



**Ninth Kumari L. A. Meera Memorial Lecture**

***The Indian Summer Monsoon and  
the Waters around India***

by

**S. R. Shetye**

National Institute of Oceanography  
Dana Paula. Goa

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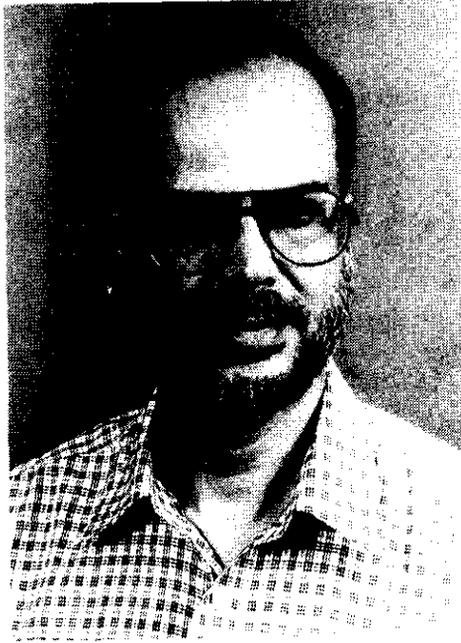
**Kumari L. A. Meera Memorial Trust**  
Palghat, Kerala



**KUMARI L. A. MEERA**  
(1961 - 1985)

Kumari L. A. Meera, the youngest daughter of Mr. and Mrs. L. K. Ananthakrishnan, was born on June 1st. 1961, in New Delhi. Her academic career was uniformly brilliant with a distinction at the higher secondary level and a University rank in the B.Sc. (Honours) examination in Physics, from St. Stephens College, Delhi. After again obtaining a rank in her MSc., which was at the Indian Institute of Technology in Madras, she took up a Masters programme in Computer Science at the same institution with a view to preparing herself for the emerging applications of this area to physics. She was strongly oriented towards research, having attended summer schools at the Indian Institute of Science and the Tata Institute of Fundamental Research. Her teachers and colleagues recognised her promise and motivation and confidently expected an outstanding career in research. Her personality was warm and friendly with a strong streak of hard work, determination, and helping others. These characteristics endeared her to those who knew her.

She joined the University of Pennsylvania in Philadelphia in September 1985 for doctoral studies in physics. But in November of the same year, her bright career was tragically cut short by her untimely death.



SATISH RAMNATH SHETYE

Dr. Satish R. Shetye was born in Panaji, Goa, on 25 October 1950. He took his M.Sc. (Physics) from the Indian Institute of Technology, Powai, and Ph.D. in Physical Oceanography from the University of Washington, Seattle, USA. Since 1982 he has been at the National Institute of Oceanography, Goa, where he studies different issues related to dynamics of the waters around India. He played an important role in identifying the relationship between monsoon winds and surface currents in the North Indian Ocean. Other areas of his interest include: tides along the coast of India, dynamics of estuaries, and interaction between the Indian Summer Monsoon and the Indian Ocean. Dr. Shetye received Shanti Swarup Bhatnagar Prize in 1992 and New Millennium Science Medal, Indian Science Congress, in 2000. He is a Fellow of the Indian Academy of Sciences and Indian National Science Academy.

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## **The Indian Summer Monsoon and the Waters around India**

by

**Satish R. Shetye**

*The Indian Summer Monsoon (ISM) represents migration of the rain-bearing Equatorial Trough (ET) to the Indian subcontinent and the surrounding waters. Interaction between the ET and the seas around India is important to sustain activity of the /SM. Sea surface temperature, determined by processes both in the atmosphere and the ocean, is an important intermediary in the interaction. Winds set up by the /and-sea heating-contrast between the Asian /and mass and waters of the North Indian Ocean cool the western Arabian Sea, leaving it incapable of sustaining any large-scale atmospheric convection and precipitation. This helps in making the Bay of Bengal the most important centre of. ISM activity. The precipitation associated with the activity keeps the upper layer of the Bay highly stable and warm throughout the /SM. The warm waters in turn sustain events that bring rain not only to the Bay, but a/so to the Indian subcontinent, where they are crucial for sustaining life.*

### **1. Introduction**

One of the familiar diagrams in school text books is a global perspective on structure of surface winds (Fig. 1). Though this structure must have been known for a long time, one of the first to attempt to understand its dynamics was George Hadley, a Briton. In 1735 he proposed a scheme for global atmospheric circulation that was similar to the one depicted in Fig. 1. An important assertion in his writings was that trade winds converge leading to formation of a region of ascent of air at the equator (belt marked "doldrums" in Fig. 1) and a region of descent farther away. The trades and the regions of ascent/descent form a system called the Hadley cells.

