Evolution of ENSO Prediction over the Past 40 years (1976-2015)

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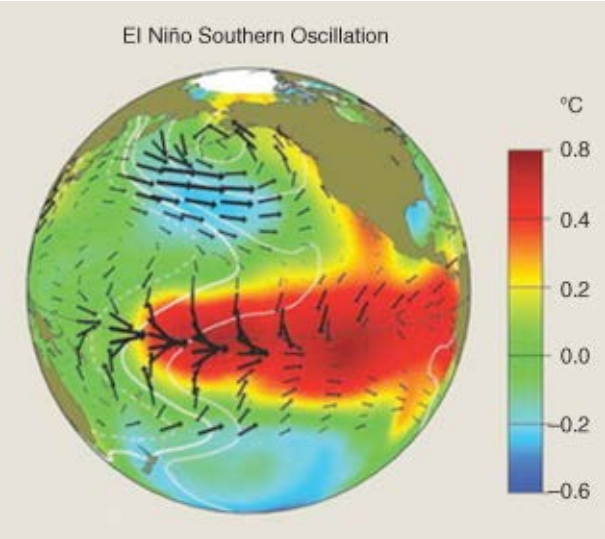
By 1976, the link between the Southern Oscillation of sea level pressure and the SST anomaly in the east-central tropical Pacific was known (Berlage, 1976).

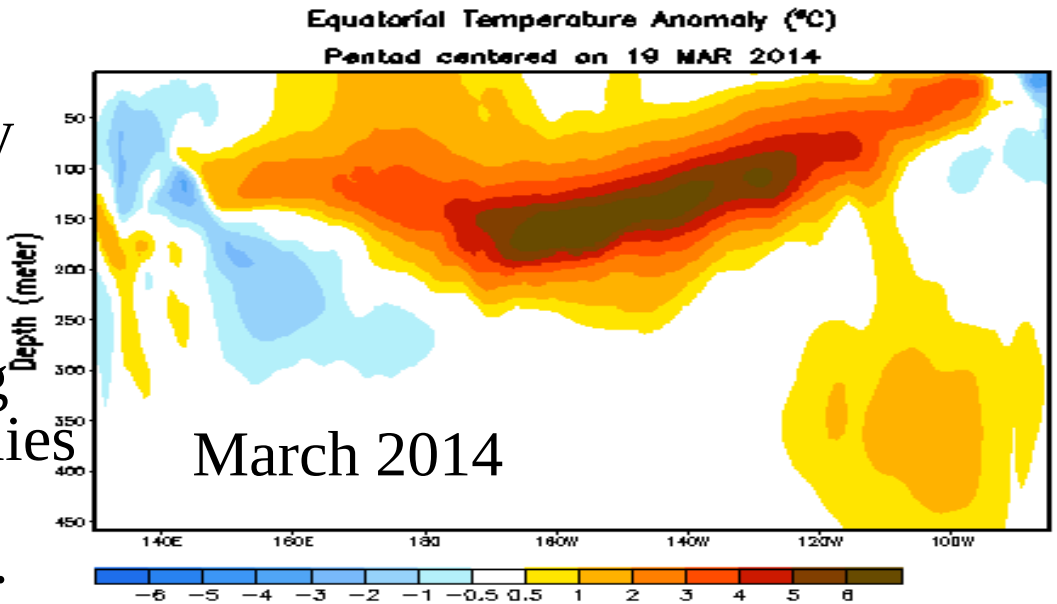
Earlier, Bjerknes (1966) had discovered the physical mechanism for the coupling of the SST anomalies to the Southern Oscillation and associated changes in the strength of the trade winds: positive feedback. Dissipation of El Nino or La Nina, and transitions, were not yet understood at all.



Anomalous winds and SSTs associated with El Nino. (from McPhaden et al. 2006)

Wyrtki (1975) noted changes in sea level associated with ENSO, and zonal wind anomalies in the western tropical Pacific. The latter led to the realization of the role of equatorial Kelvin waves in driving a strengthening El Nino. Further modeling studies in mid-1970s and early 1980s supported these concepts of large-scale ocean dynamics. But subsurface was scantily observed.

An eastward-moving Kelvin wave of highly elevated tropical Pacific subsurface sea temperature associated with strong westerly wind anomalies 1-2 months earlier in western Pacific, 2014.



In early 1980s, Zebiak applied a model from Gill (1980) to the ENSO case, and found wind response to an area of heated water in the tropical Pacific.

In 1981, Hoskins and Karoly made major advances in simulating and understanding global-scale atmospheric responses to ENSO variability.

