N000141712334 : Air-Sea Coupling in Monsoon Intraseasonal Oscillations

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Major Goals

Reliable predictions of the initiation, propagation, strength, and variability of Monsoon Intraseasonal Oscillations (MISO) constitute building blocks of monsoon forecasting, which are crucial for ensuring the socioeconomic wellbeing and safety of nearly one billion inhabitants of the Indian subcontinent. MISO are sub-seasonal weather phenomena that originate in the tropics, propagate predominantly northward over the Bay of Bengal (BOB) and then move westward over the Indian landmass. Active and break phases of monsoons are directly correlated with MISO, but significant biases and errors in current forecasts have been a bane for environmental planning beyond several weeks in advance. Mounting evidence suggests that accurate accounting of air-sea coupling is imperative for skillful forecasting of MISO and attendant outcomes such as rainfall, yet our lack of understanding of thermodynamic and physical processes, both on the ocean and atmospheric sides, has stymied the progress of forecast improvements. MISOs are a meld of multiscale physical processes working symbiotically to produce organized, migrating rain bands separated by periods of clear sky. This project seeks to study critical science questions underlying MISO dynamics. Of particular interest are the physical mechanisms responsible for heat, momentum and mass transfer across the air-sea interface, feedbacks between atmospheric and oceanic boundary layers, lead-lag relationships between the sea-surface temperature (SST), net heat flux and precipitation, as well as sustaining and dissolving MISO convection. Collectively, a suite of high-end atmospheric and oceanic instrumentation is to be deployed in the Indian Ocean, on the land over multiple countries, aboard research vessels and on an aircraft to collect data of high granularity. Ultra-high resolution coupled numerical simulations are to be used to guide field experimental designs and data interpretation. Novel autonomous measurement platforms and large eddy simulation (LES) technologies are to be developed to study MISO relevant air-sea processes. Satellite and reanalysis products are to be used to augment in situ data, allowing integration of observations across sub-meso to seasonal scales. In unison, the project will contribute to improved forecasts of MISO, and Monsoons in general, via discovery of physical mechanisms, understanding their linkages, development of model-relevant parameterizations, and providing a robust dataset for modelers. Collaboration with government agencies from the US and partnering countries (Sri Lanka, Maldives, Singapore and Seychelles) will help transition research to forecasting products. The project includes capacity building of partnering countries.