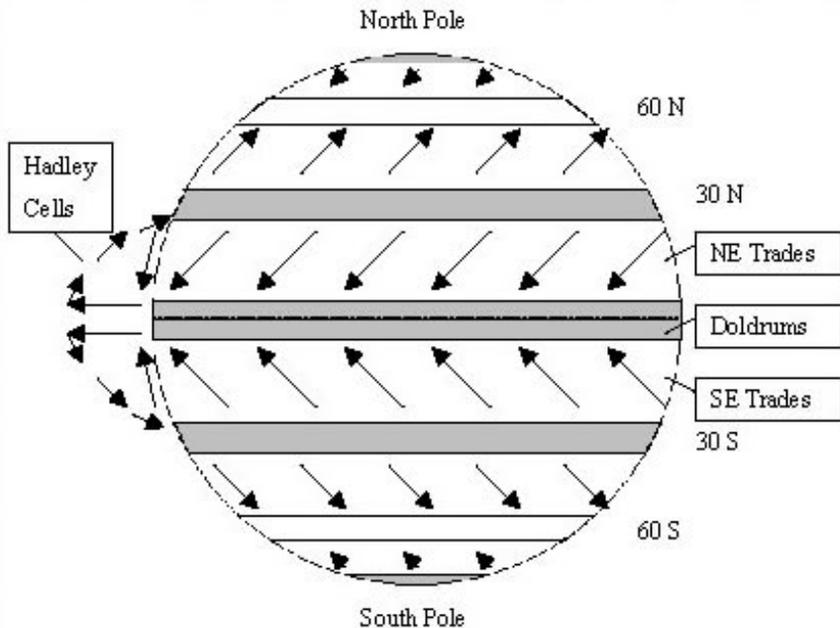


Fig. 1. Surface winds, pressure belts, and Hadley Cells.

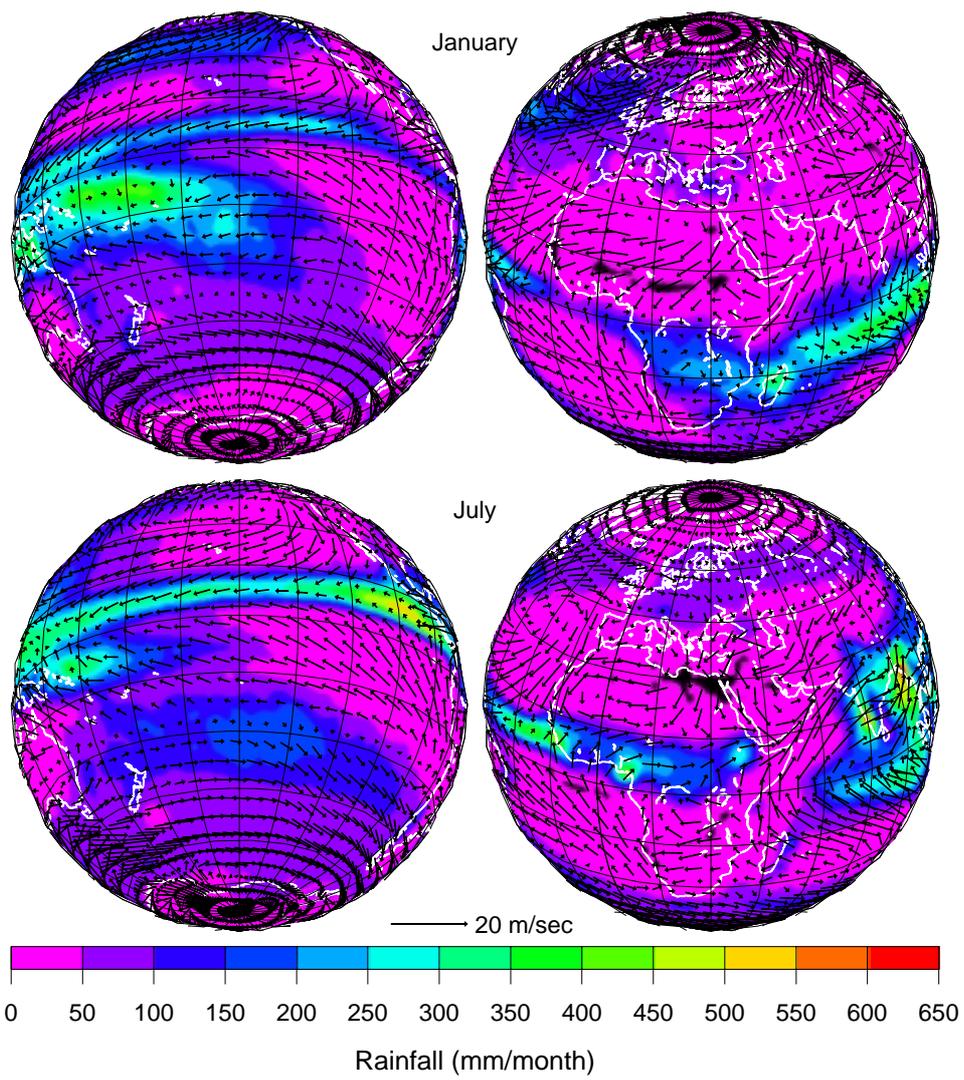
Over the last century there has been remarkable improvement in our ability both to observe the earth's atmosphere (using satellites, for example) and to understand it. The latter has particularly benefited from construction of mathematical models that can now be studied using computers. The new observations are largely consistent with the idea that there is a region of ascent between the belts of trade winds, as Hadley had noted. The region, however, exhibits considerable spatial and temporal variability that earlier scientists would not have been able to document.

