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Targeted Training Activity: Predictability of Weather and Climate: Theory and Applications to Intraseasonal Variability

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Climate Predictability on Seasonal Time Scale: Role of Boundary Forcing

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Targeted Training Activity:

Predictability of Weather and Climate

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(1) The Global Atmospheric Circulation: Observations

(2) Modeling the Weather and Climate

(3) Errors in Forecasts: Roles of Initial States, Model Errors, and Chaos

(4) Climate Predictability on Seasonal Time Scale: Role of Boundary Forcing

(5) Seasonal Mean Predictability over the Pacific - North American Region

Predictability of Seasonal Means: Predictability of the Second Kind

Predicting the mean rainfall for the coming season requires going ***beyond the limit*** at which the small errors in the initial conditions will cause loss of predictability on the large scales (several weeks)

The source of weather predictability is knowledge of the details of the initial conditions. The predictability is limited by flow instabilities and nonlinear interactions.

Charney and Shukla hypothesized another kind of predictability, one that would operate (primarily) in low latitudes, and had its source not in the initial conditions but in the Boundary Conditions:
Sea-surface temperature (SST), albedo, ground moisture and vegetation

Why might these boundary conditions engender predictability?
(1) They have the ability to affect the flow significantly
(2) They change on a slow (month to month) time scale

Flow evolves with time scale t.

Boundary conditions evolve with time scale τ

τ >> t

J. Shukla, 1981: Dynamical Predictability of Monthly Means. J. Atmos. Sci. 38, 2547-2472.

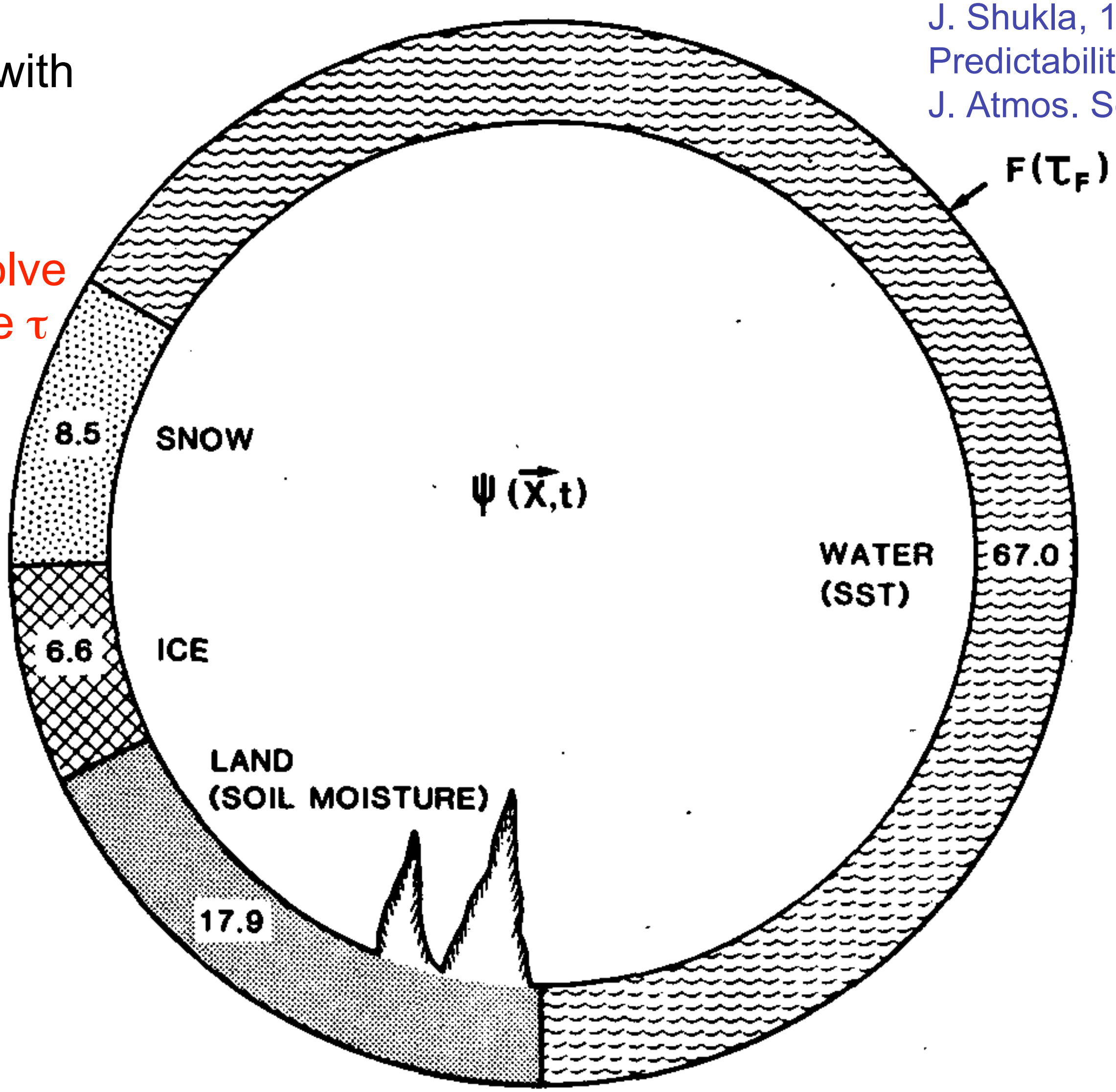


FIG. 2. Schematic illustration of the roles of internal dynamics and slowly varying boundary conditions.

