N000142312053 : DRI The Arabian Sea Transition Layer (ASTraL) Exchange across the Air-Sea Interface

Reporting Period: OCT 01, 2022 to SEP 30, 2023

Date Received:

Submitter: Harindra Fernando

Major Goals

Every year during March to May a compact region of elevated Sea Surface Temperature (SST > 30 degrees C) develops in the Southeastern Arabian Sea (SEAS). This phenomenon is believed to have strong implications on biophysical interactions and underwater acoustics in the Arabian Sea (AS) as well as initiation of boreal summer Southwest (SW) monsoons. Known as the Mini Warm Pool (MWP) because of its smaller size compared to other warm pools in the world, MWP develops over an area with solar insolation comparable to the rest of the AS, which suggests that a myriad of interacting multiscale atmospheric and oceanic processes is responsible for MWP. This project conducts research on dynamical process underpinning the lifecycle (genesis, maturation, and dissolution) of MWP by participating in the ONR-ASTraL (Arabian Sea Transition Layer) Departmental Research Initiative.

The origins of MWP can be traced to the collapse of summer SW monsoons of the yesteryear, during which oceanic coastal planetary [Kelvin] waves are generated in the Bay of Bengal. These waves together with low saline water arriving in SEAS during the winter Northeast monsoons produce a large anticyclonic eddy in SEAS, signifying a downwelling Rossby wave. This feature, known as the Lakshadweep high (LH), is the hub of MWP.

Accompanying and evolving physical processes underlying MWP are numerous: the formation of a thicker and warmer barrier layer topped by a thin low-salinity colder surface layer separated by a pycnocline, air-sea interactions regulated by boundary layers above and below the ocean surface [together known as the transition layer], development of a low-level westerly jet and its instabilities, and development of deep convection in SEAS that finally leads to the Monsoon Onset Vortex.

Four guiding hypotheses are proposed to undergird the data analysis, and they concern: (i) the development of MWP during the evolution of air-sea fluxes in the transition layer due to evolving large-scale environmental forcing and micro-scale response thereof; (ii) warming of the thin upper mixed layer of LH via entrainment at the pycnocline, temperature inversions and lateral processes; (iii) generation of the SW monsoon onset vortex as a result of instabilities of the low-level westerly jet and amplification of resulting cyclonic vortex via enhanced turbulence and fluxes ensuing from deep convection and breakdown of instabilities; and (iv) rapid dissolution of MWP with the SW monsoon onset due to a combination of intense upper ocean turbulence, development of mesoscale structures and propagating planetary waves (e.g., westward migration of LH).

The four hypotheses will be tested, and relevant research questions will be addressed by participation in all three ASTraL field campaigns in 2023 (completed), 2024 and 2025, wherein an extensive suite of atmospheric and oceanic instruments will be deployed by University of Notre Dame group. Meso- and micro-scale processes active in MWP will be further investigated using a novel large eddy simulation (LES) approach by a collaborator (and Principal Investigator) from the National Center for Atmospheric Research, whose focus will be on the impact of ocean heterogeneity on transition layer. Collaboration with southeast Asian nations (India, Sri Lanka, Maldives), Naval Research Laboratories (Monterey and Stennis) and other ASTraL PIs are sought, building upon existing partnerships. Training of STEM students, post-doctoral fellows, early career scientists and technical staff will be an integral part of the project. The results will be published in archival journals, and disseminated via presentations in national and international conferences.

Accomplishments Under Goals

Overview of the Pilot Cruise, 2023: The University of Notre Dame (UND) group participated in all ASTraL/EKAMSAT 2023 pre-cruise meetings for planning and coordination. The equipment packages left UND on 2 March, 2023 to Cape Town, South Africa, and two UND personnel Jay Orson Hyde and Griffin Modjeski loaded gear onto R/V Roger Revelle at the Cape Town Port on 03 April. Because of logistical and customs constraints, however, the instrument installations were done in Mauritius during 16-19 May. The cruise period was 11 – 26 June, with scientists' mobilization out of Marmugao, Goa. The UND had an all graduate-student crew: Griffin Modjeski, Devmi Gamage, and Selina Bolella. Ground support and directions were provided by post-doc Jayesh Phadtare and PI Fernando. The NOAA Physical Sciences Laboratory collaborated with UND to deploy meteorological and flux measurement packages.

The following instruments were deployed onboard Roger Revelle by the UND group: (a) Vaisala CL31 Ceilometer; (b) Vaisala Present Weather and Visibility Sensor PWD 22; (c) Inter Met Systems iMet-4 Radiosondes; (d) Water Temperature Sensor (Sea Snake; with NOAA); and (e) The NOAA flux package, consisting of Vaisala PTB220 Barometer, Eppley Standard Precision Pyranometer, Hemisphere Crescent VS100 Series GPS Compass, Vaisala Humidity and Temperature Meter Series (HMT) 337, Li-Cor Open Path CO_2/H_2O Analyzer LI-7500, Gill WindMaster Pro Anemometer, Systron and Donner 6 Axis Motion Detector Sensor.

Upon completion of the cruise, the instruments were retrieved from Fremantle, Western Australia during a port call on July 14. Peter Hall from ProteQ and Orson Hyde from UND conducted instrument dismantling and shipping back to the USA. Equipment arrived in the US (Los Angeles Port) on August 5, and at Notre Dame on August 15.

Results: Radiosonde Observations: The first successful radiosonde launch was on 13 June 06:19 UTC. Consecutive daily radiosonde launches were conducted every 06 hours until 12:00 UTC 24 June 2023, at 00:00, 06:00, 12:00 and 18:00 UTC (05:30, 11:30, 17:30, 23:30 Indian Standard Time). The frequency of radiosonde launches was increased to 3 hours/day later in the cruise, guided by weather forecasts. Figures 1(a,b) show, respectively, the launch locations on the ship track with respect to date and time as well as a photograph of a release. Figure 2 shows a synthesis of meteorological profiles obtained by radiosondes. The relative humidity drops drastically to near zero at altitudes ~ 600 to 300 hPa (~4200 m to ~5600 m) of the atmosphere (Figures 2a, 3 and 4), implying a dry air intrusion ~ 3 km thick at these levels. The wind speed is low (~ zero at times) within this dry layer (Figure 1b), which is essentially of northwesterly origin and sandwiched between comparatively high speed southeasterly winds on either side (Figures 2 b,c and 5). As such, the boundaries of the dry layer are expected to be highly sheared and prone to mixing. As shown in Figure 6, the shear is highest at the lower boundary of the dry air layer. The observation of dry air layer is consistent with an earlier observation noted by Fletcher et al. (2018; Quart. J. Royal Meteor. Soc 146, 2867–2890). Figure 7 shows a formation mechanism identified by Fletcher et al. (2018), where rising air from the windward side of a continental topography causes precipitation and latent-heat release, and the rise of ensuing warmer air to its equilibrium density level to spread as an intrusion. From 23 June onward, progressive moistening of dry layer can be seen, which can be attributed to moist southeasterlies that penetrate the dry air layer and mix vertically (Figures 2a and

3). Most effective mixing occurs at the lower edge of the dry layer because of enhanced shear (Figure 6).