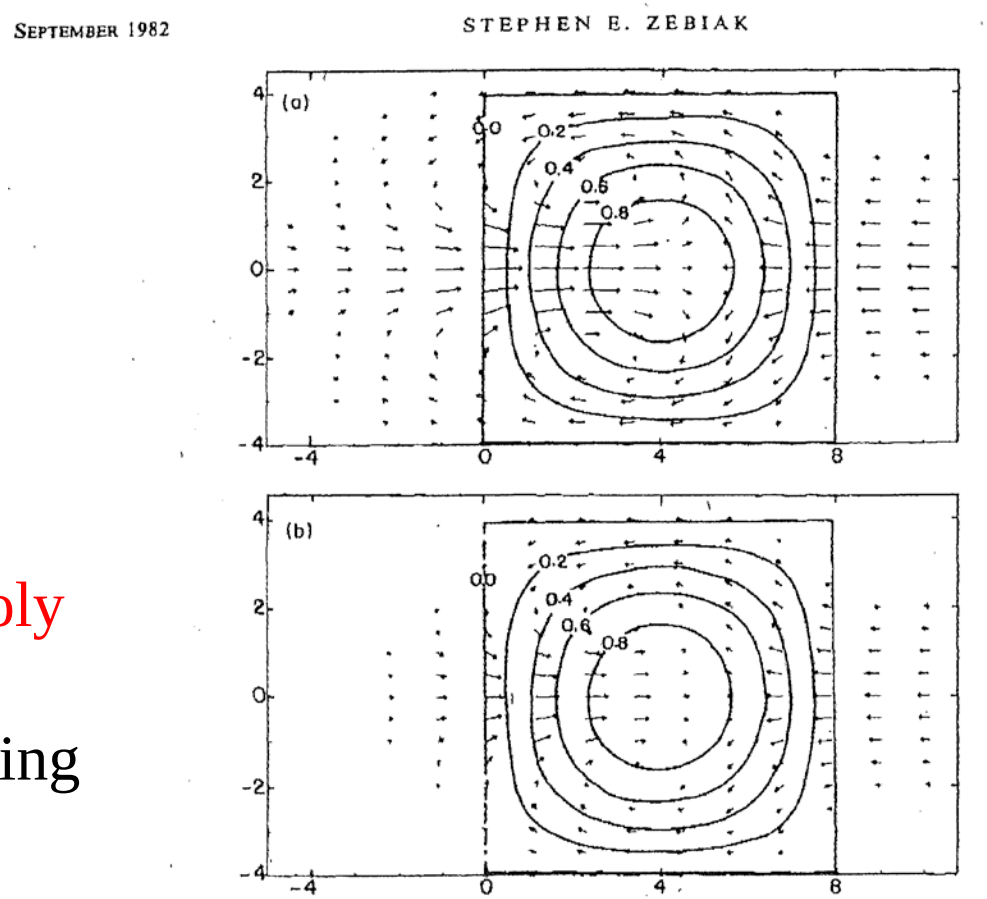


FIG. 2a. Model wind response for a heating distribution of the form $Q = Q_1 \cos[\pi(x - 4)/8] \cos[\pi y/8]$, and $\epsilon = 0.1$. Heating contours are shown in intervals of $0.2Q_1$.
FIG. 2b. As in 2a, except for $\epsilon = 0.2$.

Oceanic heating and anomalous wind simulations, Zebiak (1982)

Rasmussen and Carpenter (1982) showed in great detail the wind, SST and rainfall anomaly fields throughout an El Nino event, based on 6 major El Nino events during 1950-1976, providing a much better **observational basis for ENSO models and theory.**

Length of ENSO cycle described.

Six recognized strongest El Nino events: 1951-52, 1953-54, 1957-58, 1965-66, 1972-73.

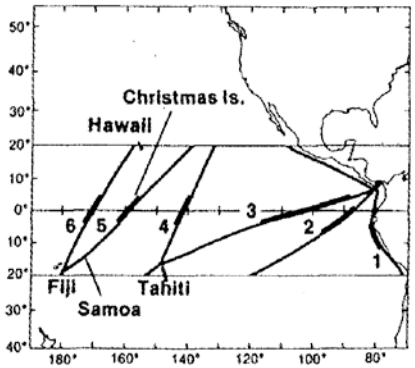


FIG. 1. Ship tracks used in the analyses. The heavy portion of each track is the 8° latitude section of maximum interannual SST variability. The time series of monthly average anomalies were computed for this section of each track.