Charney and Shukla started with four six-week integrations of a general circulation model from mid-June to the end of July. They only considered July monthly means. Each integration used the same SSTs as boundary conditions

Integration 1 = control integration

Integrations 2, 3 and 4 = "identical quadruplets"
(Initial conditions which were close to that of the control simulation)

We expect the flow differences between all pairs of runs to become large within a few weeks.

As expected, the four individual flows began to immediately differ from each other due to flow instabilities, wave-wave interactions...

Until... the flows were so uncorrelated that it seemed possible to regard the variability of the July averages as approximating the variability of the atmospheric flow from one July to another*

(*we can think of the July means for various years as independent samples of the the atmosphere's attractor)

In mid-latitudes, the variance among the four model July means of precipitation and sea-level pressure were approximately the same as the observed year-to-year July mean variability

However,
In the tropics, *the variance among the four model July means fell far short of the observed year-to-year July mean variability, which includes the effects of different SSTs each year!*

Specifically, let F either be the monthly mean SLP or rainfall on the global grid. At each point calculate the ensemble mean σ and standard deviation:

$$\sigma^2 = \frac{1}{1-n}\sum_{i=1}^{n}\left(F_i - \overline{F}\right)^2$$

$$\overline{F} = \frac{1}{n}\sum_{i=1}^{n} F_i$$

For the GCM: n=4 are the four Integrations
For Observations: n=10 are the 10 months of July, 1966 through 1975

Zonal mean of standard deviation σ_m for the model (m) and σ_o observations (o).

Note that the ratio of obs/model σ_o / σ_m ~ 1 in midlatitudes, BUT that σ_o / σ_m >> 1 in the tropics

Model experiments used same SST BUT Observed SSTs vary from year to year!

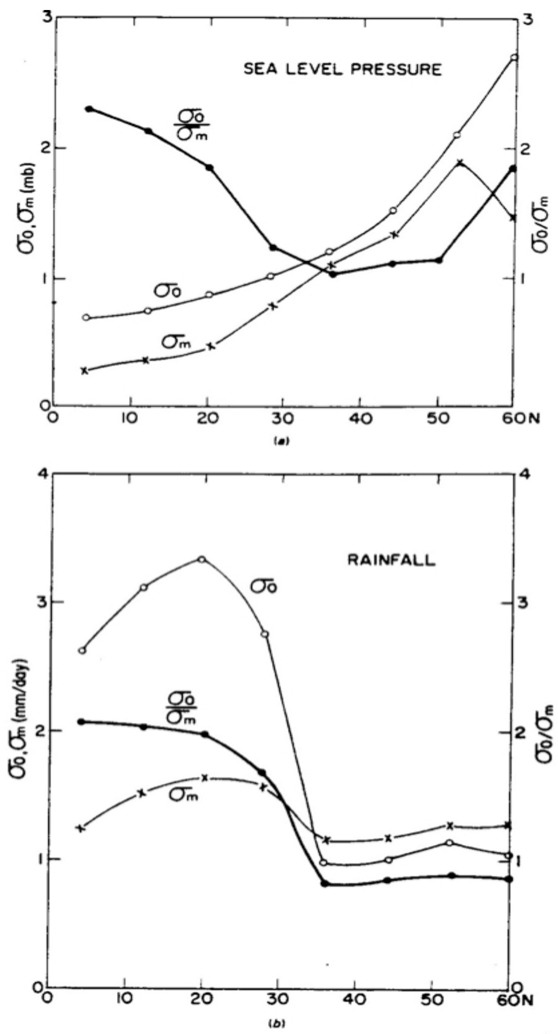


Fig. 6.1. Model and observed zonally-averaged standard deviations as functions of latitude, and their ratio, for: (*a*) mean July sea-level pressure; and (*b*) rainfall. Observed values are for land stations and model values are for grid-points over land.

What physical factors are responsible for the *variability* in seasonal means?

(1) Flow instabilities (internal dynamics) which always exist
(2) Variations in the slowly changing boundary conditions themselves - **Why?**

SST- because of the higher heat capacity of the ocean, the surface air temperature T_s = SST. Higher SST means high T_s, hence higher saturation vapor pressure e_s , defined as the maximum partial pressure of water vapor possible without condensation taking place (alternatively, as the maximum weight of water vapor that a unit weight of air can hold).

Higher T_s means that higher evaporation is likely, and a higher humidity, which in turn increases the likelihood of condensation ➪ more rainfall !

The evaporation from the ocean removes energy from the surface, and the condensation releases that latent energy into the atmosphere.

But, the latent heat release will in general occur at a different (x,y,p) compared to the location of the evaporation - *a heat source has been added somewhere to the interior of the atmosphere!*

Soil Moisture - Increased soil moisture also leads to increased evaporation - and so also gives a path to increased precipitation and a latent heat source for the atmosphere