Cloud-Base Heights Using Ceilometer: Figure 8 is a preliminary backscatter plot (raw data) obtained from the CL-31 Ceilometer. Typical cloud bases have altitudes of 0.5 km, but on some days cloud heights along the ship track rose to ~ 1.5 - 2 km (11, 12, 13 and 19 June 2023), indicating enhanced convection. Figure 9 shows an expanded view of backscatter for consecutive three days where the clouds penetrate more than 1 km.

INSAT Satellite Observations: Figure 10 shows INSAT IR and SST data for 11-13 June. Here, the ship is closer to the outer bands of Biparjoy cyclone, as evident in the SST data. The presence of a cold patch in the warm pool can be observed, possibly in the wake of the cyclone, as a result of intense vertical mixing and upwelling associated with Biparjoy. Background SSTs are above 30 deg C during this period. Following the cyclone, SST gradually decreases, records the lowest on 17 June, and again increases from 19 June onward (not shown). Current research efforts are directed toward correlating SST with local convection observed by the ceilometer.

Numerical Simulations of Coupled Atmosphere-Ocean Processes: During the past fiscal year, the NCAR PI Sullivan concentrated on developing a coupled atmosphere-ocean LES code. The new code leverages developments started during MISO-BoB Project that utilizes the Message Passing Interface to run multiple LES simultaneously. In its present configuration, the code runs atmospheric and oceanic LES with new coupling routines that link the simulations in the following order at each time step: 1) interpolate the currents and sea surface temperature (SST) from the ocean boundary later (OBL) to the first model level in the Atmospheric Boundary Layer (ABL); 2) surface fluxes are then computed in the ABL; and 3) then surface fluxes are shared between the ABL and OBL. The code is still under construction but preliminary tests find that the coupled code is able to generate coherent structures and statistics typical of an idealized convective boundary-layer regime in the ABL overlying an OBL with Langmuir cells. The horizontal domain was small, spanning a 1km x 1km area. In the (ABL, OBL) the vertical domain is (1, -0.1) km, respectively. The grid mesh in the (ABL, OBL) domains are modest (256, 256, 256) and (512, 512, 128) points, respectively.

Also, the NCAR PI submitted articles to the Journal of the Atmospheric Sciences, Journal of Physical Oceanography and Atmosphere describing atmospheric flow over a rotating ocean eddy, oceanic frontal turbulence and stable boundary layer turbulence, respectively. A highlight from the rotating ocean eddy article finds a rotating eddy induces a dipole in the momentum and temperature fluxes which shows the importance of current coupling. The research on oceanic frontal turbulence found the somewhat surprising result that along the frontogenesis axis the primary balance was between shear production and turbulent transport in the turbulence kinetic energy (TKE) budget (see Fig. 11). For the TKE energy production, separate bulk viscosities for the horizontal and vertical momentum fluxes were defined. The vertical and horizontal viscosities are estimated from the TKE shear production terms and the magnitude of their respective horizontal and vertical shear gradients. Results are shown in Fig. 12 where the eddy viscosities are made dimensionless by the mixing-length scale for convection. Inspection of the results shows that the extrema are quite large, more than 100, within the frontal zone with horizontal eddy viscosity > vertical eddy viscosity. Both down-gradient and counter-gradient eddy viscosities are observed. The simulations of the GABLS1 stable boundary layer employed a mesh with 20483 points with spacing 0.2 m in each coordinate direction; the data volumes are being incorporated in the Johns Hopkins University Turbulence Database to allow further analysis by the research community. An analysis of this stable LES showed that the results can be used to examine subfilter scale modeling in the so-called ``gray zone'', i.e., the region between the mesoscale and LES limits.

Plans Next Period

During the reporting period, UND group plans to submit one or two papers based on 2023 EKAMSAT/ASTraL Pilot cruise. Also, intense preparations are under way for the 2024 Cruise in the Eastern Arabian Sea. PIs group plans to send four or five scientists and a field technician to the 2024 cruise to support a suite of instruments. The UND group plans to staff both legs of the 2024 cruise.

The NCAR co-PI will continue the development of coupled atmosphere-ocean LES code. This includes adding moisture and salinity to the atmospheric and oceanic LES codes, respectively. Also, he plans to simulate boundary-layers typical of the Arabian Sea mini-warm pool focusing on light wind convective periods.

Results Dissemination

During the reporting period, the results were disseminated by conference presentations as well as submission of peer reviewed publications. The PI also made several invited presentations at university seminars: University of Bologna (Italy, Summer School on Physical Sensing of the Environment, July 16-21, 2023) and Columbia University (October 31, 2023).

The following conference/workshop presentations were made during the 2023 reporting period: (1) Luecke, Conrad, Jarosz, E., Wang, D., Jensen, T., Rydbeck, A., Fernando, H.J.S., Flatau, M., and Jinadasa, S.U.P., The Oceanic Response to a Tropical Cyclone in the Bay of Bengal, 487AIRSEA, AMS Annual Meeting will take place from 8 to 12 January, Denver, Colorado, 2023. (2) Sullivan, P.P., McWilliams, J.C., Weil, J.C., Patton, E.G., and Fernando, H.J.S., Impacts of SST Gradients on Marine Boundary Layers, Paper, 2A.4BLT, 103rd AMS Annual Meeting will take place from 8 to 12 January, Denver, Colorado, 2023. (3) Sullivan, P.P., Marine boundary layers with submesoscale surface heterogeneity: LES results. Atmosphere-ocean coupling at (sub)mesoscales, Lorentz Center, Leiden, Netherlands, 25-29 September, 2023 [invited]. (4) Sullivan, P.P., Stable atmospheric boundary layers: Fine mesh LES and observations. New horizons in Environmental Mechanics, NCAR, Boulder, CO, July 24-July 27, 2023 [invited]. Sullivan, P.P., Marine boundary layers coupled to ocean surface heterogeneity: Secondary circulations in LES process studies. St. Anthony Falls Laboratory, U. Minnesota, Minneapolis, MN, 2 May, 2023 [invited]. (5) Sullivan, P.P., and McWilliams, J.S., Atmospheric boundary layers coupled to ocean currents. 23rd Conference on Air-Sea Interaction, 103rd AMS Annual Meeting, Denver, CO, Jan. 2023.