Ship Tracks for SST

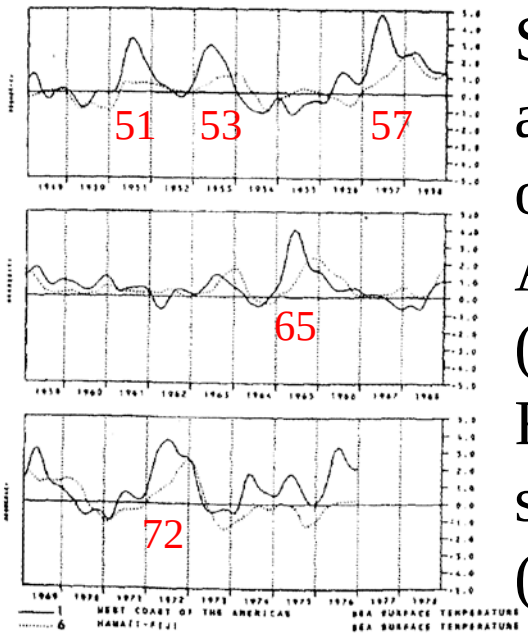


FIG. 11. Time series, SST(1), SST(6); 1921–38; 1950–76. See text.

SST anom along coast of South America (solid) and Fiji-Hawaii ship track (dashed)

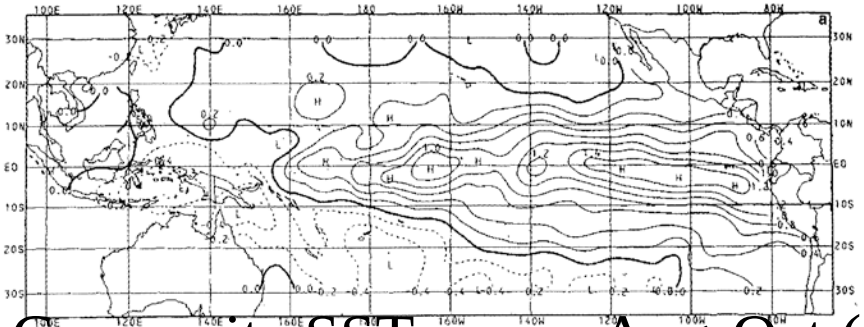
More findings from Rasmussen and Carpenter (1982): SST and wind anomalies associated with El Nino based on 6 or 7 events, 1950-1976.

Rainfall anomalies noted In central Pacific, Indonesia

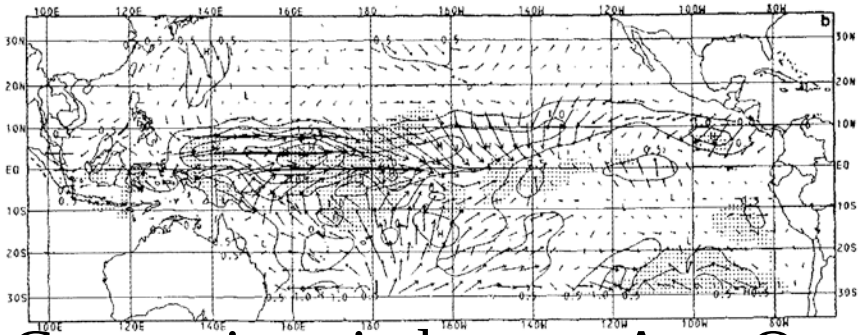
4 phases of El Nino defined:

- Onset (Dec, year -1)
- Peak (Apr, year 0)
- Transition (Sep, year 0)
- Mature (Jan, year +1)

Year of El Nino

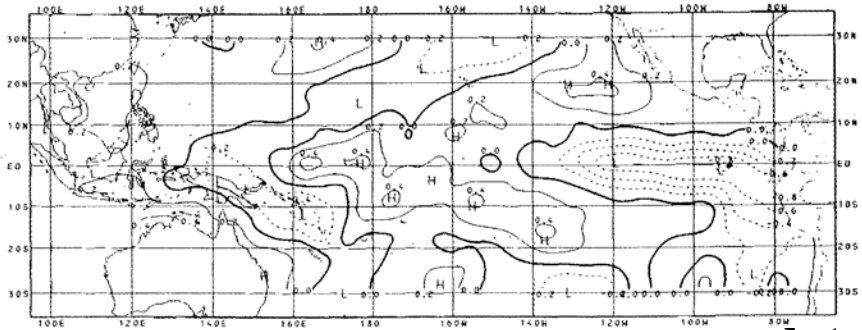


Composite SST anom, Aug-Oct (0)