Accomplishments Under Goals

The Notre Dame (ND) group participated in the MISO-BOB full field campaign, which included two cruise legs. Leg 1 was out of Phuket, Thailand during 27 May to 26 June and Leg 2 out of Chennai, India during 06 July to 04 August. Leg 1 was focused on the recovery of a moored array deployed earlier by NRL, atmospheric and upper ocean measurements in support of MISO studies and sampling in Sri Lankan coastal waters. Leg 2 conducted detailed high-resolution upper-ocean and lower-atmosphere measurements in the central and northern BOB. The ND group fielded equipment aboard R/V Sally Ride and on the ground in Sri Lanka, Maldives, and Seychelles during the entire campaign. Notre Dame Equipment included: Sally Ride R/V: Motion stabilized scanning Doppler Lidar, met sensors on the bow mast, Ceilometer, Microwave Radiometer (MWR), Remote Ocean Sensing Radiometer (ROSR), Tethered Lifting System, Disdrometer, all Sky Camera, Sea Snake, Present Weather Detector (PWD-22), Vertical Microstructure Profiler (VMP) and a Vaisala Radiosounding System. (Fig. 1) Sri Lanka (at the Sri Lanka Meteorological Department and NARA): Scanning Doppler Lidar, 10 m flux tower with sonics at 5 and 10 m AGL, PWD and a LiCOR at 8 m, T and RH at 2, 5 and 10m, Ceilometer, Rain Gauge, and Sky Camera. Radiosondes were released 2/day (0600, 1200 UTC) during 29 May to 28 July (Fig. 2a,b). Seychelles (at the Seychelles International Airport): Scanning Doppler Lidar, flux tower with sonic anemometer at 2 m along with P, T, and RH sensors, Ceilometer. During 1-30 June, daily radiosondes were launched at 1100 UTC. (Fig. 2c) Maldives (at the Gan Island Airport): Flux tripod containing a sonic anemometer and met sensors (P, T and RH) at 2m height and a Scanning Doppler Lidar. Radiosonde releases occurred 2-3/day (Fig. 2d) All ND data were saved on a google team drive maintained by the Oregon State University. The data analysis followed the cruise, and included studies on: (i) Anomalous atmospheric events during MISO propagation, (ii) Analysis of 2018 and 2019 field data to educe MISO dynamics, (iii) upper-ocean turbulence characteristics during cruises, (iv) meso and sub-mesoscale coupling between atmosphere and ocean. Training (graduate student and post-doc) was an integral component. The NCAR PI used large-eddy simulation (LES) with computational resources provided by DoD High-Performance Computing Centers and NCAR. For the upper ocean, a database of 10 LES solutions that couple sub-mesoscale currents, small-scale turbulence and surface gravity waves was generated. The LES used large horizontal domains and fine meshes with 6.4x10^9 grid points. Process studies were made with surface winds or surface cooling with waves oriented in across-filament (perpendicular) or down-filament (parallel) directions relative to the two-dimensional filament axis. Significant Results and Outcomes: An Anomalous Event during 2019 Field Campaign: On 18 July, 2019, high precipitation and high wind speeds were reported in southern and central regions of Sri Lanka (Fig. 3). The precipitation exceeded 200 mm in some areas with wind speeds ~70-80 km/hr., causing loss of lives and damage to property and ecosystems (Fig. 4). Analysis of land stations as well as NCAR/NCEP reanalysis data indicated that a baroclinic Kelvin-wave instability episode may be responsible. Hovmöller plots of TRMM and OLR datasets during the experimental period averaged over latitudes between 7.5 deg S and 7.5 deg N provided further insights (Fig. 5 a,b). High daily precipitation in the experimental region of Sri Lanka (79.8E) was noted on 18 July, which coincided with the low OLR anomaly. Both plots showed oscillations of high precipitation and low OLR propagating eastward, which appear to be related to convectively coupled Kelvin wave activity. Hovmöller diagrams based on reanalysis data for ~ 17 kilometers altitude confirm the role of Kelvin waves. Zonal wind anomaly patterns propagated east (Fig. 6a). These anomalies were above Sri Lanka during the event, and showed a period of about 17 days, as evident from the sloped dashed lines. Air-temperature anomalies peaked ~ 2 days prior to those of wind anomalies, and further supported the Kelvin wave character (Fig. 6b). High geopotential height anomaly was present (Fig. 6c), but there were no substantial anomalies of meridional wind (Fig. 6d), consistent with equatorial Kelvin-wave dynamics. Normalized wave number from the reanalysis data was 1.4 (horizontal wavelength ~ 29400 km) with a wave period of ~ 17 days. For vertical properties, the Brunt Vaisala frequency squared (averaged over 16 to 19 km) was 5.6*10^-4 (s-2), vertical phase velocity ~ -488 m/day and vertical wavelength ~ 6.6 km. These observations are in broad agreement with dispersion relation for baroclinic Kelvin waves. Instrumentation in Colombo show that Lidar-measured vertical velocity variance exceeding 2 m/s close to the surface (Fig. 7). The gradient Richardson number (Ri) based on Colombo Radiosonde profiles for July 18 shows a drop below 0.25, signaling the possibility of a shear instability event. We hypothesize that a shear instability event might have caused the Kelvin wave to break and transfer momentum downward as a wind burst. Mixing and Instabilities in the Upper Oceanic Layers of BOB: Microstructure measurements in the central part of the southern and western BoB (near Sri Lanka) along various transects were analyzed. The upper-layer stratification in the central part of the southern BOB did not show a sharp density jump below the surface mixed layer (SML ~ 50 m deep), and the pycnocline was not decoupled from the SML as was observed in the northern and western BoB and in the Sri Lanka the Dome. A slight freshening and shallowing of SML was detected during the middle of the night. The TKE dissipation rate in the SML followed lognormal distribution, whereas in the pycnocline it could be well approximated by the Burr distribution. The evolution of shear instability during a semidiurnal cycle was studied using Ri statistics. The cumulative distribution function CDF(Ri) of the pycnocline appeared to remain approximately the same during the observational period, exhibiting a layered structure and being affected by internal waves (Fig. 9), The CDF(Ri) of SML showed variability with sea-surface diurnal heat flux. The probability of $Ri < 0.25$ was ~ 50% at the dusk, increasing to ~ 70 % at dawn due to nocturnal mixing in SML, and then decreasing to ~ 45% when stable stratification reappeared due to daytime heating. The time-dependent drift currents are also a factor for this variability. Fine Mesh LES of Horizontally Inhomogeneous MABL: The imposed SST heterogeneity was a single-sided warm or cold front with temperature jumps (2, -1.5) K varying over a horizontal distance between [0.1 - 6] km; these characterize upper ocean mesoscale or submesoscale regimes. A novel Fourier-fringe technique was implemented in the LES to overcome the usual assumptions of horizontally homogeneous periodic flow. Geostrophic winds (10 m/s) oriented across or perpendicular to the fronts led to secondary circulations that vary with the sign of the frontal temperature jump. Warm fronts featured overshoots in the temperature field, non-linear temperature and momentum fluxes, a local maximum in the vertical velocity variance and an extended spatial evolution of the boundary layer with increasing distance from the SST front. Cold fronts collapsed the incoming turbulence but leave behind residual motions above the MABL. In the case of a positive SST front, the internal boundary layer grows with downstream distance, conveying the surface changes aloft and downwind. SST fronts modify the mean wind and temperature patterns in the MABL interior, and warm fronts alter entrainment fluxes and generate persistent horizontal advection at large distances from the front. Sample results are shown in Fig. 10.