Journal publications submitted or published are as follows: (1) Lozovatsky, I., Fernando, H.J.S., Jinadasa, S.U.P., and Wijesekera, H., 2023: Eddy Diffusivity in Stratified Ocean: A case study in Bay of Bengal. Environmental Fluid Mechanics, 23, 1131–1143, https://doi.org/10.1007/s10652-022-09872-3. (2) Phadtare, J., Fernando, H.J.S., Krishnamurthy, R., Perez Valente, J.M., McLaughlin, K., Black, G., Dehart, J., Tandon, A., Shroyer, E., Jinadasa, S.U.P., and Bhat, G.S., 2023: Aircraft Observations in a Tropical Supercluster over the Equatorial Indian Ocean during MISO-BOB Field campaign, Nature Scientific Reports, revised and resubmitted. (3) Wijesekera, H.W., Teague, W., Hallock, Z.R., Wang, D., Luecke, C., Jarosz, E., Jensen, T., Fernando, H.J.S., and Jinadasa, S.U.P., 2023: Near-Inertial Waves, Eddies and Mixing in the Thermocline in the Bay of Bengal (JPO-D-23-0195), submitted to Journal of Physical Oceanography (4) McWilliams, J. C., Meneveau, C., Patton, E.G., and Sullivan, P.P., 2023: Stable Boundary Layers and Subfilter-scale Motions. Atmosphere, 14,1107. https://doi.org/10.3390/atmos14071107 (5) Bodner, A.S., Fox-Kemper, B., Johnson, L., Van Roekel, L.P., McWilliams, J.C., Sullivan, P.P., and Hall, P.S., 2023: Modifying the Mixed Layer Eddy Parameterization to Include Frontogenesis Arrest by Boundary Layer Turbulence. Journal of Physical Oceanography, 53, 323-339. https://doi.org/10.1175/JPO-D-21-0297.s1 (6) Pham, H. T.,

Sarkar, S., Johnson, L., Fox-Kemper, B., Sullivan, P.P. and Li, Q., 2023: Multi-scale Variability of Turbulent Mixing During a Monsoon Intraseasonal Oscillation in the Bay of Bengal: an LES study. Journal of Geophysical Research - Oceans, 128, 1-23. https://doi.org/10.1029/2022JC018959 (7) Mironov, D.V. and Sullivan, P.P., 2023: Turbulence Structure and Mixing in Strongly Stable Boundary-Layer Flows over Thermally Heterogeneous Surfaces. Boundary-Layer Meteorology, pp.1-23. https://doi.org/10.1007/s10546-022-00766-x

---

Honors and Awards

2022-2023: The PI was elected as a Fellow of the International Association for Hydro-Environment Engineering and Research (IAHR), and he delivered the 2023 IAHR Presidential Award Lecture in December 2022.

Training Opportunities

During the project period, three STEM students were trained: Devmi Gamage (second year PhD student), Selina Bolella (first year PhD student), and Griffin Modjeski (4th year PhD student). The first two were supported by the present grant, and the third via alternative sources, and they were all trained under the PI at University of Notre Dame. All three graduate students participated in the 2023 Pilot Cruise (Figure 13), and were key to data gathering and analysis. They also interacted closely with other cruise participants during and after the cruise. Selina Bolella has had experience in weather forecasting as an undergraduate at Penn State, as she was the head of the campus weather service and oversaw forecasting shifts of the ~200 students in the Campus Weather Service. As such, she was the 'unofficial' weather forecaster of 2023 Pilot cruise and played a key role in weather discussions. Griffin Modjeski and the research technician Orson Hyde visited the Physical Science Laboratory of NOAA for a week, and worked with Drs. Elisabeth Thompson, Ludovic Bariteau and Chris Fairall to develop a flux mast for the EKAMSAT/ASTraL Pilot cruise (Figure 14). This provided extensive training and capacity building for the ND personnel for setting up flux towers on ships. In the past a NOAA person was on the ship for installation, debugging and maintenance, which was not feasible for the Pilot cruise. Given only a limited number of instruments were deployed at the Pilot Cruise, the students had ample time to concentrate on each instrument and analyze data.

Technology Transfer

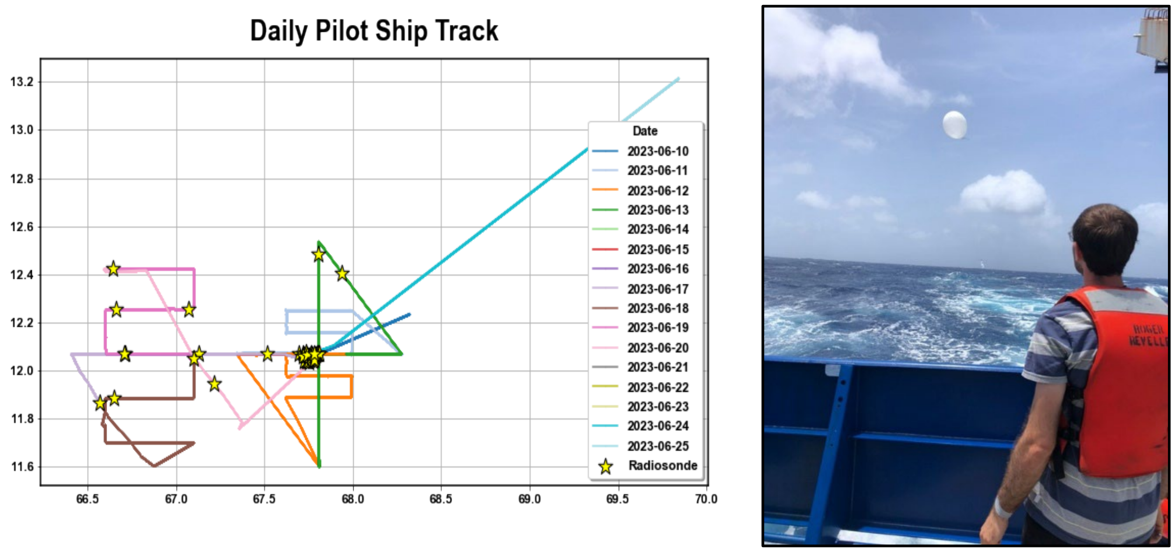
The UND PI is coordinating closely with NRL Stennis (Dr. Hemantha Wijesekera) and NRL Monterey (Drs. Sue Chen and Jerome Schmidt) in deploying instrumentation during the final (2025) EKAMSAT/ASTraL cruise. The sensor platforms of the three groups will complement each other and are carefully selected to observe as wide a parameter range as possible. Also, arrangements are being made for instrument inter-comparisons.

