Complex network based diagnostics (and forecasting) of ENSO

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Climate networks: The starting point…

WHAT DO NETWORKS HAVE TO DO WITH CLIMATE?

BY ANASTASIOS A. TSONIS, KYLE L. SWANSON, AND PAUL J. ROEBBER

Advances in understanding coupling in complex networks offer new ways of studying the collective behavior of interactive systems and already have yielded new insights in many areas of science.

(Bull. Amer. Meteor. Soc., 2006)

Mathematical background

An unweighted network (graph) is described by

- **a set of nodes (vertices) V**
- **a set of links (edges) E between pairs of vertices**

Basic mathematical structure: adjacency matrix A

$A_{ij}=1$ ⇔ **nodes i and j are connected by a link**

$A_{ij}=0$ ⇔ **nodes i and j are not connected by a direct link**

⇒ **binary matrix containing connectivity information of the graph**

⇒ **undirected graph: A symmetric**

Degree (centrality): number of neighbors of a vertex $k_v = \sum_{i=1}^{N} A_{v,i}$

Local clustering coefficient: fraction of neighbors of a vertex that are mutual neighbors of each other

Transitivity: fraction of possible "triangles" (transitive structures) that exist in the network

Climate networks

Starting point: Spatially distributed climate time series

$\Rightarrow$ **Spatial locations (individual series) = "nodes" of a network**

$\Rightarrow$ **Statistical similarity (e.g., correlation) between time series = "weights" of links**

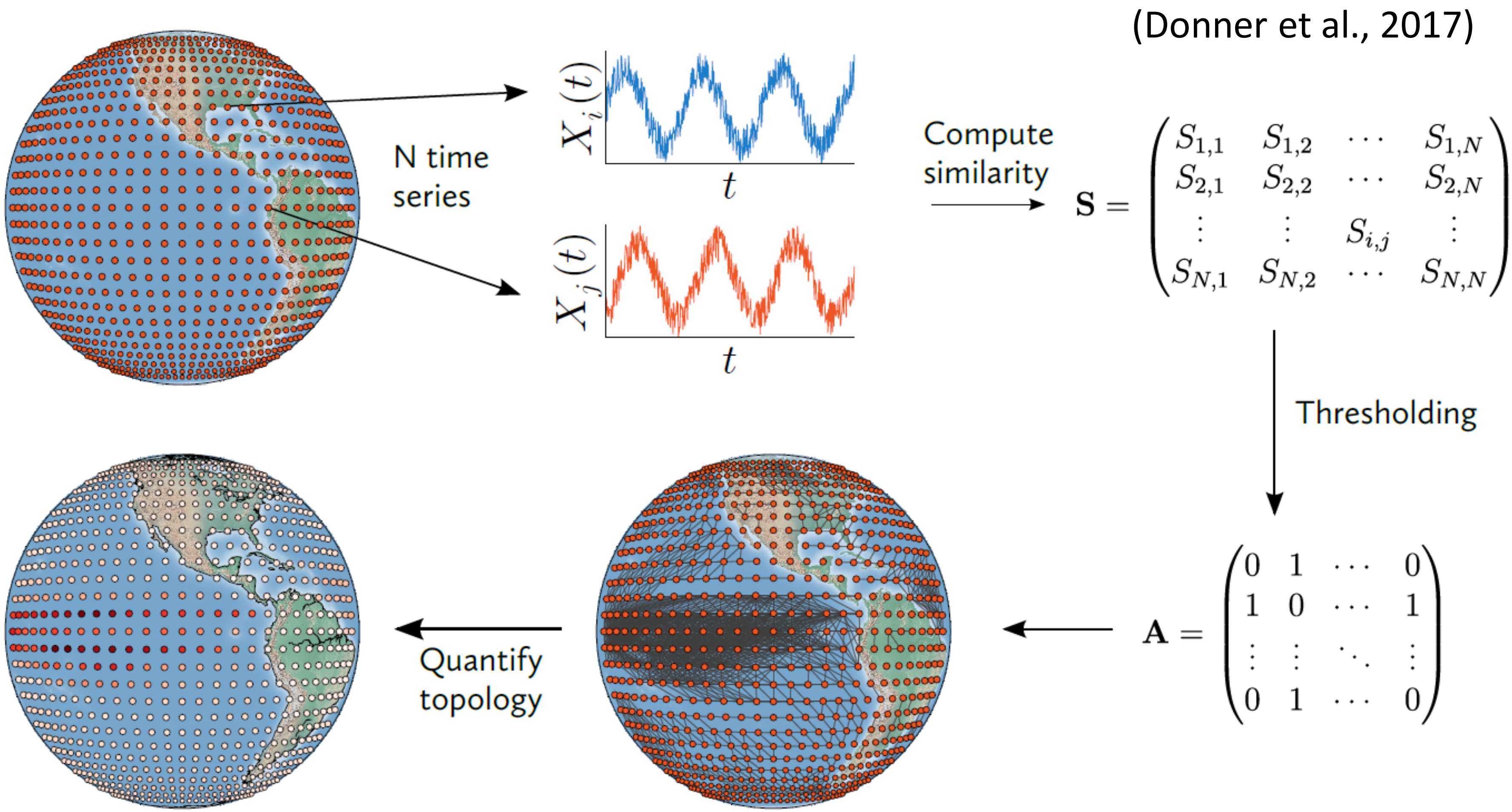
$\Rightarrow$ **Remove all links with "weak" similarity = unweighted network**

