

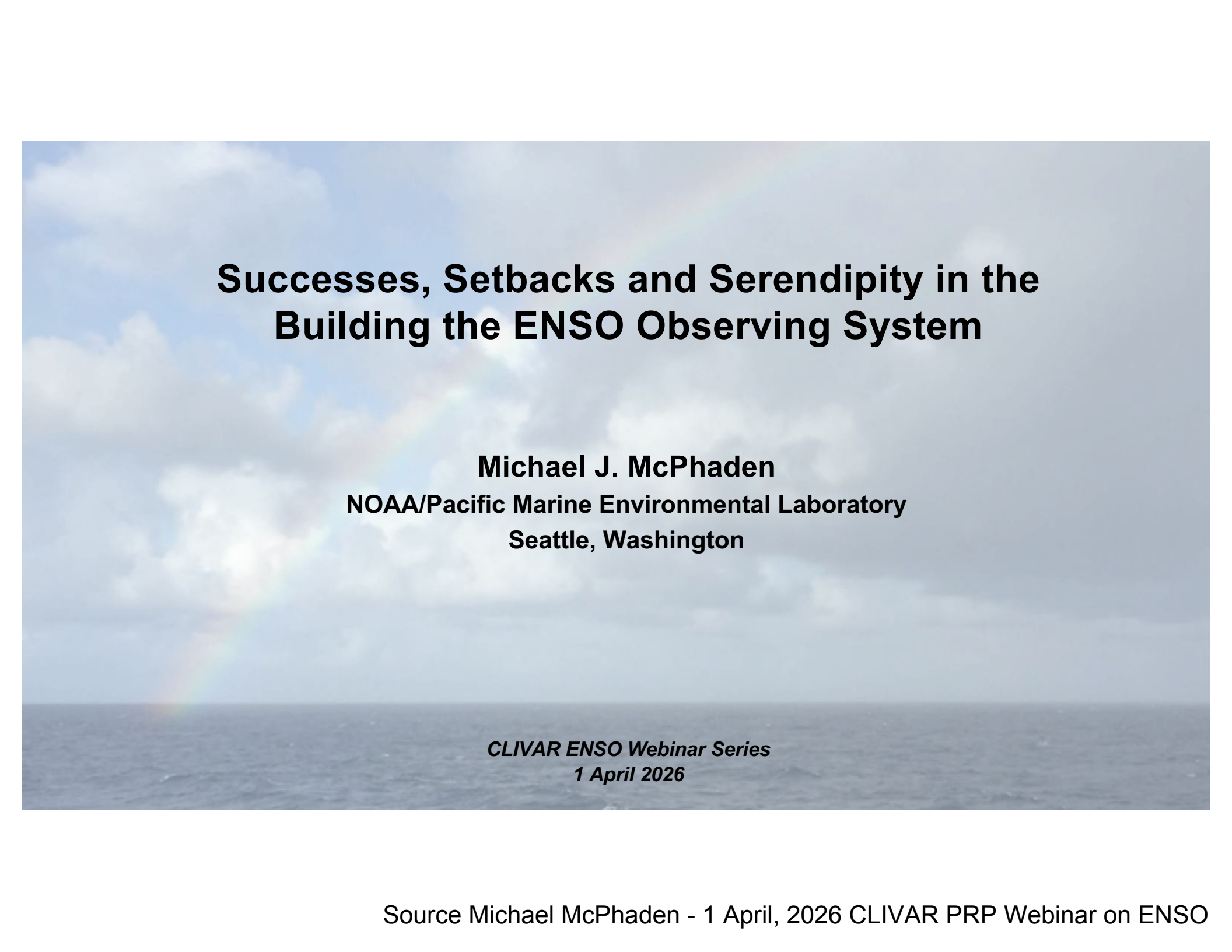
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Please contact: Michael McPhaden– NOAA/Pacific Marine Environmental Laboratory for permission requests

A photograph of a rainbow over the ocean under a cloudy sky. The rainbow is visible on the left side of the image, arching over the horizon. The sky is filled with soft, white clouds, and the ocean is a calm, greyish-blue. The overall mood is serene and hopeful.

Successes, Setbacks and Serendipity in the Building the ENSO Observing System

Michael J. McPhaden
NOAA/Pacific Marine Environmental Laboratory
Seattle, Washington

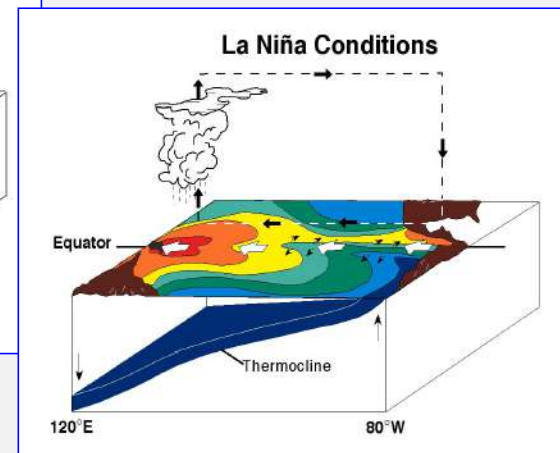
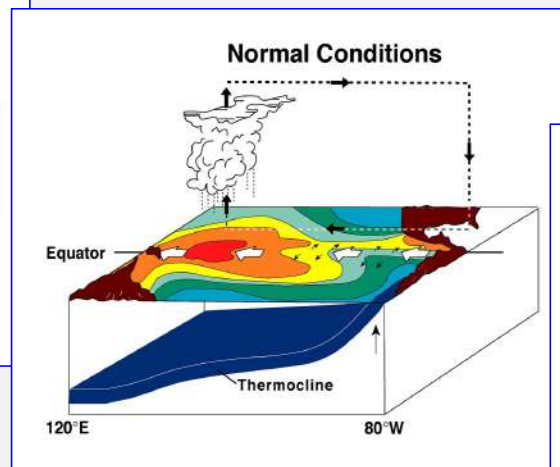
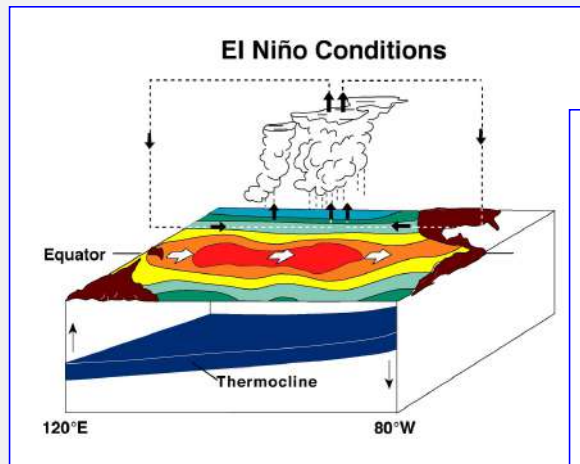
CLIVAR ENSO Webinar Series
1 April 2026



Outline:

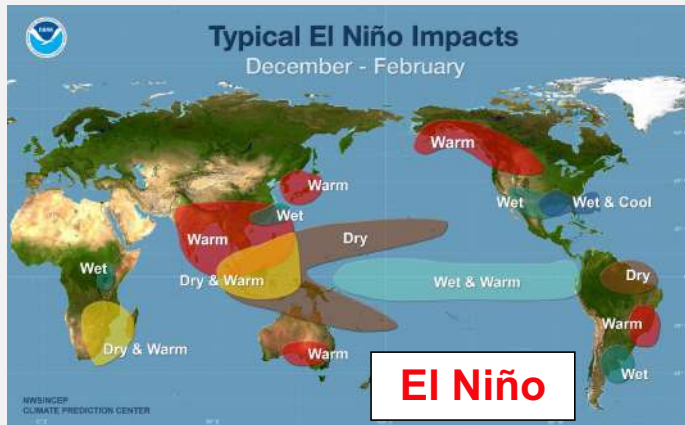
- 1) Review the scientific ideas, technological developments, and climate extremes that influenced design and implementation of the ENSO Observing System;
- 2) Illustrate how the observing system contributed to ENSO-related scientific discoveries and advances;
- 3) General thoughts on future observing system challenges

El Niño and the Southern Oscillation (ENSO): The Strongest Year-to-Year Variation of the Earth's Climate System

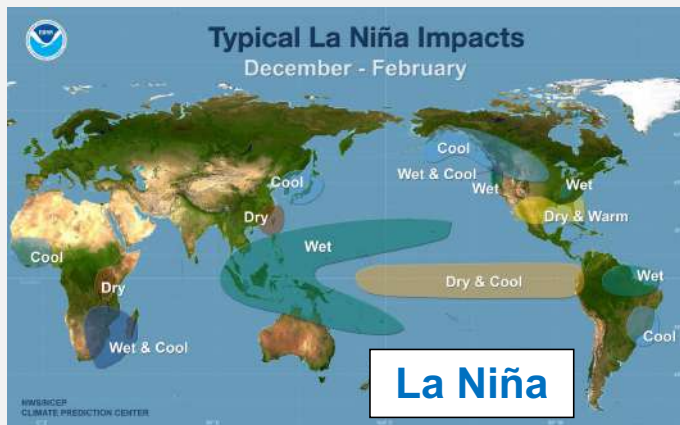


El Niño—Warm phase of ENSO
La Niña—Cold phase of ENSO

El Niño & La Niña Impacts on Patterns of Weather Variability

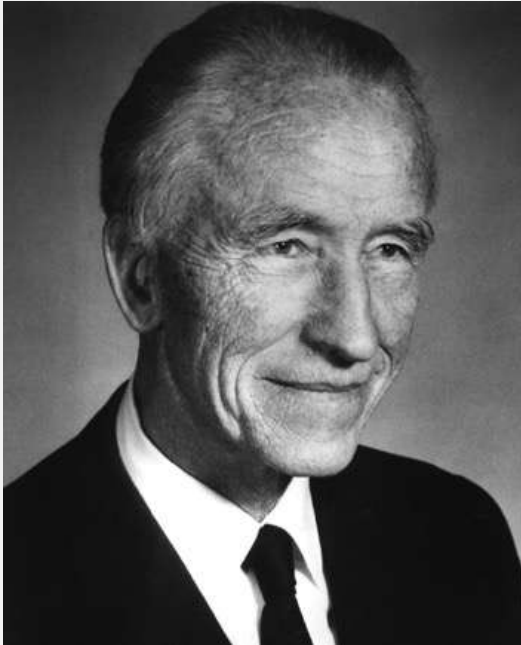


El Niño and La Niña shift the probability for droughts, floods, heat waves, extreme weather events around the globe



Jacob Bjerknes

1897-1975



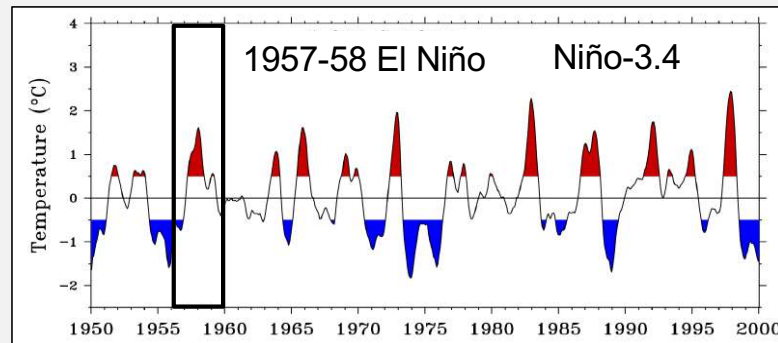
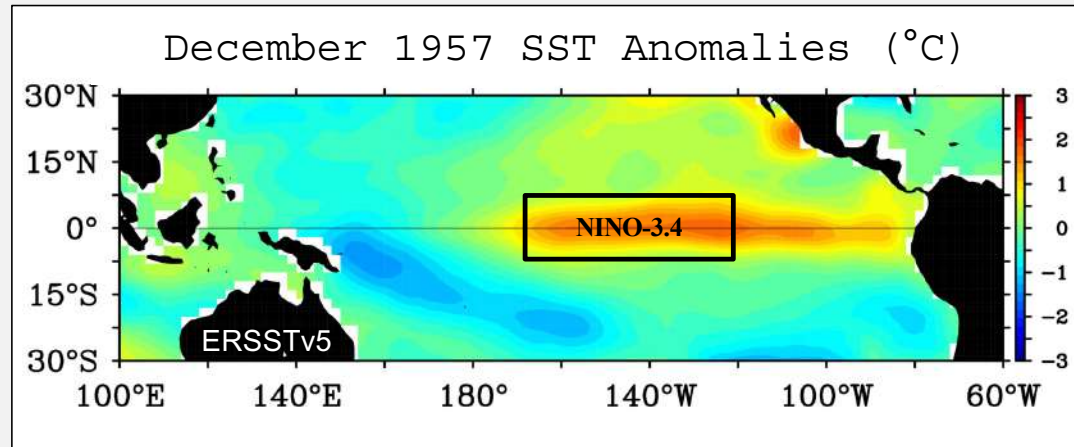
Key El Niño Concepts

- **Ocean-atmosphere feedbacks essential
(El Niño linked to Walker's Southern Oscillation)**
- **Affects weather at higher latitudes**
- **Basin scale, not just confined to coast of South America**
- **Potentially predictable because of the ocean's thermal inertia**

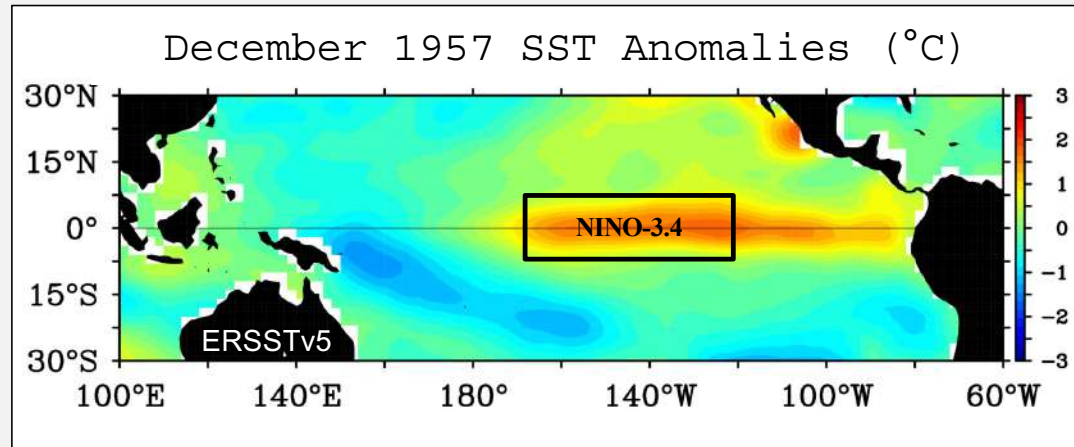
Bjerknes, 1966, Tellus

Bjerknes, 1969, Mon. Wea. Rev.

International Geophysical Year, 1957-58



International Geophysical Year, 1957-58



A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature

By J. BJERKNES, *University of California, Los Angeles*

Tellus, 1966

(Manuscript received January 18, 1966)

“Weakness...of the equatorial easterly winds... in late 1957 and early 1958 brought about a brief cessation of equatorial upwelling...”

ABSTRACT

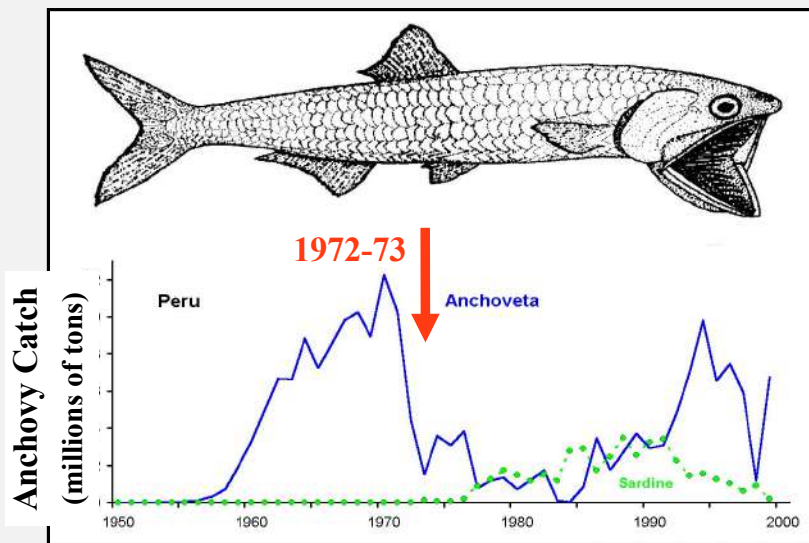
Weakness and temporary elimination of the equatorial easterly winds over the eastern and central Pacific in late 1957 and early 1958 brought about a brief cessation of equatorial upwelling which in turn caused the occurrence of above-normal surface water temperatures in the tropical Pacific from the American coast westward to the dateline. This sudden introduction of a large anomalous heat source for the atmosphere intensified its thermodynamic circulation, especially in the wintertime (northern) hemisphere. Record intensity of the westerlies resulted in the eastern North Pacific. The anomalous depth of the Low in the Gulf of Alaska had the downwind effect of weakening the Iceland Low and setting the stage for a cold winter in northern Europe.

Envisioning the ENSO Observing System

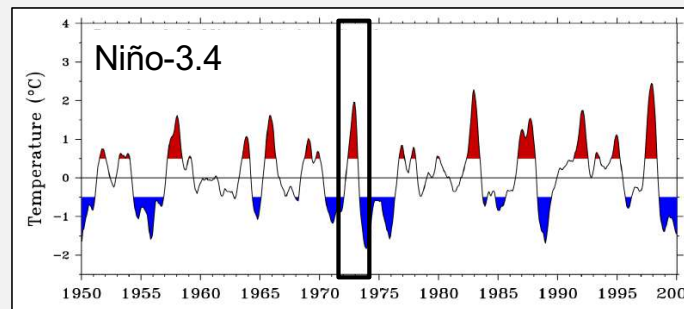
“In the future, we can envision the creation of a worldwide service of...monitoring buoys reporting by way of communication satellites data...to give electronic computers the right input for global dynamic long-range predictions...of the coupled circulations of the atmosphere and ocean.”

