$ ) and penetrated the land to sea return flow (at 3500 m height). Also in terms of its spatial coverage, the influence of this front was traced till about 100 km inland and about 250 km offshore. Around 1600 LT, most of the earlier mentioned convective features remained fairly dominant (with maximum vertical velocities around  $13 \text{ cm s}^{-1}$  on land corresponding to a maximum downdraft of about  $5 \text{ cm s}^{-1}$  over ocean) including the lower inland penetration. This breeze extended about 200 km inland within about 300 m of the lower atmosphere. This inland penetration was till a zone of intense updraft over land. A large closed cell was thus being formed along the land-sea interface. Interestingly, for this case, the influence of this land-sea differential-induced circulation could be traced till about 500-km offshore. Further, during the simulation boundary layer clouds were generated around 1800 LT which disappear subsequently. After 1800 LT, the intensity of the vertical velocities reduced. However, the closed circulation was maintained and the land breeze was initiated from about 400 km inland. This circulation dissipated around 2000 LT with reduced vertical motion. At 2400 LT, the impact of local effects was maximum with the region around 275 km with a flow-depth around 500 m contributing to the land breeze. Later, this closed circulation developed into two smaller cells around 2400 LT, which would reinitiate sea breeze the following day.

This basic experiment revealed features that can have direct relation to the observational experiments in the Arabian Sea and the Indian Ocean such as the INDOEX, particularly during the NE monsoon. First, for a significant distance offshore (even to the order of hundreds of kilometers), strong continental effect and diurnal influence could be possible. The second issue relates to the transport of tracers or aerosols from the landmass to the oceanic environment. Evidently, simulations suggest that there will be a transport from the continent to the marine boundary layer. However the quantity or amount of this transport, can be largely variable and can be an interactive function of local and large-scale variables. As an example, our results show a distinct return flow at two levels in the boundary layer. This two-level plume-like flow feature was observed in several of the ship-based soundings as shown in Figure 6 (ref. 4). In Figure 6 both the virtual potential and equivalent potential temperature profiles display a marine boundary layer about 700 m thick. Then from about 1500 m to 3000 m a land-influenced plume-like structure is evident as was also generated in the simulation results. Interestingly, if the air parcels were to travel within the land-sea breeze closed circulation then the possibility of long-range transport would be less until they were transferred by an updraft from the closed circulation to the plume-like flow above 1500 m and then into the large-scale flow towards the ITCZ. As that the pollutants can be recirculated providing a land sea breeze based, localized regional maxima in concentrations. Results from the 1998 cruise for the aerosol concentra-



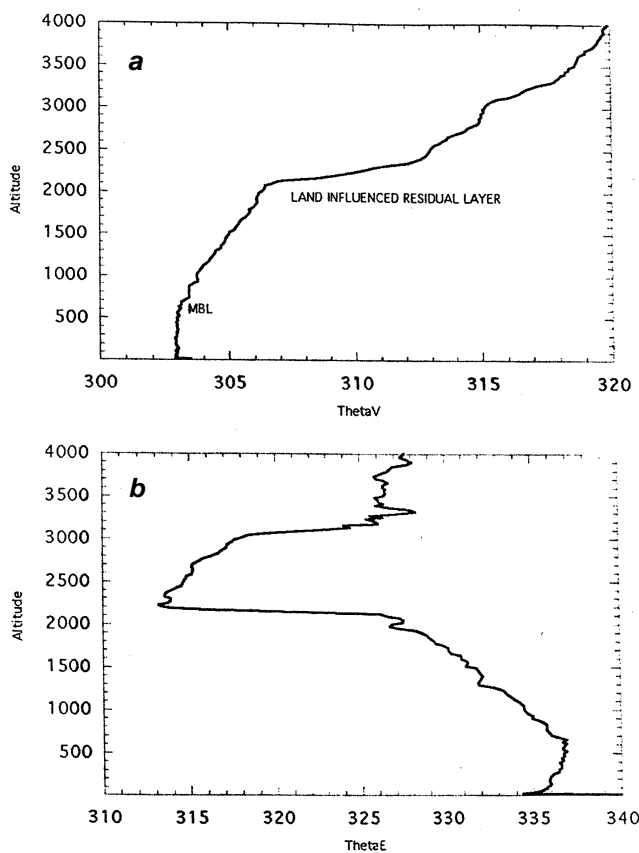
**Figure 5.** Same as Figure 4, except for addition of land in the model domain (experiment LAO). A definite circulation cell was generated along the land-sea interface. The basic NE flow (land to sea) was dominated by sea to land circulation for the daytime.

