Lecture – 34
Interannual variation of the Indian Summer Monsoon rainfall: Links to events over the Pacific and Equatorial Indian Ocean
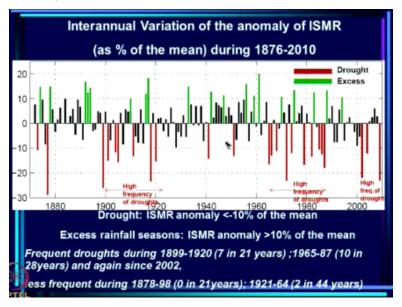
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Today, I am going to talk about the year to year or the interannual variation of the Indian summer monsoon rainfall, particular focus on links of this variation to events over the Pacific and equatorial Indian Ocean.

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The long term mean of the Indian summer monsoon rainfall (ISMR) is about 85cm. Consider the interannual (year to year) variation of the anomaly (defined as the actual value in any year minus the mean value) of ISMR as a percentage of the mean value during 1876-2010 .

We know that the Indian summer monsoon rainfall or ISMR, the long term average is about 85 cm and the inter annual variation is about inter annual variation, the standard deviation of that is about 10% of this average.

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And what we see here is the inter annual variation of the anomaly of ISMR, which is to say the actual ISMR in any year - the average ISMR, long term mean of ISMR expressed as a percentage of the mean during 1876 to 2010 for which data are available. Now, this is something we have seen before and as you can recall, we define extremes as those years in which anomaly of ISMR has magnitude more than 10% or more than one standard deviation.

So, if there is a deficit larger than one standard deviation or more than 10%, it is a drought, if the ISMR is above average and the anomaly is greater in magnitude than 10%, then it is an excess rainfall season, so there are extremes which are excess rainfall seasons and droughts and they are; droughts are marked as red, excess rainfall season as green.

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- The standard deviation of the interannual variation of ISMR is about 10% of the mean.
- Summer monsoon seasons with ISMR smaller than 90% of the mean are considered to be droughts and those with ISMR larger than 110% of the mean as excess rainfall seasons.

And this is the variation we have seen, we have also seen that there is a decadal scale variation here with high frequency of droughts in this epochs and again here and relatively few are droughts in this period here. We have seen this as well. Now, as I mentioned before the standard deviation of the inter annual variation of ISMR is about 10% and summer months' seasons with ISMR smaller than 90% of the mean are considered to be drought.

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- The Indian summer monsoon is seen to be rather reliable with a coefficient of variation close to 10% and the maximum observed deficit less than 30% of the mean.
- Although the amplitude of this interannual variation is not very large, the monsoon has a large impact on the food-grain production and a significant impact on the the Gross Domest' Product (GDP), as I shall show ii lecture towards the end of this

And those with ISMR larger than 110% of the mean as excess rainfall seasons. Now, therefore, since the standard deviation is only 10% of the mean, it is very reliable phenomena because the maximum observed deficit is < 30% of the mean, so it comes here after year and there is a variation in the quantum of rainfall received but it is not that great but even though, the amplitude of the inter annual variation is not very large.

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Thus the monsoon continues to govern the very pulse of life in our country. If it turns out to be a `normal' monsoon, as in 2010 , the nation heaves a sigh of relief and carries on with business as usual. If it turns out to be a drought (as in 2009), major drought relief programmes are launched. Thus importance of prediction of ISMR cannot be overemphasized.

It has a very large impact on the food-grain production in GDP. So, the monsoon continues to govern the very pulse of life in our country. If it turns out to be a normal monsoon as in 2010, the nation heaves a sigh of relief and carries on with business as usual. If it turns out to be a drought

as in 2009, major drought relief programmes are launched. Thus, the importance of prediction of ISMR cannot be over emphasised.
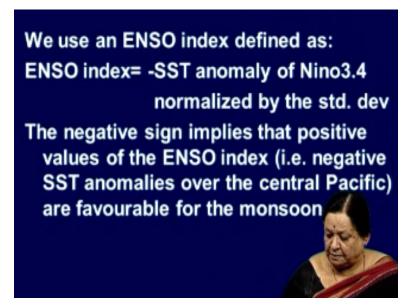
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A major advance in our understanding of the interannual variation of the monsoon occurred in the eighties with the discovery (or rediscovery) of a strong link with ENSO.

Sikka (1980), Pant and Parthasarathy (1981), Rasmusson and Carpenter (1983) etc. have shown that there is an increased propensity of droughts during El Nino and of excess rainfall during La Nina.

So, although the inter annual variation is not large, the amplitude is not large, it is very important to predict it. Now, a major advance in our understanding of the inter annual variation of the monsoon occurred in the 80s with the discovery or rather rediscovery of a strong link with a major phenomenon over the Pacific known as El Nino and Southern oscillation and so.
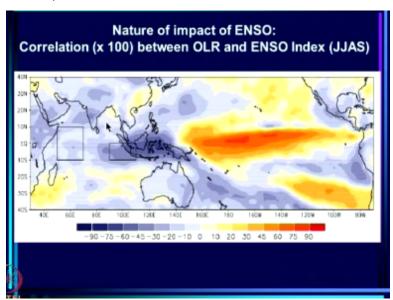
This was in fact; this advance came about by work done in our own country; Sikka 1980, Pant and Parthasarathy 81, followed by Rasmusson and Carpenter from US have shown that there is an increased propensity of droughts during El Nino.

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We use an ENSO index defined as:

ENSO index= -SST anomaly of Nino3.4
normalized by the std. dev

The negative sign implies that positive values of the ENSO index (i.e. negative SST anomalies over the central Pacific) are favourable for the monsoon

El Nino is the warm phase of ENSO and the cold phase of ENSO, there is a high propensity of excess rainfall, cold phase being called La Nina. Now, we use an ENSO index defined as ENSO index, which is negative of the SST anomaly of Nino 3.4 normalised by the standard deviation. Now, why the negative sign? So, that positive value of ENSO index which means negative SST anomalies over Central Pacific indicate the occurrence of a La Nina, that is the phase of ENSO, that is favourable for the monsoon.

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Nature of impact of ENSO:
Correlation (x 100) between OLR and ENSO Index (JJAS)

So, positive values of index are favourable for the monsoon. Now, what is the nature of impact of ENSO on the monsoon? The easiest way to see it, is actually by looking at the correlation of ENSO index, which we have defined with the OLR over the entire tropical region here. So, what

you find is over the Indo Pacific region is shown here, what you find is a; of course, this is the signal of ENSO.