Participants

Name	Role	Person Months
Sullivan, Peter	Co PD/PI	1
Bolella, Selina	Graduate Student (research assistant)	5

Gamage, Devmi	Graduate Student (research assistant)	9
Modjeski, Griffin	Graduate Student (research assistant)	2
Coppersmith, Ronald	Other Professional	1
Fernando, Harindra	PD/PI	2
Hyde, Jay	Technician	2

Figures:



Figures 1 (a,b): (a, left) Ship track with radiosonde releases, including the respective date, on a latitude-longitude map; (b, right) A picture of a radio sounding operation.

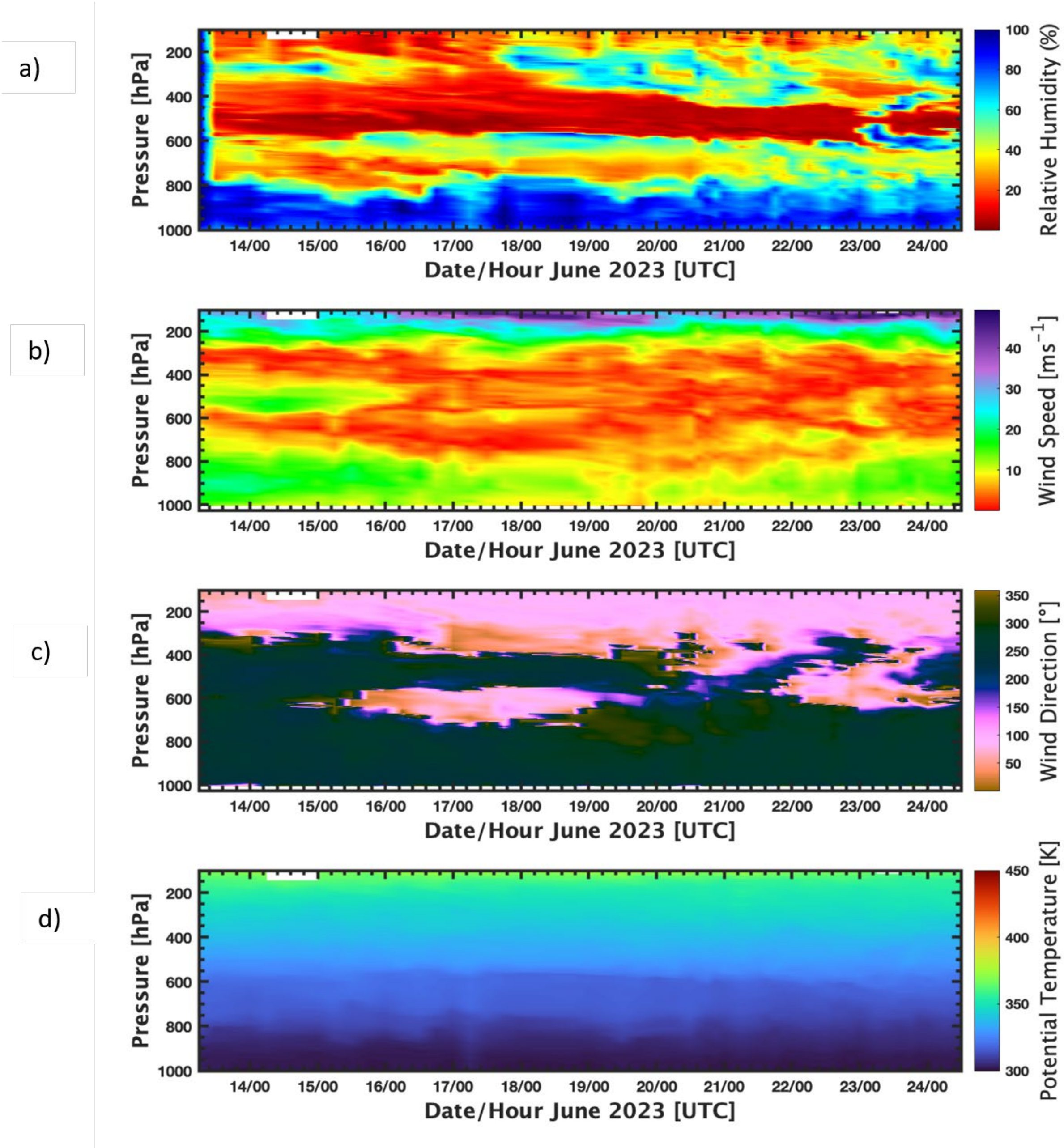


Figure 2: Time series variation of (a) Relative humidity, (b) Wind Speed, (c) Wind Direction, and (d) Potential Temperature