Plans Next Period

During the next reporting period, it is planned to: (i) continue the analysis of data from MISO-BOB cruises 1 and 2, ground stations and from enhanced radiosoundings from the Indian Meteorological Department; (ii) Complete the analysis of 18 July, 2019 anomalous weather event in Sri Lanka in collaboration of Sri Lankan Scientists; (iii) Continue analyses of multiscale processes of MISOs using MISO-BOB data as well as satellite and reanalysis products, (iv) analysis of data from WC-130J aircraft taken during the MISO-BOB pilot experiment, (v) publication of results in archival journals, (vi) presentation of results at national/international meetings and project overview workshops.

Results Dissemination

The major platforms for dissemination are national and international meetings as well as peer review publications. The project involves many universities and national laboratories, and direct communications with them through meetings and collaborations allow reaching out to scientific and user communities. Three invited presentations on the MISO-BOB project were made at the Hong Kong Institute of Science and Technology, Hohai University (China) and the Johns Hopkins University.

Honors and Awards

Nothing to Report

Training Opportunities

The project personnel included the PI, two PhD students (Edgar Gonzales and Jaynise Perez), a research professor (Iossif Lozovatsky), a research assistant professor (Raghu Krishnamurthy), a post-doctoral fellow (Sandeep Wagh), consulting scientist (Byron Blomquist/NOAA), a research engineer (Scott Coppersmith) and a field technician (Orson Hyde). In addition, the PI is supervising the PhD thesis of a Sri Lankan scientist from NARA (now at the Ocean University, Sri Lanka) who is a part of the Notre Dame project (Mr. Priyantha Jinadasa); he is a degree candidate at the Ruhuna University, Sri Lanka. The students completed the course work, received experience in data handling and analysis and participated in research cruises. Annunziata Pirro graduated 05/2019, successfully defending her PhD thesis. She continued to work for extra three months in the summer to complete her journal papers. Edward Creegan of the Army Research Office worked closely with the Notre Dame group in the field part of the project. Scott Coppersmith and Edward Creegan provided overall supervision for the Notre Dame group during the 2019 cruises whereas the PI supervised shore-based field work as well as academic work of the students. Junior researchers worked hand-in hand with senior personnel to ensure proper functioning of the state-of-the-art instrumentation and data analysis. The students and junior researchers were provided with opportunities to present papers in national and international conferences. In all, early career researchers and graduate students received experience in deploying instruments from research vessels and on land, data processing, and preparation of publications. An undergraduate researcher, Joo Sung Kim, was provided with opportunities for taking part in technology development for Lidar stabilization and instrument calibration.