And this means, this is the correlation of OLR is positive here, which means this is representing if you wish La Nina condition and this implies that everywhere here the sign of OLR anomalies is opposite to what it is over the Central Pacific and so; should we just paused for a minute, I will just switched off this mobile, okay, so what this is saying is, that when there is an El Nino, that is when the OLR anomalies here are negative.

In that case, OLR anomalies everywhere here will be positive, which means that when convection is enhanced here, it is going to be suppressed over the Indian region and also suppressed over the entire Arabian Sea, most of Bay of Bengal as well as the equatorial Indian Ocean. So, impact of El Nino which as you recall, Sikka had shown that in fact, there is a increased propensity of droughts during El Nino.

And so, when you have El Nino, you do expect that if the convection flares up here, it will be suppressed over India, which is what Sikka and others had shown but what this chose that in addition, not only the convection suppressed here but it is also suppressed very much over the eastern equatorial Indian Ocean also suppressed over western equatorial Indian Ocean and Arabian Sea and much of Bay of Bengal.
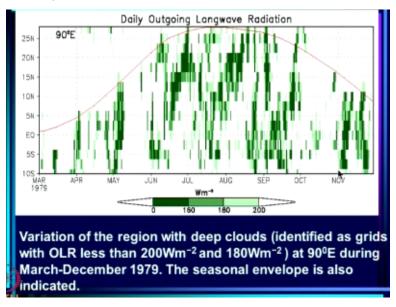
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Implications for the CTCZ and the monsoon

- Consider the implication of the suppression of the convection over the Arabian Sea, Bay of Bengal and the equatorial Indian Ocean, in association with El Nino.
- We have already seen that the onset and retreat phase involve northward propagations from the equatorial Indian Ocean.

So, this is the impact of El Nino on the Indian region. So, what are the implications for the CTCZ and the monsoon? Consider the implication of the suppression of the convection over the Arabian Sea, Bay of Bengal and the equatorial Indian Ocean in association with El Nino.

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Variation of the region with deep clouds (identified as grids with OLR less than 200Wm^{-2} and 180Wm^{-2}) at 90^{0}E during March-December 1979. The seasonal envelope is also indicated.

Now, we have already seen that the onset and the retreat phase of the monsoon involve northward propagations, so you remember this is an envelope of low LR region or the convection region at 90 degrees east and from March till November and what you see is that there is a series of northward propagation, all starting from the equatorial Indian Ocean and culminating somewhere near the red line which is the envelope.

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Spring to summer transition

- The northward shift of the TCZ from its mean location near 5^0N in April- May to 20^0N is July-August is accomplished by successive generation of northward moving epochs over the equatorial region.

And this is the onset phase of the monsoon ultimately, this is an established phase, July, August and this is the retreat phase and we have noted that both the onset and the retreat involve genesis of bands over the equatorial Indian Ocean and northward propagation. So, spring to summer transition which is a northward shift of the TCZ from its main location near 5 degree north in April, May to 20 degree north in July, August is accomplished by successive generation of northward epochs over the equatorial region.
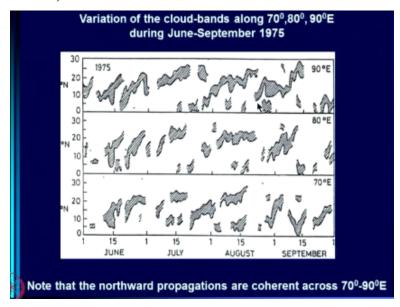
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Summer to Autumn transition

Note that, this transition also comprises northward moving epochs, just like the spring to summer transition, and not southward moving ones as would be expected from the monthly location of the TCZ.
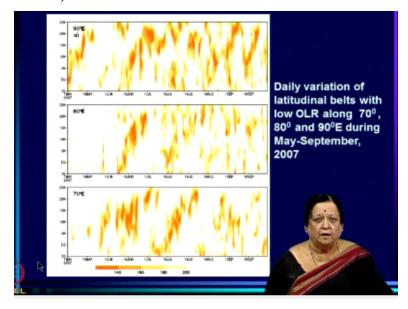
Summer to autumn transition again, as we noticed here even during summer to autumn, when on the monthly scale you see a southward movement of the envelope, it is accomplished again by northward propagations of band generated over the equatorial Indian Ocean, so genesis over

equatorial Indian Ocean and propagation northward contributes a great deal to both the spring to summer transition as well as summer to autumn transition.

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Variation of the cloud-bands along $70^0, 80^0, 90^0 E$ during June-September 1975

Note that the northward propagations are coherent across 70^0-$90^0 E$

So, summer to autumn transition also comprises northward moving epochs, just like spring to summer transition and north southward moving epochs as we would have taught. So, there are the; this is the onset, this is 75, this is at 70 degrees over the Arabian Sea and a part of India 80 degree central longitude of India, 90 degrees is across the Bay going partly through Calcutta. So, what we see is that very coherent northward propagations which occur during the transitions here.

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Daily variation of latitudinal belts with low OLR along 70^0, 80^0 and $90^0 E$ during May-September, 2007

But which also seen in July, August, so these northward propagations are the prominent feature throughout the monsoon season. This is the same picture for 2007, this is again with OLR and what you see is very prominent northward propagation which is coherent across 70, 80 and 90 and several of them occurring through the monsoon season from April to November shown here.

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- Sikka and Gadgil (1980) showed that the convective days associated with the CTCZ over the monsoon zone in July-August are dominated by epochs generated over the equatorial Indian Ocean which move northward.
- Hence the contribution of northward moving epochs of the oceanic TCZ to the maintenance of the CTCZ is substantive.

So, now we have seen that in the transition seasons, these northward propagations are very important. Sikka and Gadgil also showed that the convective days associated with the CTCZ over the monsoon zone in July-August are dominated by epochs generated over the equatorial Indian Ocean which move northward, so they have quantified the contribution of these northward moving epochs to the maintenance of the CTCZ over the Indian region and show it to be a very large fraction.

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- Northward propagations of the TCZ are generated over the equatorial Indian Ocean and generally involve northward propagations of the synoptic scale systems over the Arabian Sea and the Bay of Bengal.
- We thus expect the variability of the CTCZ on different scales to be linked to the variability of convection over the equatorial Indian Ocean, Bay of B___ and the Arabian Sea.

So, the contribution of northward moving epochs of the oceanic TCZ to the maintenance of the CTCZ is substantive. Now, northward propagation of the TCZ are generated over the equatorial Indian Ocean and generally involve northward propagations of the synoptic scale systems over the Arabian Sea and Bay of Bengal. Therefore, we expect the variability of the CTCZ on different scales to be linked to the variability of convection over the equatorial Indian Ocean, Bay of Bengal as well as Arabian Sea.