tions<sup>3</sup> support such a local maxima possibility. Hence for chemistry-related studies, the vertical gradient of the species (aircraft sampling) could provide vital information regarding the continental transport. Similarly, the oceanic measurements would require interpretation *apropos* such diurnal variability so as to become more generalized and the assumption for lateral homogeneity may be invalid at least till about 1000 km offshore. (This could be particularly important for non-continuous, mobile measurements.)

In these simulations the basic feature was the land-sea contrast which resulted in the diurnal variability in the circulation pattern. A plume-like flow between 1500 m and 3500 m and a closed circulation in the first 1000 m above sea level were the principal features. An additional aspect that could be considered for the NE monsoonal flow over Indian Ocean was the mountains on the Indian west coast and is described in the following section.

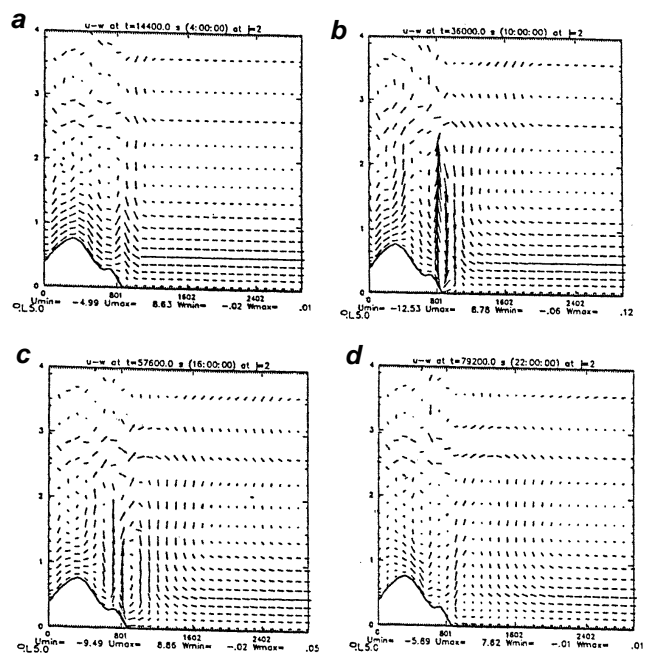
*Effect of topography for the INDOEX domain*

In the 2-D sense for the western Indian coast, the air parcels would have to travel over the mountain and then



**Figure 6.** Observed sounding for (a) virtual potential temperature (K), and (b) equivalent potential temperature (K) from ORV *Sagar Kanya* during the 1997 pre-INDOEX cruise. The sounding was taken about 1°N. Both the profiles show a definite land influence in the layer above 1500 m to about 3000 m consistent with the simulation results.

over the ocean, while during the sea breeze occurrence, they attempt going over the mountain. Thus the role of coastal topography is of direct relevance to our present study. The topography along the western India and Sri Lanka is prominent surface feature along the western Indian subcontinental landmass, as was discussed. The same model setup and initial conditions as the previous experiment were maintained and the topography shown in Figure 3 was adopted. With the inclusion of mountains, a change in the circulation pattern particularly over the land was perceived. Figure 7 shows the six hourly plots of the **u-w** vectors in the X-Z plane. In the morning, there was a closed circulation over the mountains and the sea breeze influence was lesser than the previous experiment (75 km compared to 100 km in previous case). Additionally, the front was more offshore compared to the no-topography (LOA) case. Only around noon, an organized sea-breeze front was generated along the shore. This front was fairly localized compared to the no topography case. However, with inclusion of topography, the influence of the continental feature was more pronounced on the offshore circulation. Comparing with the earlier case, the effect could be visualized till about 1° to 2°N. During evening, the no-topography case tended to reduce its convective intensity, however with topography, the intensity of the vertical updrafts was maintained probably due to the slope of the terrain and around 2000 LT it started weakening. Also in the no-topography case, two weak cells were formed along the coast as discussed earlier while with mountain only a single off-shore closed cell was generated. Addi-



**Figure 7.** Same as Figure 4, except for addition of land with topography in the model domain (experiment LOT). A strong sea breeze front was developed which was confined till about 100 km inlands. The circulation pattern was altered till about 700 km off shore.