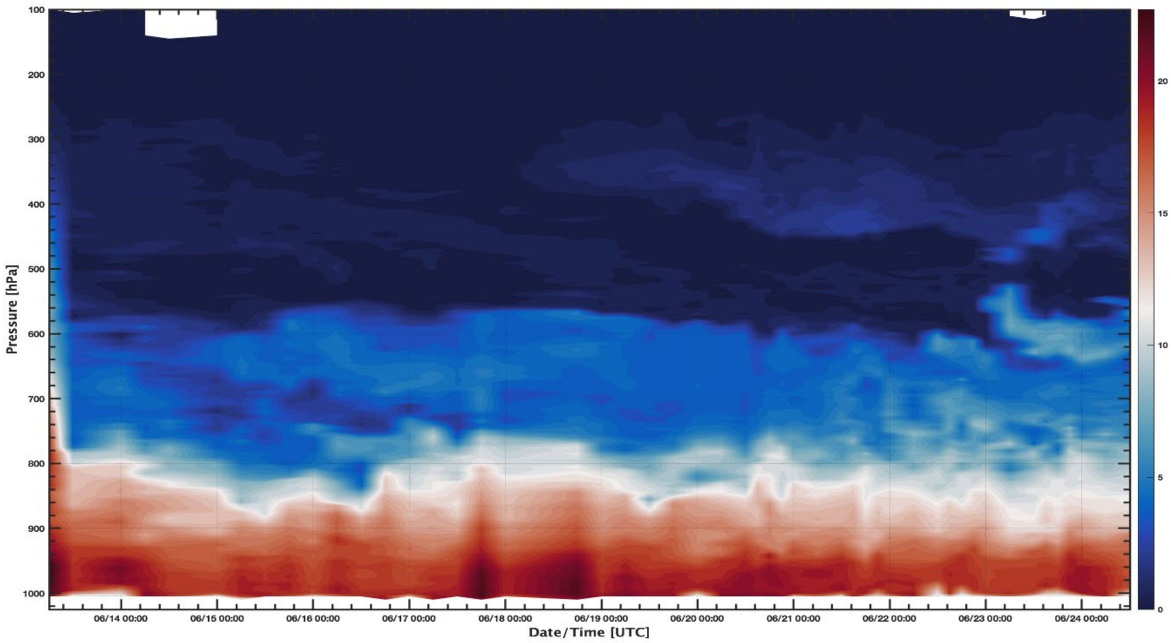


Figure 3: Mixing ratio (right color bar) versus height data from Radiosondes

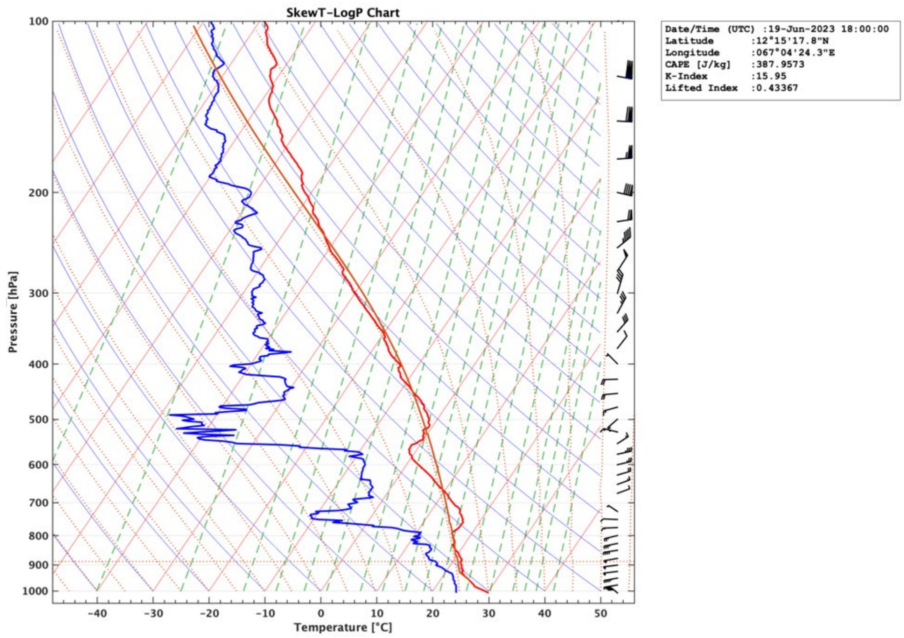


Figure 4: Skew -T log-P plot: from radiosonde data taken on 19 June 18:00 UTC.

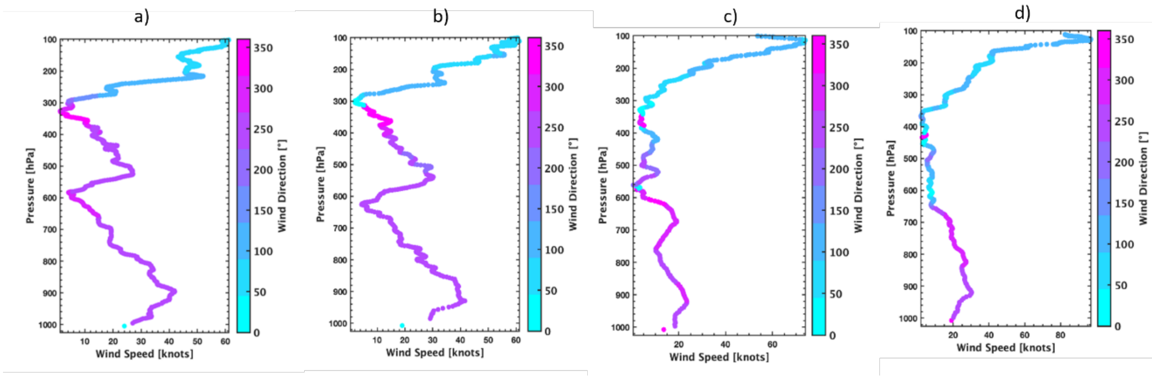


Figure 5: Wind speed and direction profiles: a) 2023/06/12/12:00; b) 2023/06/14/06:00; c) 2023/06/21/12:00; d) 2023/06/23/12 [UTC]