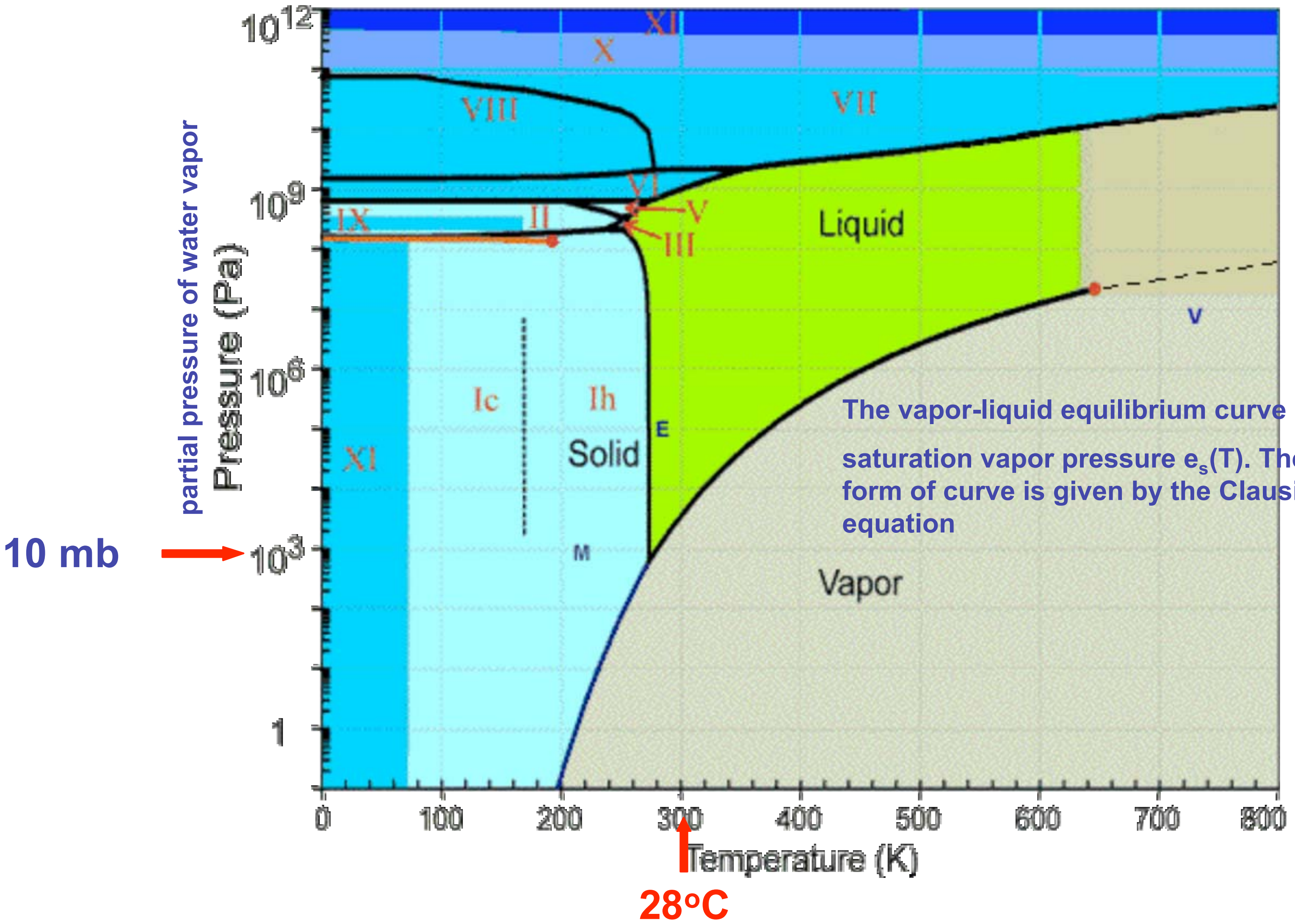
Vertical heat transport: increased soil moisture means that the incoming (solar + downward long wave) radiation goes towards evaporation, and not towards heating the ground directly. So from the atmosphere's point of view, the increased heating takes place in the interior (latent heating) rather than at the surface

In summary, both SST and soil moisture changes lead to changes in the latent heat sources in the atmosphere. The subsequent change in atmospheric seasonal means occurs for 2 reasons:

(1) Direct Response of the mean flow to changes in heating
(2) Indirect Response; the geographically preferred region of instabilities will shift as the mean flow changes (vertical shear, horizontal shear)

London South Bank University
http://www.lsbu.ac.uk/water/phase.html

Phase Diagram of Water



The vapor-liquid equilibrium curve gives the saturation vapor pressure $e_s(T)$. The functional form of curve is given by the Clausius-Clapeyron equation

How does boundary forced variability lead to predictability?

Variability due to **internal dynamics** is expected to be **unpredictable** on the seasonal time scales. This time scale is beyond the the predictability limit for predictability based on initial conditions - *in fact internal dynamics severely limits the predictability of seasonal means in mid-latitudes!*

Variability due to **boundary condition** changes **is potentially predictable**, since the boundary condition changes occur on a very slow time scale.

How can internal dynamics (instabilities, wave-wave interaction), lead to (unpredictable) variations of the seasonal mean?

- Although individual instabilities or mid-latitude storms have time scales less than a season, there are lower frequency phenomena whose time scale is not much less than a season. These include blocking events and variability of the jet stream, which controls the number of disturbances and their paths.

- A simple example of chaos causing unpredictable variations in long-time means: Lorenz 1964

$$X_{n+1} = AX_n - X_n^2$$

Note: Think of the parameter A as controlling the exact strength of the instabilities: we don't know A perfectly perfectly well.

The problem of deducing the climate from the governing equations

The problem of deducing the climate from the governing equations

By Edward N. Lorenz, *Massachusetts Institute of Technology*[1]

(Manuscript received January 22, 1964)

ABSTRACT

The climate of a system is identified with the set of long-term statistical properties. Methods of deducing the climate from the equations which govern the system are enumerated. These methods are illustrated by choosing a first-order quadratic difference equation in one variable as a governing equation. The equation contains a single parameter. Particular attention is given to the climatic mean of the single variable.