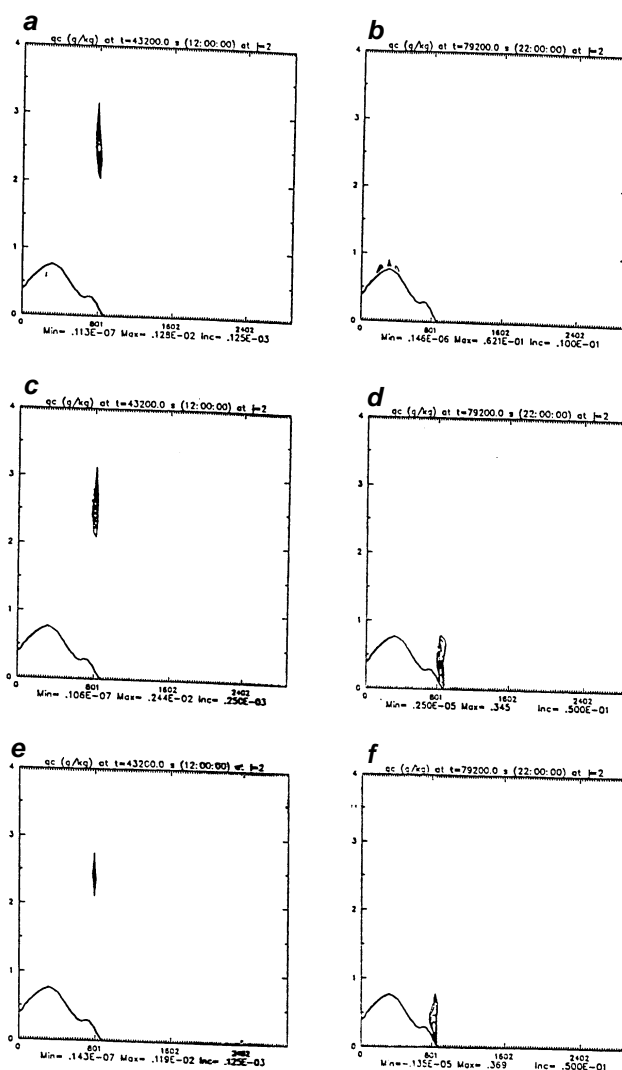
tional evidence of the enhanced continental effect on the offshore circulation was found in the sea breeze pattern. Sea breeze was initiated in the simulation with topography consistently farther away from the land compared to the no-topography case by an order of 200 km or so. However with mountains, the sea breeze could not penetrate inland as much as in the no-topography simulation, and was found stationed around 75 to 100 km inland for majority of duration. Other differences noticed in the simulation results with the inclusion of topography were related to the cumulus formation. Figure 8 show the cumulus formation for two time periods (1400 LT and 2400 LT) over the simulation domain. It could be noted that for the OCN case, there was no cloud formation while for the LOA (land-sea basic experiment), for the early evening period (1800 LT), some medium-level clouds were generated at the land-sea interface in the simulations. These clouds were mostly above 2000 m with an average thickness of about 500 m. Clouds were absent for any other hour in the simulations. With the inclusion of topography, the morning period (0800 LT) generated boundary layer clouds around 1300 m above sea level. These clouds dissipated with further surface heating and were regenerated around the land-sea interface at 1600 LT (between 1700 and 2500 m, above sea level) and 1800 LT (between 2000 m and 3300 m, above sea level). Interestingly, at night a nocturnal drainage flow over the mountains lead to several low level cumulus formations in the simulations. Thus in the night, the model generated low level clouds about 200 m above ground and about 100 m thick over land.