*J. Bjerknes
25 Sept 1969
Dublin, Ireland*

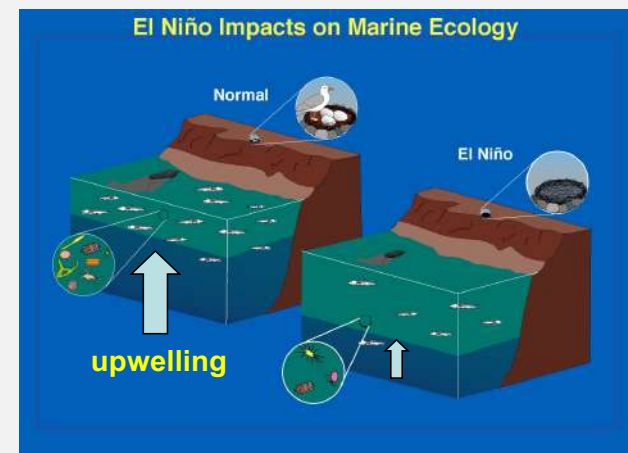
1972-73 El Niño Causes Collapse of Peruvian Anchovy Fishery



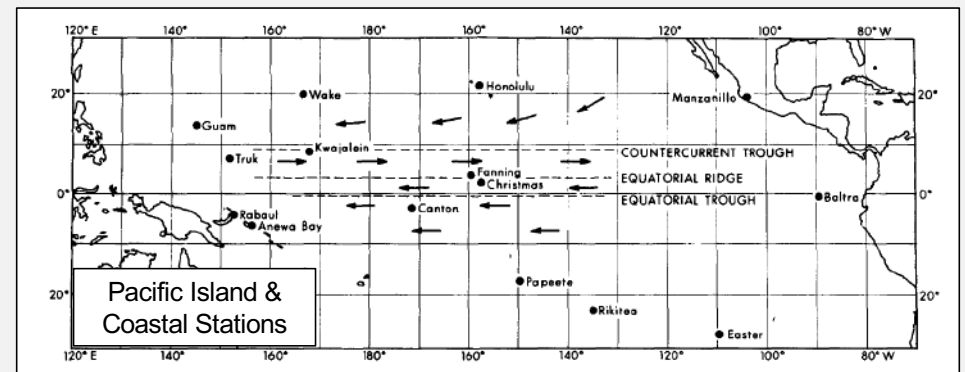
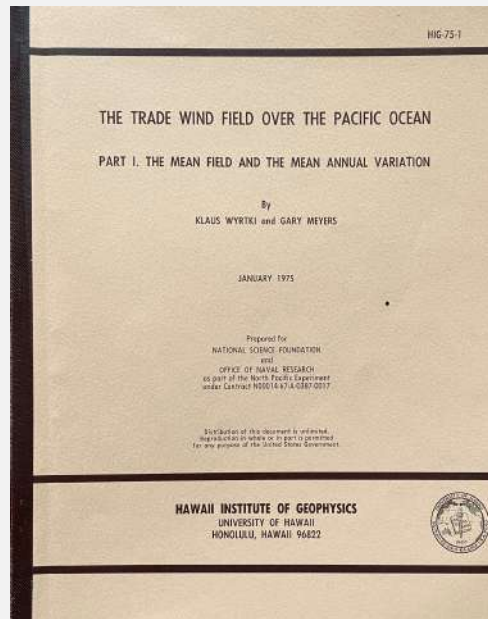
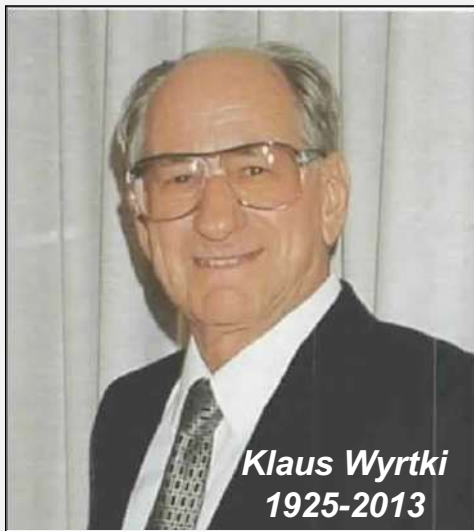
Anchovy fishmeal used as a feed supplement for cattle and poultry → worldwide impacts on food supply and prices



Weakened upwelling led to warming and reduced nutrient supply to the surface layer. Combined with over fishing → collapse of fishery

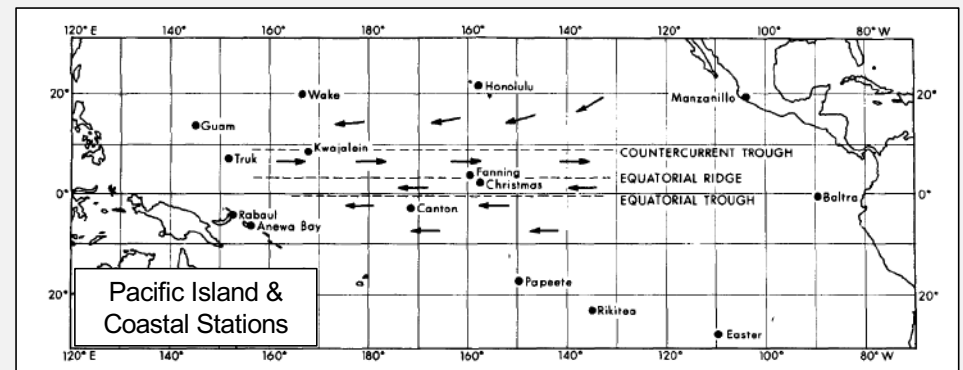
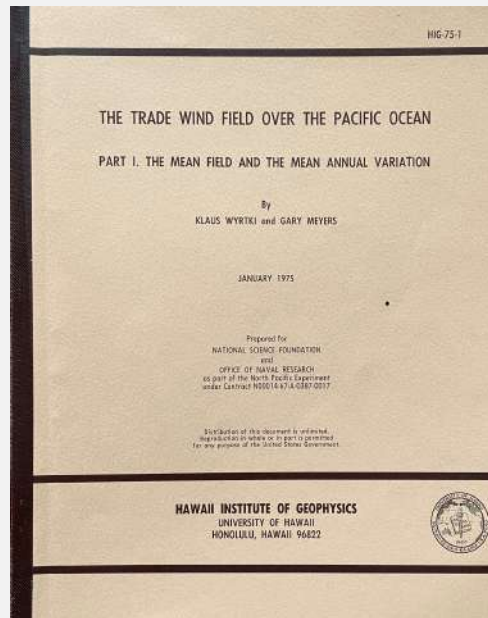
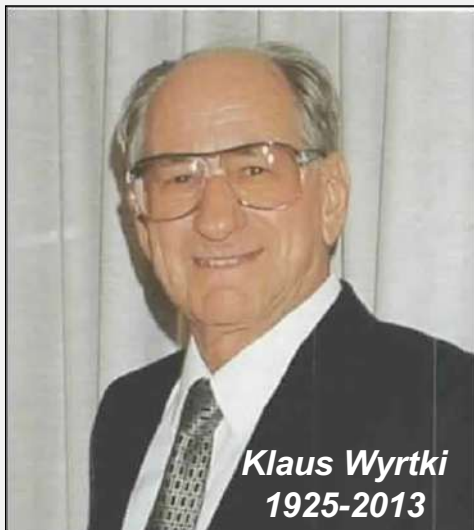


Early 1970s: Klaus Wyrтки Establishes the UH Sea Level Center and Trade Wind Data Base



The first systematic attempt to study basin scale variations relevant to El Niño development

Early 1970s: Klaus Wyrтки Establishes the UH Sea Level Center and Trade Wind Data Base



West Pac Winds Weaken $\xrightarrow{2-3\text{ Months}}$ East Pac Warming

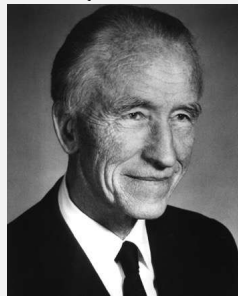
“As soon as the wind stress relaxes, the accumulated water flows eastward, probably in the form of an internal equatorial Kelvin wave.”

--K. Wyrтки, 1975, *J. Phys. Oceanogr*



Unusually Cold Winter of 1976-77 in the U.S. focuses attention on ocean's role in North American climate

Tropical Pacific forcing!



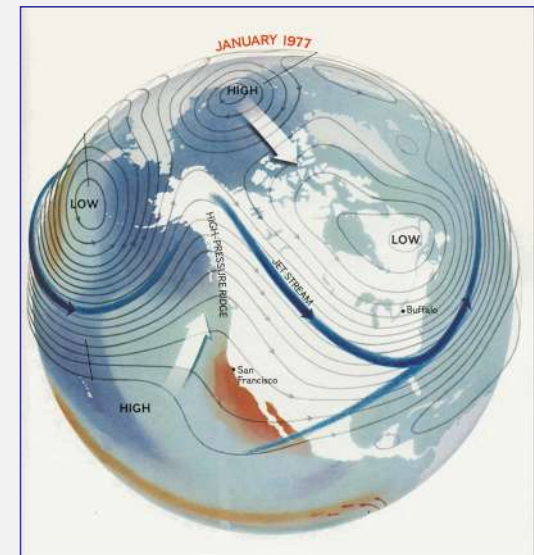
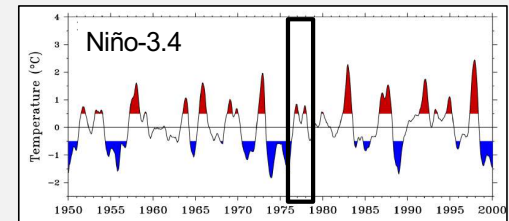
Jacob Bjerknes
1897-1975

Nope! Mid-latitude SSTs!



Jerry Namias
1910-1997

North Pacific Experiment (NORPAX) established to test competing of ideas

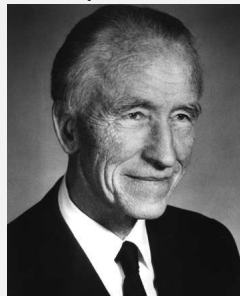


National Geographic, Dec 1977



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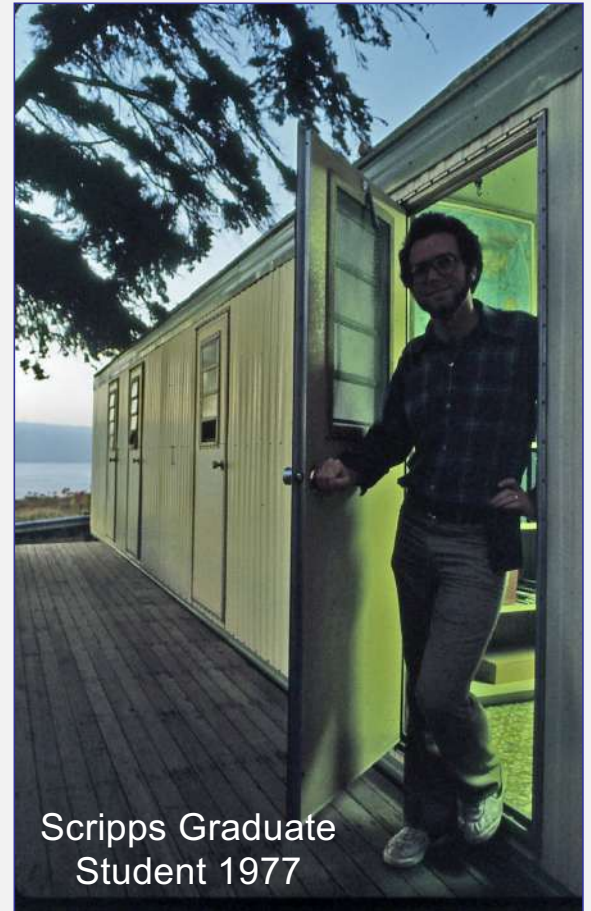
Jacob Bjerknes
1897-1975

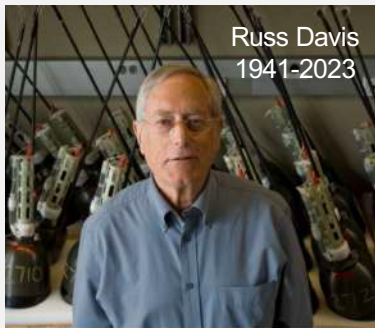
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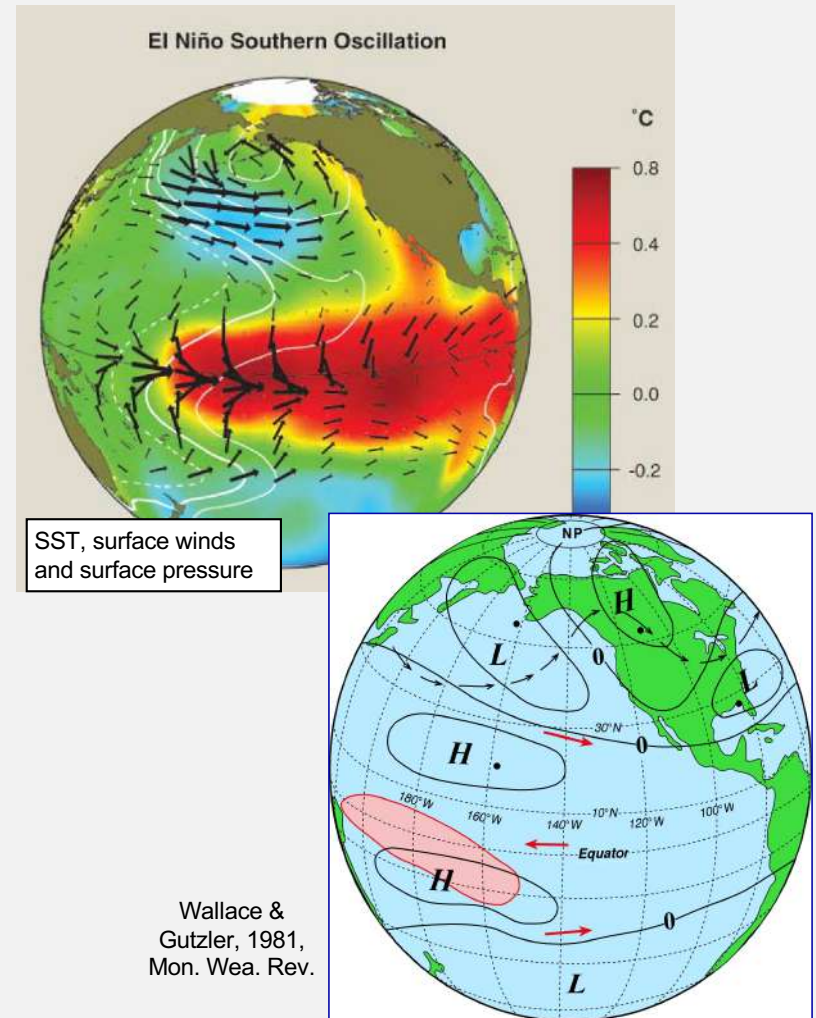
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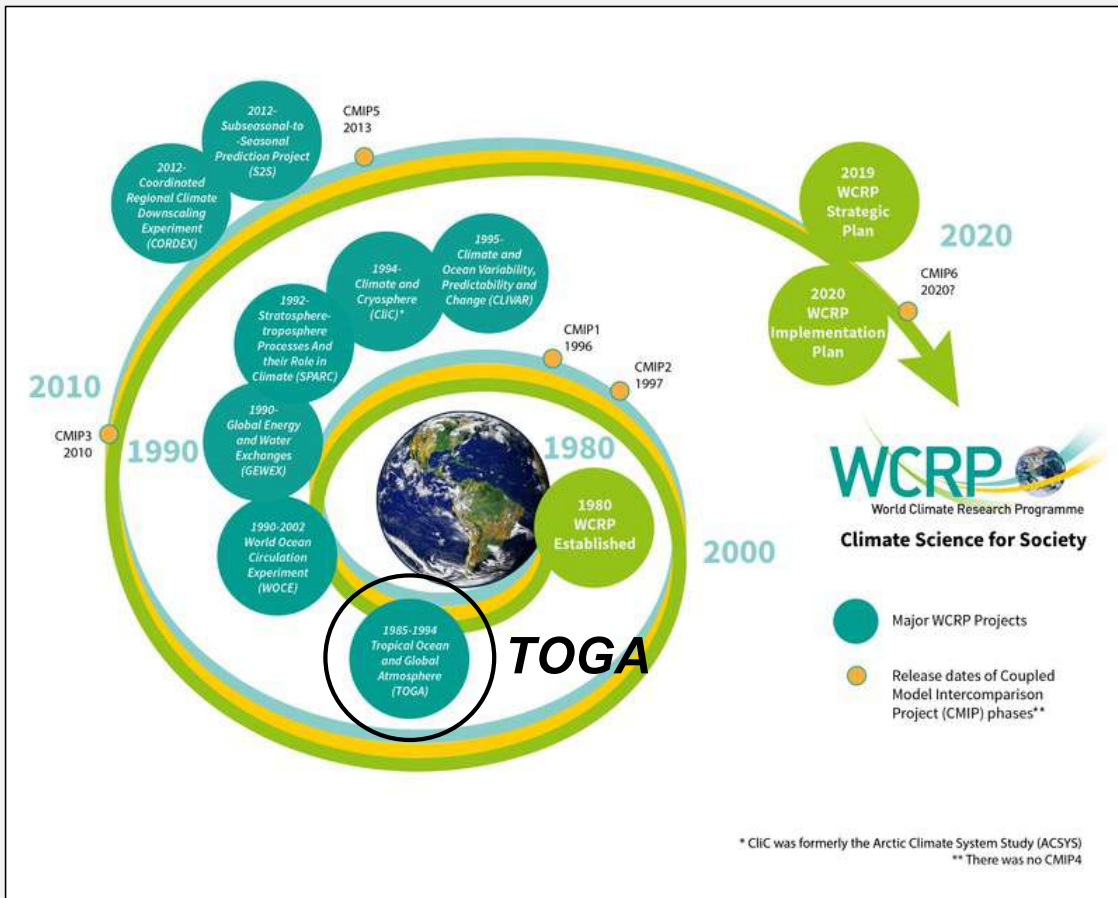




Bjerknes Prevails

- Davis, 1976: SLP leads SST variations
→ NPac atmosphere forces the ocean rather than the other way around
- Wallace and Gutzler, 1981: PNA pattern
→ Mid-latitudes (atmosphere, ocean and land) are forced by anomalous tropical Pacific heating





World Climate Research Program established in 1980

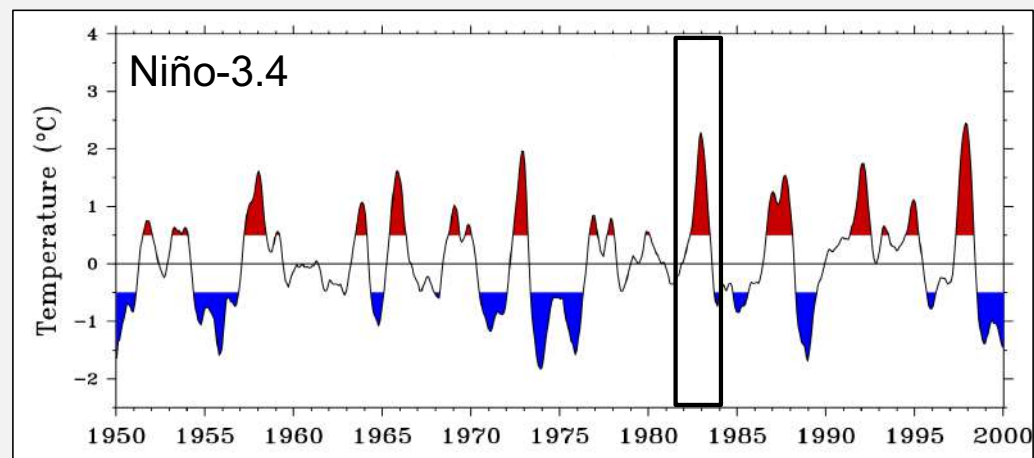
“to determine the predictability of climate and assess the influence of human activities on it through coordinating global efforts to understand the Earth’s climate system.”

*First Major Initiative:
A study of El Niño named TOGA*



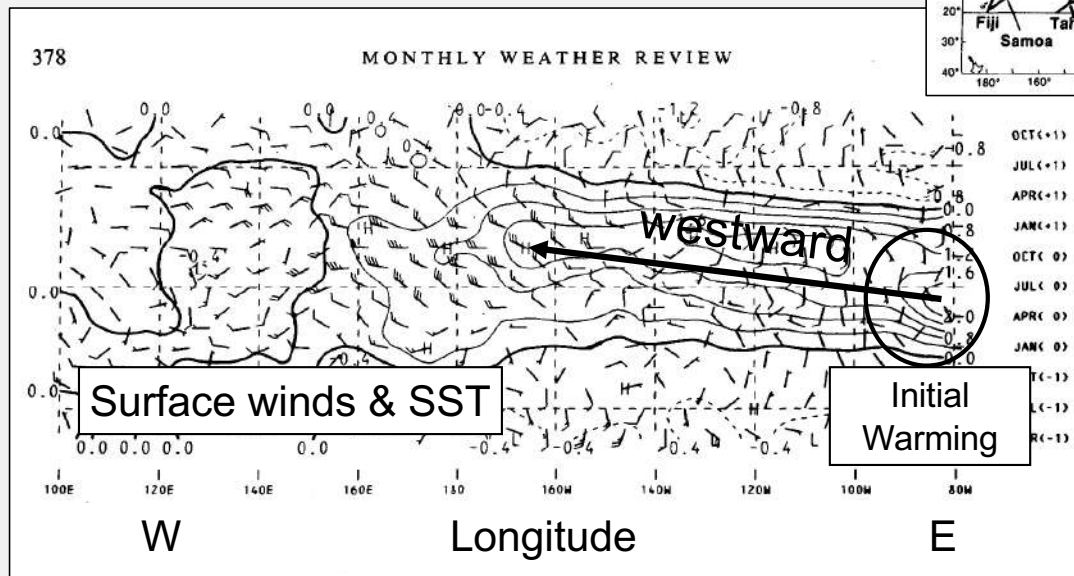
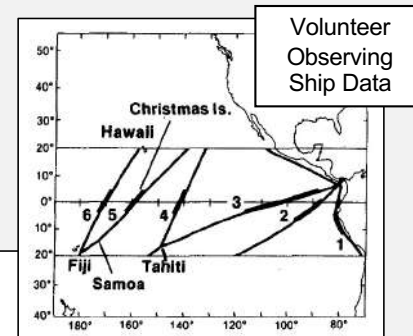
1982-83 El Niño:

- Strongest of the 20th century
- Not predicted
- Not detected until at almost its peak:
 - ✓ Satellite sea temperatures biased cold by El Chicon
 - ✓ No real-time ocean data





Rasmusson & Carpenter Composite El Niño



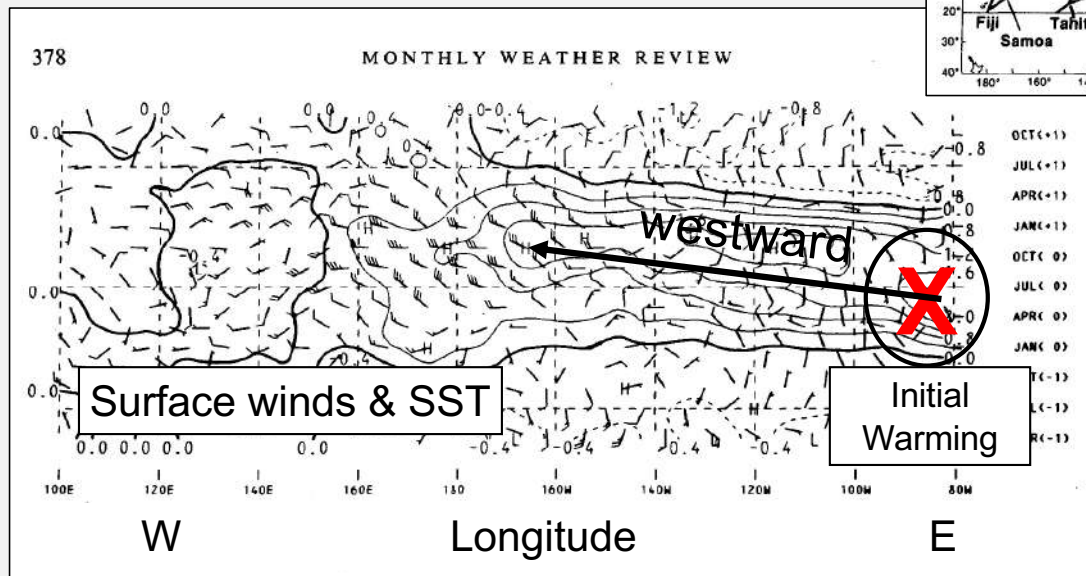
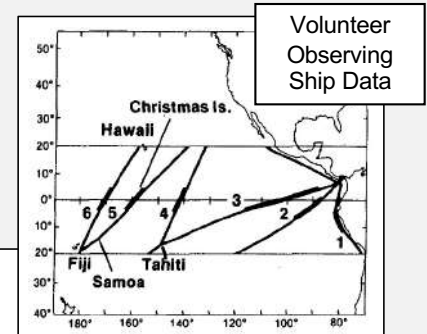
Phases of El Niño

- Onset: Nov (-1)-Jan (0)
- **Peak: Mar-May (0)**
- Transition: Aug-Oct (0)
- Mature: Dec (0)-Jan (+1)
- Demise: May-Jul (+1)

Composite El Niño based on 6 events, 1950-72
Mon. Wea. Rev., 1982



Rasmusson & Carpenter Composite El Niño



Phases of El Niño

- Onset: Nov (-1)-Jan (0)
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Composite El Niño based on 6 events, 1950-72
Mon. Wea. Rev., 1982

Confusion

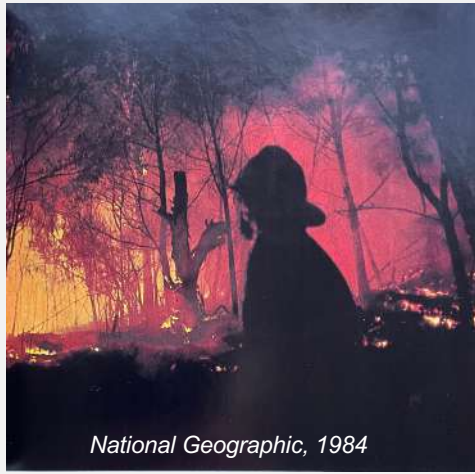
“To call this El Niño would be a case of child abuse!”