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- We have noted that the relationship between the CTCZ and the TCZ over the equatorial Indian Ocean is complex.
- While the oceanic TCZ contributes towards maintaining the CTCZ with northward propagations, it also competes with the CTCZ with active spells of one generally coinciding with the weak spells of the other.

So, the surrounding seas are all going to be involved in determining the variability of the band over India the CTCZ. Now it must be borne in mind so far, we are saying that these oceanic TCZ is very good because it contributes to the maintenance of CTCZ via northward propagation but
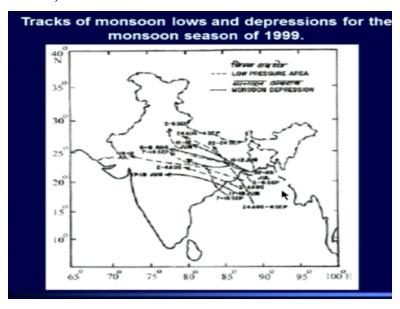
you know the relationship is complex as we have noted before and while the oceanic TCZ contributes towards maintaining the CTCZ with northward propagation.

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- Synoptic systems generated over the Bay of Bengal which move westward onto the Indian region also contribute significantly to the maintenance of the CTCZ.
- An example is the systems of the summer monsoon of 1999 (next slide)

It also competes with the CTCZ because you have 2 tropical convergence zone over the same longitudinal belt, each can suppress the other and therefore generally weak spells of one coincide with active spells of the other, so there is not only contribution of oceanic TCZ to maintaining CTCZ, oceanic TCZ also competes with the CTCZ. Now, so we have seen that as far as the oceanic TCZ is concerned and as far as convection over Bay and Arabian Sea are concern, which are all involved in northward propagation.

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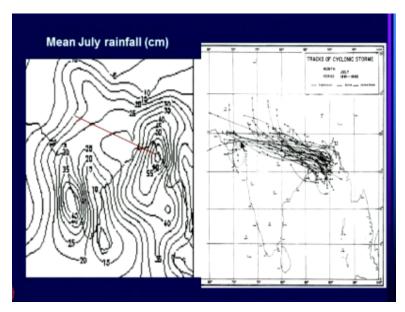Tracks of monsoon lows and depressions for the monsoon season of 1999.

Certainly, the variability of convection over these regions will be related to the variability of CTCZ will contribute to the variation of CTCZ. We have also seen that apart from these northward propagations, CTCZ is maintain by synoptic scale disturbances generated over the Bay which more westward onto the Indian region and an example is, what we have seen before 1999, when we saw so many systems, lows, depressions and so on.

Actually, get generated over the Bay and move across here, so this is a typical example of a year in which you had several systems move across and this is of course, the monsoon zone and this is where the CTCZ is. So, the maintenance of the CTCZ by these systems is very clear from this.

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- The tracks of all cyclonic storms (i.e. depressions, cyclonic storms and severe cyclonic storms for July from 1891-1960 (next slide) are seen to be along the monsoon zone.
- Thus a large fraction of the large scale monsoon rainfall associated with the CTCZ is associated with the embedded cyclonic systems.

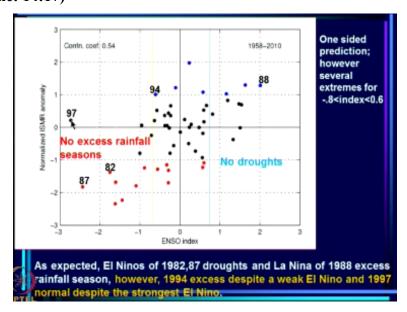**(Refer Slide Time: 13:25)**

Mean July rainfall (cm)

In fact, the tracks of all cyclonic storms for July, this is over a very large period of almost 100 years and what it shows is that in fact, all the tracks are along the monsoon zone along where the rainfall is non orographic rainfall, so these synoptic scale systems also contribute to the monsoon rainfall, so the variation of monsoon rainfall will naturally depend also on convection over the head Bay region particularly.

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- In view of the critical role of convective systems generated over the surrounding ocean/seas in the monsoon rainfall over the Indian subcontinent, it is not surprising that the suppression of convection over these oceanic regions during El Nino is associated with deficit rainfall over the Indian region.

So, all convection over Bay of Bengal, Arabian Sea as well equatorial Indian Ocean all plays a very important role in maintaining the monsoon rainfall over the Indian subcontinent, so it is not surprising that the suppression of convection over these oceanic regions during El Nino is associated with deficit rainfall over the Indian region.

So, now you see, if we plot the normalised ISMR anomaly, this is ISMR anomaly divided by the standard deviation and plotted against the ENSO index, then when ENSO index is negative, remember this is the El Nino condition and this is when there is a higher propensity of droughts, so negative ISMR anomaly means deficit ISMR larger than one in magnitude means, these are all droughts.

All these red dots represent droughts, then of course, ENSO index < -1 means El Nino, but in general, negative ENSO index means unfavourable ENSO, positive ENSO index means favourable ENSO and you can see that many blue dots are in the positive ENSO domain, so you have a higher propensity of excess rainfall years; excess rainfall seasons for which the ISMR anomaly is positive and larger than one.

In the positive ENSO phase and particularly during La Nina, in fact, one can using this graph make a one sided prediction because you know, now it is becoming increasingly possible to predict ENSO because a lot of the ENSO physics has been understood in the 80s and 90s, so models are become pretty good in predicting ENSO, so if you could predict the ENSO index okay and if you knew that it was a < -0.6, that is this line here, then there is no chance at all of excess monsoon years.

You see, there are no blue dots, if ENSO is < -6 and there are no red dots, if ENSO is > +8, so it is -8; sorry this is -8 and +6 and so there are many; most of the droughts are in this reason, most of the excess are here but there are several droughts in the intermediate region also, so we can make one sided prediction saying, if ENSO is in this range, they will not be droughts.

And if ENSO is in this range here up to here, there would not be excess rainfall here but there will be a lot of years here in between, where you will not be able to say anything okay and just wanted to mention that 82 and 87 were very famous El Nino years and as expected they are droughts, 88 was a famous La Nina year and it is an excess rainfall year but note, 97 and 94, we will keep coming back to these.

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- It is seen that when the ENSO index is favourable (>0.6), there are no droughts and when it is unfavourable (< –0.8) there are no excess monsoon seasons. droughts.
- The variation of ISMR for the favourable (La Nina), unfavourable (El Nino) and other phases of ENSO during 1871-2002, shown in the next table is consistent with this.

These are 2 years, in which ENSO phase was favourable but still 90; was unfavourable because remembered it is a negative year but 94 was still an excess monsoon year and 97 was normal although, it was the strongest El Nino of the century, so we will come back to these intriguing features. Now, so I have said that it is seen that when the ENSO index is favourable, there are no droughts and when it is unfavourable, there are no excess monsoon season.