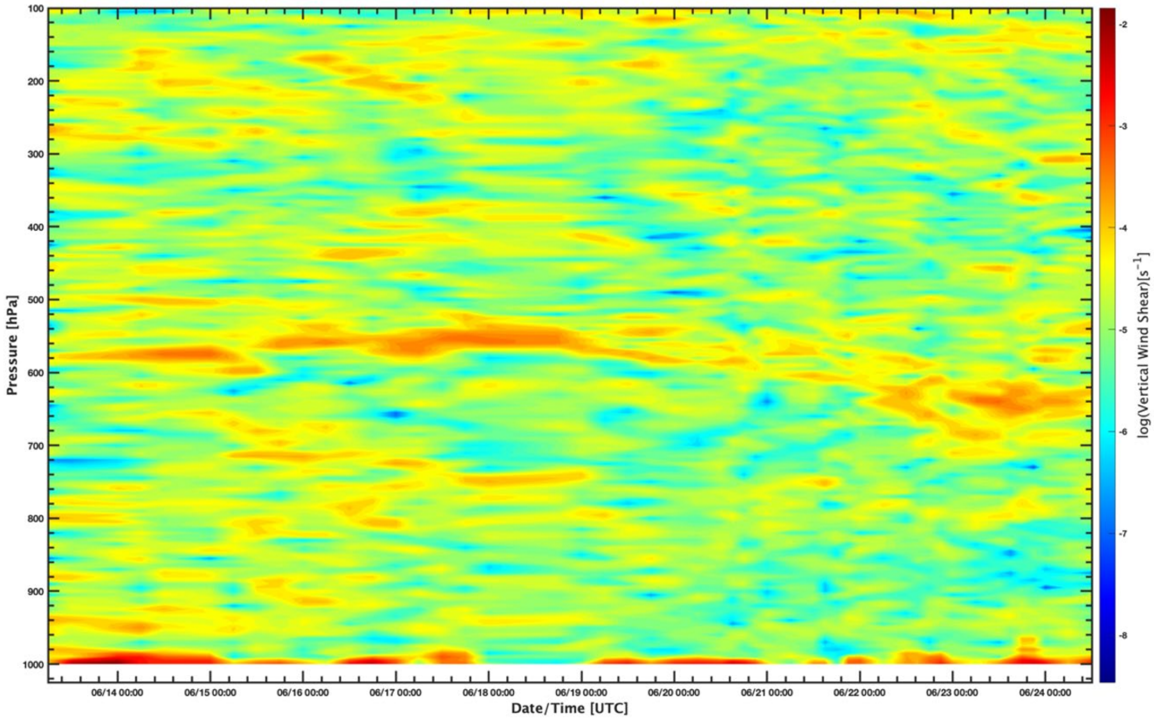


Figure 6: Vertical wind shear $[\sqrt{(\frac{du}{dz})^2 + (\frac{dv}{dz})^2}]$ reckoned using radiosonde data

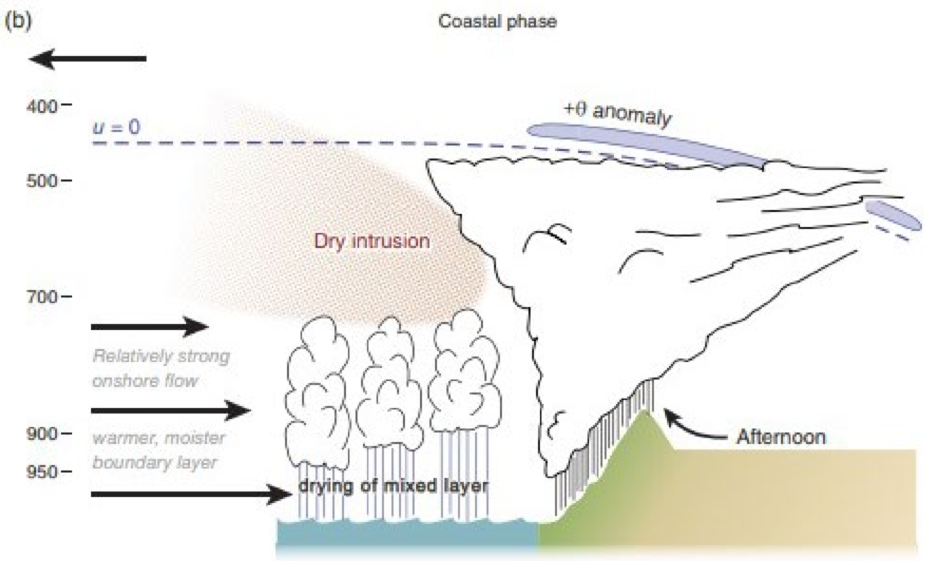


Figure 7: Schematic of the dry layer genesis, from Fletcher et al. (2018, https://doi.org/10.1002/qj.3439)

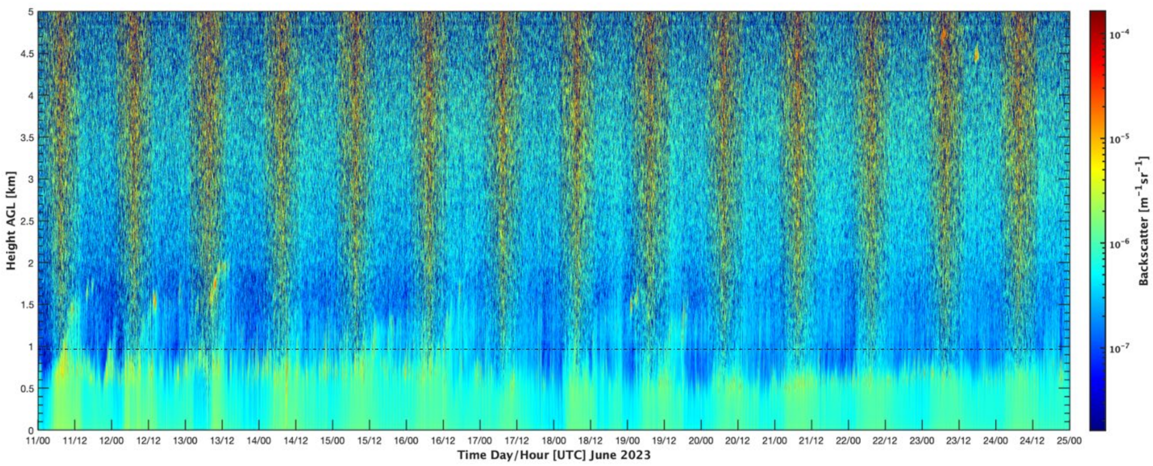


Figure 8: Ceilometer backscatter (11 – 24 June 2023). For reference, the 1 km height is indicated by a horizontal dashed line.

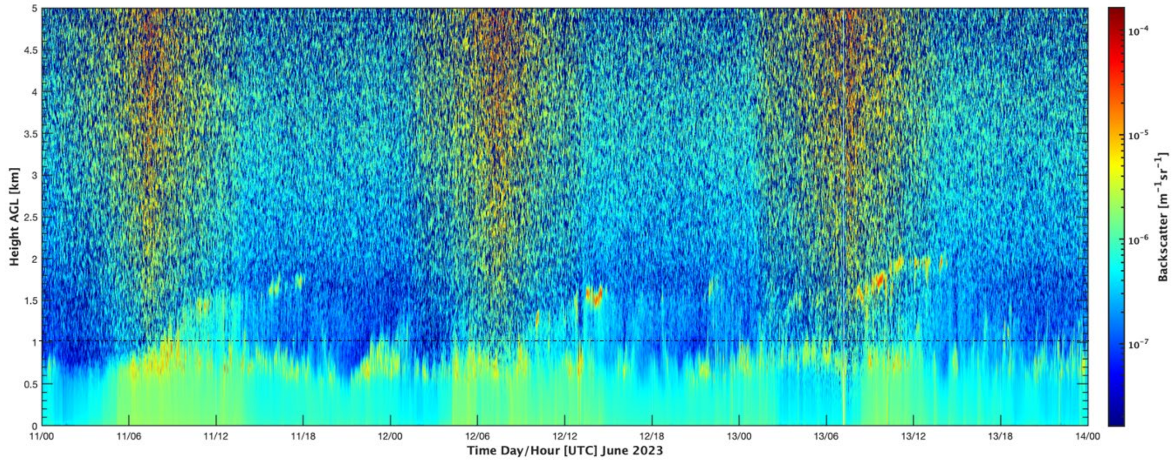


Figure 9: Backscatter data for 11, 12 and 13 June, with larger maximum boundary layer heights