$\Rightarrow$ **Analysis of structural properties of the resulting climate network (spatially coarse-grained representation of climate variability)**

Different options for threshold selection:

- **Global correlation threshold (% of strongest correlations)**
- **Global edge density (implies global correlation threshold)**
- **Global significance level of correlations (for removing artifacts due to different serial correlation properties)**

Climate networks: General workflow



Climate networks

Basic assumptions:

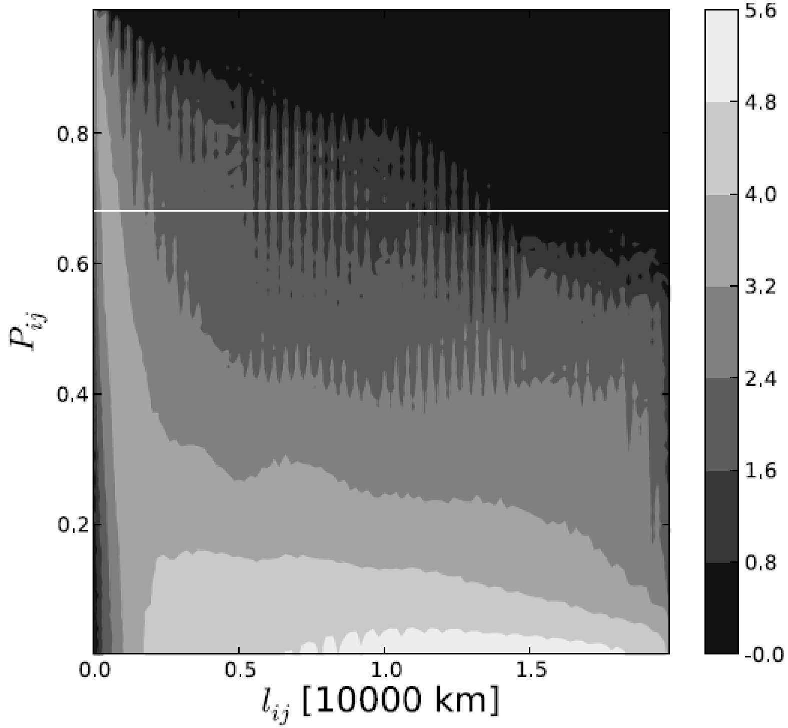
Relevant processes in the (continuous) climate system can be approximated by an underlying spatial network structure (spatial coarse-graining is reasonable)

Statistical interdependences between climate variations at different locations reveal corresponding network topology - "functional" network (statistics reflect dynamics) – also used in other fields (e.g., functional brain networks, economics)

Different possible types of climate networks based on climatological variable and employed similarity measure (e.g. Pearson correlation, different types of mutual information, event synchronization)