In this talk I will examine how this region of ascent and the accompanying winds evolve during a typical year and the role that the seas around India play in this evolution over the Indian subcontinent and the surrounding waters. This exercise gives us important clues on how the seas around India and the Indian Summer Monsoon (ISM) interact.

## 2. The trades and the Equatorial Trough (ET)

The word “tropic” is derived from a Greek word meaning turning. As seen in Fig. 1, at the Tropic of Cancer and the Tropic of Capricorn winds turn and change their directions. Between the Tropics sit the “tropics”, the region that has been found to be dynamically distinctly different from the sub-tropics. As pointed out by Herbert Riehl in his delightful book “Climate and Weather in the Tropics” (1979), the source of all momentum and most heat for the engine we call the atmosphere are the tropics. The processes of this engine that we are interested in take place in a layer that is approximately 16 km in height (a typical commercial jet airliner cruises at an altitude of about 10 km). Comparing this with circumference of the earth (approximately 40,000 km), we realize that the atmosphere is a rather strange fluid: a “thin” layer of gas, on a rotating platform. The gas is held in place by the gravitational pull of the earth, and set into motion by heating, the heat energy being ultimately derived from the Sun. Our day-to-day experience fails to appreciate how different the rules governing the motion in the atmosphere are. It is important therefore to get a feel for how the atmosphere behaves, leaving the question “why” for later.

Observations have repeatedly shown that the region of the doldrums (Fig. 1), i.e. the region of ascent that Hadley identified is also the region of high precipitation. The region has been described by different names, the two popular versions being the Equatorial Trough (ET), and the Inter Tropical Convergence Zone (ITCZ). Following Riehl, we will use ET. The air of the tropics, particularly that over the oceans, is moisture laden because the temperatures here are warm and can therefore retain moisture. When the moist air rises in the ET, some of the moisture condenses out as precipitation. Hence the ET is a belt of high precipitation. The condensation is accompanied by release of latent heat, which then warms the surrounding air. The warming makes the air lighter and leads to a drop in pressure in the water column below the warm region. The low pressure in turn leads to convergence of air from the surroundings, encouraging further ascent of air and condensation. The net result is that the ET forms a complex chaotic regime with rain-bearing clouds, high precipitation and ascent of air. On the two sides of the ET lie the