Technology Transfer

The Lidar stabilizing platforms developed for ONR CASPER-West and MISO-BOB (2018 Pilot) projects were greatly improved in performance by introducing new hardware and (locally-generated) software. It was developed in collaboration with Motion Picture Marine Inc., who plans to commercialize the system. The system is under further development. Throughout the entire project, the PI maintained close collaboration with DOD laboratories, including Naval Research Laboratory (Stennis and Monterey), Army Research Laboratory (White Sands Missile Range, New Mexico) and 53d Weather Reconnaissance Squadron (403d Wing) of the US Air Force (Hurricane Hunters). During 10 to 30 June 2018, a WC-130J aircraft was deployed by the Hurricane Hunters as a part of the MISO-BOB project, with the PI handling agreements between the US and Sri Lanka. The collaboration with DOD laboratories is well evident from the publications reported in this report.

Participants

Name	Role	Person Months
Sullivan, Peter	Co-Investigator	3
Krishnamurthy, Raghavendra	Faculty	1
Lozovatsky, Iossif	Faculty	3
Fernando, Hiranth	Graduate Student (research assistant)	3
Gonzales, Edgar	Graduate Student (research assistant)	12
Perez, Jaynise	Graduate Student (research assistant)	12

Coppersmith, Scott	Other Professional	3
Fernando, Harindra	PD/PI	4
Pirro, Annunziata	Postdoctoral (scholar, fellow or other postdoctoral position)	3
Wagh, Sandeep	Postdoctoral (scholar, fellow or other postdoctoral position)	3
Blomquist, Byron	Staff Scientist (doctoral level)	1
Hyde, Jay	Technician	6
Kim, Joo	Undergraduate Student	3

Attachment: Figures

Figure 1: Instrumentation on the R/V on Sally Ride.

(a) (c)

(b) (d)

Figure 2: (a) Instrument deployment at NARA premises in Sri Lanka; (b) Radiosonde launches at the Sri Lanka Meteorological Department. Two launches per day were conducted (0500 UTC, 1100 UTC). Sri Lanka default radiosonde launches were limited to 1100 UTC, 4/week. Students from local high schools and universities visited the sites, and presentations were given on the role of radiosondes in weather prediction; (c) Instrument deployment in Seychelles Airport, hosted by Seychelles Meteorological Authority; (d) Deployment at the Gan Airport, Maldives hosted by the Maldivian Meteorological Services,. Radiosondes were released at 0000 UTC, 0600 UTC and 1200 UTC during 28 May to 28 June, and 0600 UTC and 1200 UTC from 29 June to 28 July. Default launchings were one per day, 0600 UTC.

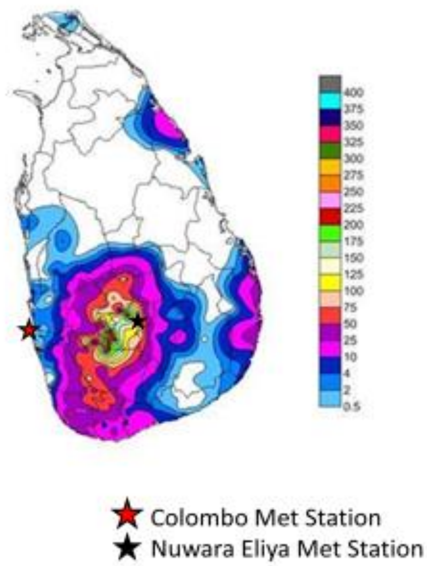


Figure 3: Precipitation distribution over Sri Lanka for 18 July, 2019. Locations for Colombo (Experimental site) and Nuwara Eliya (Highest precipitation recorded >200 mm) are marked on the map. (Courtesy of Sri Lanka Meteorological Department)

Figure 4: During the anomalous weather event, mobilization of sea spray caused damage to coastal vegetation located at distances as far as 0.5 km.