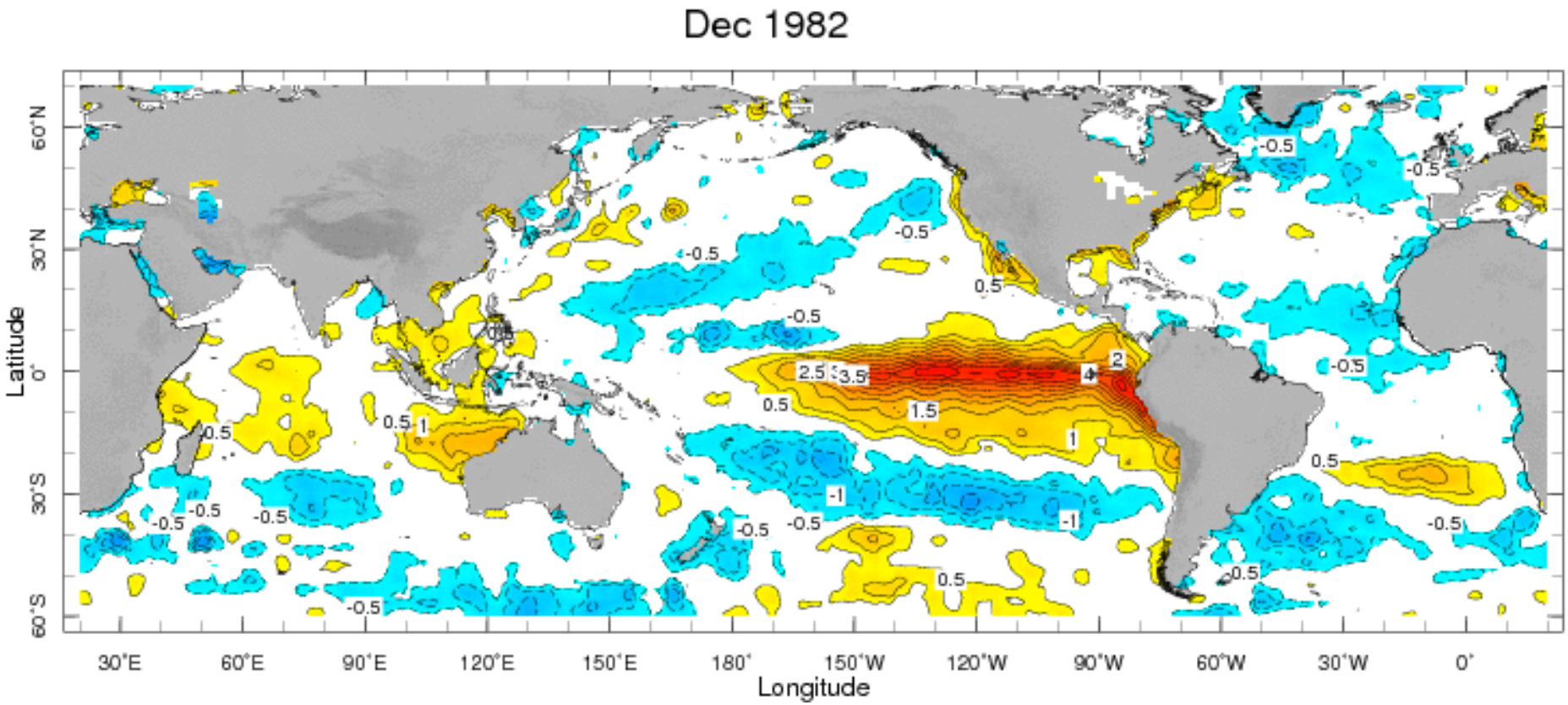


Composite wind anom, Aug-Oct (0)

Year after



Composite SST anom, May-Jul (+1)



The 1982-83 El Nino took us by surprise. The above SST anomaly map, based on gauge plus satellite data, was developed long afterwards; in 1982 the ship track data was viewed separately, and some of it "failed the QC check" because it was >3 SDs above average. The satellite data had a very short climatology, so had little meaning.

The 1982-83 El Nino failed to confirm some of the features observed by Wyrtki (1975) (sea level) or shown in the composites of Rasmussen and Carpenter (1982) (e.g., westward SST anomaly propagation):

--Sea level did not build up in the western basin the year prior
--SST anomaly did not begin in the far eastern part of basin
--”New” regions seemed to have ENSO-related climate impacts

The 1982-83 event spurred a new wave of ENSO research. The Tropical Ocean-Global Atmosphere (TOGA) 10-year project was launched, to study and predict ENSO and its global impacts.