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El Nino/La Nina association with all-India summer monsoon rainfall anomalies during 1871-2001

Number of years with …	Deficient monsoon Deficit>10%	Normal monsoon(-ve)	Normal monsoon (+ve)	Excess monsoon excess>10%	Total
El Nino	11	11	4	0	26
La Nina	0	1	9	8	18
Other	11	23	42	11	87
Total	22	35	55	19	131

(after Rupakumar et al 2002)

NOTE:As many droughts with El Nino as without!

The variation of ISMR for the favourable and unfavourable and other phases shown in the next table is consistent with this. So, this is something computed by Rupakumar et al for 1871 to 2001, so these are the number of years with El Nino, La Nina and other years. This is the deficient monsoon, normal monsoon, normal monsoon positive and excess okay. So, deficient monsoon is our droughts.

And you see that of the total number of 26 droughts that occurred, 11 were El Nino years, but of the total number of droughts that occurred which were 22 years only 11 were El Nino, 11 were some other phenomena working, so ENSO alone cannot explain everything, La Nina again there are no droughts associated with La Nina and there are 8 excess monsoon years associated with La Nina but there are other 11 years, which were also excess monsoon years.

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Since one of the major achievements of the past two decades is the ability to predict ENSO, it is possible to use this relationship for inputs into the prediction of ISMR. We consider five categories of ISMR such that all are equally probable (20% chance) for the observed variation during 1958-2009, viz.

So, droughts are not associated with an El Nino and more than half of La Ninas; sorry more than half of excess monsoon seasons are not associated with La Nina, so there is definitely a relationship between monsoon and ENSO that but it is by no means of one to one relationship. Now, since one of the major achievements of the past 2 decades as I mentioned before is the ability to predict ENSO.

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large deficit: ISMR <75 cm,

deficit rainfall: 75cm<ISMR< 83 cm,
normal rainfall: 83 cm<ISMR< and 86cm
above normal rainfall: 86 cm<ISMR < 91cm
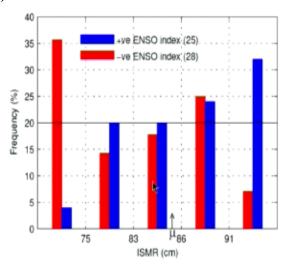large excess: ISMR >91cm.

The chance of occurrence of rainfall in each of these categories when ENSO index is negative or positive is shown in the next slide.

It is possible to use this relationship for inputs into the prediction of ISMR. Now, for this, we consider 5 categories of ISMR such that they are all equally probable, so we take the data in ISMR and divided into 5 categories such that each is likely a 20% of the time, now taking this

observed variation between 58 and 2009. So, what are the 5 categories? These limits are determined by the data itself, data in ISMR; the time series of ISMR.

So, large deficit is < 75 cm, deficit is 75 to 83; normal is 83 to 86, above normal is 86 to 91 and above 91 is large excess or excess years. So, these are 5 categories which we have divided the ISMR into; because climatologically, they are equally likely, each is likely 20% of the time. So, the chance of occurrence of rainfall in each of these categories, how does this probability distribution, which is flat, right, each category chances 20%.

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Frequency of occurrence (as percentage) of different categories of
ISMR for negative and positive ENSO index.

How does it change? If we put in some information of ENSO index and the kind of information we have put in of ENSO index is rather crude, will ENSO index be negative or positive, that is all we are asking. So, blue corresponds to ENSO index negative; I am sorry, positive and negative ENSO index is red okay and what you find is; remember 20% is the climatological probability that is to say, if we had no information other than the historical data set.

Then, we would said all these categories are equally likely, now what happen when we put in the fact that El Ninos is likely to be negative, then immediately, the chance of drought has increased from 20% to 35%, very substantive increase and chance of excess rain has decreased from 20% to < 5%, so the extremes have been very much affected, okay. Although, there will be some, it is not as if there is a zero chance of excess.

There is some chance of excess even during a El Nino years, it is very much smaller than climatological probability and the chance of drought is very much larger than climatological probability, go to the other extreme, if the ENSO index is favourable, then again the chance of excess as increased beyond 20 by more than 10% points, 12 or so. So, again there is an enhancement of probability of excess rain.

And there is a substantive decrease in the probability of drought from 20%, so even if one has some reliable predictions of the sign of the ENSO index during June, July, August, September, we could actually give definite predictions on the probabilities of extremes but note, that as far as non-extremes are concerned, you cannot really say very much because in this case, for example you know the probability is just 20% of excess when El Ninos is positive.

And it is slightly reduced, when ENSO is negative and same thing here, see the difference between positive and negative is not spectacular for the intermediate cases, so important take home lesson is that if one can predict and so, you will be able to say something about how the probabilities of the extremes are going to change from the climatological probability but you will not be able to say much about what happens to years that are in between.
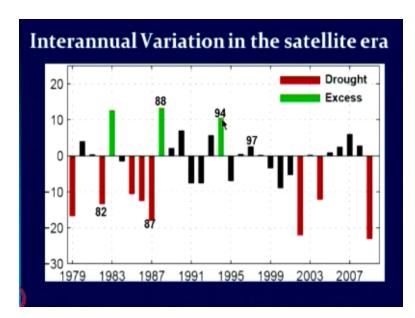
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The 3 categories in between, this is very interesting. So, note that the probabilities substantially different from climatological one for the extremes and we just noted that the probability of a large deficit decreases from 20 to 7% and increases to over 35% for appropriate signs of the ENSO index. So, the probability of large deficit will decrease, when ENSO was favourable to 7% and increased to 35% when ENSO is unfavourable.

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- If we consider the interannual variation of the monsoon since 1980, consistent with the links of the monsoon with ENSO, the El Ninos of 1982 and 1987 were associated with droughts and the La Nina of 1988 with excess rainfall (next two slides).
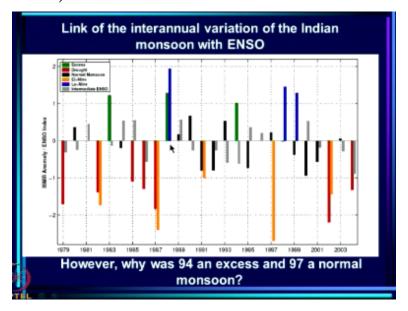
And similarly for the excess, that the probability of large excess will increase to 30% from 20%, when ENSO is favourable and decrease to 4%, when it is unfavourable. So, there is a very clear signal we can get from ENSO. Now, let us consider the interannual variation of the monsoon season since 1980.