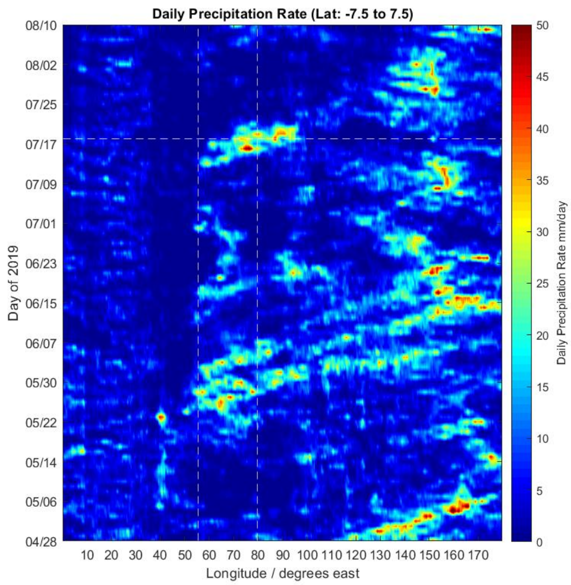


Figure 5(a): Latitude averaged Hovmöller plots of daily precipitation rate from Tropical Rainfall Measurement Mission (TRMM)

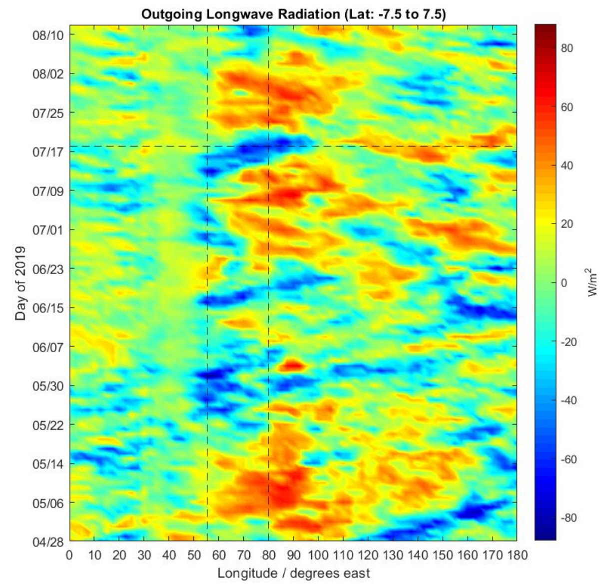
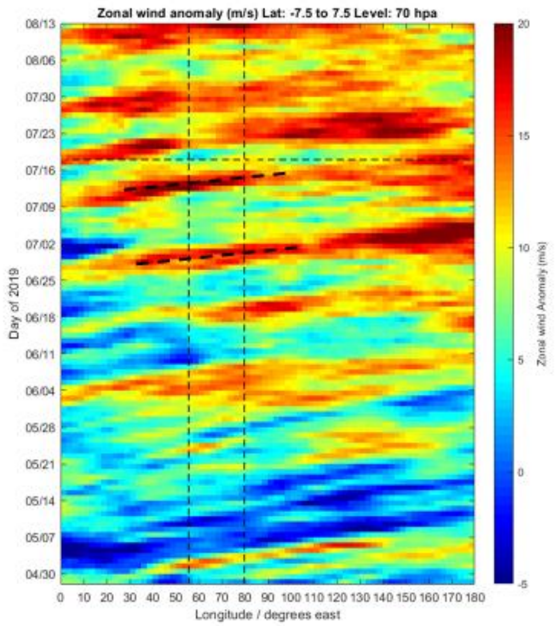
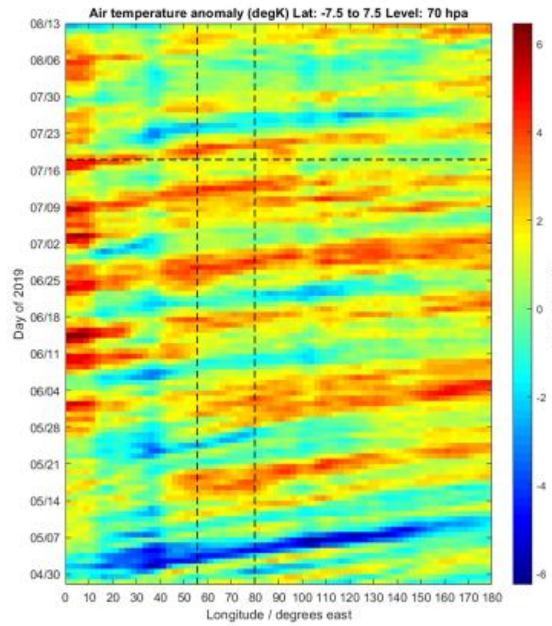