Thus, consistent with previous studies, several significant features were noticed with the inclusion of topography in the simulation. The mountains generated a complex land circulation with a deeper offshore influence (~ 1° to 2°S for the lowest 1000 m with a diurnal variation; and till ~ 2°S in the upper, i.e. 1500 to 3000 m layer) and an overall higher cloud cover for the nocturnal conditions. The sea breeze front remained mostly stationary around the coast with maximum inland penetration of about 100 km. Thus for a homogeneous ocean case, inclusion of land resulted in generation of significant circulation cells, while topography maintained and interactively intensified the circulation and transport potential for the air parcels over the ocean.

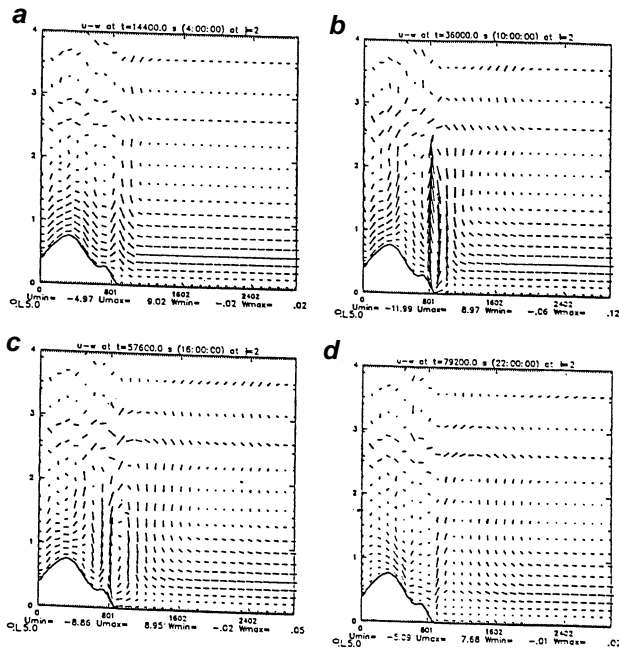
*Role of surface temperature gradients*

In the previous section, the interactive influence of topography on the circulation pattern was obtained. Another surface feature, which can influence the circulation pattern, is the gradient in the surface temperatures. The temperature gradients lead to differential fluxes that can result into local scale meso-circulations<sup>17</sup>. Two experiments were performed: first with SST gradient and constant (with space, but temporally varying) land tem-

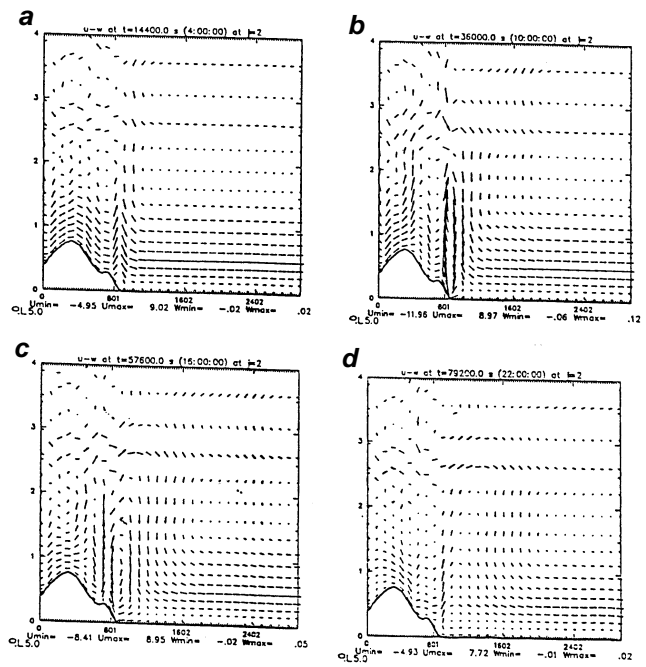
perature and next with gradients in both sea surface and land temperatures (temporally and spatially varying). For both these experiments, the domain contained topography as in the previous experiment. As discussed before, SST was obtained from the LDEO archive and land surface temperature data were obtained from the NCMRWF analysed fields. The latitudinal variation of the surface temperature adopted in the model integration is shown in Figure 3. A significant feature, on introducing surface temperature gradients, was that the model predicted precipitation in the simulations. The mean circulation pattern did not change significantly. This was expected, as the principal driver for the monsoonal circulation is the mean differential temperature between land and water. The



**Figure 8.** Cumulus cloud formation over the model domain for (a) Experiment LOT at 14 LT, (b) Experiment LOT for 24 LT, (c) Experiment LOTS at 14 LT, (d) Experiment LOTS at 24 LT, (e) Experiments LOTS-L for 14 LT, and (f) Experiment LOTS-L for 24 LT. There was no evidence of cloud formation for the other two cases (OCN and LAO). With the gradients in surface temperature (Experiments LOTS and LOT-L), the model also generated precipitation at the land-sea interface around 22 LT.