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Interannual Variation in the satellite era

And look at it more closely, so this is the inter annual variation from 1980 and these were the 2 years I have pointed out before 82 and 87 and they are in fact, El Nino years and 80 till 88 is a La Nina year okay, but I also pointed out the excess of 94 and the normal of 97.

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Link of the interannual variation of the Indian monsoon with ENSO

However, why was 94 an excess and 97 a normal monsoon?

And what we see here is the link of the inter annual variation of the Indian monsoon with ENSO, so the first one; the first bar tells you what the ENSO index is like, so negative would mean I am sorry; the first bar tells you the ISMR, the second ENSO, so you have in this case 82 and 87, this is 82 and 87, both are; this is 82 and you have very unfavourable ENSO in 82 and 87 years but and you also have an 88 very favourable ENSO here, okay.

So, this is the favourable ENSO giving life to excess rainfall year but then, you have a case in which 1997, where the El Nino was the strongest El Nino of the century so, ENSO was highly unfavourable, we still got very near normal monsoon and in 94, El Nino was not that unfavourable but it was unfavourable, it was a weak El Nino and still we got excess monsoon years.

It turned out that for 14 consecutive years beginning with 1988, there were no droughts; furthermore, during the strongest El Nino event of the century in 1997, the ISMR was higher than the long-term mean (last slide) and Krishna Kumar et al. (1999) suggested that the relationship between the Indian monsoon and ENSO had weakened in the recent decades.

So, these are odd things that we have to understand, the years in which they do not seem to go with ENSO, okay but there are several years that do go with ENSO like 82, 87 and 88, okay. Now, what happen after 88 is that for 14 consecutive years beginning with 1988, there were no droughts and you can see it here. See beginning with 88, there were 14 years from here to here, where there were no droughts at all.

And this despite the fact, that they were weak El Ninos occurring but there were no droughts at all, so furthermore, during the strongest EL Nino event of the century in 97, ISMR was higher than the long term mean, which we noted and Krishna Kumar and other suggested that the link between Indian monsoon and ENSO had weakened in the recent decade. So, they just suggested that look monsoon is no longer responding to El Nino as it was before.

Then came the drought of 2002, which occurred in association with a much weaker El Nino than that of 1997 and

neither the statistical nor the dynamical models could predict it. The experience of 1997 and 2002 suggested that the link with ENSO had yet to be properly understood.

And people took their results seriously but then came a relatively mild El Nino of 2002, which turned out to be a very severe drought and we can see that here, see this is the El Nino of 97 and you can see here, how is the unfavourable ENSO signal was, compared to that, the yellow line here is not so unfavourable and yet while this monsoon was above normal little bit, this monsoon turned out to be a severe drought okay.

More than; deficit was more than 2 standard deviations, more than 20% of the mean, so it was the most severe drought for the period that we have plotted here and so these were; till 97, people thought okay, the link between El Nino and the monsoon seems to have weakened but then came this drought of 2002, which occurred in association with the much weaker El Nino, then that of 97 and neither the statistical nor the dynamical models could predict it.

So, this suggested the experience of 97, which was a strongest El Nino of the century but which had above normal rainfall and 2002, which with a relatively weak El Nino turned out to be a very severe drought, one began to wonder whether one understands completely the link between ENSO and monsoon, given 2002, we could not say that the monsoon ENSO link as weakened, so it was an intriguing point, what is happening to El Nino, what is happening to the monsoon ENSO link.

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Monsoon and EQUINOO

- The intriguing monsoon seasons of 1997 and 2002 triggered studies which suggested a link to events over the equatorial Indian Ocean.
- Gadgil et al.(2003, 2004) showed that in addition to ENSO, the phase of the equatorial Indian Ocean Oscillation (EQUINOO), makes a significant contribution to the interannual variation of ISMR.

In fact, what was happening becomes very clear because while ENSO is important, it was found that another mode is also important, this mode is EQUINOO, so the intriguing monsoon seasons of 97 and 2002 regards studies which suggested a link to events over the equatorial Indian Ocean, so not only the monsoon related to events over the Pacific, it is also related to events over the equatorial Indian Ocean.

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Our first encounter with this mode of convection over the equatorial Indian Ocean was while anxiously observing sat pictures in 2003 after the intriguing season of 2002 .

Fortunately, the monsoon of 2003 has turned out to be far better (all India monsoon rainfall 2% above average).
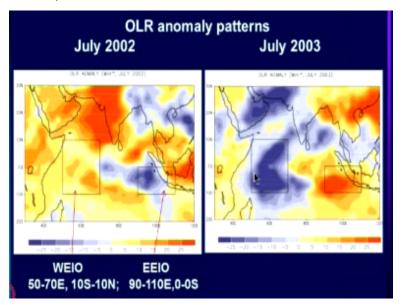
In particular, whereas there was an unprecedented deficit of 49% in all-India rainfall, in July 2003 there was excess of 7%. Comparison of the OLR anomaly patterns for July 2002,2003 is revealing.

And Gadgil showed et al in 2003 and 2004 showed that in addition to ENSO, the phase of the equatorial Indian Ocean oscillation or EQUINOO makes a significant contribution to the inter annual variation of ISMR. Now, how did you find this mode? Our first encounter with this mode

of convection over the equatorial Indian Ocean was while anxiously observing the satellite pictures in 2003, after the intriguing season of 2002.

You know that 2002 season was so intriguing that we had a meeting at the request of the DJ; then Director General of a meteorology at Bangalore to try and understand what was the special feature of 2002 that led to the severe drought and why could no model predicted. So, when 2003 monsoon commenced, we were all worried about what is going to happen in 2003 and we were watching the satellite pictures.

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As we saw the satellite pictures, then this mode became very evident and I will show you, why? Now, it turned out that were a July 2002 was a huge deficit almost 50%, see in particular whether there was an unprecedented deficit of 49% in all-India rainfall in July 2002. In July 2003, there was excess of 7% okay and if we compare the 2 OLR anomaly patterns, this is July 2000 okay.

This means convection is highly suppressed over Indian region as well as here and convection is active here, is enhanced here. Whereas July 2003, what you see is the opposite over here, convection is enhanced over the western equatorial Indian Ocean suppressed over the eastern equatorial Indian Ocean, here convection is enhanced over the eastern equatorial Indian Ocean and suppressed here.

And note this also and we will come to this point again that the OLR anomalies over the Indian region here; these purple ones tend to be of the same sign as the OLR anomalies over the western equatorial Indian Ocean, whereas they tend to be of opposite sign to OLR anomalies over the eastern equatorial Indian Ocean. This is interesting because you may recall, I had said that the relationship between CTCZ and the tropical convergence zone in the equatorial region is bit complex.