Analytic methods yield the climate in some cases where the system varies periodically, but generally fail when the system varies nonperiodically. Numerical integration yields a value of the climatic mean for any individual value of the parameter. Additional analytic reasoning is needed to determine the nature of the climatic mean as a function of the parameter.

The progression from steady-state to periodic to nonperiodic behavior, as the parameter increases, is compared to the progression from steady-state to periodic to irregular flow in the rotating-basin experiments, as the rate of rotation increases.

$$X_{n+1} = AX_n - X_n^2$$

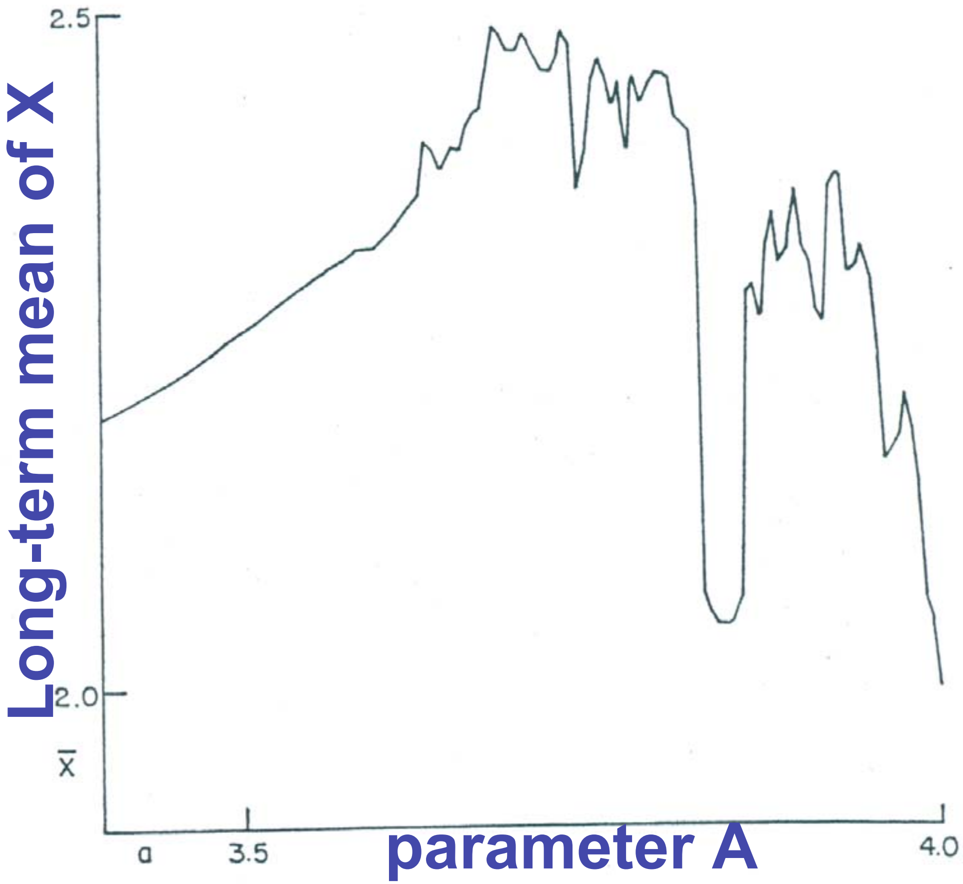


FIG. 3. Graph of $\bar{X}$ as a function of a, as estimated for the interval $3.4 \leqslant a \leqslant 4$.

Climate depends sensitively on the value of A

How does boundary forced variability lead to predictability?

Variability due to **internal dynamics** is expected to be **unpredictable** on the seasonal time scales. This time scale is beyond the the predictability limit for predictability based on initial conditions - *in fact internal dynamics severely limits the predictability of seasonal means in mid-latitudes!*

→ Variability due to **boundary condition** changes **is potentially predictable**, since the boundary condition changes occur on a very slow time scale.

Realizing this predictability means understanding the dynamics of the changes in circulation forced by changes in boundary conditions

Why is boundary forcing so much more effective *in the tropics*?

Direct Mechanism

- High SST occurs in the tropics, hence high T_s.
- The curve of e_s vs. T_s has a strongly positive slope at values of T_s ~28^{o}C, typical of the tropics ("Clausius-Clapeyron" equation -see figure)
- Hence a given SST anomaly (or change) yields a much higher evaporation change in the tropics than in mid-latitudes.

Indirect Mechanism:

- The flow instabilities (internal dynamics) plays less of a role in causing variability of seasonal means in the tropics (compared to mid-latitudes) because the instabilities are weaker.

- Baroclinic instability (growth of baroclinic waves) is strongest in regions of vertical wind shear / horizontal temperature gradients
- Horizontal temperature gradients are much weaker in the tropics; vertical wind shears are therefore also weaker (thermal wind relationship)

Conventional View:

- Convective instabilities in the tropics grow and saturate in a very short time - and here there *is* a distinct time scale separation- convective time scale is much shorter than a season.
-Seasonal tropical mean rainfall is due to mean of all convective instabilities, and this is well controlled by SST

However:

- Planetary and large scale waves are still active in the tropics; convectively coupled Rossby and Kelvin waves are also active. All these play a role in internal dynamics of the tropics - conventional view is too simple!!