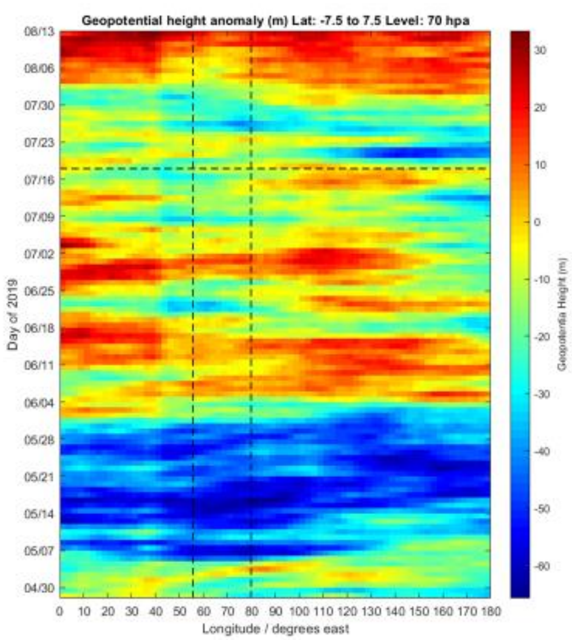
Figure 5(b): Hovmöller plots of Interpolated Outgoing Longwave Radiation (OLR) from NOAA



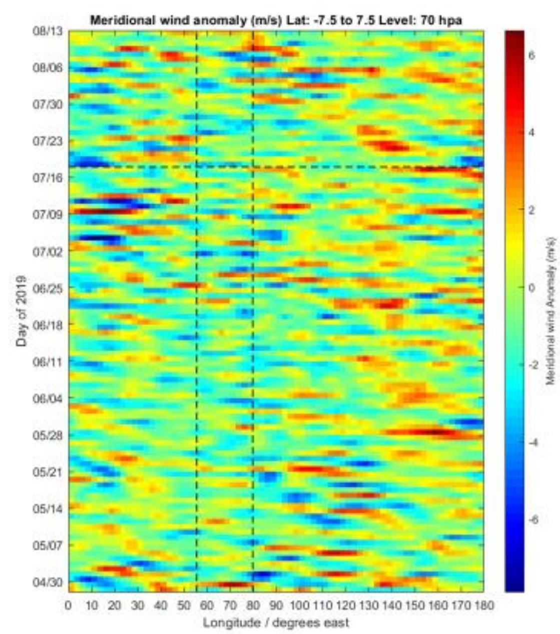
(a)



(b)



(c)



(d)

Figure 6: Latitude-averaged Hovmöller plots of the anomalies for (a) zonal wind, (b) air temperature, (c) geopotential height, and (d) meridional wind anomaly, based on NCEP/NCAR reanalysis products. The focus was on a window of 0-180^o east longitude and 7.5^{o}S-7.5^{o}N latitude.