On the one hand, it supports the CTCZ; on the other hand, it competes with it. Now, it is very clear from this kind of pictures that convection over western equatorial Indian Ocean is the one that supports the CTCZ; it is favourable for CTCZ, whereas convection over the eastern equatorial Indian Ocean for some reason is the one that takes charge of the competition with CTCZ.

So, the complexity is resolved in a way with division of labour, the convection over the western equatorial Indian Ocean taking care of maintaining the CTCZ, it is positively correlated with the Indian region rainfall or convection and the one over the eastern equatorial Indian Ocean is negatively correlated with the one over India and so this is the; convection over this region is the one who has taken charge of the competition, this is the one that promotes the monsoon, okay.

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Equatorial Indian Ocean Oscillation

- Suppression of convection over the eastern equatorial Indian Ocean (90-110E, 10S-EQ, henceforth EEIO) tends to be associated with enhancement over the western equatorial Indian Ocean (50-70E,10S-10N, henceforth WEIO) and vice versa .

So, what is the equatorial Indian Ocean Oscillation? Now, we have seen here that when convection is intense here, it tends to be suppressed here, when it is intense here, it tends to be suppressed here, so there is a sea saw in convection between the western equatorial Indian Ocean and eastern equatorial Indian Ocean. These are the boxes by which we denote these and I will call them WEIO, western equatorial Indian Ocean and EEIO hence forth.

And these other longitudes and latitudes of the boxes we have drawn. So, what we are saying is that there is a tendency of sea saw between convection over these 2 regions, if this is enhanced, this is suppressed, if this is enhanced, this is suppressed, that is what seems to be happening. So, suppression of convection over the eastern equatorial Indian Ocean tends to be associated with enhancement over the western equatorial Indian Ocean and vice versa.

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- The oscillation of a state with enhanced convection over the WEIO and reduced convection over EEIO (positive phase) and another with anomalies of the opposite signs (negative phase) is the equatorial Indian Ocean Oscillation (EQUINOO).
- Associated with this, changes occur in the sea level pressure gradient and in the zonal component of the surface wind over the central equatorial Indian Ocean.

The oscillation of a state with enhanced convection over the western part and reduced convection over EEIO and this is one state with enhanced over WEIO, suppressed over EEIO and the opposite anomalies which means suppressed over WEIO and enhanced over EEIO, these are 2 states and the oscillation between these 2 states is what we call the equatorial Indian Ocean oscillation.

Positive phase of the oscillation, we have taken corresponds with enhanced convection on WEIO and you will see; why? Because, if you have enhanced convection over WEIO, then that is

favourable for the monsoon, so this we consider as positive phase of EQUINOO and this is negative phase of EQUINOO, okay. Now, associated with these changes in convection, we will get changes in the sea level pressure gradient and in the zonal component of the surface wind over the central equatorial Indian Ocean.

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- Note that the OLR anomalies over the Indian region are of the same sign as those over WEIO and opposite to those over EEIO.
- Thus a positive phase of the EQUINOO favours the monsoon while thenegative phase is unfavourable.

So, these are in fact, to again examples of opposite extremes and if you recall 94 was another intriguing case like 97, 94 also, although ENSO was unfavourable, you can see that EQUINOO is highly favourable, so this is the positive phase and this is our 2002, which is a negative phase of EQUINOO. So, as I mentioned OLR anomalies over the Indian region are of the same sign as those of over WEIO and opposite to those over EEIO.
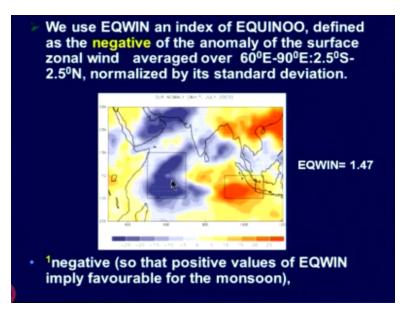
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The positive phase of EQUINOO is associated with easterly (i.e. from the east to the west) anomalies in the equatorial zonal wind; whereas the negative phase (i.e. with enhanced (suppressed) convection over the EEIO (WEIO)), is associated with westerly anomalies of the zonal wind at the equator.

Thus, the positive phase of EQUINOO favours the monsoon, while the negative phase is unfavourable. Now, positive phase of the EQUINOO is associated with easterly that is from east to west anomalies in the equatorial zonal wind, whereas negative phase is associated with westerly anomalies. Let me just explain why it is very simple to see. This is a positive phase, so there is a lot of heating in this column.

So, you will get lower pressure here, then here, so, higher pressure here and lower pressure here and remember we are at the equator. So, at the equator like in non-rotating fluids, air will tend to more from high to low pressure, there is no Coriolis force acting on the equator. Therefore, we will get winds for the positive phase, which are coming from the east to the west. So, these are easterly component, whereas in the opposite phase, they will be westerly component.

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We use EQWIN an index of EQUINOO, defined as the **negative** of the anomaly of the surface zonal wind averaged over 60^0E-90^0E:2.5^0S-2.5^0N, normalized by its standard deviation.

EQWIN= 1.47

[1]negative (so that positive values of EQWIN imply favourable for the monsoon),

They will come from west to east okay. Now, we have used as an index of this equatorial Indian Ocean oscillation of wind index and this is called EQWIN and we take it as a negative of the anomaly of the surface zonal wind averaged over 60 to 90, so our central equatorial Indian Ocean, if we take the zonal wind anomaly and then take the negative of that; negative, so that positive values of EQWIN correspond to positive phase as we have defined.
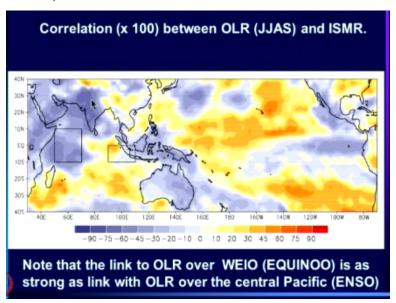
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- That a positive phase of EQUINOO with enhanced convection over WEIO is favourable for the monsoon is clearly seen from the pattern of the correlation of ISMR with OLR (next slide).
- It should be noted that the magnitude of the correlation of ISMR with the convection over WEIO is comparable to that with the convection over the central Pacific corresponding to the link with ENSO.

Then, for this situation which we have seen before where the positive phase of the EQWIN is very strong, EQWIN in fact, turns out to be 1.47 okay. So, this is a large positive value of the EQWIN corresponding to a strong positive phase of EQUINOO, okay, that a positive phase of

EQUINOO with enhanced convection over WEIO is favourable for the monsoon is clearly seen from the pattern of the correlation of ISMR with OLR.