Presence of a time scale "window"

SST and soil moisture are variables in the climate system, but they vary on time scales longer than months. So during a season, they do not change very much.

One of the most significant changes that occurs in tropical SSTs, with large consequences for mid-latitudes, is the

ENSO = "El-Nino Southern Oscillation"

ENSO is an irregular oscillation of the tropical atmosphere / ocean system (period of ~ 2 - 7 years)

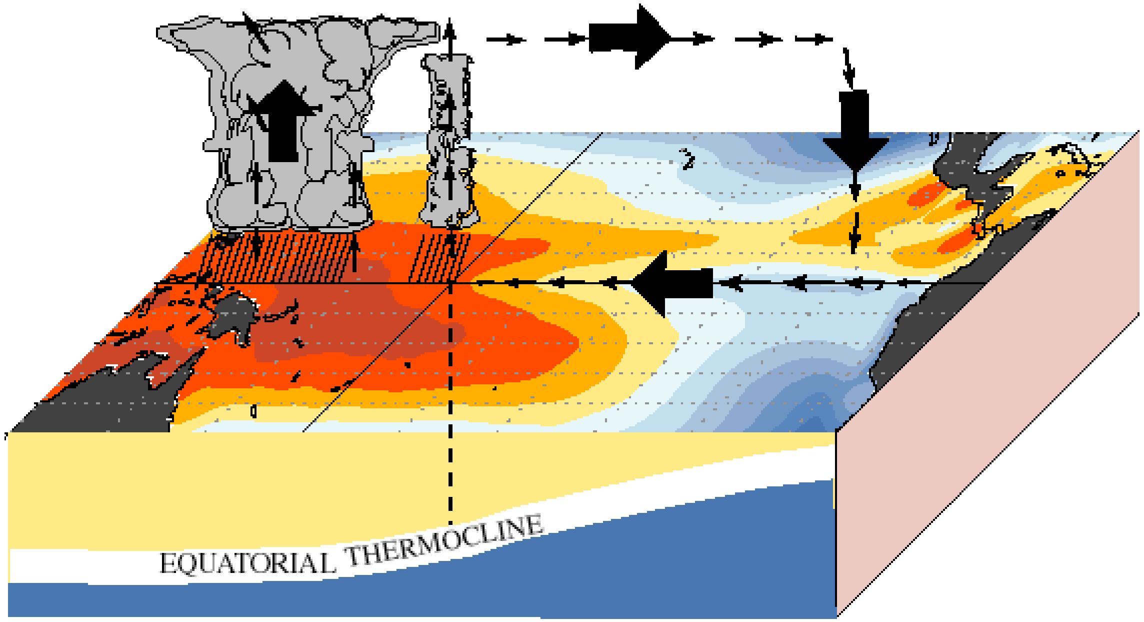
ENSO involves *coupled ocean-atmosphere dynamics*

Normal Winter Conditions, Equatorial Pacific

"Walker Circulation" driven by sea surface temperature gradient

Rainy west

in West, "warm pool" of surface water



Dry east

in East, "cold tongue" of water upwells from below

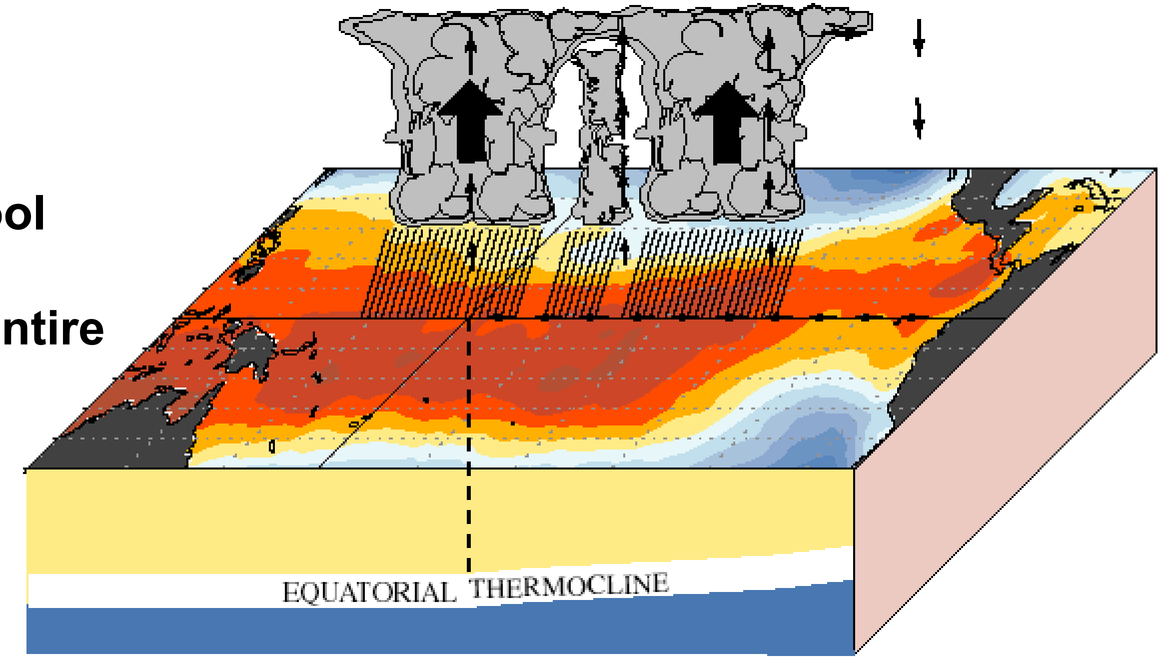
Thermocline tilt/upwelling driven by westward wind stress