Spatial range of correlations

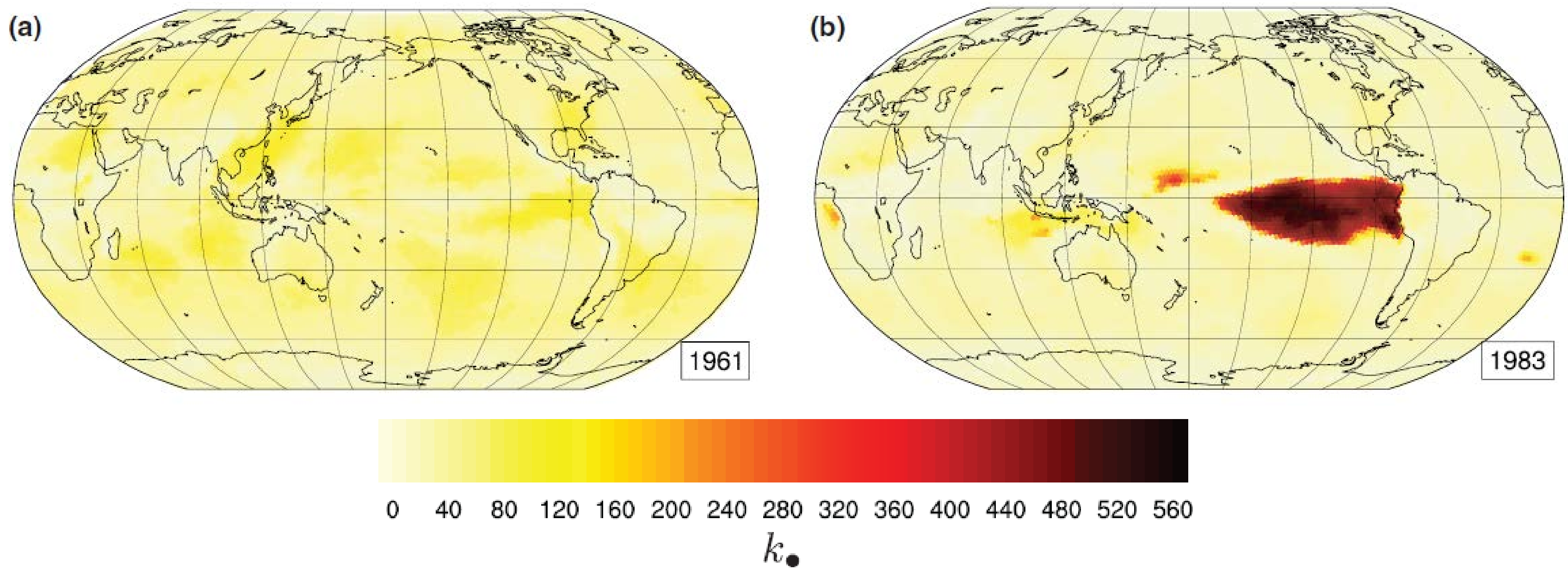
Surface air temperatures: correlations decay with spatial distance – implications for degree and edge length distributions



Donges et al., EPL, 2009

Evolving global surface air temperature network

What can we learn from the temporal variation and spatial patterns of network properties?