Some important TOGA-related ENSO research:

Dynamical models began successfully reproducing ENSO behavior (e.g., seasonal timing, ~4-year periodicity): Zebiak and Cane (1987), Schopf and Suarez (1988)

Delayed oscillator theory (Suarez and Schopf 1988): Besides Kelvin waves, westerly wind anomalies produce westward propagating Rossby waves that reduce subsurface sea temperature, and, after reflecting off the western boundary, "kill" El Nino ~6 months after the wind anomaly. So the Bjerknes positive feedback process gets interrupted months later, terminating an El Nino event, as occurs early in "year+1".

Observational studies depicted typical climate impacts of El Nino, based on Southern Oscillation (Ropelewski and Halpert 1987). Vectors show strength and seasonal timing of precipitation effects.

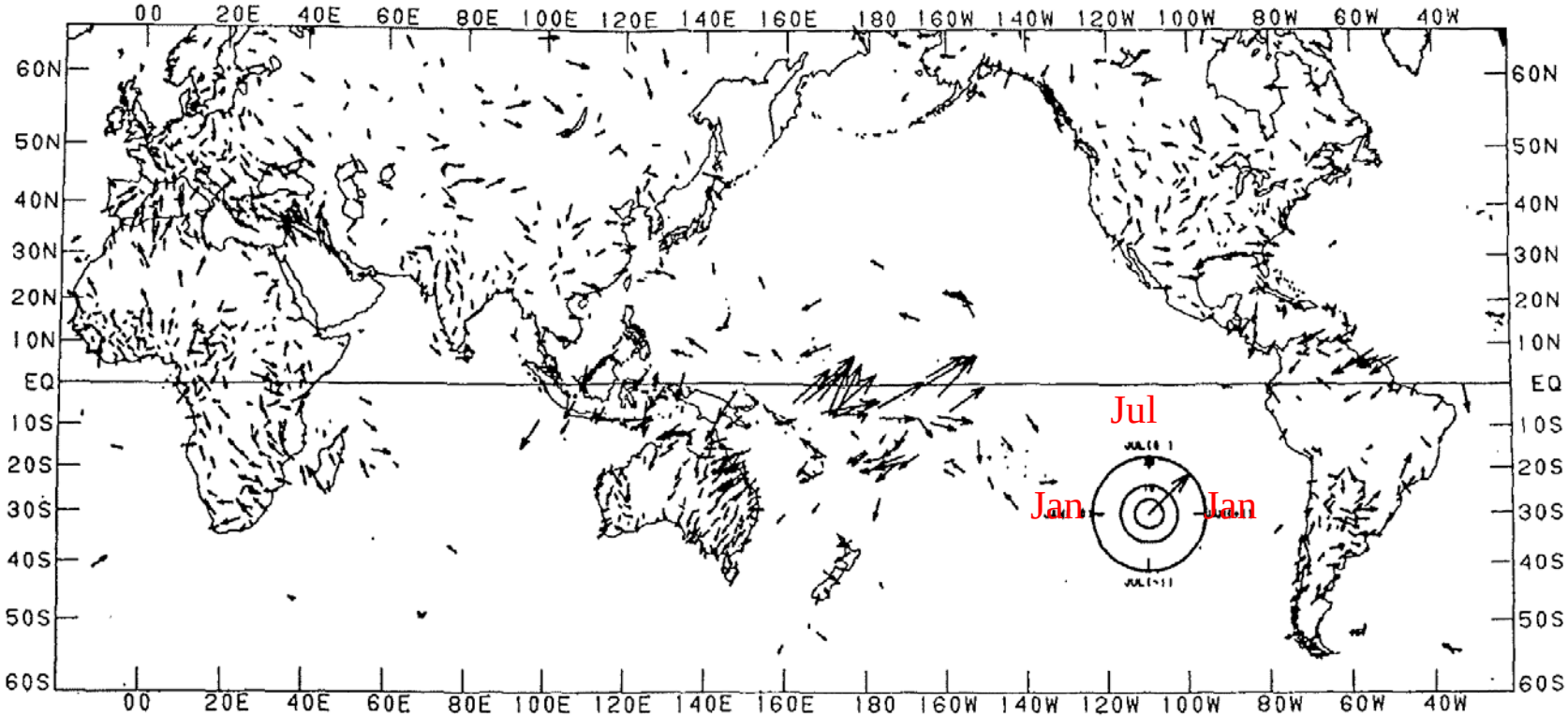


FIG. 1. The amplitudes and phases of ENSO composite ranked precipitation plotted as vectors. The vectors are based on a 24-month harmonic fitted to ranked precipitation composites for ENSO episodes. The phases and relative magnitudes of these vectors are indicated by the "vector clock" in the figure.