www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm_impacts.html

El Nino Winter Conditions, Equatorial Pacific

Warm SSTs in the Eastern Pacific -->Increased evaporation in the Eastern Tropical Pacific, increased deep convection and rainfall, increased rising motion, and finally increased tropical divergence near the top of the troposphere

warm pool extends across entire Pacific

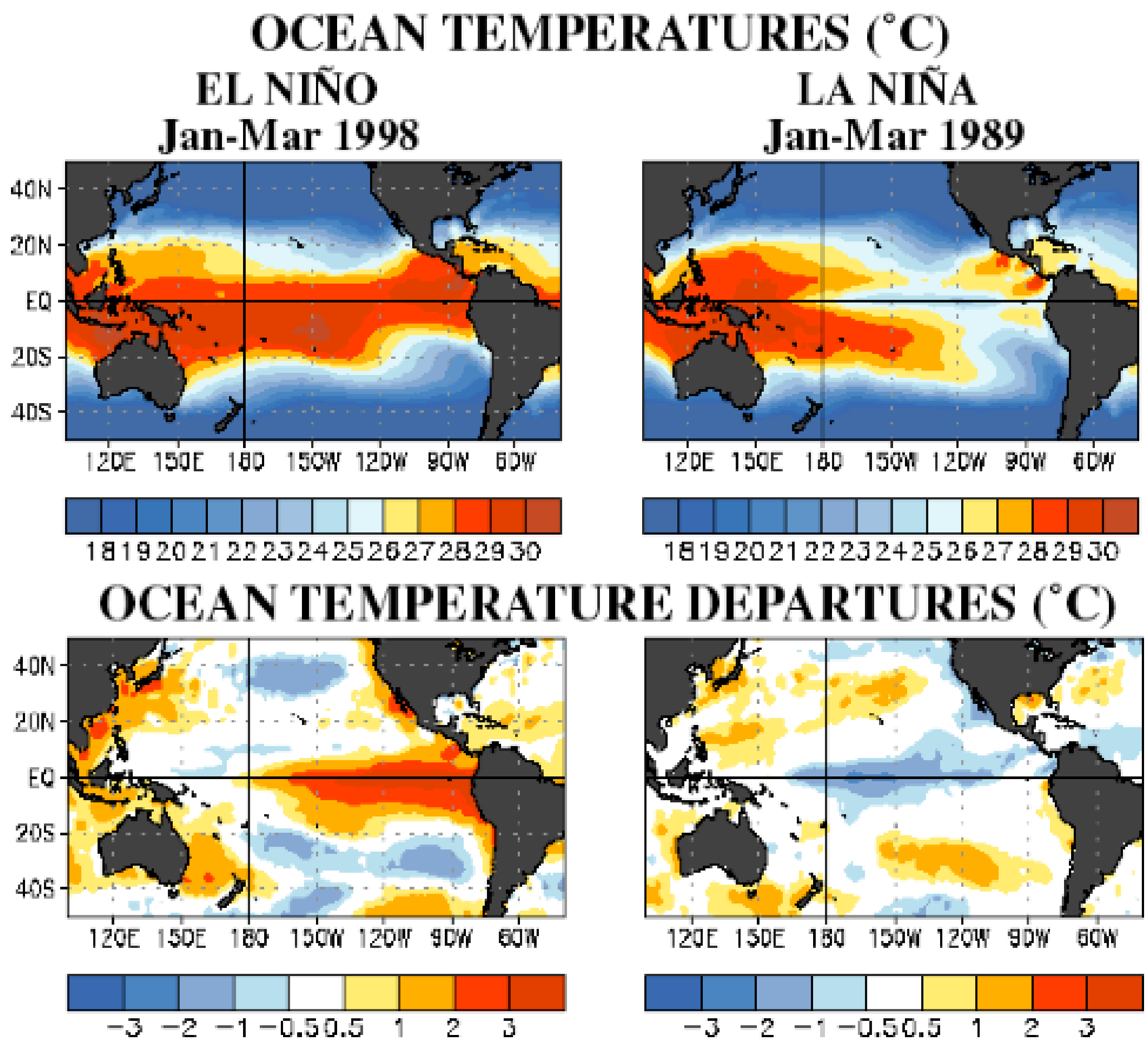


cold tongue disappears

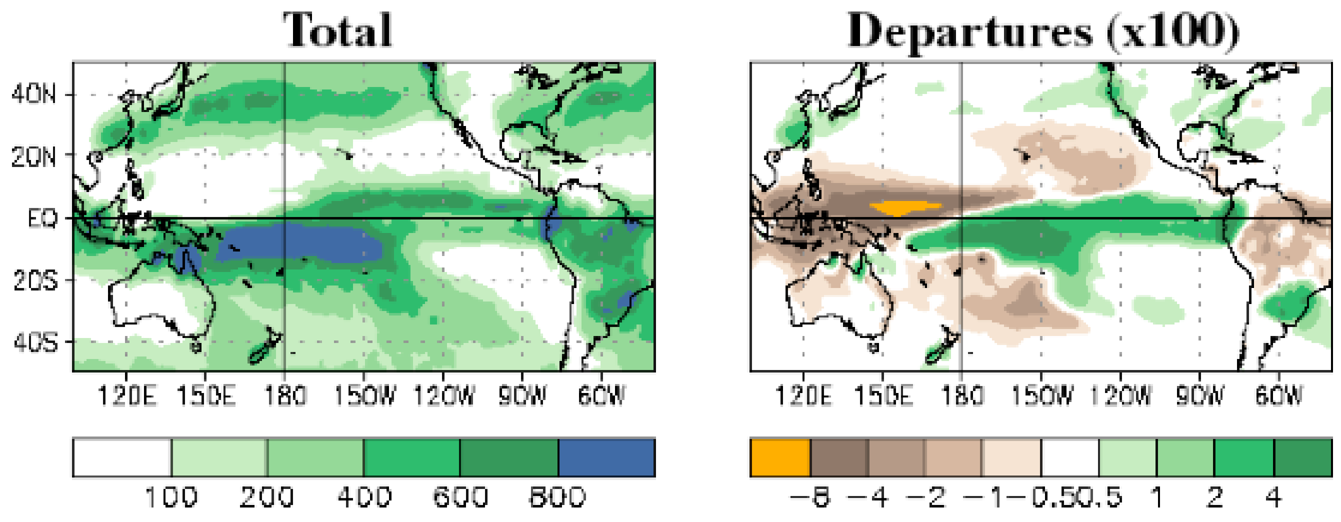