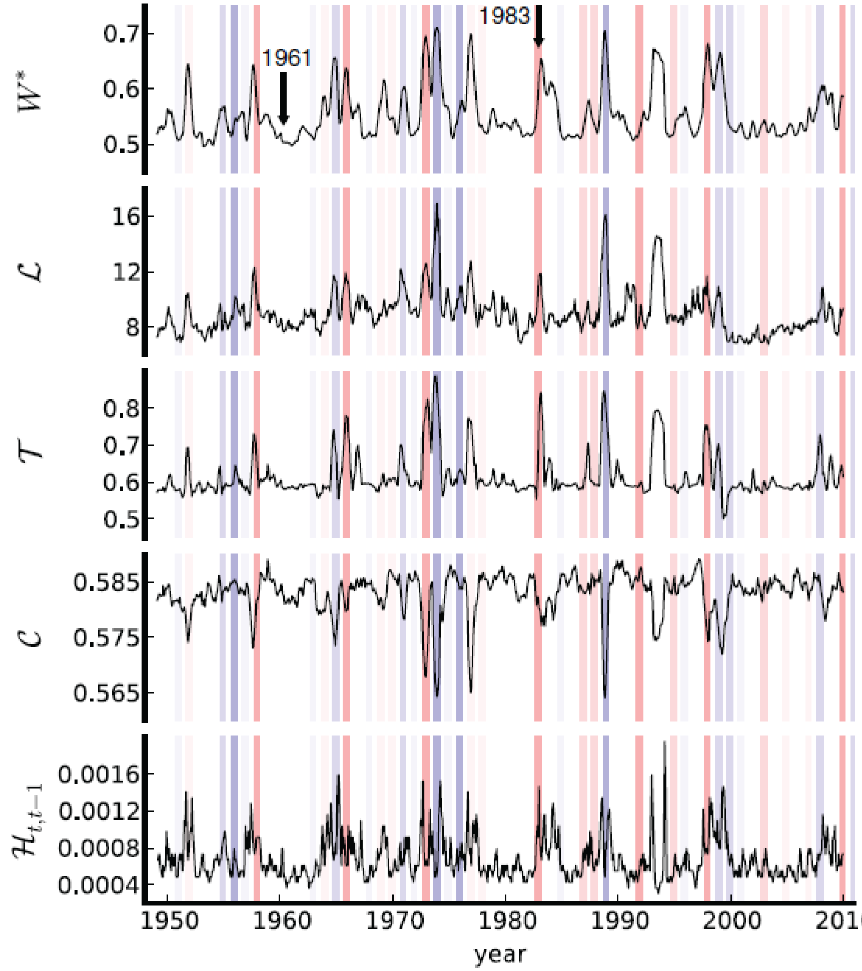


(Radebach et al., Phys. Rev. E, 2013)

Evolving global surface air temperature network

Climate network analysis for running windows in time: evolving climate networks

Global network characteristics show distinct temporal variability profile strongly related to ENSO



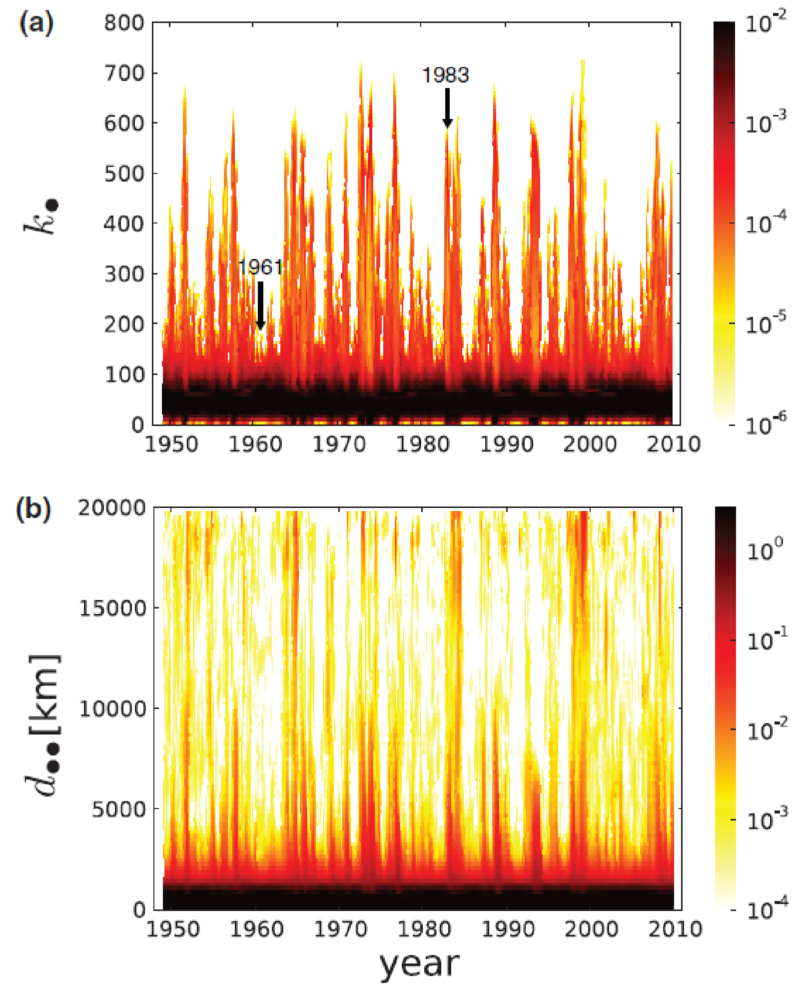
(Radebach et al., Phys. Rev. E, 2013)