Klaus Wyrcki
TOGA Planning Workshop
Princeton University
October 1982

Monster 1982-83 El Niño With Devastating Worldwide Consequences

- How little we knew
- How we failed to observe
- How ill-prepared we were

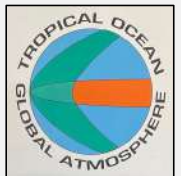


Tropical Ocean Global Atmosphere (TOGA) Program

1985-1994

Goals:

- Understand underlying mechanisms for El Niño
- Develop forecast models for predicting seasonal climate variations
- Establish a real-time observing system to support research and forecasting



First Successful Prediction 1986-87 El Niño



Mark Cane

NATURE VOL. 321 26 JUNE 1986 ARTICLES 827

Experimental forecasts of El Niño

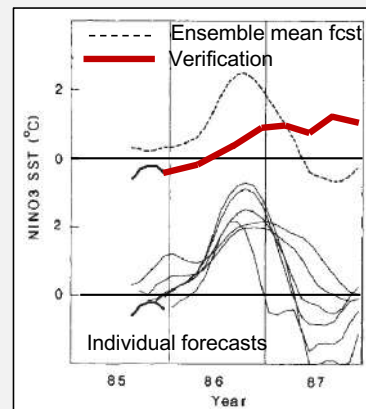
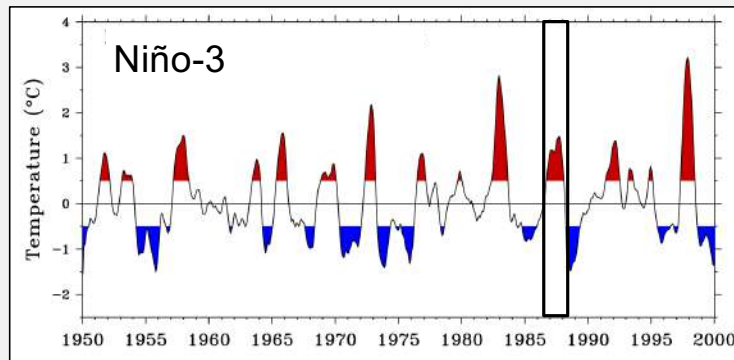
Mark A. Cane, Stephen E. Zebiak & Sean C. Dolan

Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964, USA

Experimental forecasts of El Niño events occurring since 1970, made with a deterministic model of the coupled ocean-atmosphere system, indicate that El Niño is generally predictable one or two years ahead. A forecast for 1986 is also presented.

THE devastating climatic events of 1982-83 were the most recent extreme phase of the irregular cycle of atmospheric and oceanographic changes known collectively as El Niño and the Southern Oscillation (ENSO)¹⁻⁵. If forecasts could provide sufficient

phere and oceans, allowing his original framework to be bolstered and elaborated. Our theory and model design draw on this collective progress^{1,14}, only a brief sketch of which is possible here.



Simplified coupled ocean-atmosphere dynamical model of the tropical Pacific based on physical principles

Heat content: the Source of ENSO Predictability

“Our focus on heat content of the equatorial band arose from theoretical considerations and numerical model results....On the basis of tide gauge data, Wyrтки has independently advanced a similar hypothesis.”

--Cane et al, *Nature*, 1986

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. C4, PAGES 7129–7132, JULY 20, 1985

Water Displacements in the Pacific and the Genesis of El Nino Cycles

KLAUS WYRTKI

Department of Oceanography and Hawaii Institute of Geophysics, University of Hawaii, Honolulu

Sea level observations are used to estimate the amounts of warm water exchanged during the 1982–1983 El Nino event, indicating an eastward flux of about $40 \times 10^6 \text{ m}^3 \text{ s}^{-1}$. At the end of El Nino the equatorial Pacific is depleted of warm water which is lost toward higher latitudes. The duration of a complete El Nino cycle is determined by the time required for the slow accumulation of warm water in the western Pacific. The cycle constitutes an energy relaxation of the ocean-atmosphere system.

“The duration of a complete El Niño cycle is determined by the time required for slow accumulation of warm water in the western Pacific.”

--Wyrтки, *JGR*, 1985

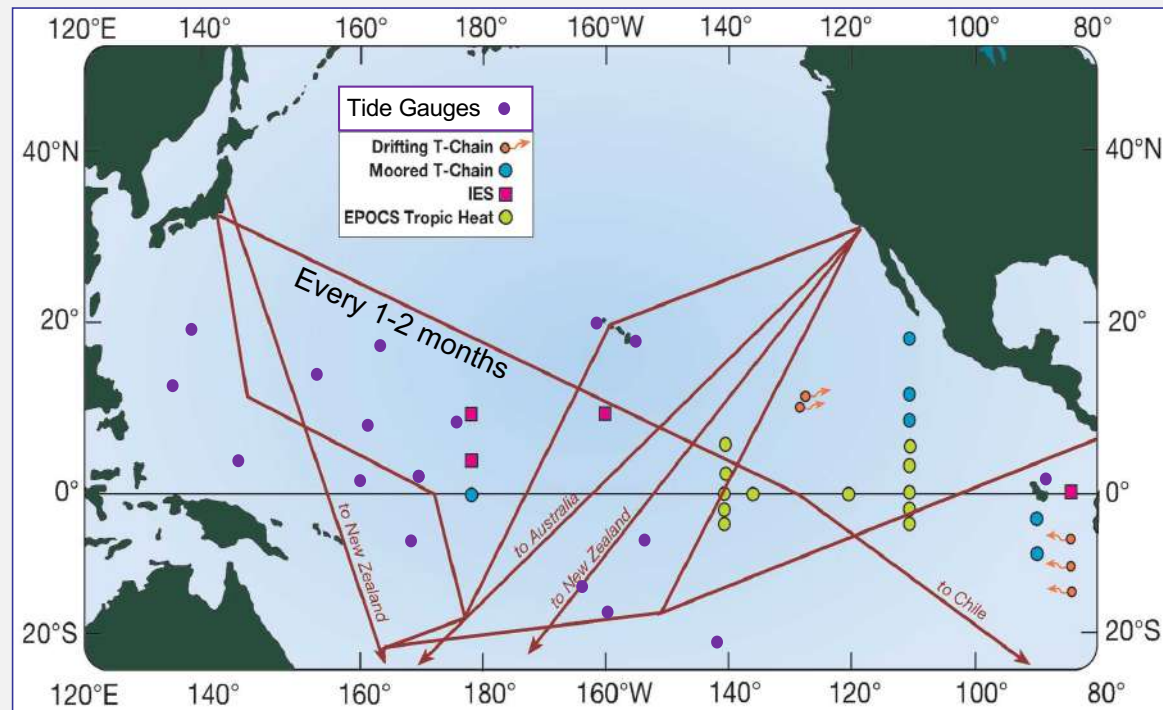
“Throw spaghetti at a wall to see what sticks”



An Early Concept (Spaghetti)

The challenge:

- Basin scale
- Real-time
- Daily resolution

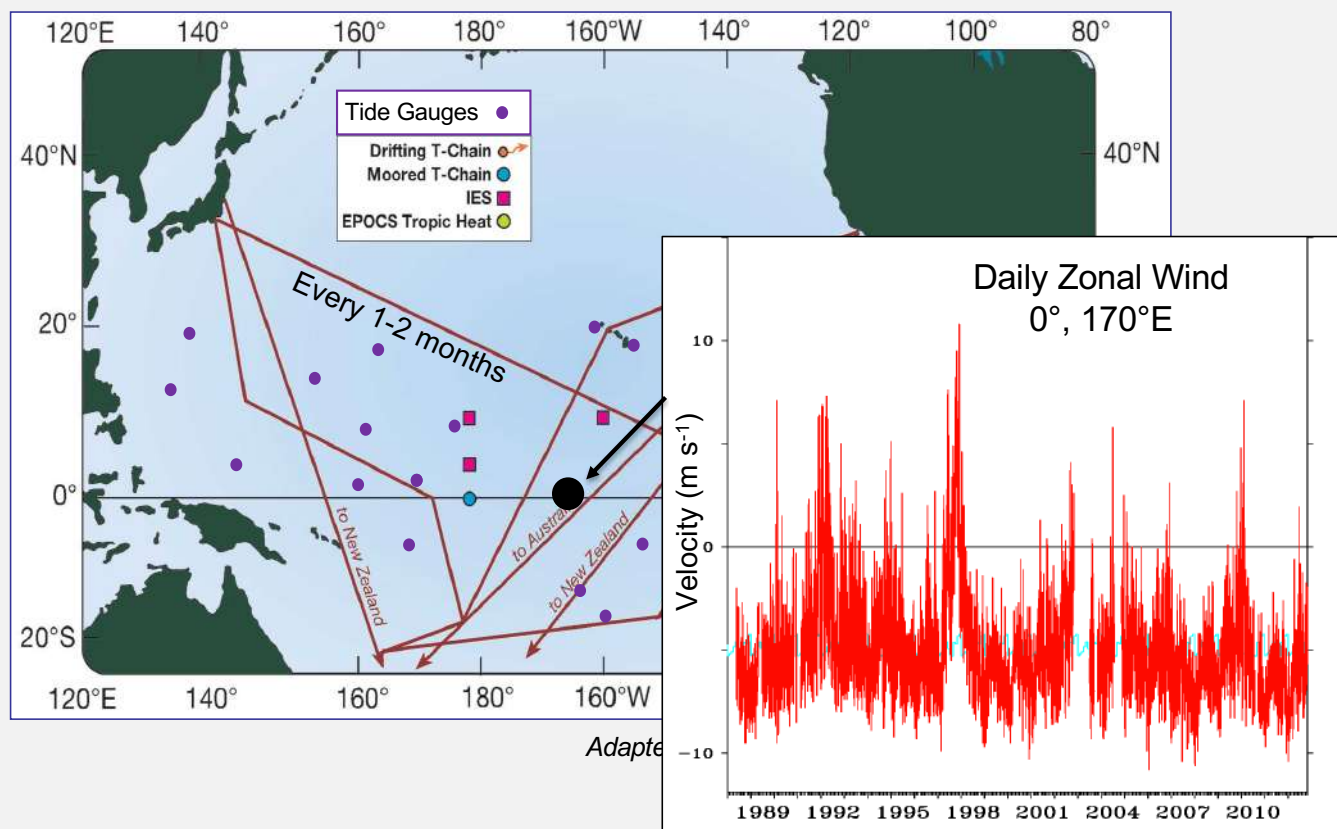


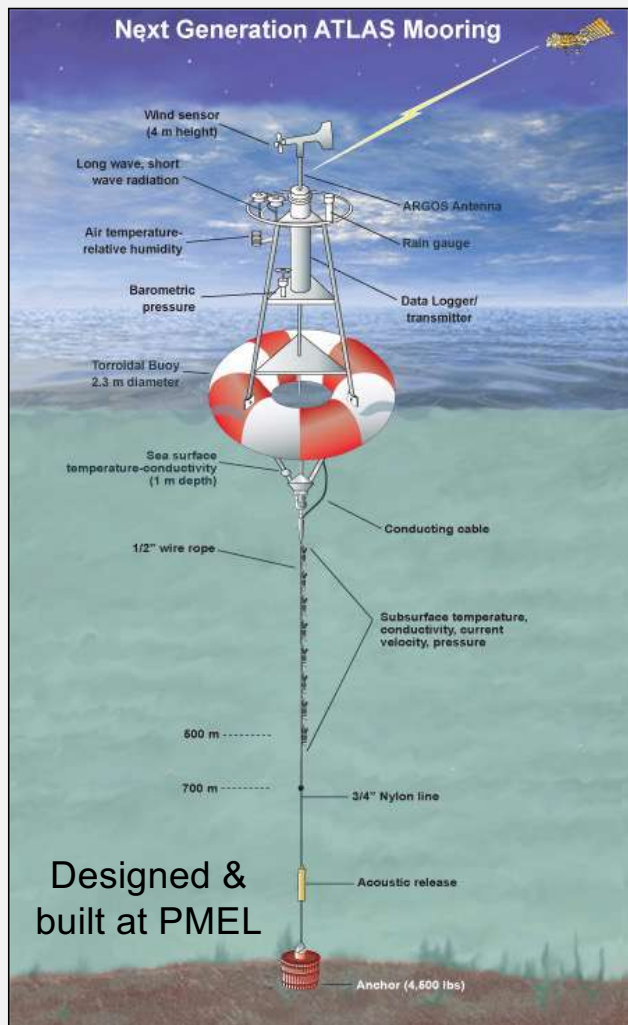
Adapted from McPhaden and Taft, 1984, USTOGA3

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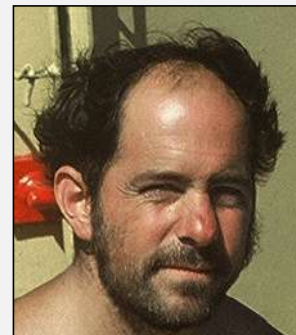




ATLAS* Mooring

Key measurements:

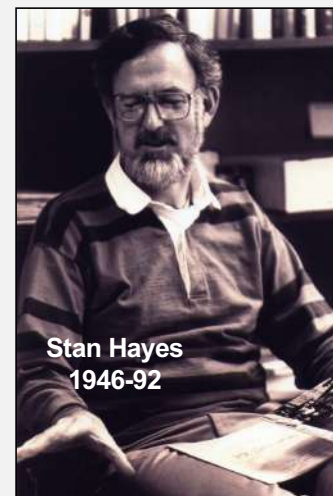
- Surface winds
- SST
- Temperature in the upper 500 m (Heat content)



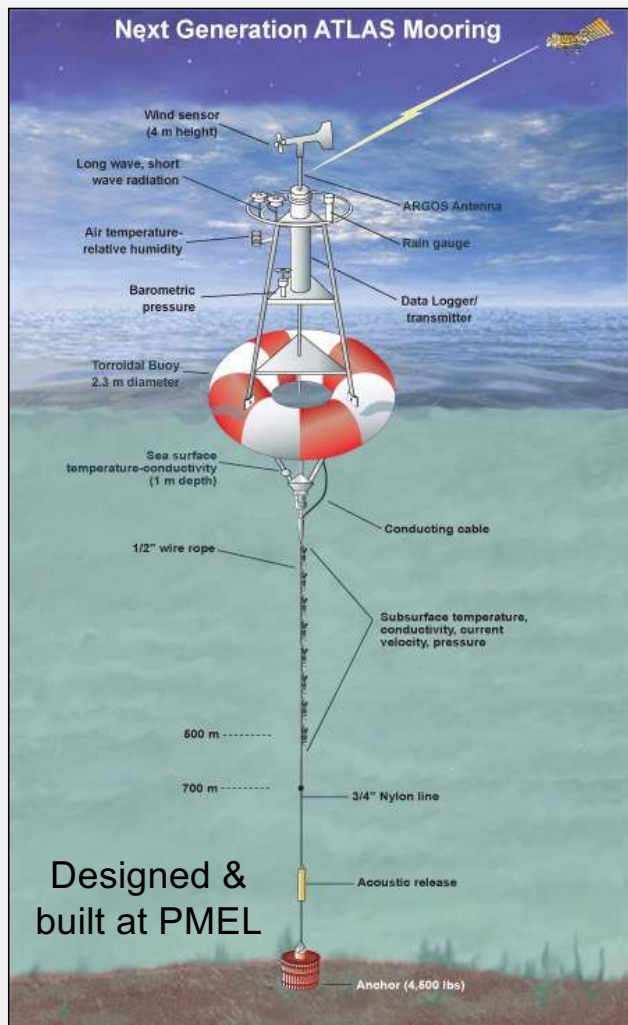
Hugh Milburn
1944-2020

- ✓ Real-time data
- ✓ Data every day
- ✓ Low cost

*ATLAS=Autonomous Temperature Line Acquisition System



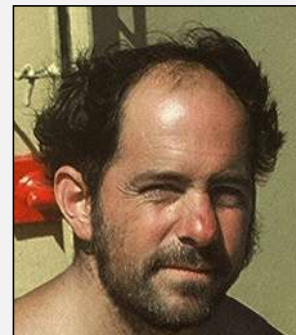
Stan Hayes
1946-92



ATLAS* Mooring

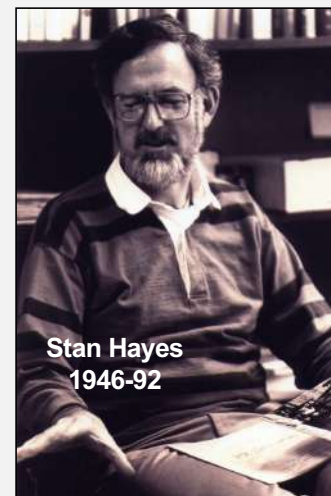
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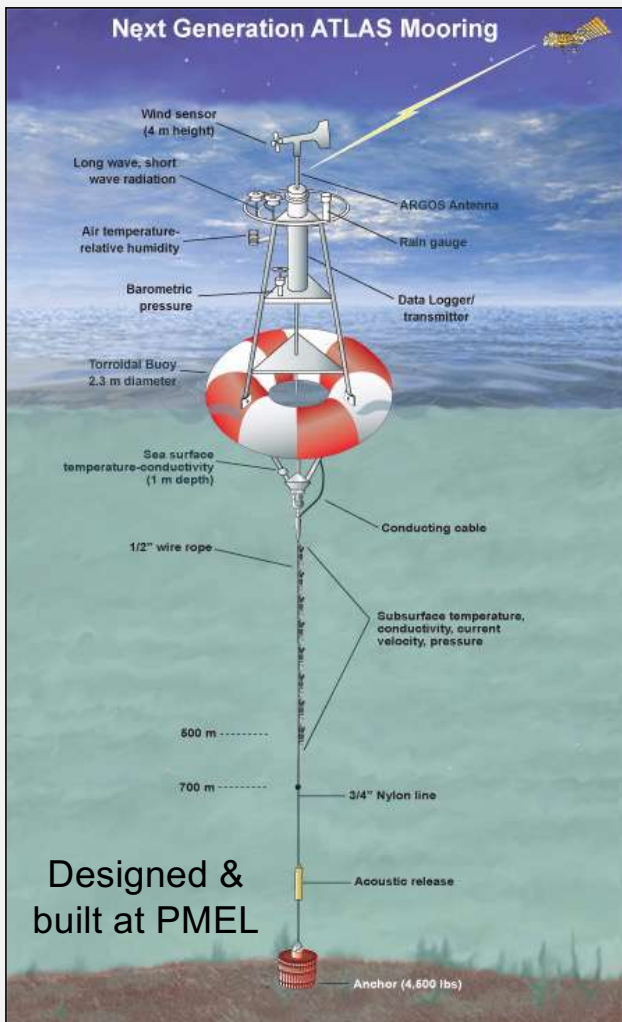


Hugh Milburn
1944-2020

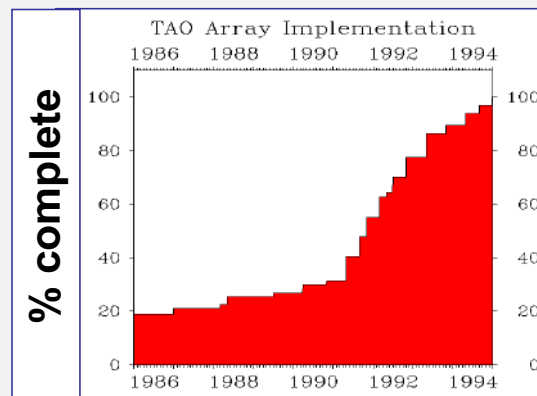
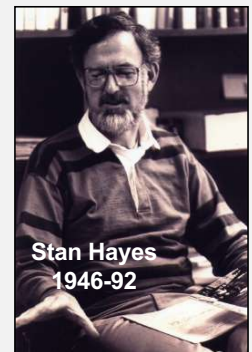
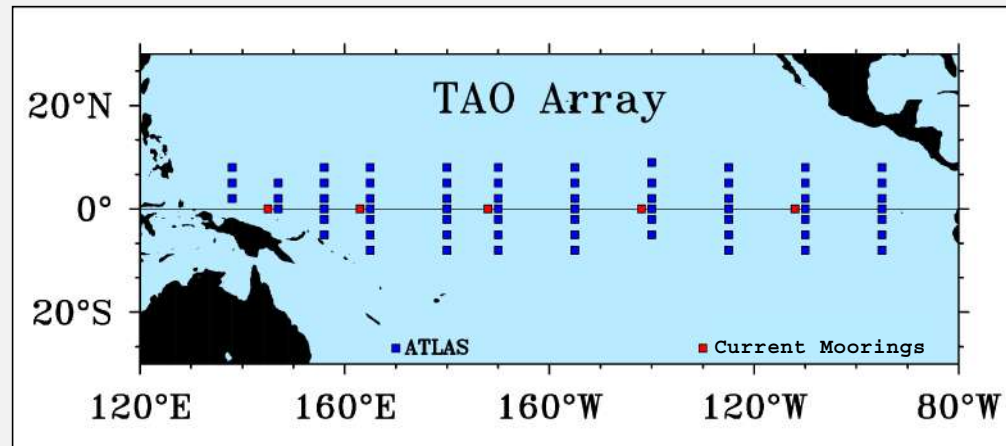
Eliminate current meters!