weakening of westerlies allows flattens thermocline, weakens upwelling

www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm_impacts.html

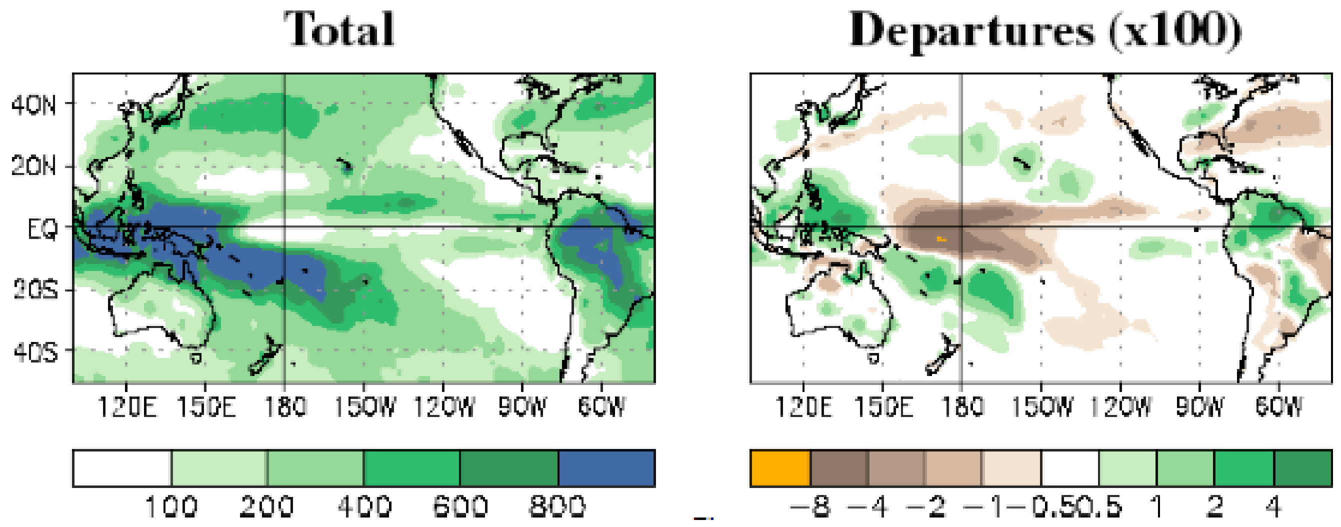
www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/ensocycle.shtml



Jan-Mar 1998 Precipitation (mm)



Jan-Mar 1989 Precipitation (mm)

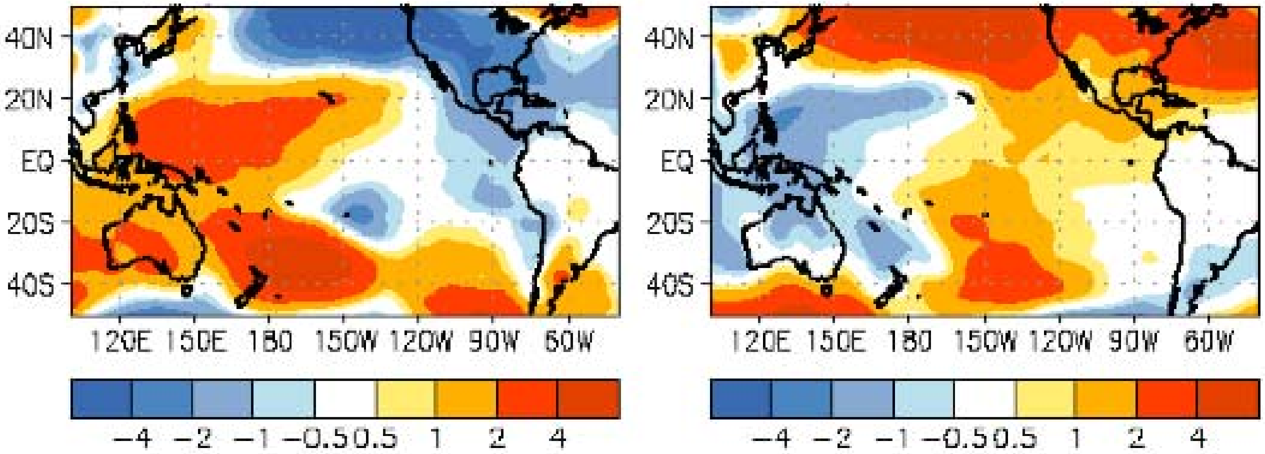


http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/soilink.shtml

PRESSURE DEPARTURES (mb)