Evolving global surface air temperature network

Climate network analysis for running windows in time: evolving climate networks

Global network characteristics show distinct temporal variability profile strongly related to ENSO: El Nino and La Nina episodes can create hubs with long-range links (global impact)

(Radebach et al., Phys. Rev. E, 2013)



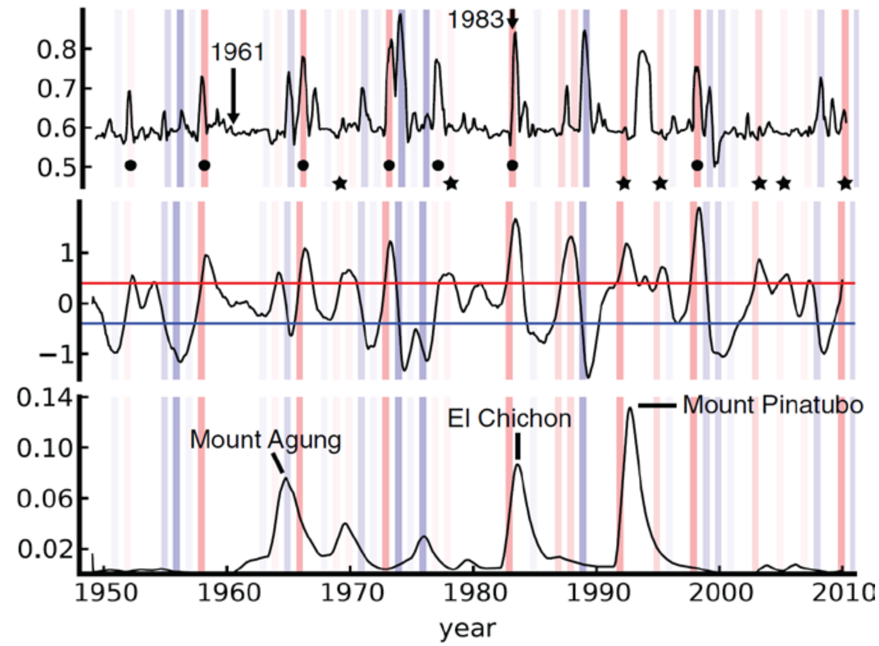
Evolving global surface air temperature network

But: peaks in global network characteristics do not coincide 1:1 with timing of known El Nino and La Nina episodes

Reason: peaks indicate the formation of "localized structures" of high connectivity

- **Can also arise after strong volcanic eruptions (common regional cooling trend – increase of correlations)**