ENSO Forecasts Lead to Seasonal Climate Forecasts

Mainly empirical (statistical) methods to predict ENSO based on anticedent conditions (e.g. wind anomalies) were developed by Hasselmann and Barnett (1981), Barnett (1984), Inoue and O'Brien (1984). These suggested predictive potential.

Successful dynamical simulations of ENSO led to real-time forecasts of ENSO-related SST. First successful dynamical ENSO forecasts were those of Cane et al. (1986), where the late forming El Nino of 1986-87 was predicted by this model.

Three types of predictions models: (1) statistical, (2) hybrid (stat + dyn), and (3) dynamical

Statistical: Barnston and Ropelewski (1992) used CCA to predict tropical Pacific SST, based on recent observed field of sea level pressure and SST.

Hybrid: Barnett et al. (1993) used physical ocean model, with statistically atmosphere where wind stress is specified from ocean model's SST.

Dynamical: Progression from simple or intermediate coupled models like Cane et al. (1986) to fully comprehensive general circulation models with advanced data assimilation (e.g. Latif et al. 1993; Ji et al. 1994; Stockdale et al. 2011)

Has the skill of ENSO forecasts improved over time?

In the 1980s and 1990s, much (not all) of the potential skill was already captured by statistical models and also by some hybrid and dynamical models (Barnston et al. 1994).

Over the course of the 2000s and 2010s, dynamical models gradually became more skillful, while statistical models mainly did not, so that today's dynamical models slightly outperform statistical models (Tippett et al. 2012; Barnston et al. 2012).

Intrinsic predictability is low during the ENSO transition period of March – June ("predictability barrier"), but somewhat overcome with use of subsurface sea temperature anomalies.

Has the skill of ENSO forecasts improved over time?

Even with a healthy set of state-of-the-art dynamical models, plenty of examples of large forecast errors still exist today:
--aborted El Nino in late summer 2012 was forecast to continue
--borderline El Nino of 2014-15 was forecast to be stronger

Chen and Cane (2008) discuss the extent to which forecasts are limited by intrinsic predictability, vs. our suboptimum modeling.

Weak points in today's best dynamical ENSO prediction models:
--Incomplete model representation of physics (parameterizations)
--Insufficient observational data (e.g. subsurface); is costly
--Imperfect initialization (data assimilation)
--Computer power (need higher spatial resolution, more ensembles)

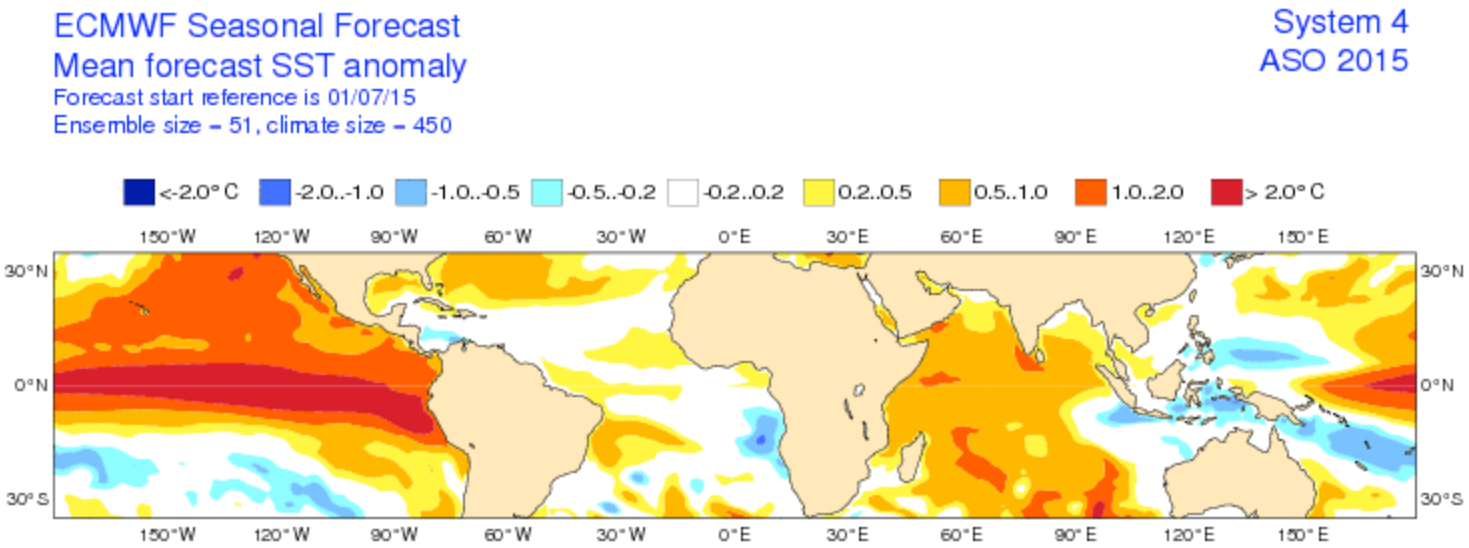
Better ENSO forecasts ➔ Better seasonal climate forecasts