Stan Hayes
1946-92



Tropical Atmosphere Ocean (TAO) Array



Partners: US, France, Japan, Taiwan, Korea

Took the entire 10 years of TOGA to build

Satellite Missions



SST

NOAA Weather satellites (1981-)



SSH

GEOSAT (1985-1989)



SSH

Vector Winds

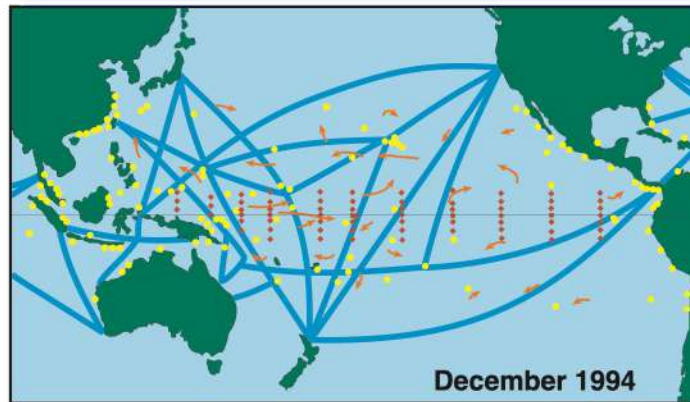
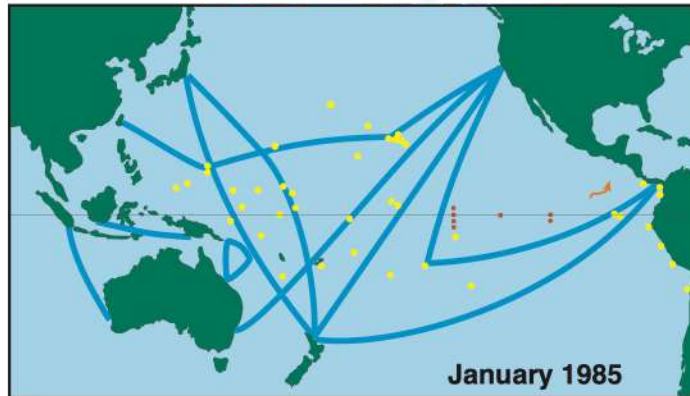
ERS-1/2 (1991-)



SSH

TOPEX-Poseidon (1992-)

TOGA In Situ Observing System



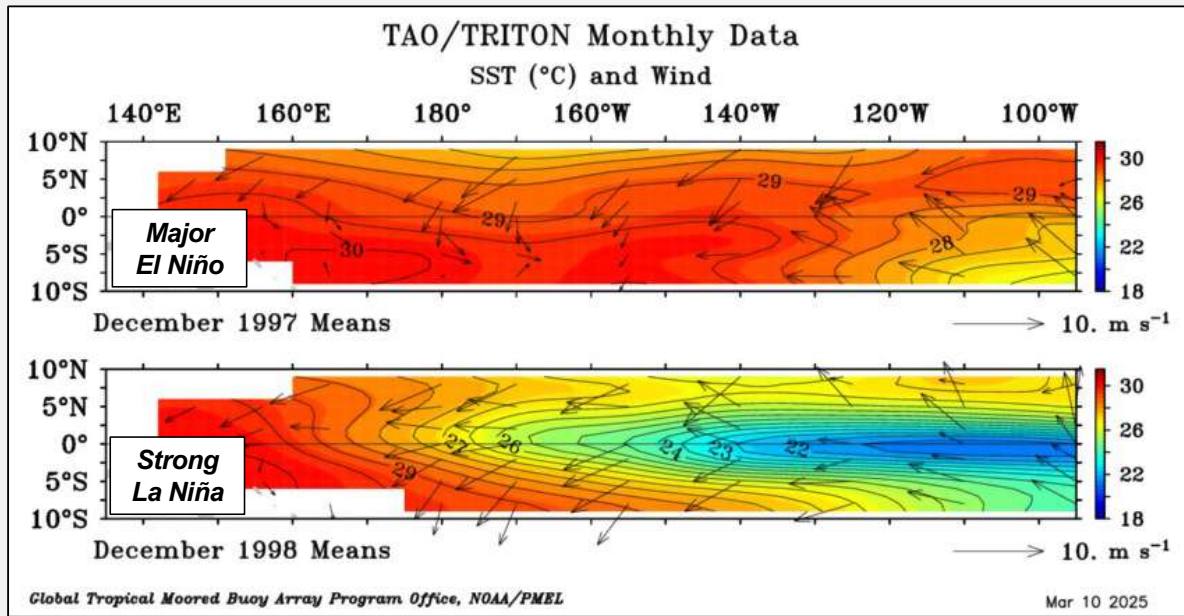
McPhaden et al, 1998, JGR

First Month
of TOGA

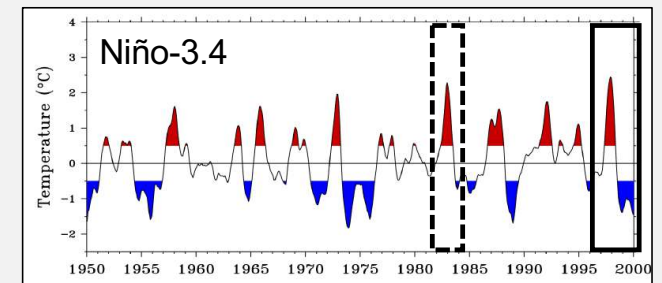
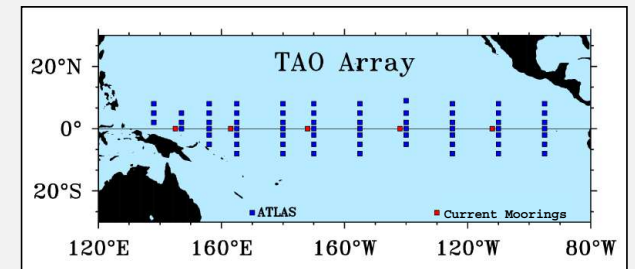
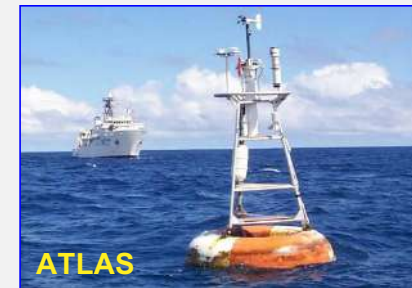
Last Month
of TOGA

“...the crowning achievement of TOGA was the development of the TAO array...”
--EOS, Trans. AGU, 1997

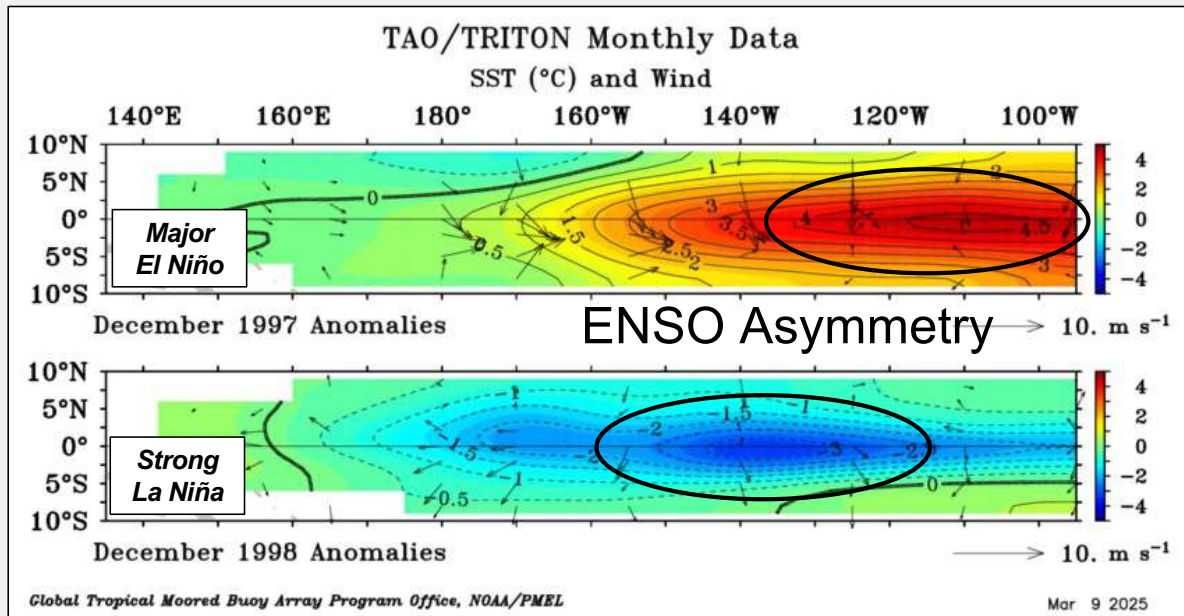
December 1997 vs December 1998



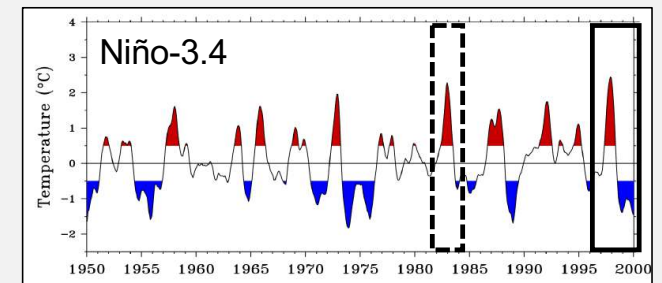
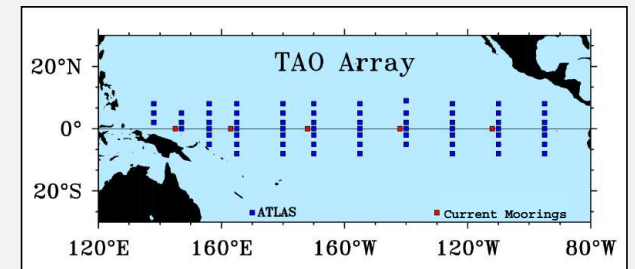
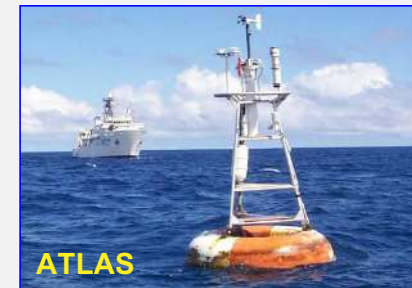
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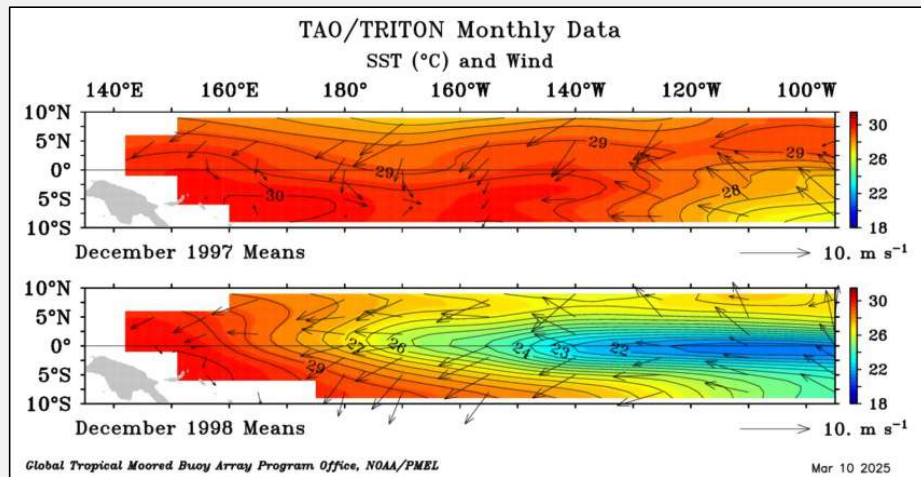


December 1997 vs December 1998

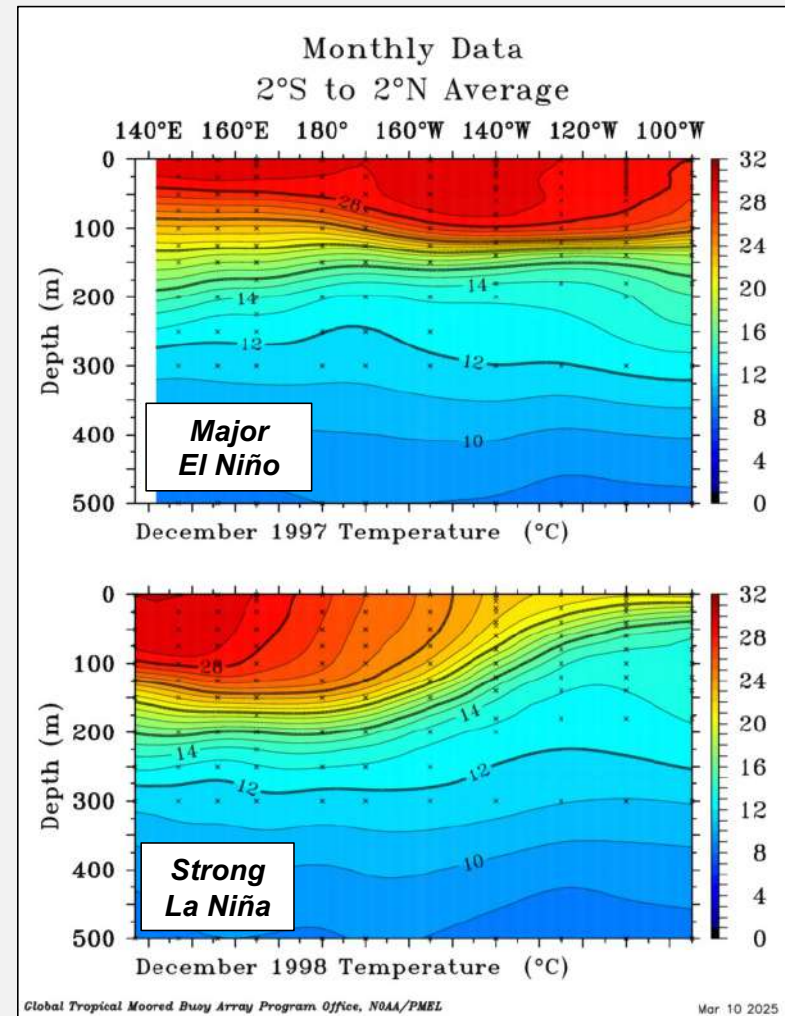


<https://www.pmel.noaa.gov/tao/drupal/disdell/>





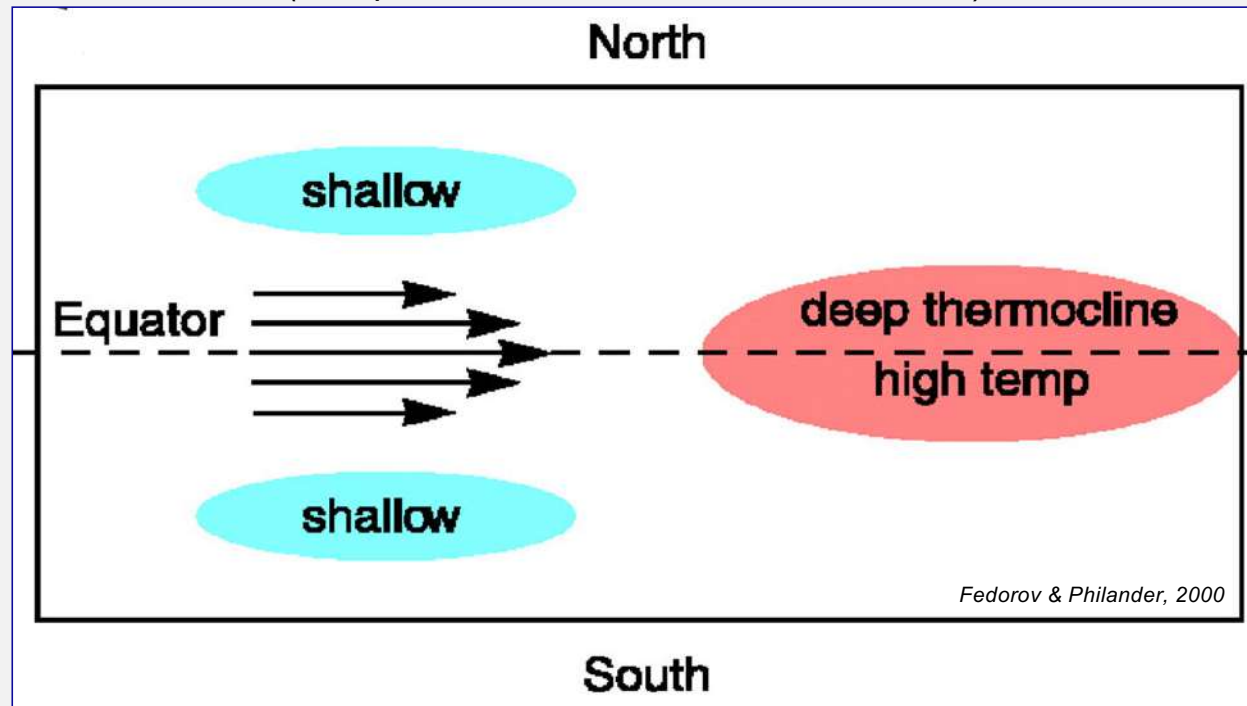
December 1997 vs December 1998



<https://www.pmel.noaa.gov/tao/drupal/disdel/>

Delayed Oscillator

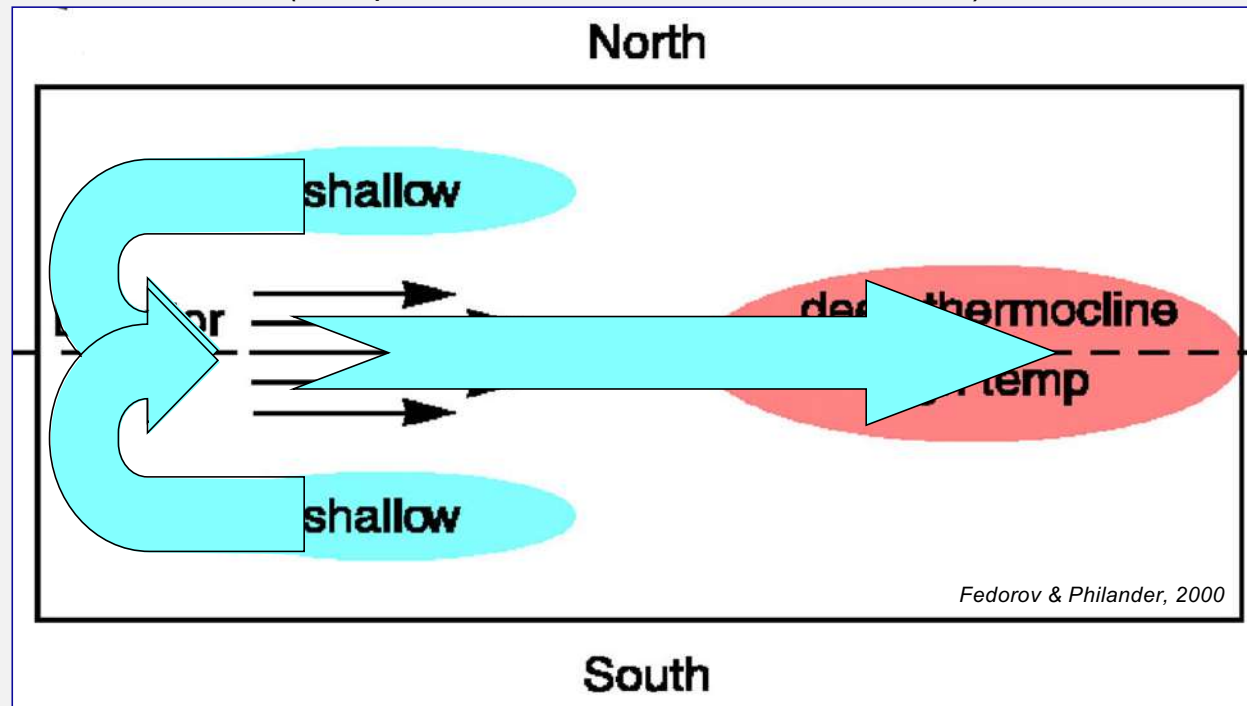
(Schopf & Suarez, 1988; Battisti & Hirst, 1989)



1. Winds weaken \Rightarrow Downwelling Kelvin wave to the east, upwelling Rossby wave to the west.
2. Upwelling Rossby wave reflects at western boundary as upwelling Kelvin wave.
3. Upwelling Kelvin wave shoals thermocline, cools the eastern Pacific cold tongue, shutting down El Niño and triggering La Niña.