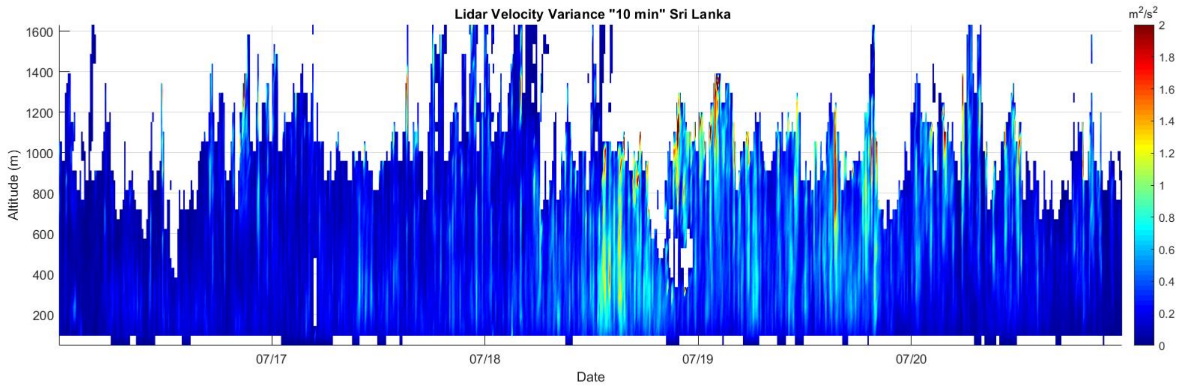


Figure 7: Doppler-Lidar vertical velocity variance for Colombo during 16-20 July, 2019

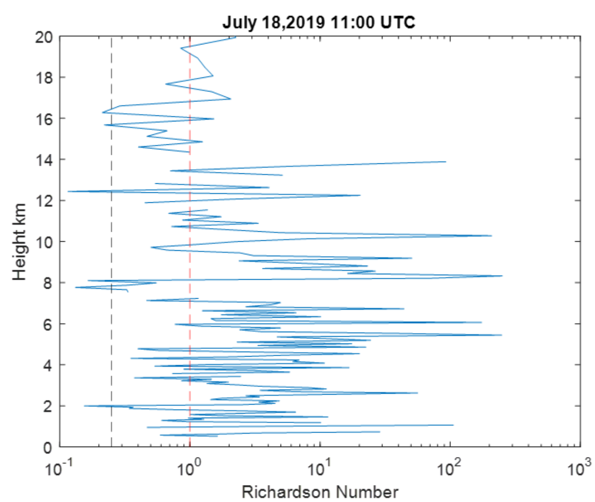


Figure 8: Richardson number (50 m averaged) plot for July 18, 2019 based on radiosonde profiles taken in Colombo Sri Lanka.

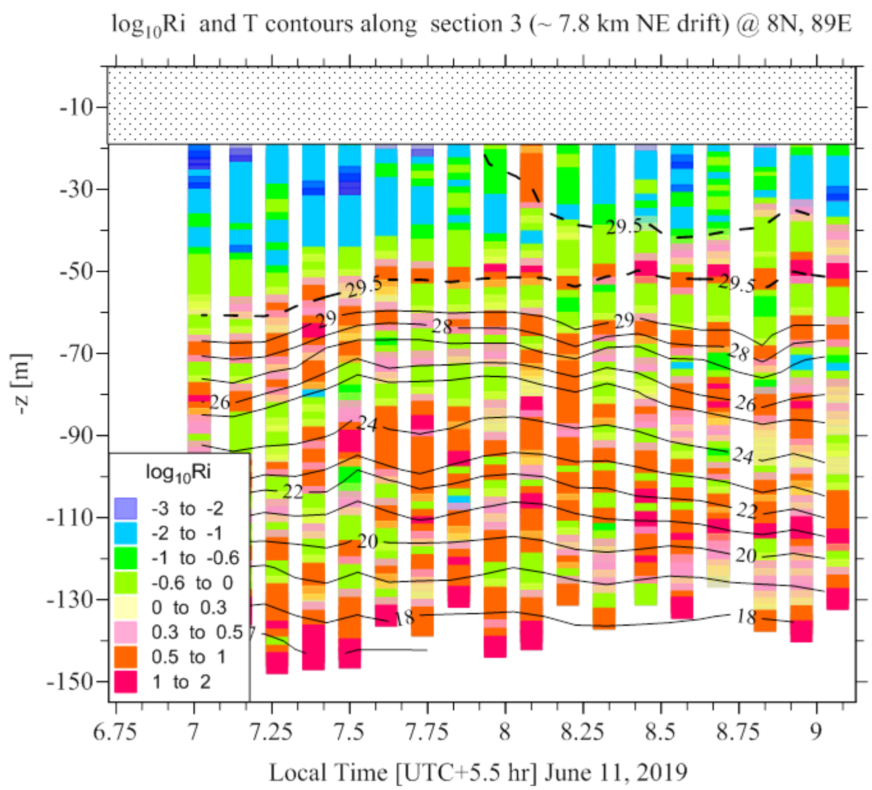


Figure 9: The $\log_{10}$Ri along the 3rd section (morning hours). Note the alternative layers of lower (green/yellow) and higher (pink/red) values of gradient Richardson number Ri in the pycnocline, shaped by the structure of the sheared layer.