Transitivity, NINO3.4, strat. opt. depth

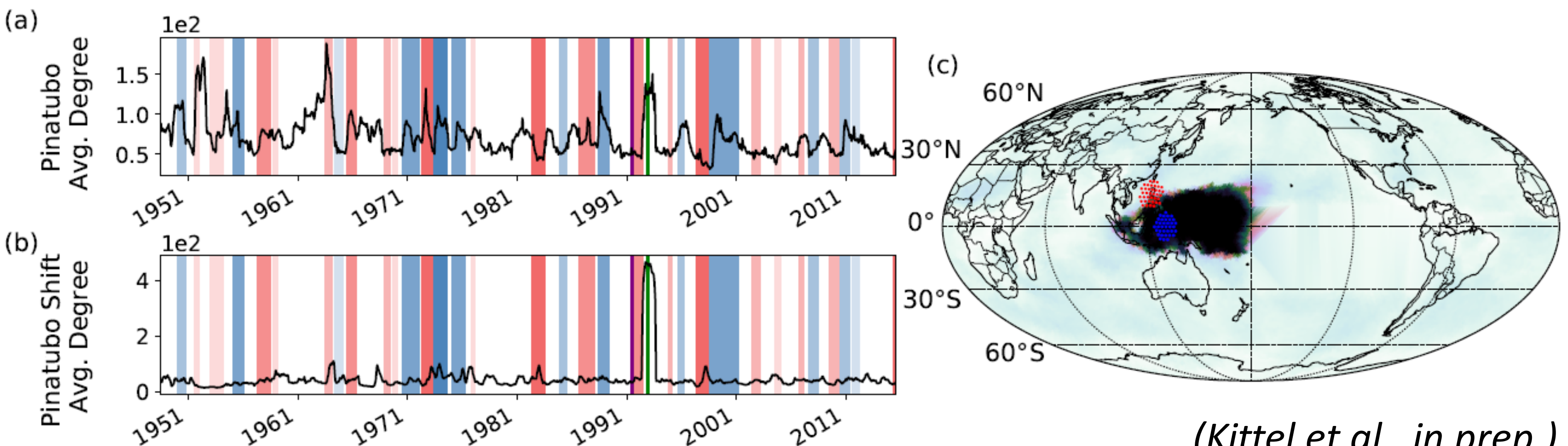


(Radebach et al., Phys. Rev. E, 2013)

Evolving global surface air temperature network

Strong eruptive volcanism: Mt Pinatubo as example

- ⇒ **Injection of large amounts of aerosols into stratosphere**
- ⇒ **Large-scale regional cooling (with spatial shift and lag of 12-18 months)**
- ⇒ **Elevation of correlations in confined region**
- ⇒ **Introduction of spatially confined correlations in affected region**



(Kittel et al., in prep.)

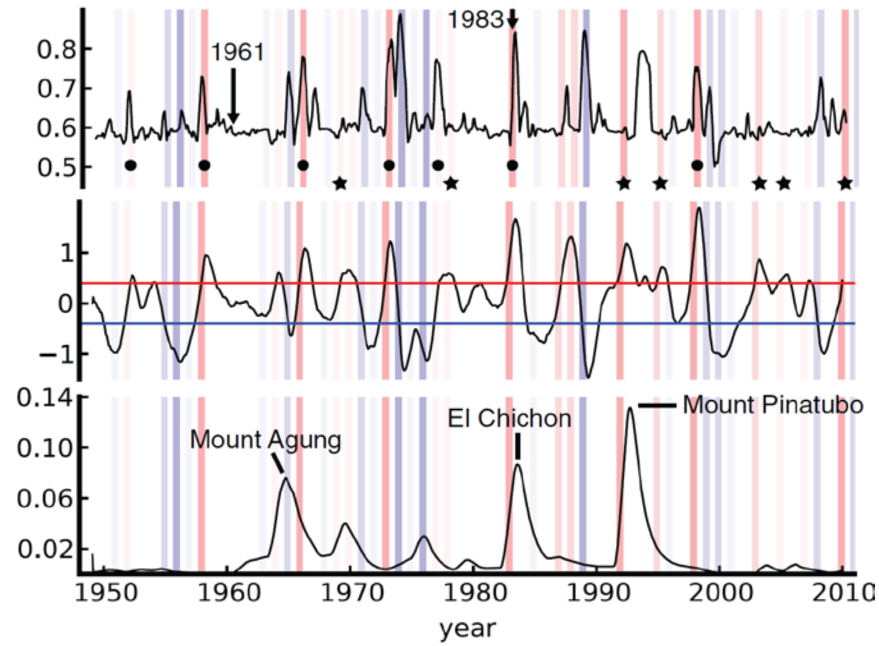
Evolving global surface air temperature network

But: peaks in global network characteristics do not coincide 1:1 with timing of known El Nino and La Nina episodes

Reason: peaks indicate the formation of "localized structures" of high connectivity