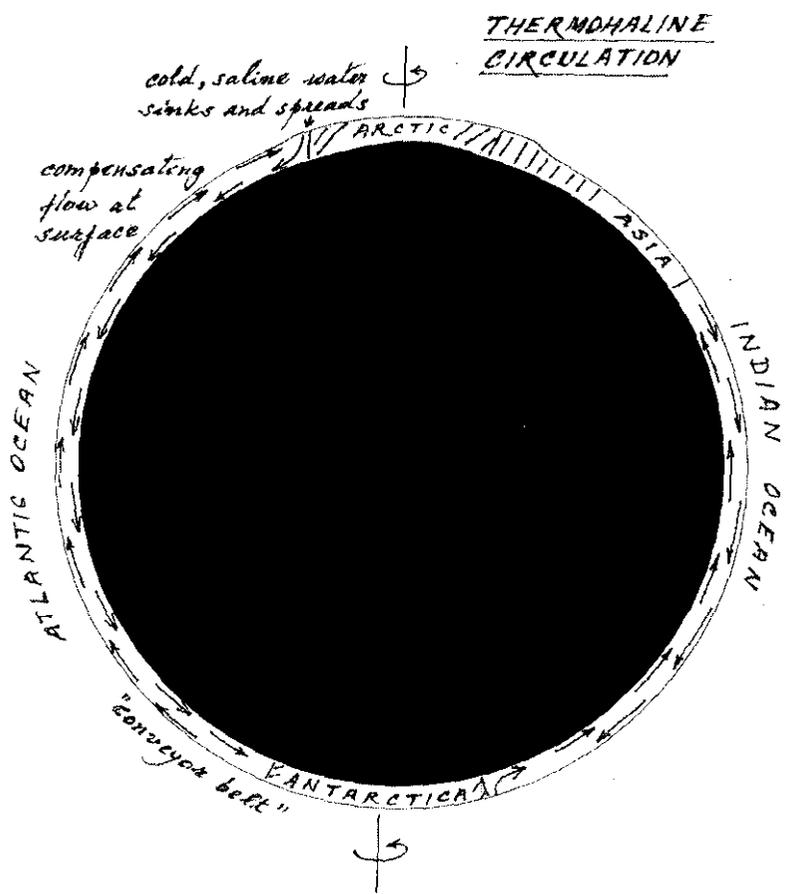


Fig. 3. Schematic representation of global thermohaline circulation.

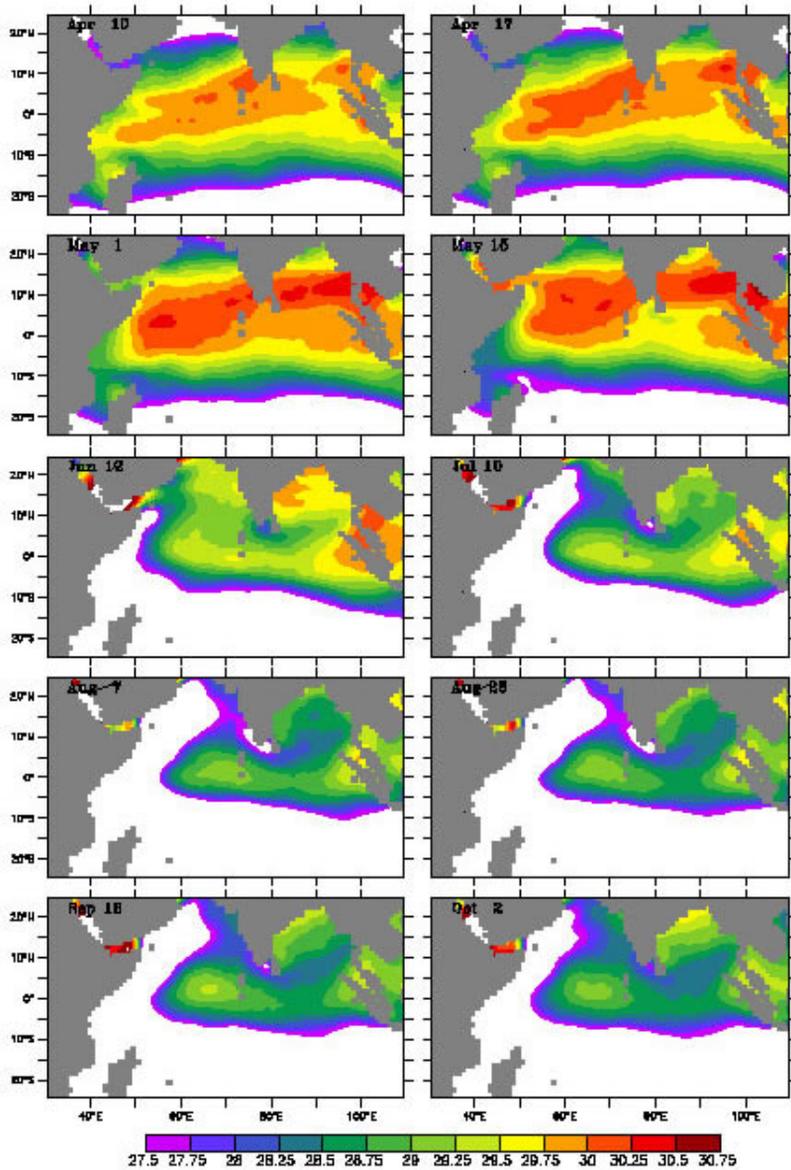


Fig. 4. Evolution of climatological weekly sea surface temperature during April-October. Temperatures less than 27.5 C are shown in white; the colour palette for higher temperatures is at the bottom.