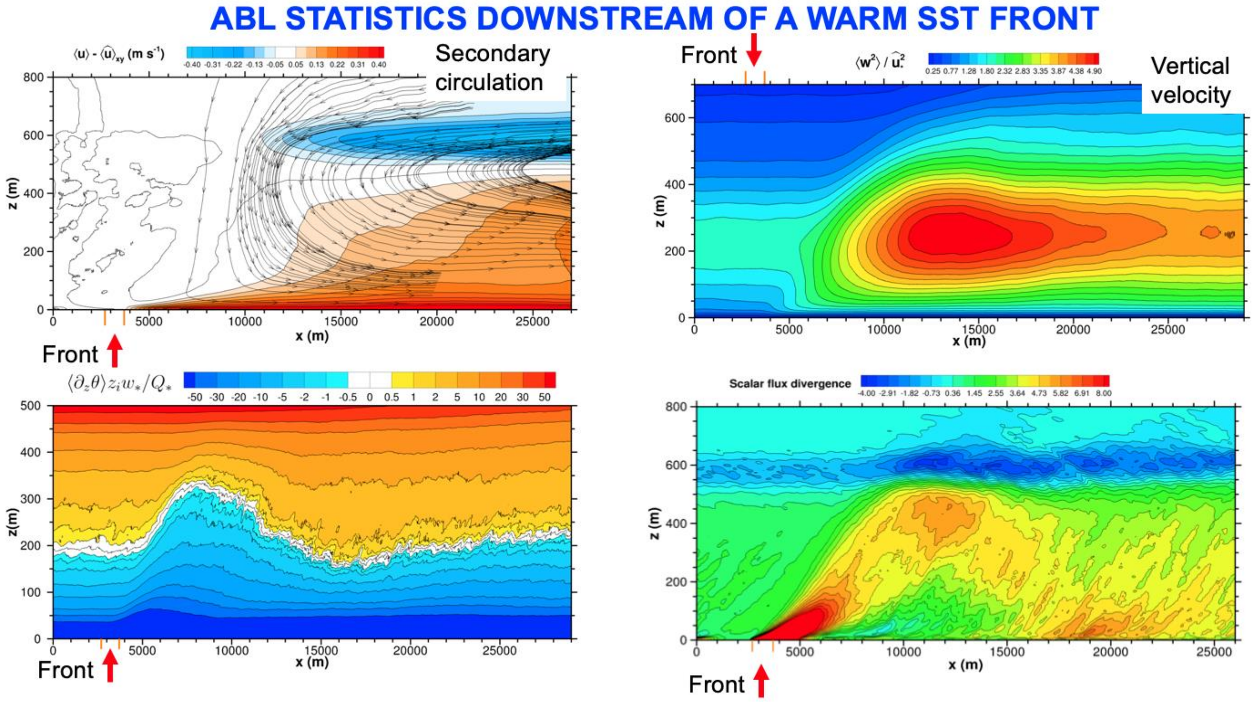


Figure 10: Statistics in the marine atmospheric boundary layer (MABL) forced by SST heterogeneity. Upper left panel: contours of the horizontal perturbation wind component downstream of a warm SST front. The large-scale winds are left-to-right and the vertical orange lines mark the beginning and end of the SST jump. The width of the 2 K jump is 1 km. Lower left panel: contours of the normalized mean vertical temperature gradient. Notice the overshoot in the contours near x = 9 km and gradual relaxation as the flow tends to the far field at x~30 km. Upper right panel: contours of resolved normalized vertical velocity variance showing a local maximum in the middle of the boundary layer far downstream of the SST front. Lower right panel: contours of the vertical divergence of temperature flux. Note its interaction with the overlying stable inversion.