EL NIÑO
Jan-Mar 1998

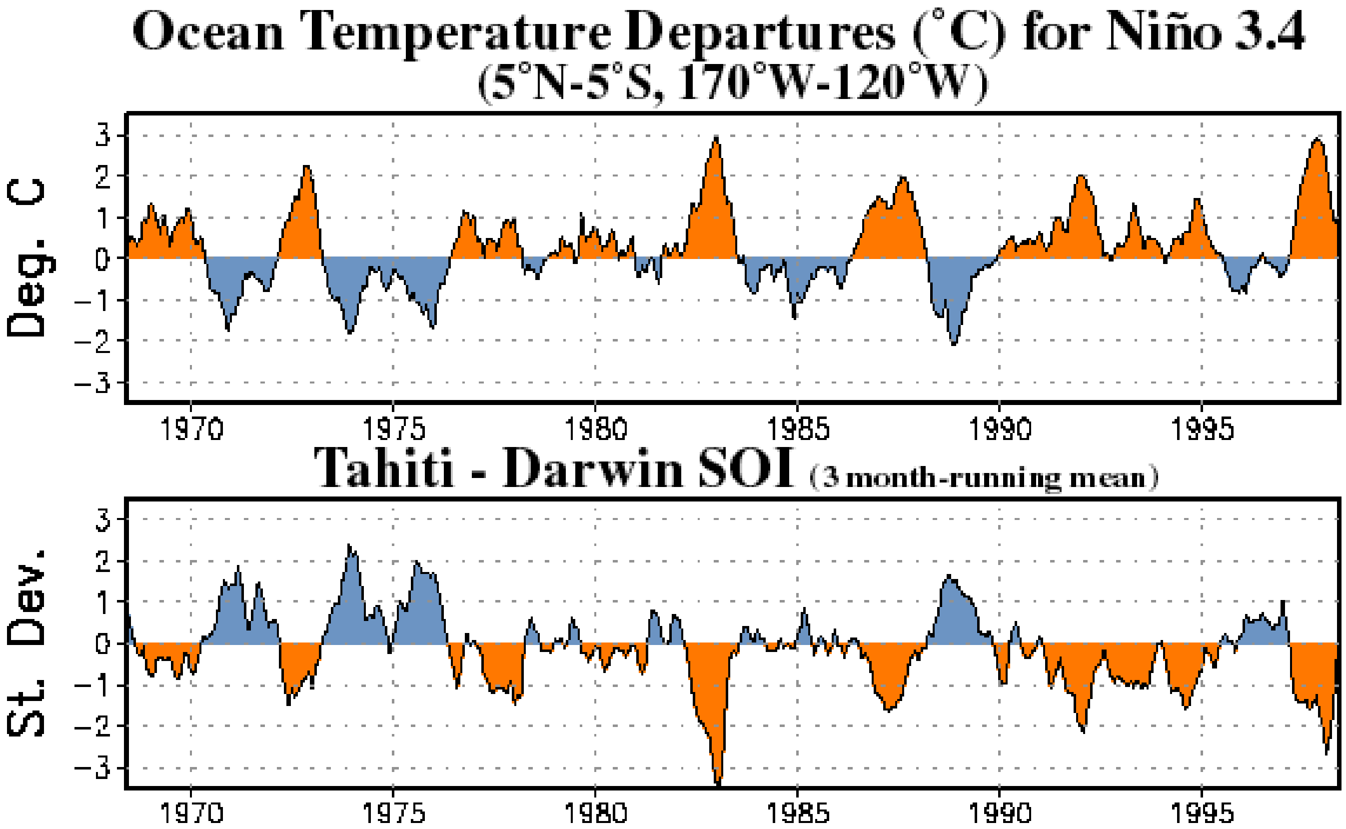
LA NIÑA
Jan-Mar 1989



Tahiti is located at 17°40′S, 149°30′W.
Darwin is located at 12°27′S, 130°50′W.

(maps on previous page from:)
http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/laninarain.shtml
http://www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/ensorain.shtml

www.cpc.noaa.gov/products/analysis_monitoring/ensocycle/soi.shtml



There are a few different methods of how to calculate the SOI. The method used by the Australian Bureau of Meteorology is the Troup SOI which is the standardised anomaly of the Mean Sea Level Pressure difference between Tahiti and Darwin. It is calculated as follows:

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SOI = 10 x [ Pdiff - Pdiffav ] / SD(Pdiff)
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Pdiff = (average Tahiti MSLP for the month) - (average Darwin MSLP for the month)

Pdiffav = long term average of Pdiff for the month in question

SD(Pdiff) = long term standard deviation of Pdiff for the month in question.

The multiplication by 10 is a convention. Using this convention, the SOI ranges from about –35 to about +35, and the value of the SOI can be quoted as a whole number. The SOI is usually computed on a monthly basis, with values over longer periods such a year being sometimes used. *Daily or weekly values of the SOI do not convey much in the way of useful information about the current state of the climate, and accordingly the Bureau of Meteorology does not issue them. Daily values in particular can fluctuate markedly because of daily weather patterns, and should not be used for climate purposes.*

www.bom.gov.au/climate/glossary/soi.shtm