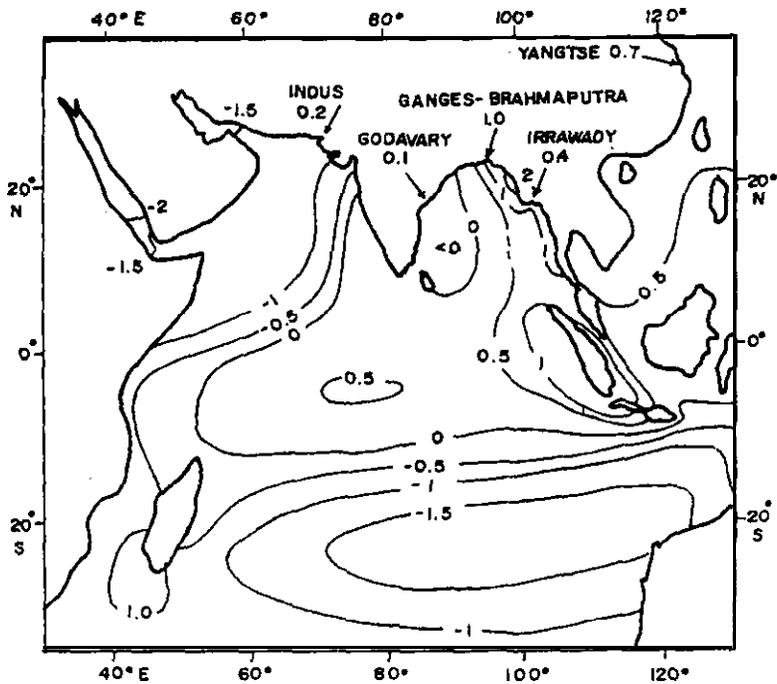


Fig. 5. Field of precipitation minus evaporation and runoff from major rivers in the North Indian Ocean. The contours show precipitation minus evaporation in units of m/year. Location of a point of discharge from a major river is shown with an arrow. The number next to a river's name gives its discharge in trillion cubic metres per year

belts of trade winds. This structure is more complex than that depicted in Fig. 1. Fig. 2 shows what the pattern of monthly-mean climatology of precipitation and surface winds based on modern data sets. Following are some of the observed features of the ET and the trades:

- (1) The ET forms more or less a continuous belt that girdles the globe. It shuns the equator, but stays within the tropics.
- (2) Along with the belts of trade winds, the ET migrates seasonally. During southern (northern) summer it reaches its southernmost (northernmost) location.
- (3) The ET has a complex structure. Embedded in it are intense convective systems, including cyclones and other atmospheric disturbances. One can appreciate the complexity of the structure by the satellite pictures of tropical cloud bands often seen in TV weather reports.
- (4) Though seasonal migration of the ET is observed over the Atlantic and the Pacific Oceans too, it is particularly pronounced over the Indian Ocean. Here, during the northern summer the ET becomes a wide band stretching over the eastern Arabian Sea, the Indian subcontinent, the Bay of Bengal, and then merging with the Pacific ET over the maritime continent consisting of Southeast Asia and Indonesia. At this time the precipitation associated with the ET is most pronounced over the Bay of Bengal.
- (5) A conspicuous feature of the ET during the northern summer is its absence over the western Indian Ocean leading to a discontinuity in its structure. The discontinuity forms in June and lasts till about November. Hence there are striking differences in the atmospheric activity exhibited by the two seas on either side of the Indian subcontinent: the Arabian Sea, particularly its western part shows weak activity, whereas the Bay of Bengal remains extremely active throughout the ISM.

The migration of ET as described in (4) above, is what we call the ISM. It is a time of strong winds, intense cloudiness, high precipitation, and generally disturbed atmospheric conditions over the Indian subcontinent and the surrounding waters. When the ET moves in the Indian region, we say the monsoon has set in over India.

It is generally accepted that helping in the large northward migration of the ET over the Indian Ocean is the heating of the land mass of Asia, particularly the elevated area of the Tibetan Plateau, where the area with elevation of 5,000 m or higher exceeds a million square kilometres. The plateau therefore acts as an elevated source of sensible heat. Such high altitude heating is efficient *in* setting up a circulation *in* which air rises up due to heating, and is replaced by air from elsewhere, in a fashion similar to that seen in land- and sea-breeze. It is for this similarity that ISM has often been described as a global scale land-sea breeze. This classical picture of the monsoon, however, misses one important feature of the ISM moist convection and precipitation. To understand the large-scale winds associated with the ISM, the classical land-sea breeze paradigm is fine. But to understand the precipitation associated with the ISM we must examine what happens to the ET once it moves over the seas around India. These seas are an integral part of the global oceans. Hence it is useful to have an overview of the oceans.