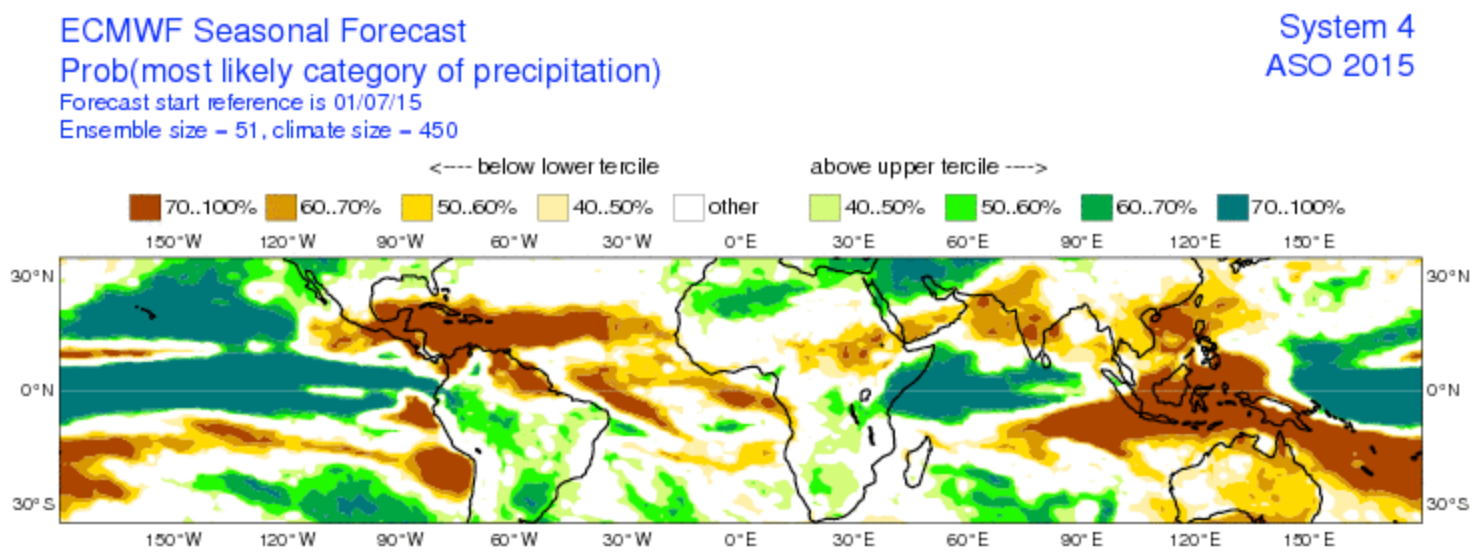
Known ENSO teleconnections (Ropelewski and Halpert 1987; Ropelewski and Halpert 1996; Mason and Goddard 2001) imply ability to forecast seasonal climate anomalies, given an ENSO forecast.

Today's coupled GCMs forecast the global SST and the global climate simultaneously.