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Correlation (x 100) between OLR (JJAS) and ISMR.

Note that the link to OLR over WEIO (EQUINOO) is as strong as link with OLR over the central Pacific (ENSO)

And we have seen this before; this is the correlation of ISMR with OLR everywhere okay. So, you can see here, more convection means less OLR, right. So, the negative correlation represents positive correlation between rainfall and ISMR here are convection and ISMR and you can see that this and this are the same sign, so if you have more convection here, more rain here, you will have more convection and rain here.

So, it is clear that the positive weak phase of EQUINOO is favourable for the monsoon okay and this is the negative correlation corresponding to the negative phase. Note, that this correlation is as strong as a negative correlation between here and here, which corresponds to the ENSO link; this is the central Pacific and the Indian region okay. So, it is as strong as the negative correlation, so we have seen that convection over WEIO is clearly favourable for the monsoon.
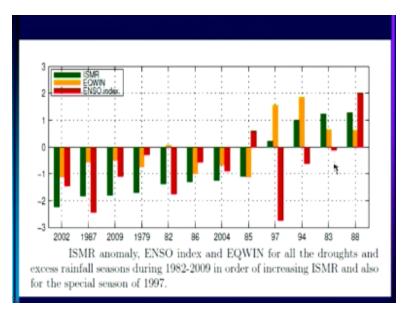
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And magnitude of the correlation of ISMR with the convection over WEIO is comparable to that with the convection over central Pacific corresponding to link with ENSO. So, this link is equally important and we should not ignore the EQUINOO link, this is what this is telling us. So, we have to look at both ENSO and EQUINOO okay in fact, it turns out that for June to September, the correlation between the ENSO index and EQWIN.

ENSO index is the index for the El Nino Southern oscillation and a EQWIN is the index for EQUINOO, which is the equatorial Indian Ocean oscillation, so the correlation between these 2 indices is not significant, it is some 0.052, suggesting that they can be considered as independent modes. So, as far as this season is concern; June to September, they can be considered as independent modes.

And therefore we can use them as x axis and y axis okay, for any year, we know the value of ENSO index and we know the value of EQWIN, right so we can use one of them as the abscissa and the other as the ordinate x axis and y axis and on using those, the location of any year is determined and we can actually plotted on the phase plane but before we do that, let us see how these look.

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ISMR anomaly, ENSO index and EQWIN for all the droughts and excess rainfall seasons during 1982-2009 in order of increasing ISMR and also for the special season of 1997.

So, the ISMR anomaly, the ENSO index and EQWIN, for all the extremes that occurred during 79 and 2010 and also the special season of 97 is what we will see here okay. So, the first bar is ISMR, the second one is EQWIN and the third bar is ENSO index okay, so this is 2002, the most severe drought, this is the rainfall and you can see that both of these were unfavourable; both EQWIN and ENSO were unfavourable.

Then comes 87, for which also they were unfavourable and so on and so forth, 85; one was opposing the other okay, it was not as severe drought as the rest, then comes 97 and you can see here that it is tug of war, there is a very strong negative unfavourable ENSO but a strong positive EQWIN and in the tug of war, we are getting a very near normal; very near zero in fact, the ISMR anomalies.
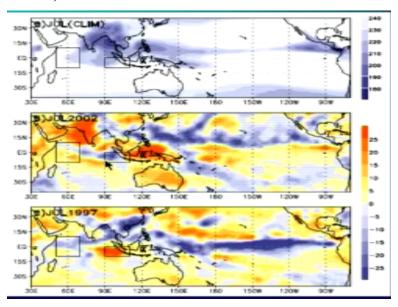
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It is seen that each drought (excess rainfall season) is associated with

- unfavourable (favourable) phases of either ENSO or EQUINOO, or both.

And we get to 88, where again both are favourable and then 2 years in between 94, a weak El Nino but it was an excess and 83 was a case of a complex El Nino, which I come to later and again a favourable EQUINOO and we get an excess, so it appears that each drought or excess rainfall season is associated with unfavourable, so let us take it one at a time; each drought is associated with unfavourable phase of either ENSO or EQUINOO or both.

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Each excess rainfall season is associated with favourable phase of either ENSO or EQUINOO or both. Now, we come back to this intriguing year of July of 1997 and 2002. This is the climatology for July, so this shows where the convection generally is and this is the part of a

central Pacific where during El Nino year, you had enhanced convection and these are the OLR anomalies and you see that here.

You see enhanced convection here in 2002, enhanced convection here in 97 much stronger because this was a stronger El Nino but look at an equatorial Indian Ocean, what has happened? In 97, it was a positive phase of EQUINOO, you see the convection over West is flared up; convection over east is very much suppressed. On the other hand, you see 2002 exactly opposite, convection over East is enhanced convection over West is suppressed.

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- It is seen from the last slide, that while the phase of ENSO in 1997 is the same as that in 2002, the phase of EQUINOO is positive in 1997 and negative in 2002.
- While ENSO and EQUINOO had opposite phases in 1997 (with EQUINOO being favourable), they reinforced one another in 2002 (with both being unfavourable).
- Hence while 2002 turned out to be a severe drought, in 1997 the tug of war led to a normal monsoon.
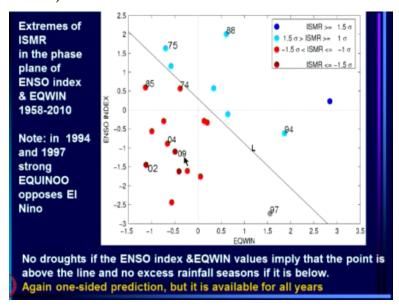
So, what is happening is that although, the ENSO is unfavourable for both these. In 97, EQUINOO was favourable and this is why I talked of the tug of war but in 2002, EQUINOO was also unfavourable, so it colluded with ENSO in making it a severe drought. So, what we have seen is that while the phase of ENSO in 97 is the same as that in 2002, the phase of EQUINOO is positive in 97 and a negative in 2002.

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- We find that with the two modes: ENSO and EQUINOO, we can 'explain' all the extremes of ISMR.
- Droughts occur when one or both of the modes are unfavourable (with the most severe droughts associated with both unfavourable) and excess rainfall when one or both are favourable.

Hence while ENSO and EQUINOO had opposite phases in 97 with EQUINOO being favourable, they reinforce one another in 2002 with both being unfavourable. Hence, while 2002 turned out to be a severe drought in 1997, the tug of war led to a normal monsoon. Now, we find actually, we have been looking at extremes here in the last slide also and we find that with these 2 modes ENSO and EQUINOO, we can 'explain' or understand all the extremes of ISMR.