**Figure 9.** Same as Figure 4 except with the addition of land topography and SST gradients in the model initialization (experiment LOTS). The circulation pattern was generally similar to the LOT case, however the model predicted precipitation and a cloudier lower atmosphere in the domain.



**Figure 10.** Same as Figure 4 except with land topography and SST and land surface gradients in the model initialization.

observed gradients introduced in setting the model initial conditions were not dramatic ( $\sim 2$  K compared to the mean land and sea temperature difference where a 5 K differential was possible) rather fairly small ( $\sim 2$  K). Figure 9 shows the 6-hourly plots of the wind vectors in the  $X-Z$  plane over the simulation domain for the SST gradient case (LOTS, Table 1). Figure 10 shows the circulation pattern on the introduction of land temperature gradients (LOTS-L, Table 1). Once again, both these cases showed fairly similar circulation patterns as the observed surface temperature gradients were relatively small. However, the occurrence of precipitation in the simulation outcome was an important result as it provided evidence for synergistic interaction between the local-scale features (surface temperature gradients) with large-scale dynamics (precipitation).

For the simulation results from the two experiments (SST and land temperature gradient, and only SST gradient with constant land temperature) only minor differences could be perceived. Hence in the following discussion, only the SST gradient case and constant SST simulation results are compared. For the constant surface temperature case, clouds were present for 0800 LT, 1600 LT through the midnight. With gradient in surface temperature, clouds were generated more often in the domain principally around the land-sea interface. For the surface gradient case, clouds were generated around 0800 LT, and then from 1800 LT through midnight along with precipitation with low-level clouds. There was no

rain simulated for the constant (spatially) surface temperature case. Overall, the convective forcing associated with the constant surface temperature case was smaller.

Thus inclusion of the local features such as surface temperature gradients had a distinct interactive role with the large-scale thermodynamic and circulation patterns in the Indian Ocean domain.

### Conclusions

A detailed numerical experiment was undertaken to study the role of land-air-sea interaction on the circulation pattern over the Indian Ocean during the northeasterly monsoon. Observations made during the design phase of INDOEX, provided the initial impetus for a need of such a study. Recent observations suggest that the north hemispherical continent could have an impact on the offshore environment for a distance of the order of 500–1000 km off shore during the northeasterly monsoon. The hypothesis that such deep offshore plume-like penetration can be a cumulative effect of local as well as large scale features linking to topography and SST gradients was successfully tested. The results also highlighted the need of considering the Indian Ocean domain during the NE monsoon as a transient, nonhomogeneous region. Three factors can have an interactive impact on the concentration of the transported material offshore: distance from the land mass, relative separation from the ITCZ, and the local time over land. Any interpretation of the observa-



tions would need to consider these three factors in the analysis. Presence of a plume-like circulation between 1500 m and 3000 m ranging till about equator needs to be further studied using 3-D modelling approach and aircraft observations.

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ACKNOWLEDGEMENTS. Majority of the work was performed when U.C.M. was visiting North Carolina State University (NCSU). We thank the enthusiastic support of the crew from ORV *Sagar Kanya*. The numerical experiments were performed using resources provided by the North Carolina Supercomputing Center, while visualization was performed using the Facility for Oceanic and Atmospheric Modeling and Visualization Laboratory at NCSU. The State Climate Office of North Carolina is a public service center for Climate–Environment interactions funded in parts by the College of Physical and Mathematical Sciences and the College of Agriculture and Life Sciences at NCSU. We also thank Sonali Aditya, NCSU for her help with the graphics. This study was partially supported by grants from Division of Atmospheric Sciences, National Science Foundation, Naval Research Laboratory, Office of Naval Research, Washington DC, Council of Scientific and Industrial Research, New Delhi and Department of Space, Govt of India.