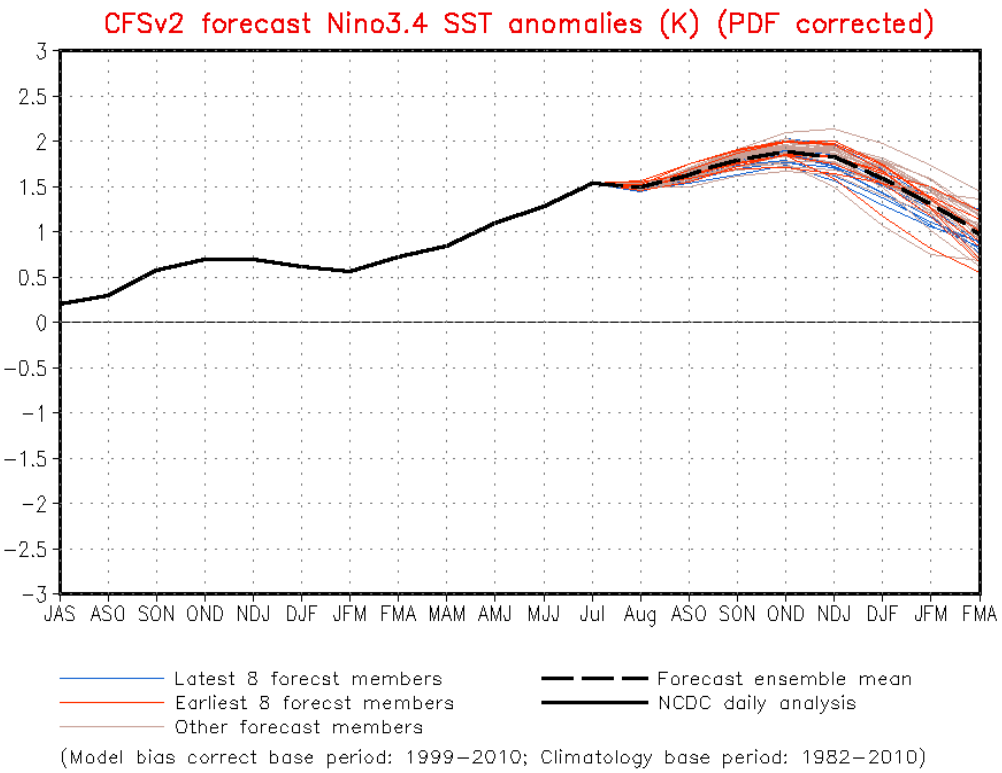
The seasonal climate forecasts of global forecast producing centers now often do not use humans to interpret or judge the model output, but issue the model output itself as the official prediction. Bias corrections may be applied.

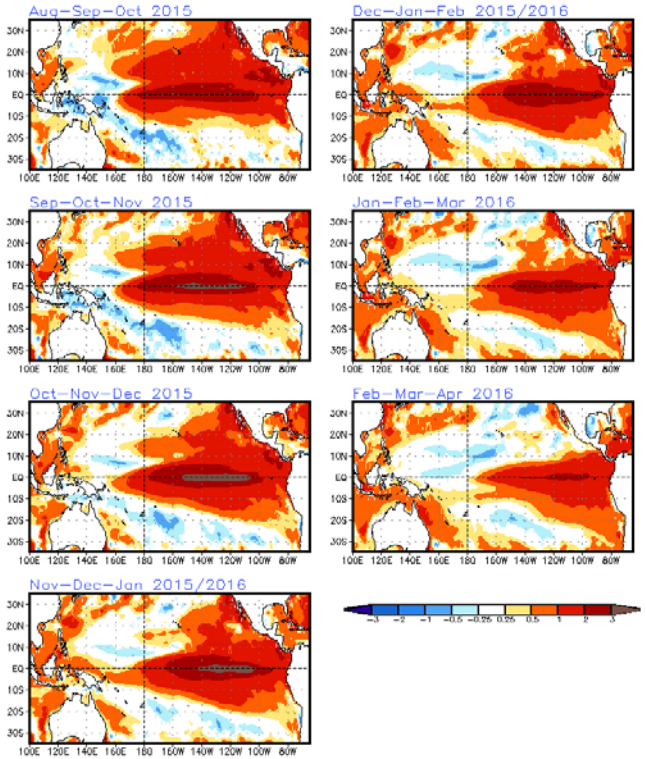
Example: the European Center forecast for SST and precipitation, directly from their System 4 coupled model.





NOAA/NCEP CFSv2 model forecasts of SST issued Aug. 10





Summary and Conclusion

In 1976, about 40 years ago, we knew something about ENSO but had no idea how spatially extensive it was, and how far-reaching its climate effects were.

In the 1980s, due to better global data (e.g., satellite sensing), we finally saw the ENSO-related SST signal fully, and also learned of the season-specific global impacts on climate. Simple statistical and dynamical prediction models emerged.

In the 1990s, 2000s and 2010s we greatly advanced our ENSO and climate prediction models, largely based on better data and more powerful computers.

Today we still need faster computers, better model physics, and more (and better) initialization data. Also, we will always be limited by inherent limit of predictability.