### 3. The global oceans and the Seas around India

The earth is almost spherical in shape with about two thirds of the surface covered by oceans. Its radius (~6000 km) is much larger than the average depth of the oceans (~4 km). Thus, the oceans, like the atmosphere, form a system that is rather strange: a thin layer, stretched out on a sphere that rotates. The modern view of the characteristics of the *oceans* began appearing with the *Challenger Expedition* (1872-1876). One of the most valuable data generated by the expedition consisted of vertical profiles of temperature and salinity at stations distributed around the globe. During the last century the number of such profiles increased sharply, and this has helped us to appreciate some important features:

- 1) Most of the ocean is in stable hydrostatic equilibrium (denser waters sit under lighter ones). There are two exceptions. First, there is a shallow (-10-100 m) layer near the ocean surface that is constantly stirred by winds and by heat loss at the surface. Second, in some polar areas, most notably in the North Atlantic and in parts of the seas around Antarctica, intense cooling at the surface owing to contact with cold air leads to the formation of dense waters that sink to great depths. Both these areas exhibit predominantly turbulent motions.
- 2) The density at any location in the stably-stratified areas is determined by: temperature, salinity (generally expressed as parts per thousand, ppt, by weight of dissolved salts), and pressure at the location. The ranges of these variables are: temperature  $\sim 0-30^{\circ}\text{C}$ ; salinity  $\sim 30-36$  ppt; pressure  $\sim 0-4000$  decibars (about 400 times the atmospheric pressure). Taking these variations into account, the range of density seen in the oceans is  $\sim 1.020-1.030$  gm/cm<sup>3</sup>, i.e. the variation in density is a small fraction of the mean density.
- 3) The most important factor that determines the characteristics of this stratification is the global-scale "thermohaline circulation." The temperature and salinity at a location at surface of the ocean is determined by local air-sea exchange of heat and freshwater: salinity is low at places that receive high rainfall; temperatures are lower where loss of heat to the atmosphere is higher. Turbulent mixing in the oceans is weak enough that once a parcel of water leaves the surface and moves at subsurface levels, it retains its identity over long distances (thousands of kilometres). Sinking and spreading of denser water formed in polar areas can be traced over the entire ocean basin of the earth. The circulation associated with this motion is called the thermohaline circulation.
- 4) When compared to the scales we are used to in day-to-day life, the scales associated with thermohaline circulation are unusual: length scale  $\sim 10,000$  km; horizontal velocity  $\sim 0.1 - 1.0$  cm/sec; time scale  $\sim 100 - 1,000$  years.

- 5) Deep water does not form in the North Pacific because high precipitation keeps surface density low enough to prevent surface cooling from forming dense deep waters. The thermohaline circulation is closely linked with the Earth's climate, and it is the primary circulation that determines the characteristics of vertical profiles of temperature and salinity at any location, including those in the seas around India.

The characteristics of vertical profiles of temperature and salinity in the Arabian Sea and the Bay of Bengal are thus determined largely by events that occurred elsewhere quite some distance away, and perhaps a few centuries ago. However, temperature and salinity near the top ten percent of a water column are strongly influenced by events local in space and time. It is these changes that are important in determining how the atmosphere will interact with the ocean on time-scales ranging from hours to months. For our discussion the most important characteristic that is determined locally is near-surface salinity. It is much lower in the Bay of Bengal than in the Arabian Sea. In fact, surface salinity in the Bay is one of the lowest found anywhere in the world. This difference in salinity between Arabian Sea and the Bay of Bengal arises primarily owing to differences in precipitation and evaporation in the two basins. The Bay of Bengal experiences one of the largest inputs of freshwater anywhere in the world. This reduces the surface salinity. We shall see in the next two sections that there exists, at least in part, a positive feedback between the strength of the monsoon activity over the Bay and the low salinities there.

#### 4. The ET and the seas around India

The first clue that the seas around India may be playing a critical role to sustain the convection associated with the ET during the ISM came from studies carried out in Bangalore. In 1984 studies at the Indian Institute of Science by Sulochana Gadgil, P.V. Joseph, and Niranjana Joshi showed that for the ET to exhibit large-scale convection over the seas, the sea surface temperature (SST) has to exceed a critical temperature of approximately 28°C. In 1987 N. Graham and T. Barnett generalized this result to

include the entire tropical belt. Note that these findings say that SST  $> 28^{\circ}\text{C}$  is a necessary condition to sustain convection; they don't spell out what the sufficient conditions are. This is still an unanswered question.

The critical role bestowed on the SST for making convection in the atmosphere possible has its roots in the thermodynamics of moist air. SST determines how much moisture can become available under given conditions of wind flow. Small changes in the availability of moisture can have a big impact on atmospheric dynamics because when the moisture condenses on reaching a height of about a kilometre, the heat released has important implications. In essence, thermodynamics of moist air dominates other processes, and SST by influencing the rate of evaporation, plays an important role.

As seen in Fig. 4, the SST in the Arabian Sea is distinctly lower than that in the Bay of Bengal. More important is the fact that the entire western Arabian Sea has SST less than  $28^{\circ}\text{C}$ , i.e. it is too low to sustain deep convection. No wonder therefore, that the only discontinuity anywhere in the precipitation belt in Fig. 2 occurs over the Arabian Sea. Why is there this difference in SST between the two seas adjoining India? In the next section we will examine their heat budgets to address this question.