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And how do we do it? As I mentioned before, remember, ENSO index and EQWIN are not correlated, so they are perpendicular to one another and so we can use them as axis and plot in the phase plane of these indices each year because for each year, the value of each of these

indices is known. So, what we get is what I will show you here, this is EQWIN x axis, ENSO index.

Now, you can take any year such as 75 okay, 75 it so happened that EQWIN was unfavourable -0.5 but ENSO was highly favourable, you see here, this is the case. So, for 75, we know what is ENSO index, we know what is EQWIN. So, we can plot a point here as 75. Now, I have coloured in blue, why? Because it happens to be an excess monsoon season, so the colour shows the location shows what are the values of the indices for that season 75.

And the coloured one indicates whether it is an excess or a drought and remember we are looking at only excess or drought except for this special year of 97. So, we are looking only at all the extremes and you can see what we find, it is amazing. It is that in fact, there is a separation in this phase plane of EQWIN and ENSO between drought, which are all red and excess monsoon years which are all blue.

So, this is that if you are below this line l, that we have drawn, then there are no excess monsoon season. If you are above this line l, then there are no drought, so this is a very clean separation and we talked a one sided prediction, if ENSO index was given. Remember, that if magnitude of the ENSO index was greater than some 0.6 or 0.8 or something, then we could say something about whether if ENSO index was favourable and its magnitude greater than some quantity.

Then, you cannot have drought and also equivalent statement about excess rainfall season but we noted that many years did not meet these criteria of ENSO index either being above a certain value or below a certain value, there were many years which had ENSO index between the 2 values. But, in this case on the other hand, what we find is that every values accounted for any point that you have in this phase plane.
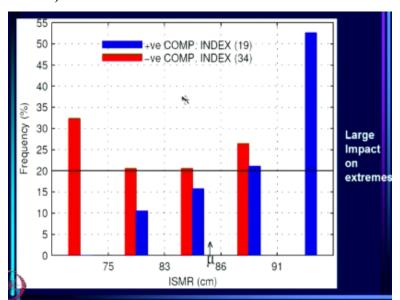
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We can say whether; which of the excess will be ruled out, so if the point is here, then no excess rainfall seasons, if the point happens to be here, no drought. So, this is true for all years now and this is an amazing thing and in fact, subsequent to our paper, Ihara et al looked at a much longer period; there 58,2003 and they just asked the question, how does one linearly reconstruct ISMR on the basis of multiple regression from a ENSO index, which they took as Nino3.

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And EQUINOO index with they took as EQWIN and they said that multiple regression from Nino3 and EQWIN better specifies ISMR, then Nino3, so they also showed that it is important to incorporate information on EQWIN, if you want to understand the inter annual variation of the

ISMR. Now, this is something that we have seen last time with the ENSO. Suppose, we could actually predict the composite index.

Now, what is the composite index? See, since there is a straight line which determines the separation between these 2 here, since this line determines the separation between the droughts and the excess rainfall season, we can determine a composite index which is the distance from this line, right, perpendicular distance from this line and if we say, distance from this line it is 0 here, it is negative everywhere here and it is positive everywhere here, right.

So, in terms of a composite index, which is simply the distance from this line, we can say if that composite index is negative, then you would not get excess years, if the composite index is positive, then you would not get droughts. So, composite index being positive is a favourable situation from the point of view of ENSO and EQWIN together and composite index negative is an unfavourable situation from the point of these 2 together okay.

So, now we are talking in terms of composite index values and negative composite index and positive composite index, there are 2 sets here and remember we are chosen the categories of ISMR such that the climatological probability is actually 20% and what happens now, if we had information on composite index, a prediction of what the ENSO index and EQWIN would be for next season and therefore, we could compute what the composite index is.

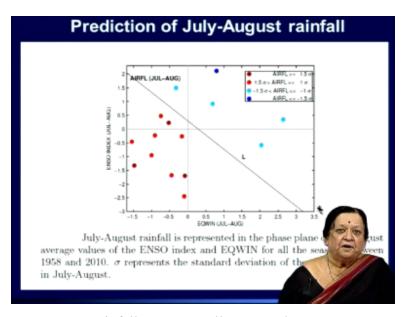Then, if the composite index is positive then no droughts. If the composite index is negative, then no excess rainfall season so again, we are getting a very nice prediction for; only for the extreme categories. Category 1, which is the lowest rainfall drought and category 5, which is the highest rainfall; excess rainfall season, so category 5 then has no droughts at all. Remember, when we looked at ENSO alone, it had a little percentage of droughts.

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Prediction of July-August rainfall

July-August rainfall is represented in the phase plane of the August average values of the ENSO index and EQWIN for all the seasons between 1958 and 2010. σ represents the standard deviation of the [...] in July-August.

And this one has no excess rainfall years at all, so we have got a very clean probability distribution given the composite index, which is better then what we would have gotten with ENSO alone. Now, so the whole, it is very clear now that if we had to predict, what the all-India summer monsoon rainfall is going to be for next season, then it would be very very useful to have prediction of both ENSO index and EQWIN.

We have already made some progress towards getting ENSO predictions, these are phenomenal progress in this direction was made in the 80s and 90s globally and now the question is supposed, we knew some; at some point in the season what EQWIN and ENSO were? Can we say something about the; what will happen in the rest of the season and interestingly enough we find that if we took; in fact, I do not have it here, I will show it in the next class.

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We define a composite index as a linear combination of the ENSO index and EQWIN, so that it measures the distance from the line L separating the droughts from the excess rainfall years in the phase plane of the two indices. The composite index is taken to be positive in the region above the line (with no droughts) and negative below the line. The frequency distributions of the five categories of ISMR for positive and negative values of this composite index are shown in the next slide.

This is simply showing that July + August is also well separated even better separated than JJAS and in the next class I will show that if you plotted July + August in the phase plane of June indices, again we have a separation, so again, we will a one sided prediction possible. So, what we have found then is that; what we have found that there are 2 modes which are important for understanding the inter annual variation of the all-India rainfall.

There; ENSO and EQUINOO, and if we can predict these modes, we will be in a very good position to say something about the non-occurrence of extremes, remember if the composite index is negative, this says that there will be no excess rainfall but you could still have either droughts or a normal monsoon. Similarly, if the composite index is positive, you can say there will be no droughts.

So, one sided prediction of this kind will certainly be possible, if we can predict both EQUINOO and ENSO and in the following lectures, we will try and see to what extent we can understand how this EQUINOO evolves and to what extent will be able to generate the prediction and what is our prediction for when we will be able to predict this. This is what we will cover in the next lecture. Thank you.