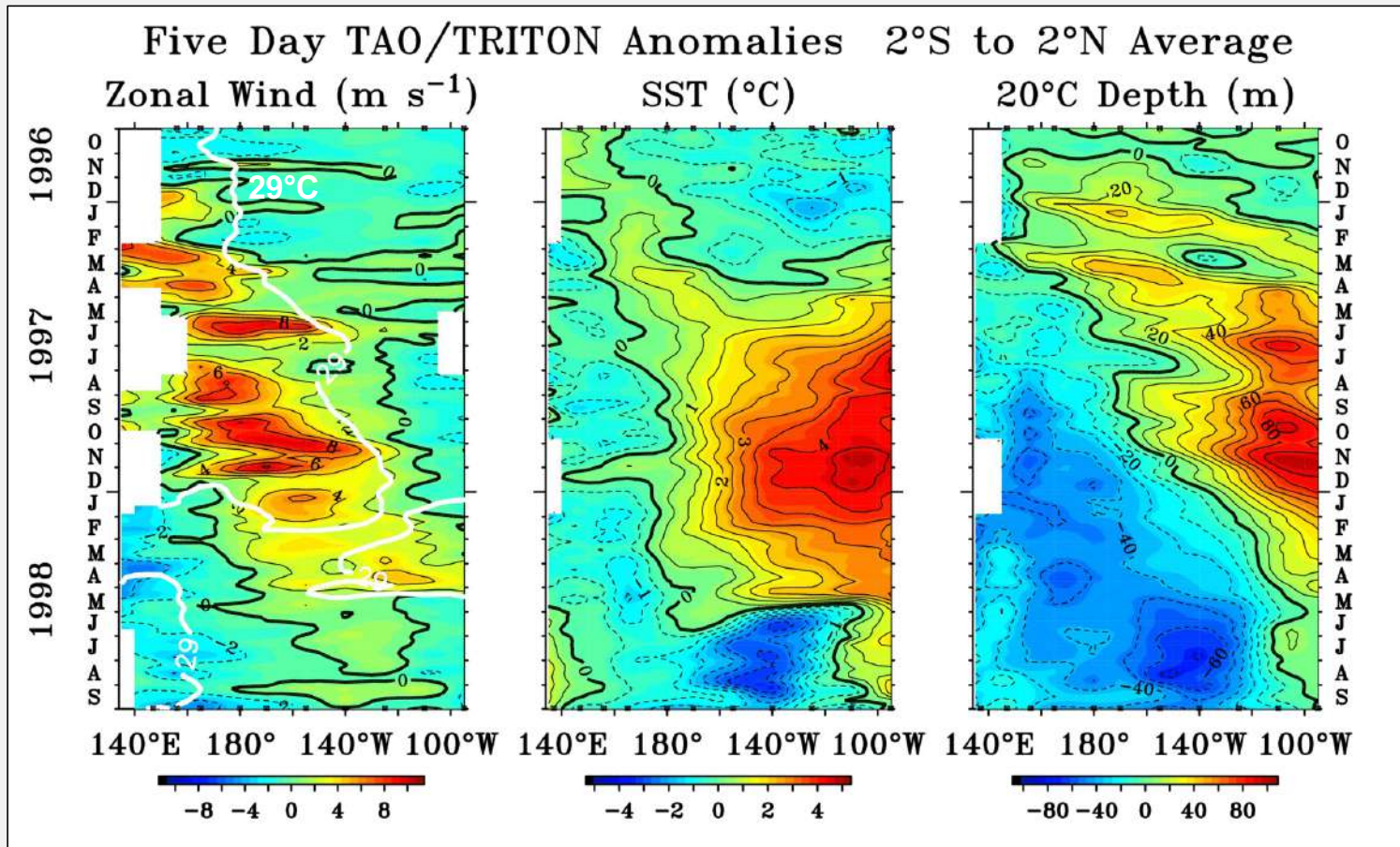
Delayed Oscillator

(Schopf & Suarez, 1988; Battisti & Hirst, 1989)



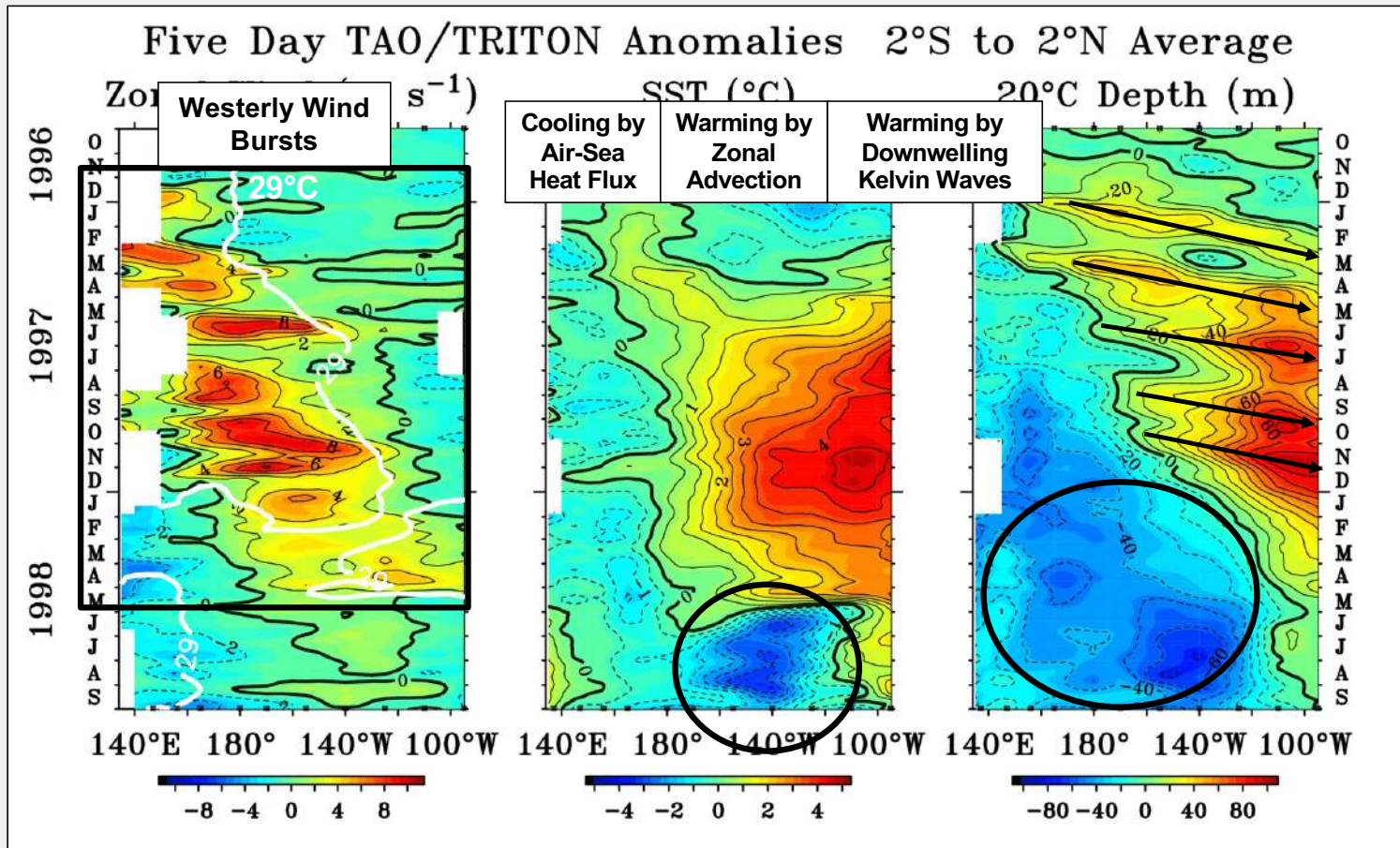
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Evolution of the 1997-98 El Niño



McPhaden, 1999, *Science*

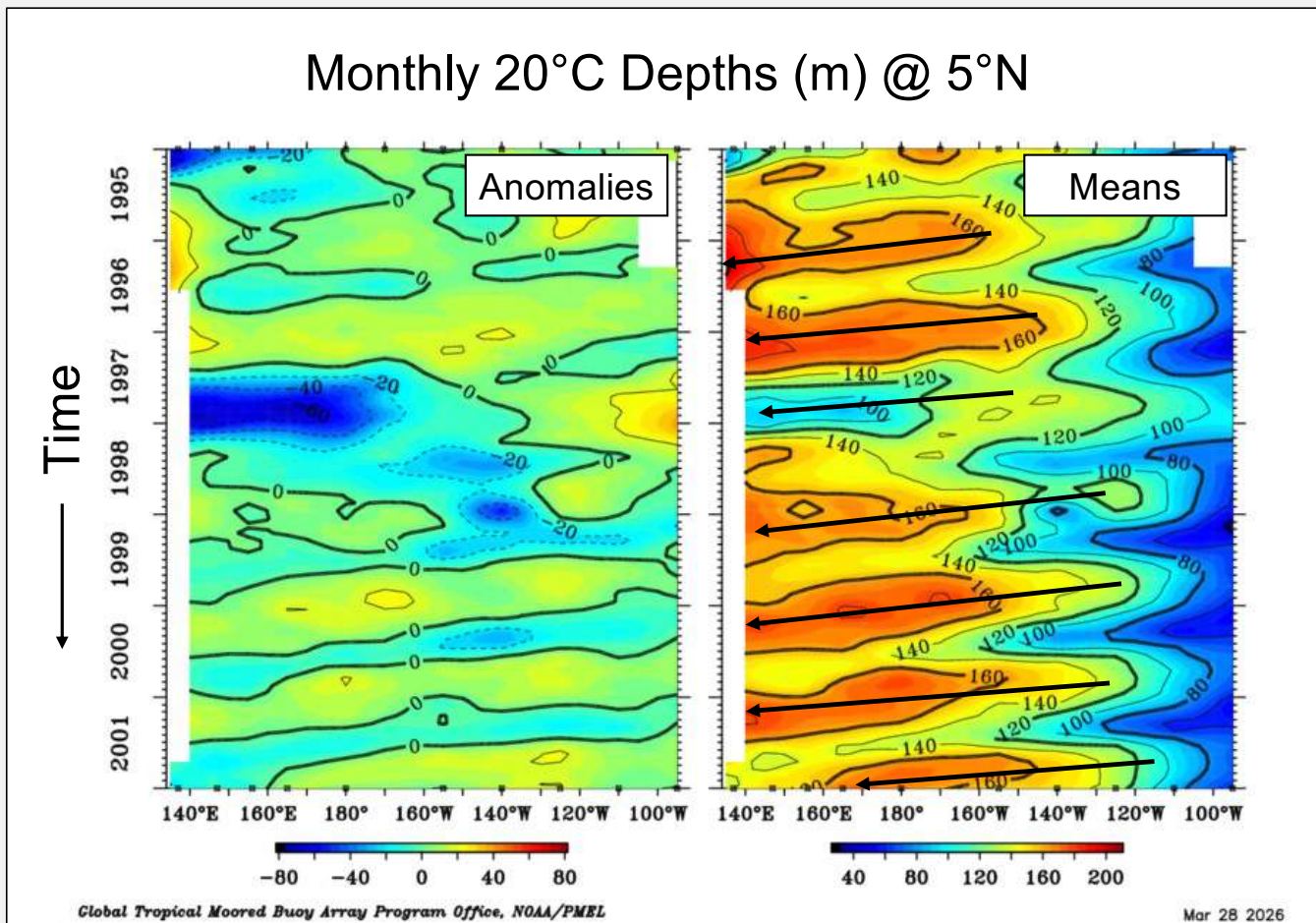
Evolution of the 1997-98 El Niño



McPhaden, 1999, Science

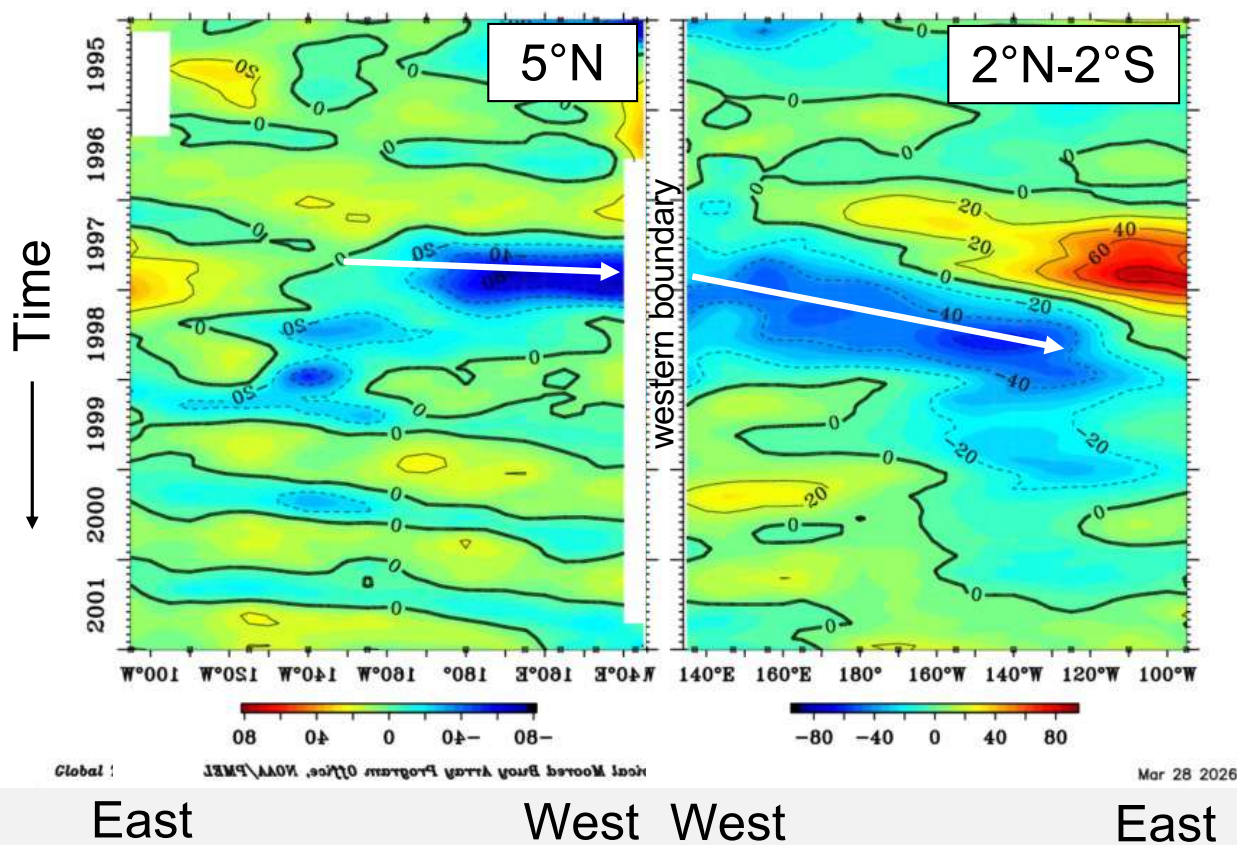
Equatorial Rossby Waves

Monthly 20°C Depths (m) @ 5°N



Rossby Wave to Kelvin Wave Reflection

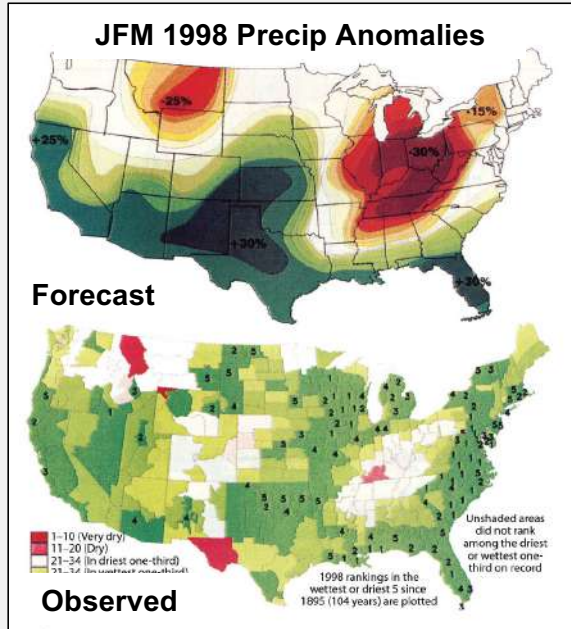
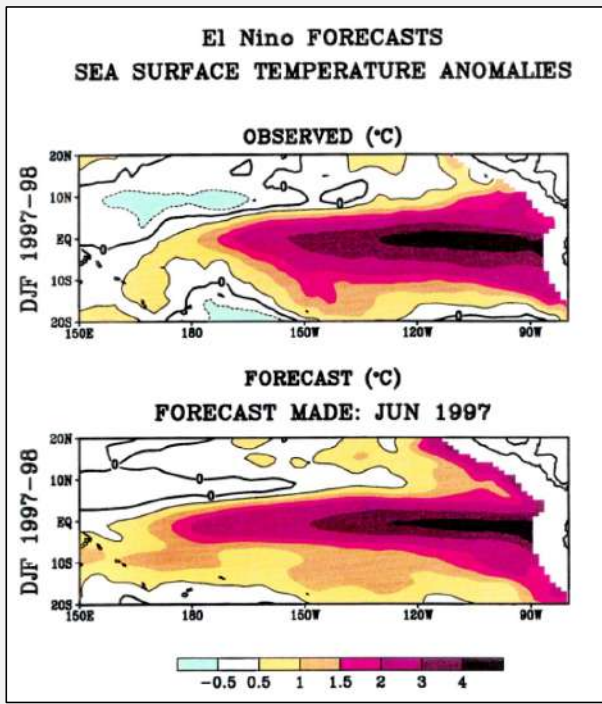
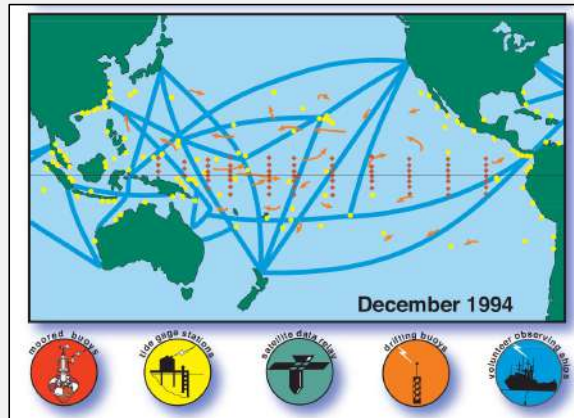
Monthly 20°C Depths (m)



McPhaden & Yu
1999, GRL

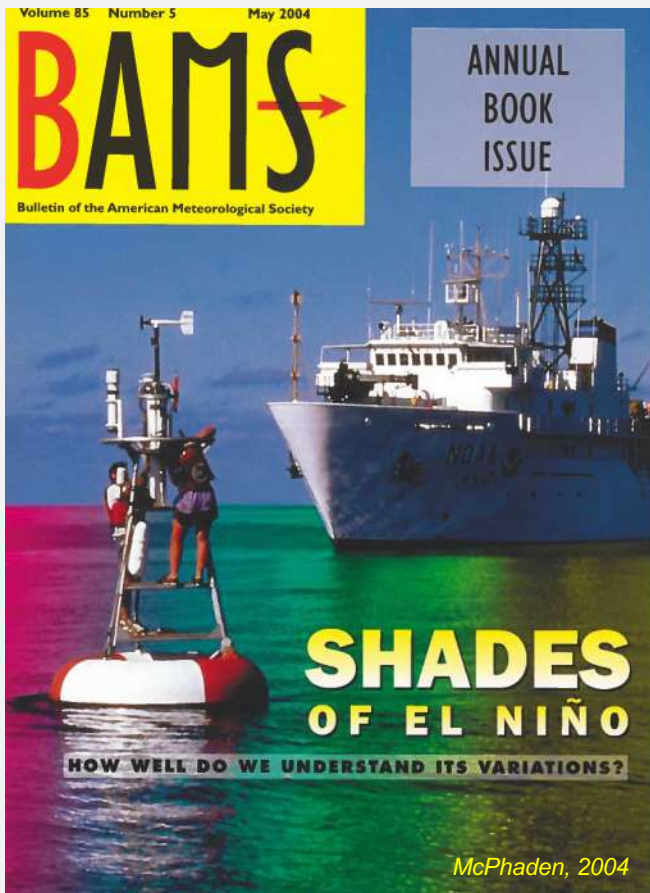
The TAO array was an "...invaluable source of data for monitoring and modeling...." the 1997-98 El Niño.