## **5. Heat budgets of the seas around India**

Circulation in the ocean up to a depth of about 500 m is driven by the stress exerted by winds. In the Arabian Sea the nature of winds is such that a strong jet, called the Findlater Jet occurs along the western boundary of the basin (Fig. 2). The jet forms because the East African mountains block winds from moving farther west over the African continent. The winds then turn northward forming the jet. The stress (proportional to square of wind speed) exerted by the winds of the jet have a profound impact on the Arabian Sea circulation. They form an important driving mechanism for the strong seasonal coastal current, the Somali Current, whose seasonality is a unique feature of the horizontal circulation in the basin. More importantly, the winds of the jet induce strong upward velocity (or upwelling) along the western boundary of the basin, which brings colder and deeper

waters of the basin to the surface. Downwelling, i.e. downward vertical velocity elsewhere in the basin must accompany such upwelling. The resulting vertical circulation helps to spread the heat in the surface layer to a depth of a few hundred meters. Winds over the Bay of Bengal are much weaker. As a result, the strength of the vertical circulation too is weaker. This helps to keep the heat gained across the air-sea interface close to the surface.

There is another factor that discourages transfer of heat to deeper layers in the Bay of Bengal: stratification. As pointed out earlier, the Bay receives a large amount of freshwater in the form of precipitation and runoff from rivers discharging into the Bay (Fig. 5). The amount of freshwater received by the Bay from the two sources is approximately 4 trillion cubic metres per year. If spread out over the area of the Bay north of 6 N, it would form a layer about a metre and half thick. It mixes with the underlying *water*, leading to a strong density gradient near the ocean surface. It is difficult to mix heat downward across strong gradients of density. In essence, the density gradient forms a “cap” that prevents heat from penetrating to layers below about 75 m. In contrast, the Arabian Sea is a region of net loss of freshwater. There is no layer that acts as a cap, making it easy to mix the heat downward.

Hence two factors help to restrict heat received across the air-sea interface to a region close to the surface in the Bay: weak vertical circulation and strong stratification. The net result of these differences is that the Bay stays much warmer than the Arabian Sea. The warm waters of the Bay make it more likely to have the ET hang over it.

The precipitation associated with the ET over the Bay often spreads to areas towards the west and the northwest. This generally takes place in two forms. The first is as atmospheric currents that transport moisture that ultimately precipitates. This type of precipitation is often found along the foothills of Himalayas and on the Gangetic Plain south of the foothills. The other mode of transport is in the form of atmospheric disturbances – depressions, cyclones, etc. -that originate over the Bay and then propagate westward or northwestward bringing precipitation along the path followed by a disturbance. Both these modes are critical

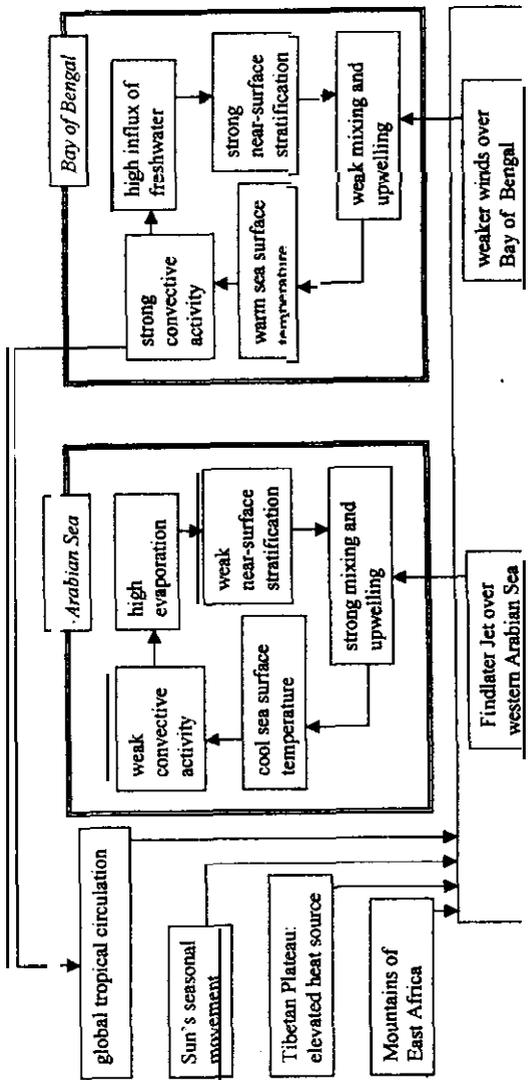


Fig. 6. The array of processes that link the ISM to the waters around India.

to bring rain to the Indian subcontinent. Without them, the availability of freshwater would have suffered immensely.