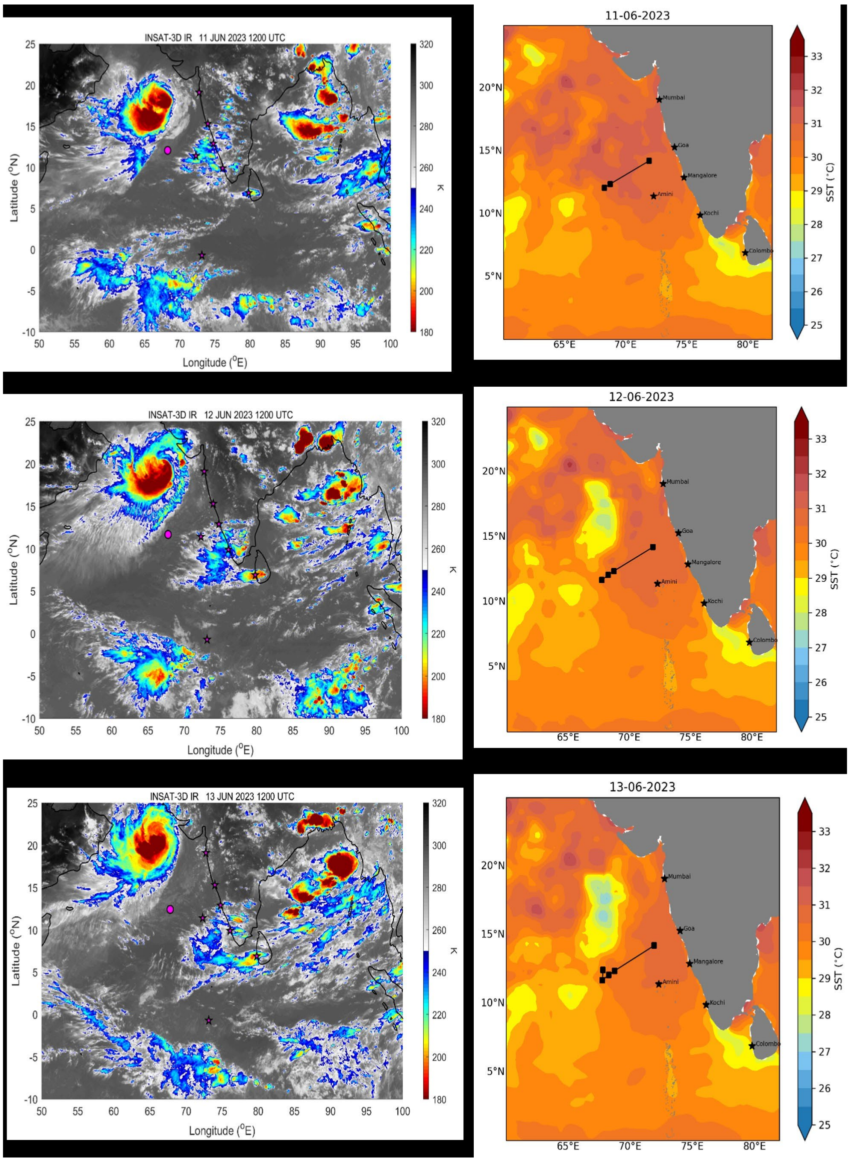


Figure 1: Satellite infra-red (IR) and sea-surface temperature (SST) data for the Eastern Arabian Sea, during 11-13 June. (a) INSAT IR Data, (b) SST data. In IR images, the daily-averaged ship location is shown by a purple dot. The ship track is indicated on the SST maps.