--Secretary General, WMO, 1998

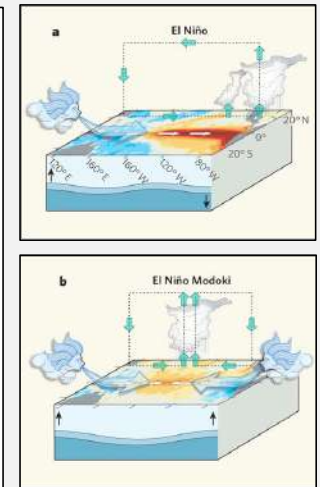
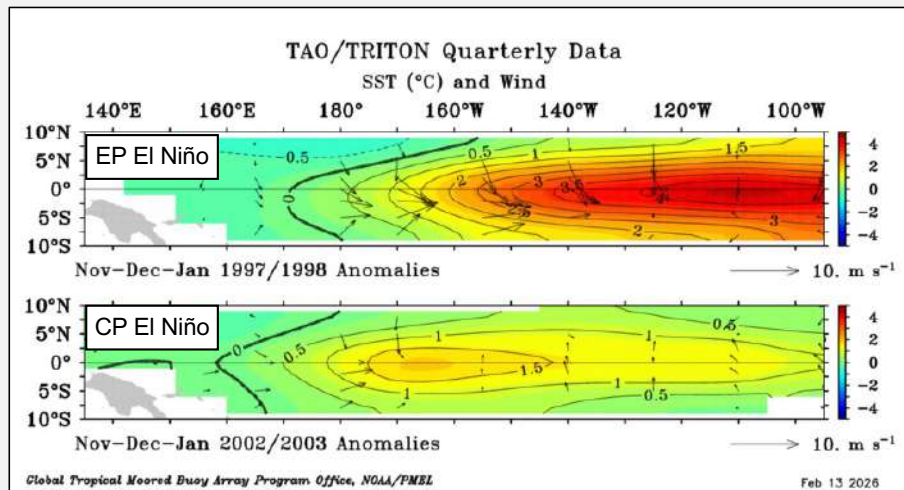


1997-98 El Niño

Highlights the success of TOGA (1985-94) – a revolution in observing, understanding and predicting seasonal climate variability



Startling Contrast Between 2002-03 and 1997-98 El Niños



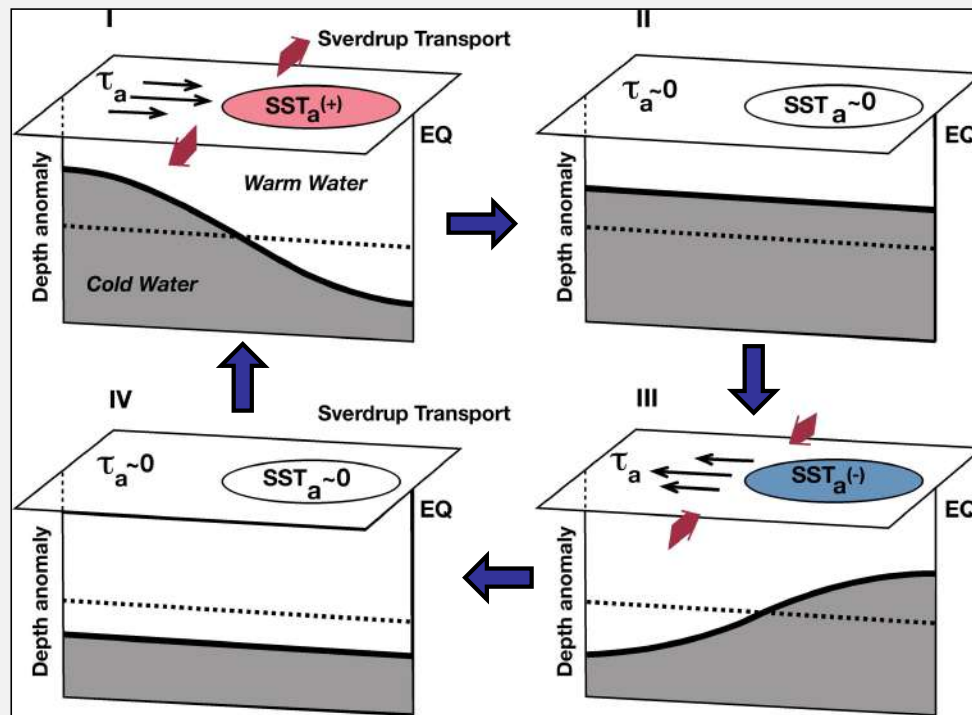
Ashok, 2009, Nature

“The uniqueness of the 2002/03 El Niño illustrates the point that no two El Niños are exactly alike and that event-to-event differences can have significant socioeconomic consequences.”

Ashok et al., 2007, JGR, El Niño Modoki
 Yu and Kao, 2009, J. Clim., EP and CP El Niño
 Capotondi et al, 2015, BAMS, ENSO Diversity
 Timmerman et al, 2018, Nature, ENSO Complexity

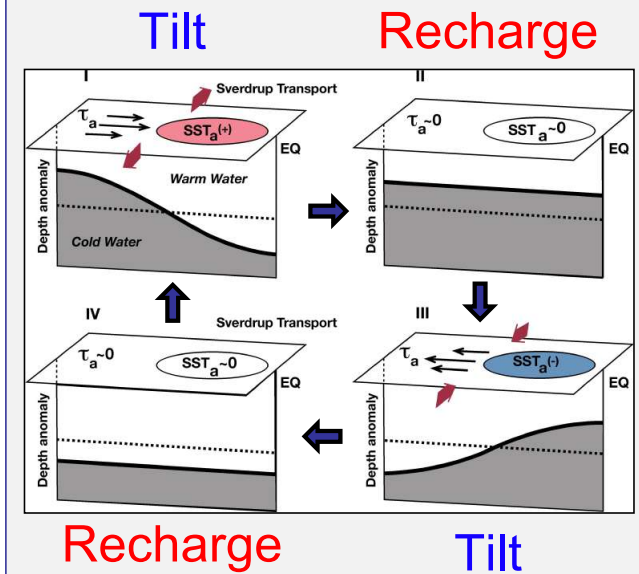
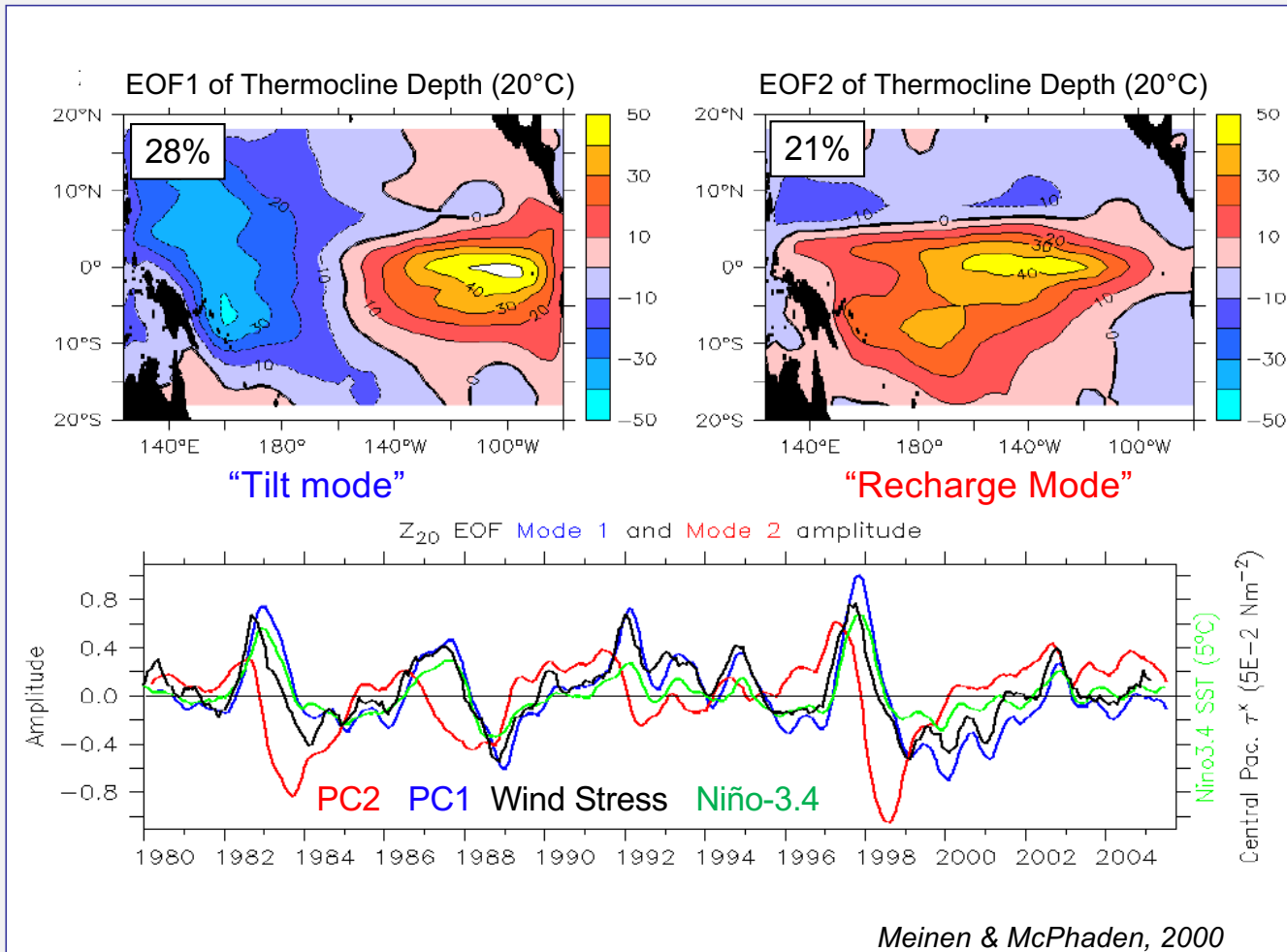
Recharge Oscillator Theory

(Wyrtki, 1985; Cane et al, 1986; Jin, 1997)

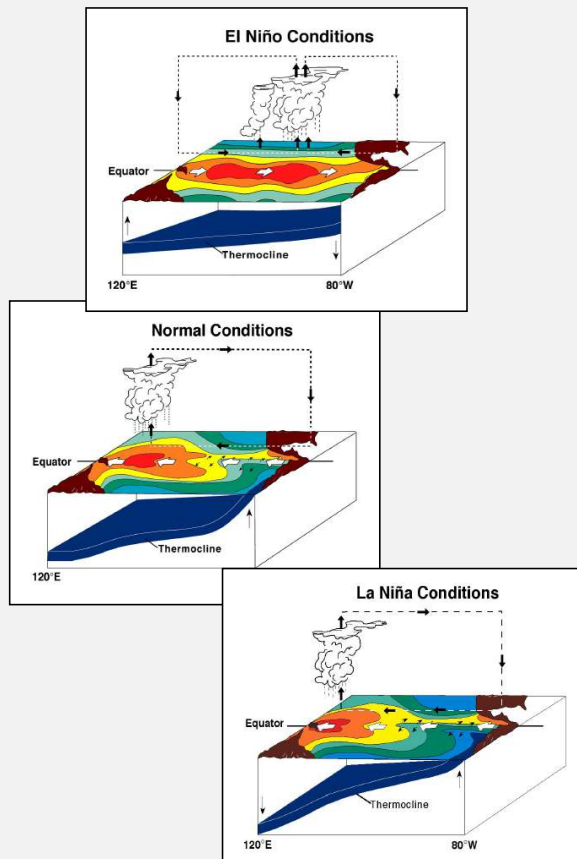


- Build-up of excess heat content along equator is a necessary precondition for El Niño to occur.
- El Niño purges excess heat to higher latitudes, which terminates event.
- The time between El Niños is determined by the time to recharge.

Validation of Recharge Oscillator Theory



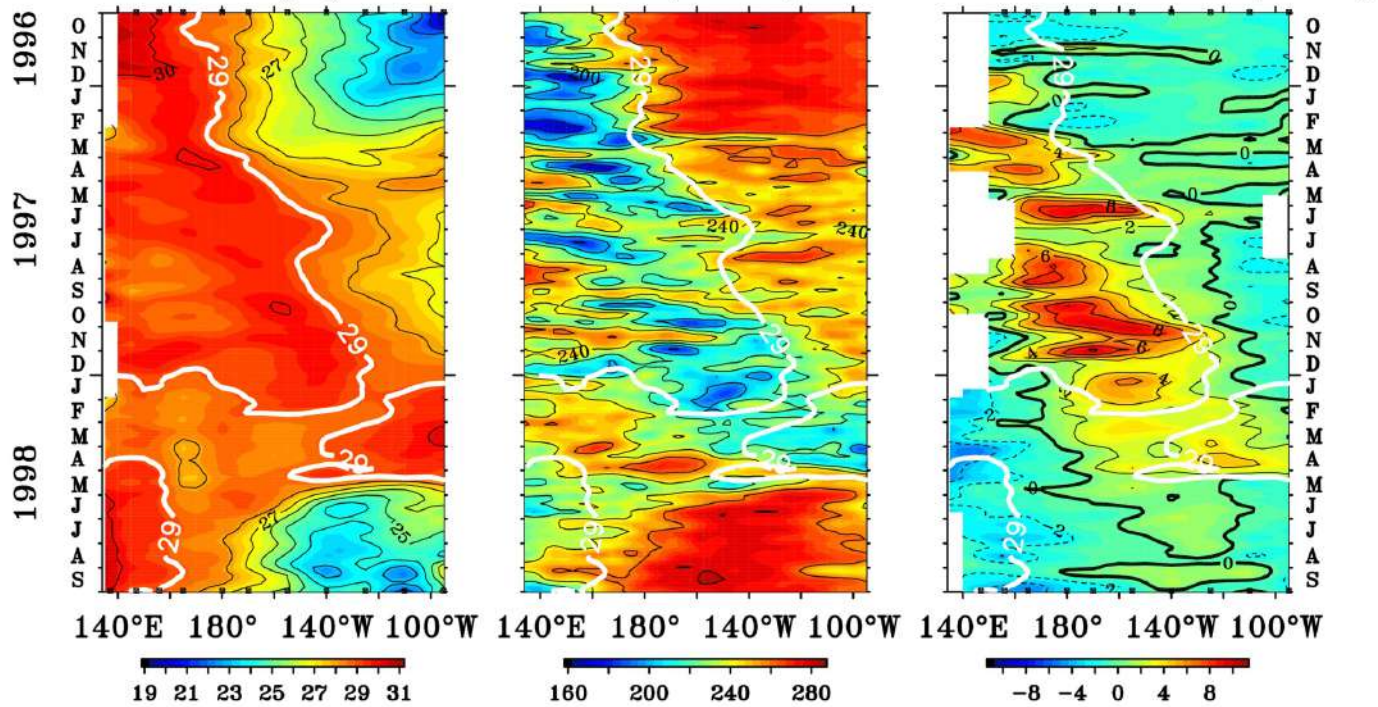
ENSO Evolution Governed by Multi-Time Scale Processes



- Deterministic seasonal time scale dynamics
 - ✓ Coupled feedbacks between ocean and atmosphere
 - ✓ Wind forced changes in ocean circulation that redistribute heat
- High frequency (days to weeks) weather noise forcing
 - ✓ Westerly winds bursts most prominent
 - ✓ Introduces irregularity (timing, duration, amplitude)

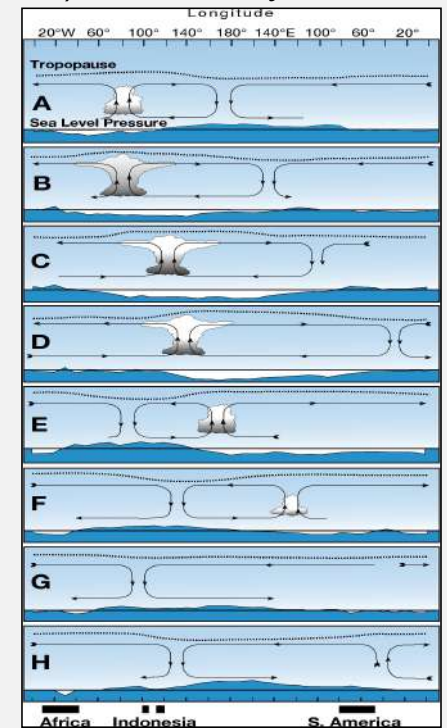
State Dependent (or Multiplicative) Noise Forcing

Five Day Mean SST, OLR, and Zonal Wind 2°S to 2°N Average



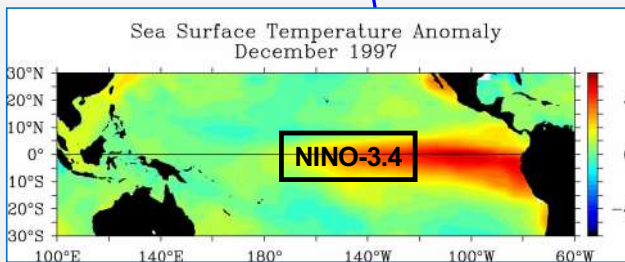
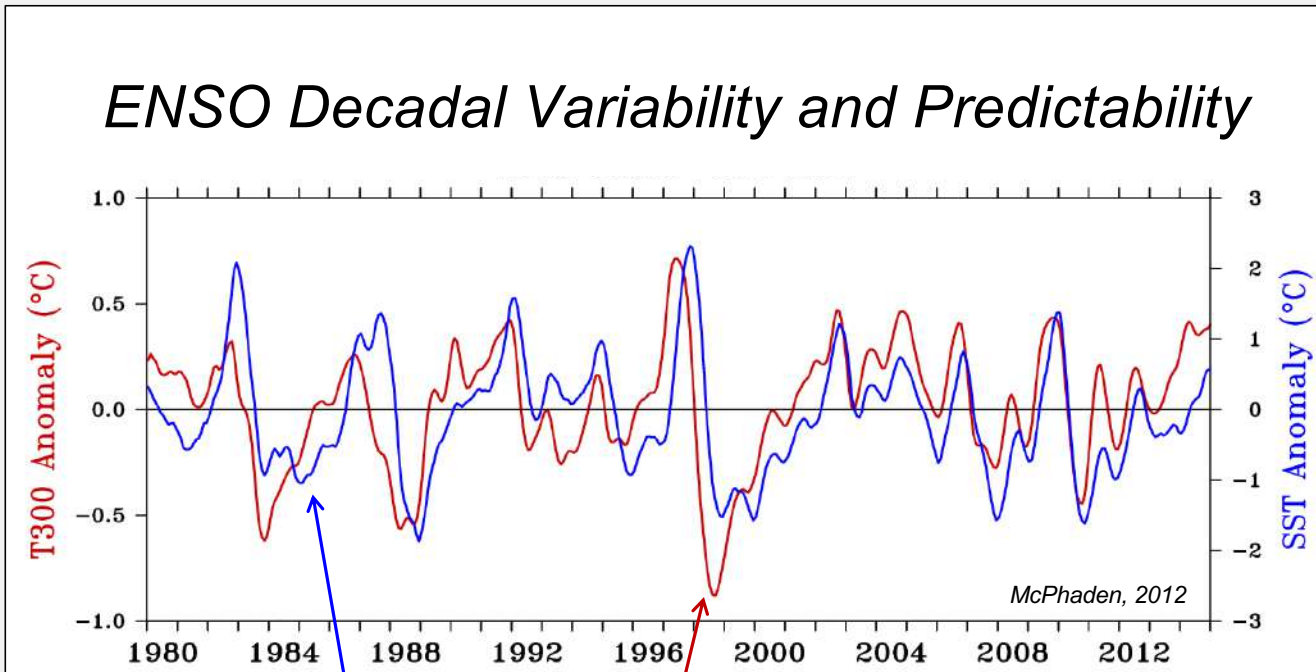
Eisenman et al., 2005, *J. Clim.*; Gebbie et al., 2007, *J. Clim.*; Levine et al., 2016, *J. Clim.*