## **6. Concluding comments**

By staying warm, the Bay plays a critical role in making India habitable. We conclude this talk with a diagram (Fig. 6) that summarizes the many elements that cooperate to make the ISM happen. An interesting feature of the series of processes we have examined is positive feedback. Over the Bay of Bengal it acts as follows. A warm Bay sustains high convective activity in the atmosphere; this leads to high precipitation and runoff; this ensures that the near surface regime of the Bay is well stratified; this ensures that the Bay remains warm. Another positive feedback occurs over the Arabian Sea, but acts in the opposite direction.

It is important to note that though the processes summarized in Fig. 6 by themselves make a rather complex system, there are other processes that are important in the ISM phenomenon. Prominent amongst these are: role of the El Nino in the Pacific; contribution of the subtropical system; influence of the dynamics of the upper atmosphere. Indeed, the ISM is a complex system. It is truly a wonder of nature that such a complex system self regulates to produce precipitation with a regularity that has permitted life to not only survive, but even to thrive, in the Indian subcontinent.

We live in an age that offers new opportunities to study complex natural systems. New advances in the field of computers, and new thinking in physics (nonlinear dynamical systems, for example) offer new prospects to examine old problems with new insights. Kumari Meera, after whom this Lecture Series is named, studied the very topics that bear the new promise: physics and computers. I would like to conclude this talk by paying my respects to her. I never met her, but whatever little I have come to know about her brings into focus India's greatest resource: brilliant youth charged with enthusiasm to take on new sciences and technologies. It is a pity that Meera did not live -to practice the profession of her choice. I thank the Kumari L.A. Meera Memorial Trust for giving me this opportunity to share my thoughts.

## **KUMARI L. A. MEERA MEMORIAL TRUST**

(Reg. No. 239 of 288.1989)

The Kumari L. A. Meera Memorial Trust was established on 28.8.1989 by Mr. L. K. Ananthkrishnan in Palghat, Kerala State in memory of his daughter, Kumari L. A. Meera. The Trust is dedicated to the service of mankind, with a wide range of activities in the fields of Physics, Mathematics and Computer Science besides Anthropology, and welfare and charitable activities. The Trust is managed by a Board of Trustees, the Managing Trustee being Mr. Ananthkrishnan until his demise in March 1998. The present Managing Trustee is Prof. V. Balakrishnan.

The main focus of the Trust is to foster scientific interaction and activity in the fields of Physics, Mathematics and Computer Science in various scientific institutions, and encourage scientific education and advanced scientific research in these and interface areas by providing scholarships/stipends/awards for meritorious and deserving students. The Trust is committed to the development of excellence in Physics, Mathematics and Computer Science. It has instituted awards and scholarships in memory of Meera in several schools and colleges and has provided financial grants for upgradation of library, laboratory and computer facilities in a number of institutions in India. In addition it assists in the promotion of Sanskrit and traditional cultural values.

The Trust has instituted awards and prizes for the encouragement of excellence in Physics in the Indian Institute of Technology, Madras, St. Stephen's College, Delhi, the Indian Institute of Science, Bangalore and other educational institutions.

The Trust also organises each year the Kumari L. A. Meera Memorial Meeting on Frontier areas in Physics. The first meeting in the series, on the topic "Geometry and Topology in Physics", was held at Dhvanyaloka, Mysore from February 8 to 14, 1996. The second meeting, on "Chaos, Complexity and Information" was held from February 1 to 7, 1997; the third on "Optics: Modern Trends" from January 31 to February 5, 1998; the fourth on "Probability and Physics" from January 25 to January 30, 1999; and the fifth on "Soft Condensed Matter" from January 27 to February 2, 2000; all at the same venue.

## The Kumari L. A. Meera Memorial Lectures

- N. Mukunda - *'The Task of Picturing Reality'* (1990)
- V. Radhakrishnan - *'Flying s/owly'* (1993)
- G. Venkataraman - *'Parallel Computers'* (1994)
- V. S. Ramamurthy - *'Molecules to Materials - The novel transition domain of Clusters and Nano Structures'* (1995)
- J. V. Narlikar *'Myths, Beliefs and Facts in Astronomy'* **(1996)**
- D. Balasubramanian - *'Expanding Visions of the New Biology'* (1997)
- S. Ramanan - *'The Role of Groups in Arts and Sciences'* (1998)
- R. Rajaraman - *'Can Relativity and Quantum Mechanics Co-exist?'* (1999)

## Special Kumari L. A. Meera Memorial Lectures

- R. Chidambaram - *'Nuclear Energy and Safety'* (1996)
- D. D. Bhawalkar - *'Laser Applications in Medicine'* **(1998)**

## Sri L. K. Ananthakrishnan Memorial Lectures

- V. Rajaraman - *'Video on Demand'* (1999)