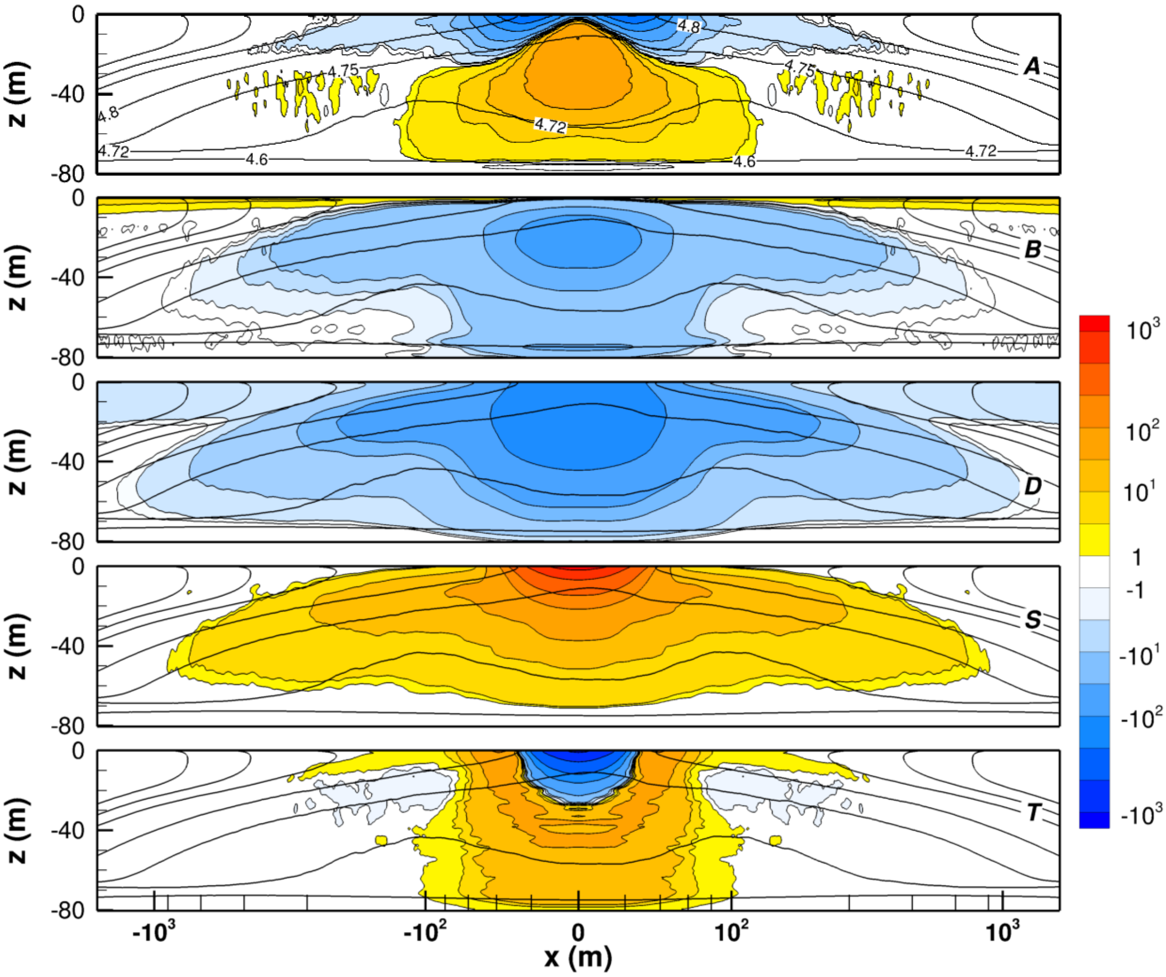


Figure 11: Spatial variation of the terms in the TKE balance in an x-z plane from a simulation with a strong filament: advection A, buoyancy B, dissipation D, shear production S, and turbulent transport T, are shown in panels top to bottom, respectively, at the time of peak frontogenesis. All terms are normalized by appropriate scaling parameters. The heavy contour lines in each panel are the mean thermal structure.

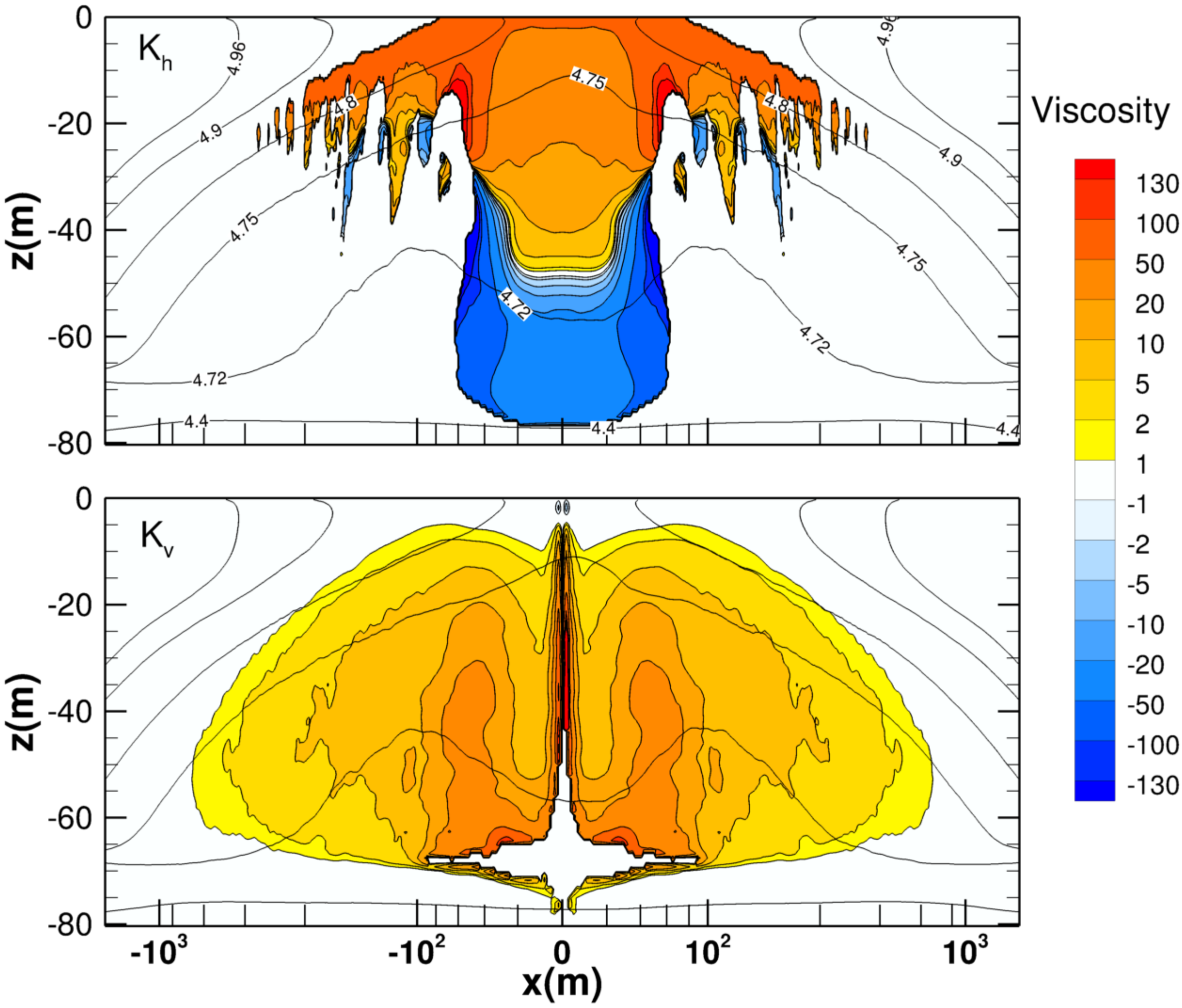


Figure 12: Horizontal and vertical eddy viscosities K_h and K_v for the mean flow from the simulation with a strong filament at the time of peak frontogenesis. The horizontal Viscosity K_h is computed from the horizontal fluxes and horizontal shear (upper panel), and the vertical eddy viscosity K_v is computed from vertical fluxes and vertical shear (lower panel). Appropriate normalizations have been applied to viscosities. The panels are overlayed with identical line contours of the mean thermal structure, as in Figure 11.

Figure 13: Notre Dame EKAMSAT/ ASTraL Pilot 2023 participants

Figure 14: UND Group developed a flux-sensing package for the ship bow mast under the guidance of Physical Science Laboratory Personnel at NOAA