The Madden-Julian Oscillation (MJO) and Westerly Wind Bursts

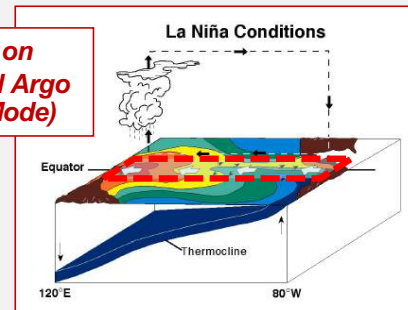


Adapted from Madden & Julian, 1972

ENSO Decadal Variability and Predictability



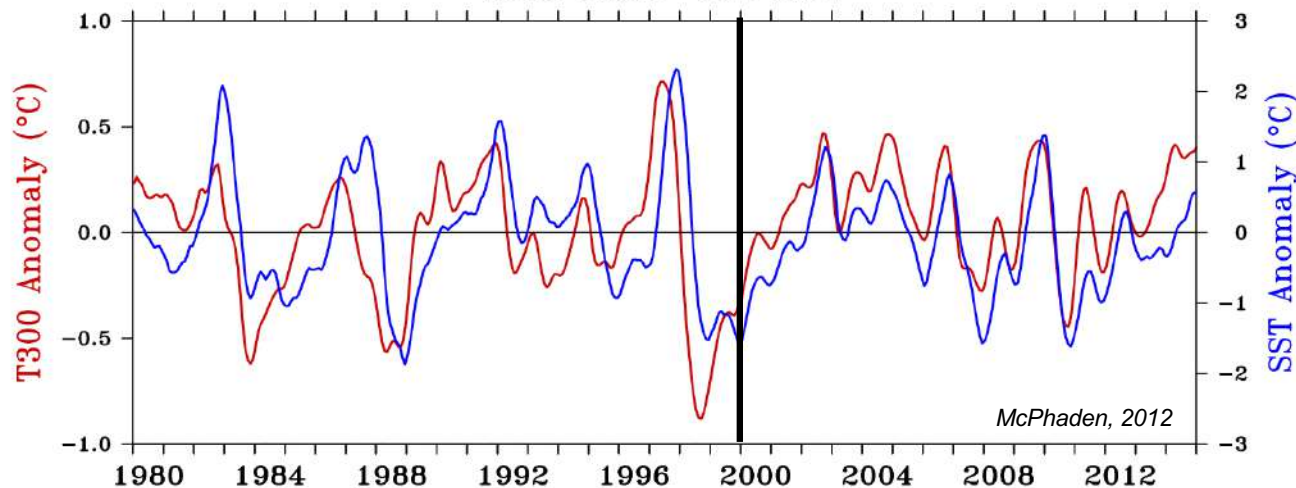
Heat content based on TAO/TRITON, XBT, and Argo (Index for Recharge Mode)



After 2000:

- Weaker, higher frequency ENSO SST and heat content variations (McPhaden, 2012; Horii et al, 2012)
- Shortening of lead time between heat content and SST, reducing the efficacy of heat content as predictor for ENSO (McPhaden, 2012; Hu et al, 2020)
- Shift from strong EP El Niños to Weaker CP El Niños (Lee & McPhaden, 2010; McPhaden et al, 2011; Hu et al, 2020)
- Weakened Thermocline Feedback: BJ Index (Kug et al, 2009, 2010)
- More damped ENSO cycle (Lübbecke & McPhaden, 2014)
- Noise forcing more prominent (Neske & McGregor, 2018)
- Forecast skill declined (Wang et al, 2010; Barnston et al, 2012)

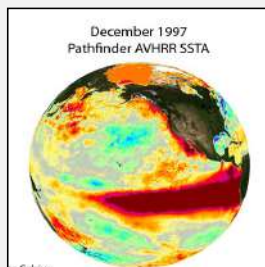
ENSO Decadal Variability and Predictability



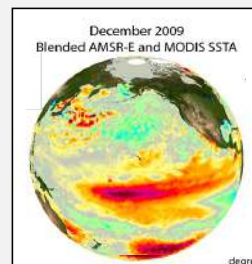
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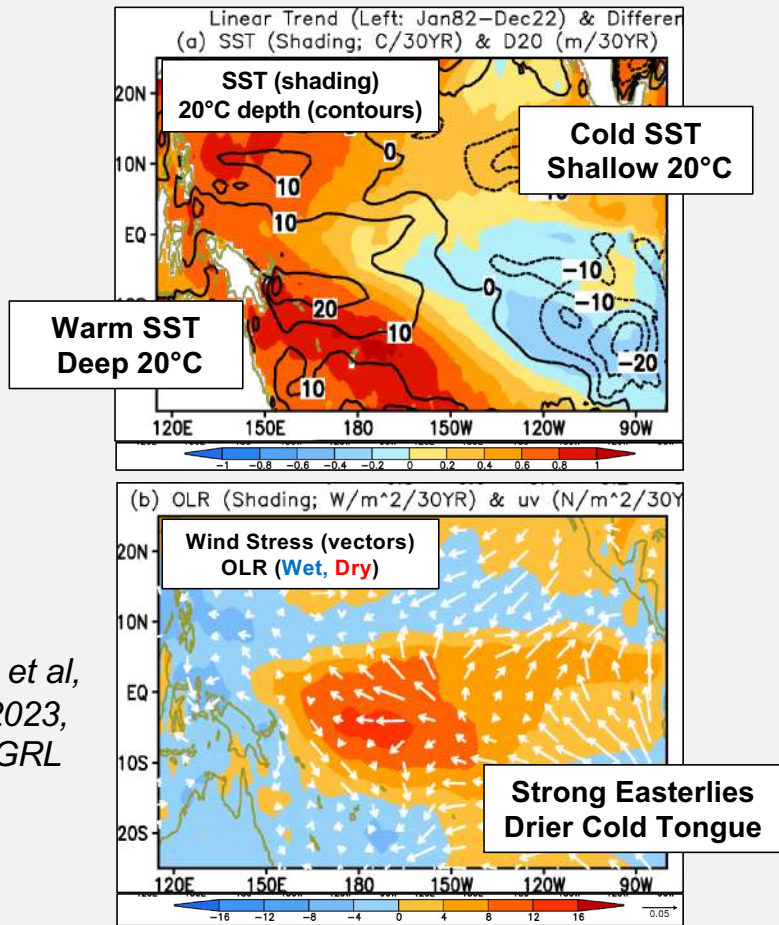
Eastern Pacific (EP) El Niños



Central Pacific (CP) El Niños



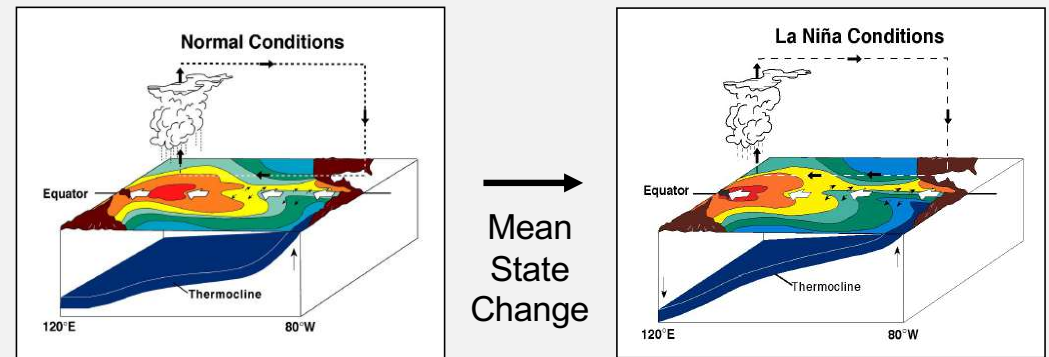
GODAS Reanalysis 40 yr Trends



*Li et al,
2023,
GRL*

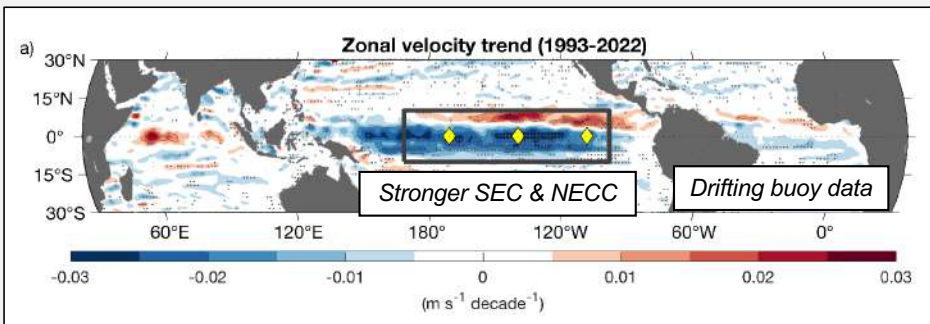
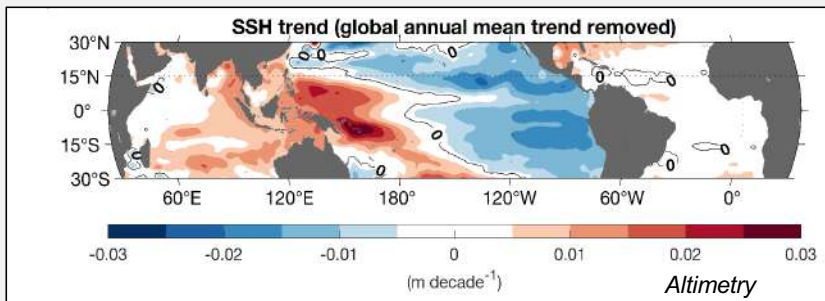
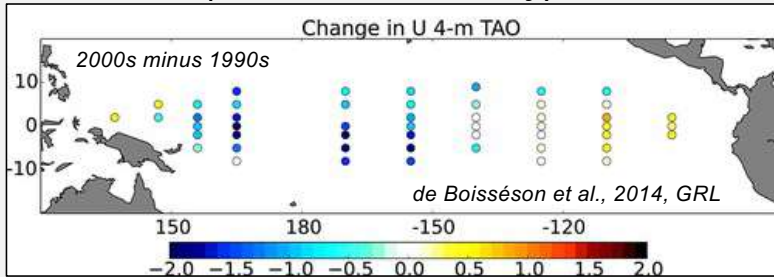
Changes in ENSO variability and predictability linked to a long term La Niña-like cooling trend

(Zhao & Fedorov, 2020, J. Clim.; Li et al, 2023, GRL)



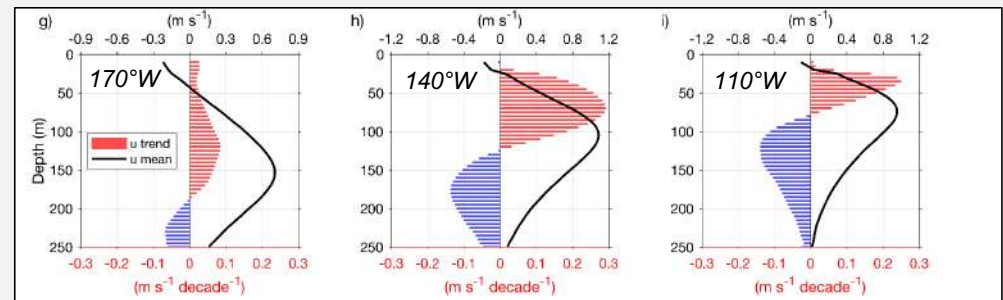
Multi-decadal trends are evident in both observations and in atmospheric and oceanic reanalyses constrained by observations (TAO, Argo, drifters, XBT, satellites).

Multi-decadal Trends in Wind-Forced Tropical Pacific Circulation (observations only)

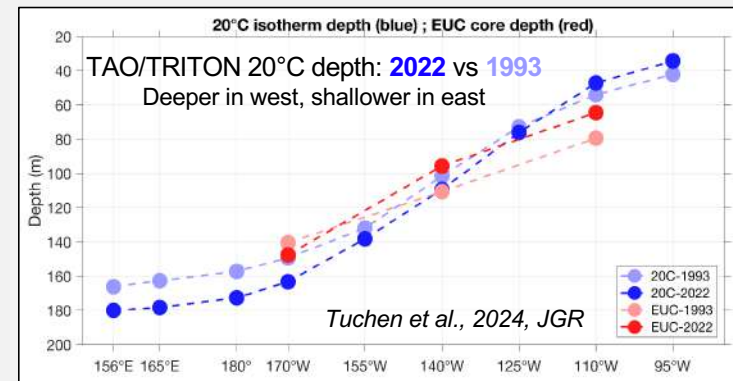


JGR Oceans Strengthening of the Equatorial Pacific Upper-Ocean Circulation Over the Past Three Decades 2024

Franz Philip Tuchen^{1,2}, Renellys C. Perez², Gregory R. Foltz², Michael J. McPhaden³, and Rick Lumpkin²



TAO Current Meter Moorings: EUC stronger; deeper in west, shallower in east



Multi-decadal Trends in Wind-Forced Tropical Pacific Circulation (observations only)

nature climate change

Article

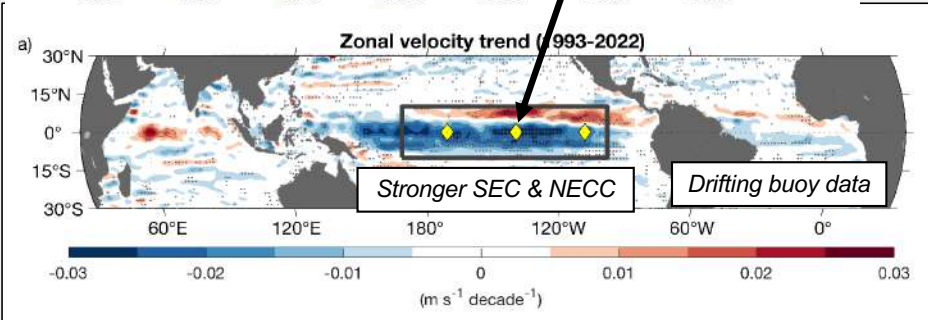
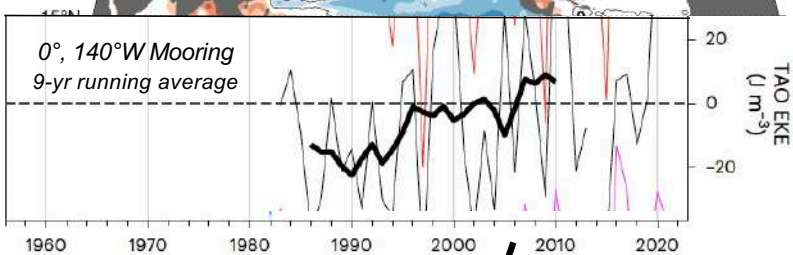
<https://doi.org/10.1038/s41558-023-01915-x>

Intensification of Pacific tropical instability waves over the recent three decades

Received: 18 May 2023

Minyang Wang¹, Shang-Ping Xie², Hideharu Sasaki³, Masami Nonaka³ & Yan Du^{1,4}

Accepted: 13 December 2023

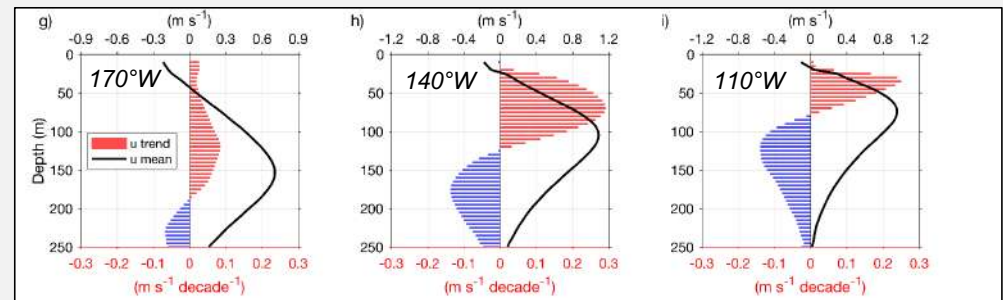


JGR Oceans

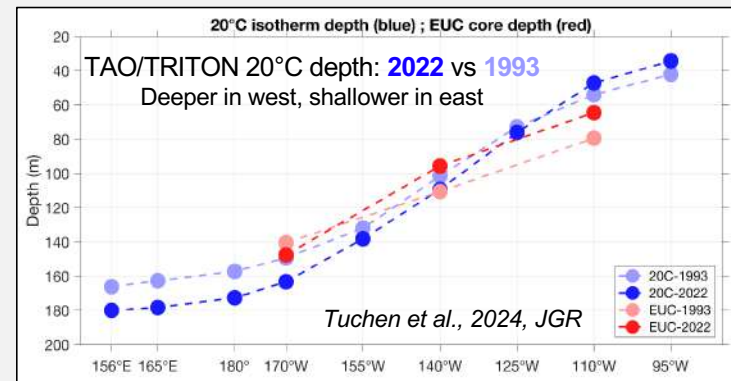
Strengthening of the Equatorial Pacific Upper-Ocean Circulation Over the Past Three Decades

2024

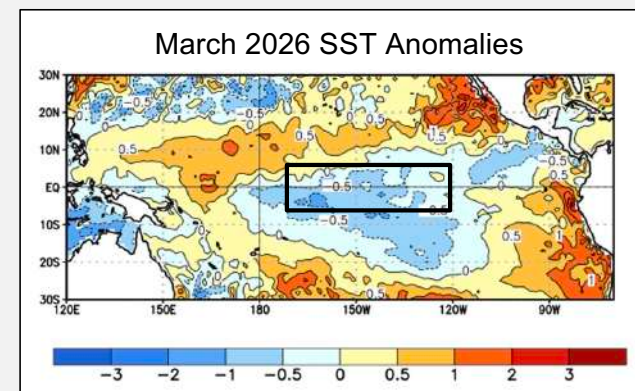
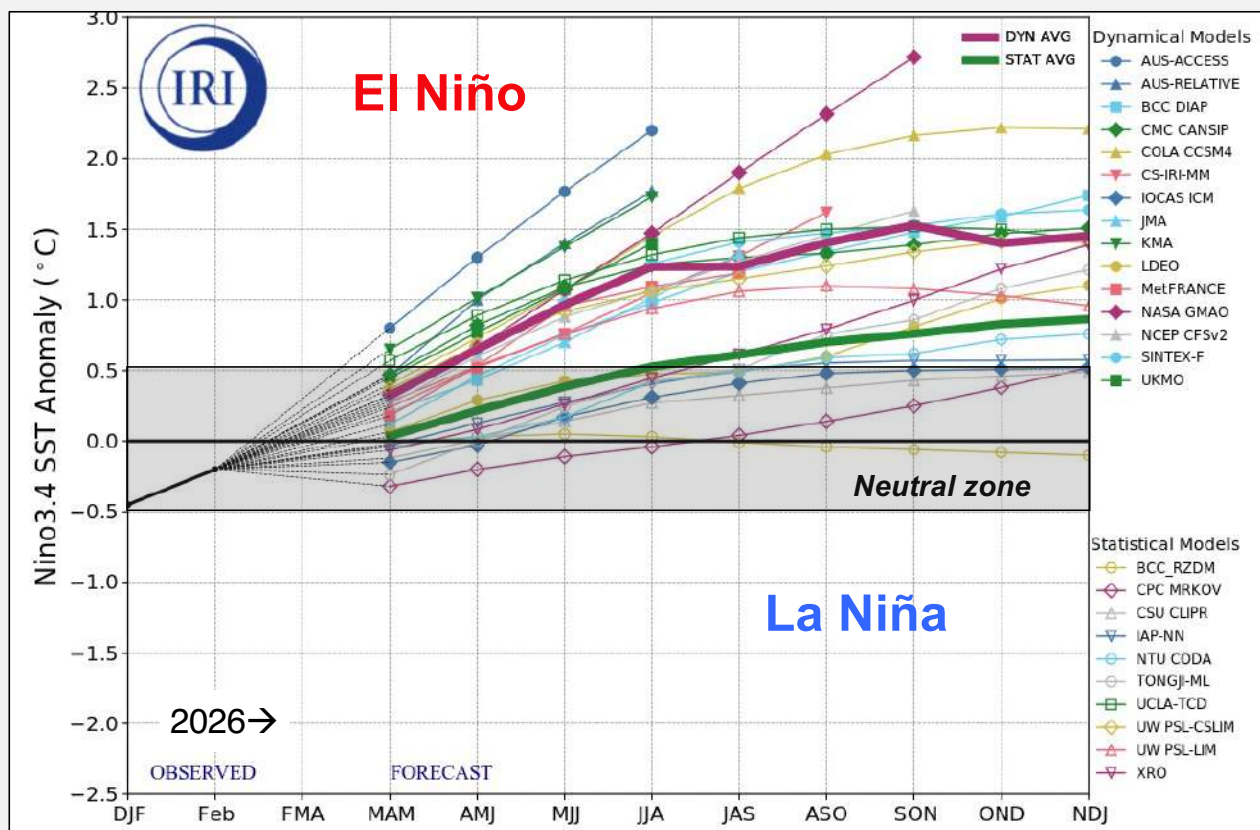
Franz Philip Tuchen^{1,2}, Renellys C. Perez², Gregory R. Foltz², Michael J. McPhaden³, and Rick Lumpkin²



TAO Current Meter Moorings: EUC stronger; deeper in west, shallower in east



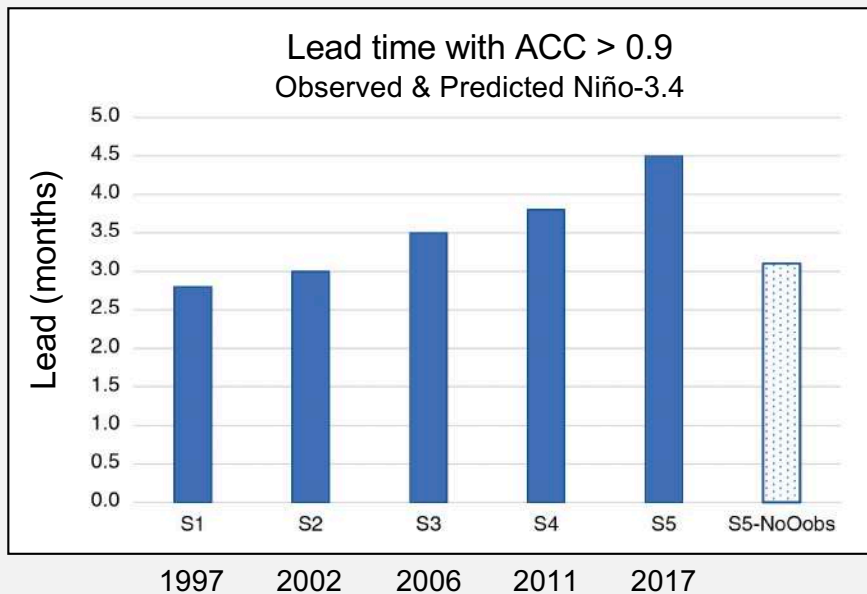
Model Predictions for Niño-3.4: March 2026 Initial Conditions



"In June-August 2026, El Niño is likely to emerge and persist through at least the end of 2026."

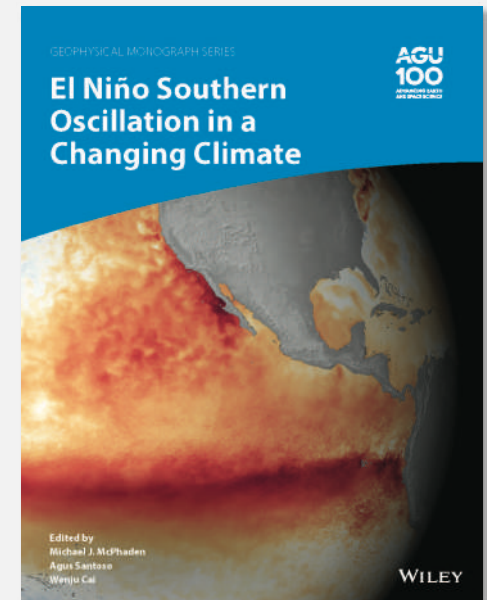
NOAA/CPC
12 March 2026

The Impact of Subsurface Ocean Data for ENSO Forecast Initialization



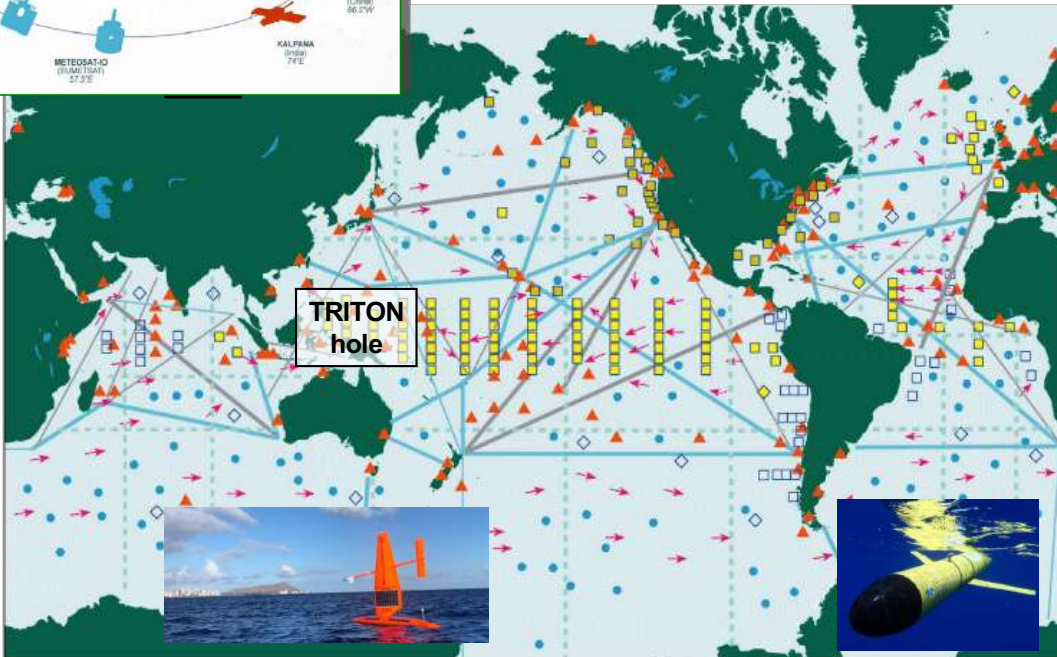
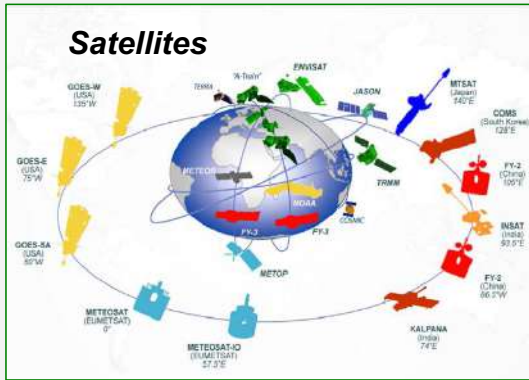
ECMWF Forecast Model Generation (S1-S5)

With no subsurface ocean information assimilated into the initial conditions, the drop in skill is equal to ~20 years of progress in forecast model development.









Chapter 3: ENSO Observations

The Global Ocean Observing System



In Situ Components

- 
Surface measurements from volunteer ships (VOSclim)
 200 ships in pilot project
- 
Global drifting surface buoy array
 5° resolution array: 1250 floats
- 
Tide gauge network (GCOS subset of GLOSS core network)
 170 real-time reporting gauges
- 
XBT sub-surface temperature section network
 51 lines occupied
- 
Profiling float network (Argo)
 3° resolution array: 3000 floats
- 
Repeat hydrography and carbon inventory
 Full ocean survey in 10 years

Reference time series

58 sites



Global reference mooring network

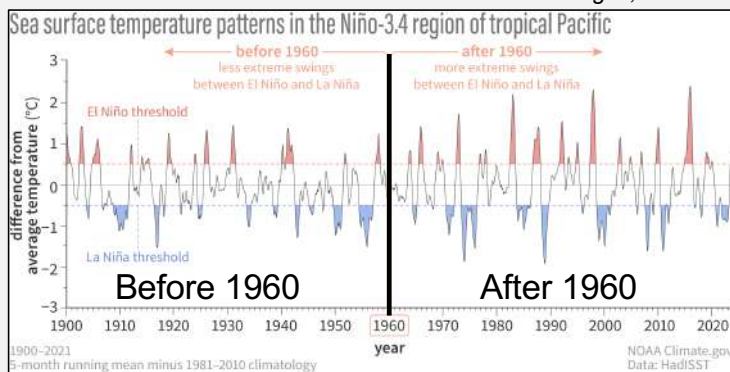
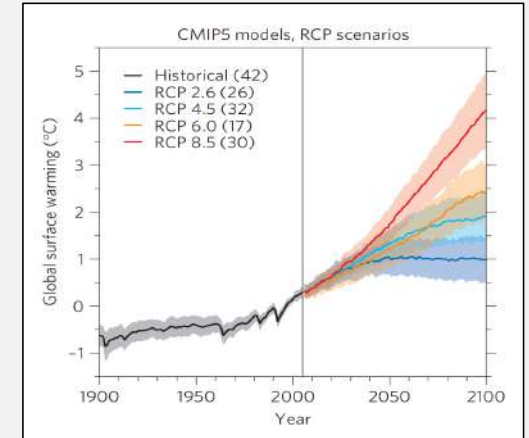
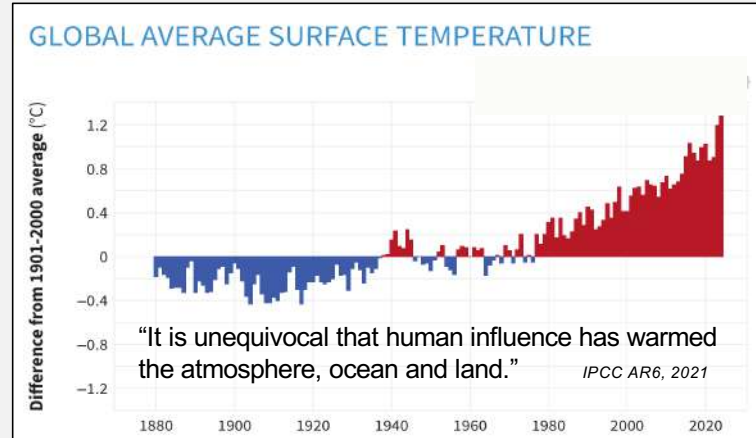
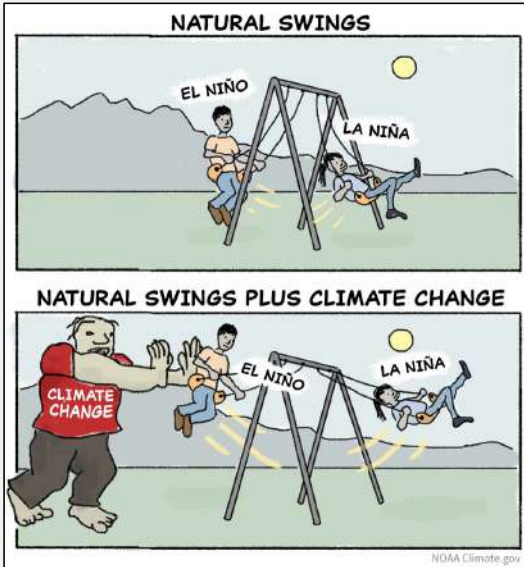
29 moorings planned



Global tropical moored buoy network

119 moorings planned

Climate Change and ENSO



Climate.gov, 2023

nature climate change

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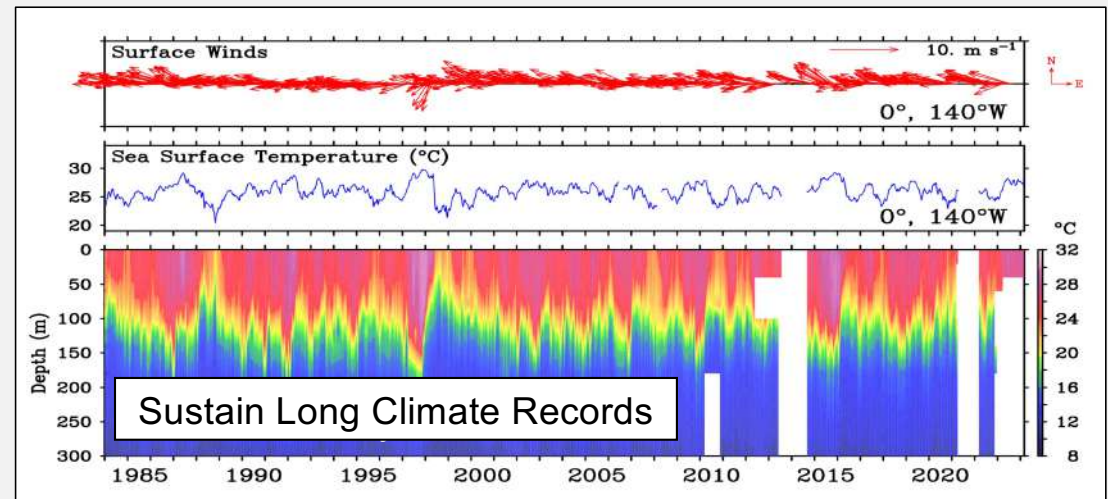
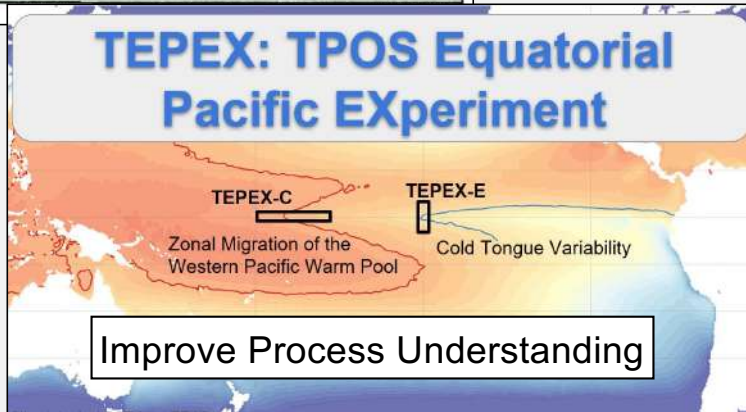
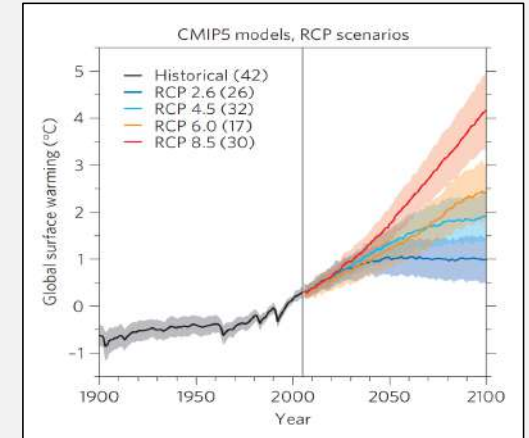
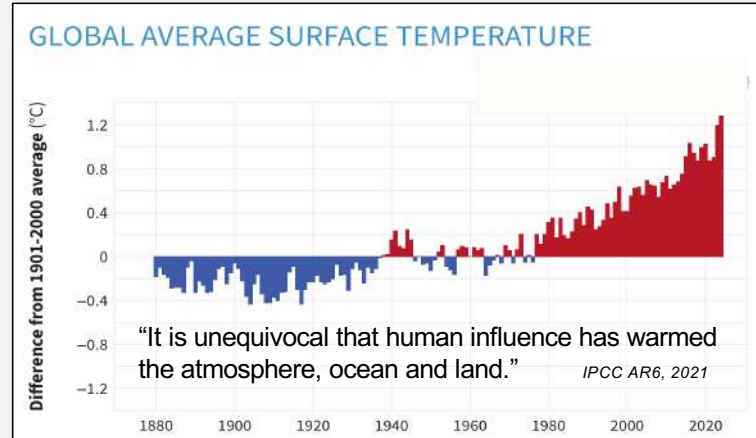
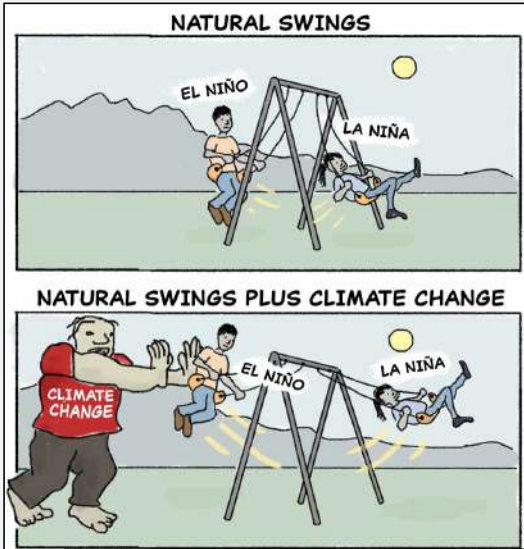
[nature](#) > [nature climate change](#) > [brief communications](#) > article Cai et al, 2022

Brief Communication | [Open access](#) | Published: 31 January 2022

Increased ENSO sea surface temperature variability under four IPCC emission scenarios

[Wenju Cai](#) ✉, [Benjamin Ng](#), [Guojian Wang](#), [Agus Santoso](#), [Lixin Wu](#) ✉ & [Kai Yang](#)

Climate Change and ENSO



Two-Way Inter-basin Interactions Affect ENSO Variability and Predictability

Article | Published: 26 June 2024

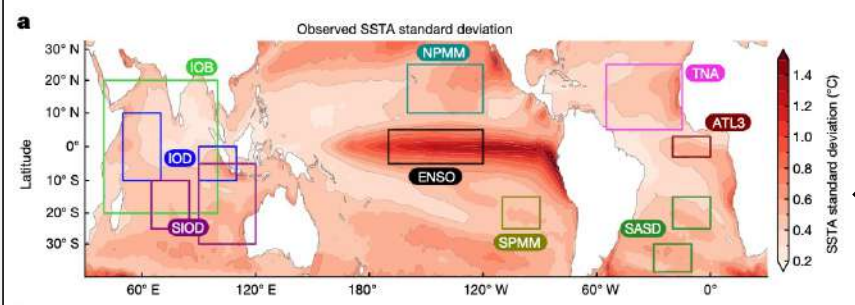
Explainable El Niño predictability from climate mode interactions

Sen Zhao, Fei-Fei Jin, Malte F. Stuecker, Philip R. Thompson, Jong-Seong Kug, Michael J. McPhaden, Mark A. Cane, Andrew T. Wittenberg & Wenju Cai

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Improved ENSO dynamical model forecast skill including global tropics

Science

REVIEW

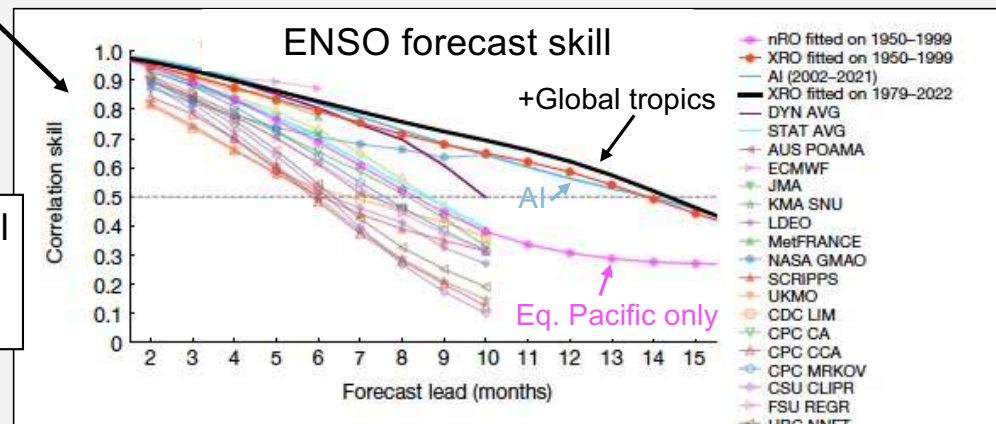
Pantropical climate interactions

WENJU CAI, LIXIN WU, MATTHIEU LENGAINNE, TIM LI, SHAYNE MCGREGOR, JONG-SEONG KUG, JIN-YI YU

AND PING CHANG | +24 authors | [Authors Info & Affiliations](#)

Cai et al, 2019

SCIENCE · 1 Mar 2019 · Vol 363, Issue 6430 · DOI: 10.1126/science.aav4236



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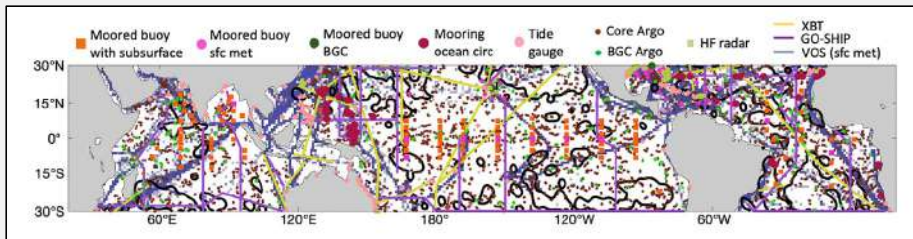
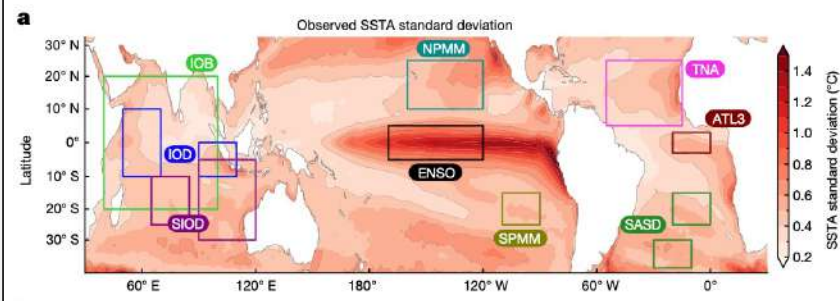
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REVIEW article

Front. Mar. Sci., 07 February 2025

Sec. Ocean Observation

Volume 12 - 2025 | <https://doi.org/10.3389/fmars.2025.1539183>

Toward an integrated pantropical ocean observing system

A photograph of a rainbow over the ocean under a cloudy sky. The rainbow is visible on the left side of the frame, arching over the horizon. The sky is filled with white and grey clouds, and the ocean is a dark blue-grey color. The text "Thank you!" is centered in the middle of the image in a black, italicized font.

Thank you!