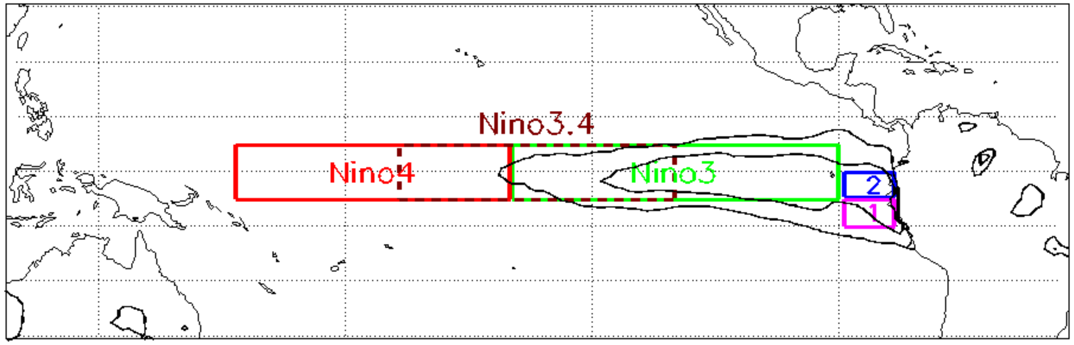
- **Can also arise after strong volcanic eruptions (common regional cooling trend – increase of correlations)**
- **Different types ("flavors") of El Nino and La Nina episodes: functional discrimination based on global impacts?**

Transitivity, NINO3.4, strat. opt. depth

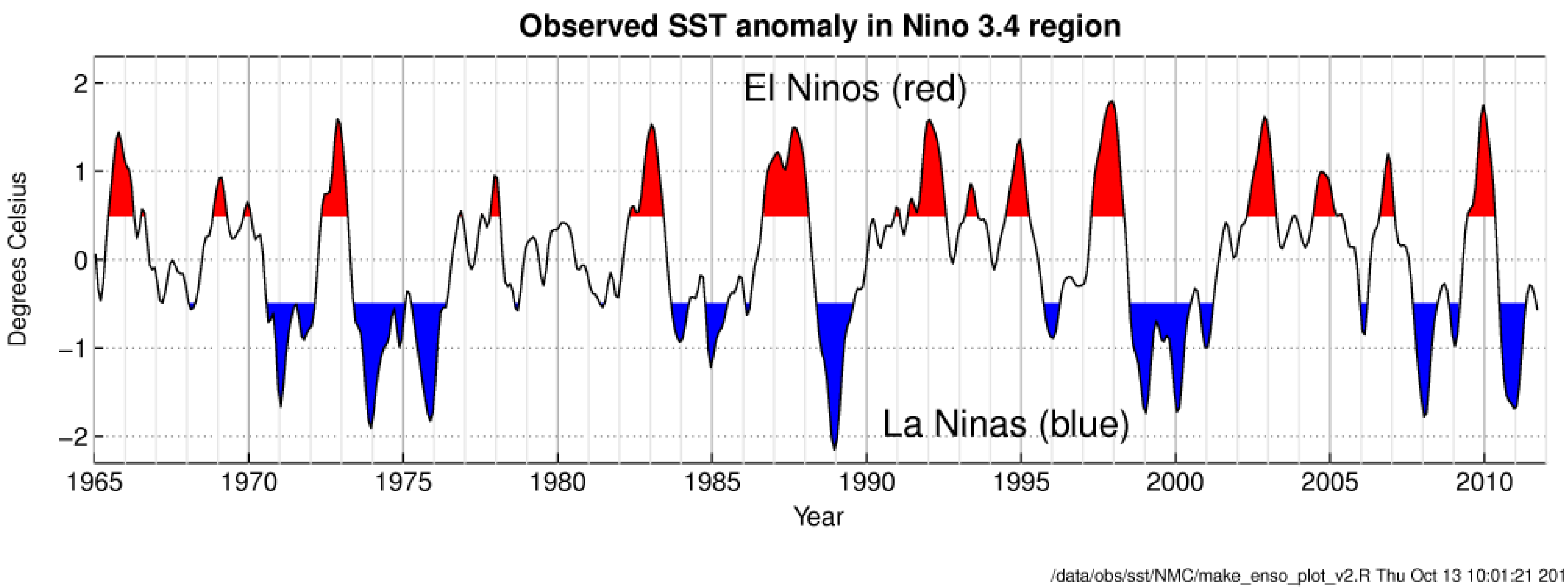


(Radebach et al., Phys. Rev. E, 2013)

Characterizing the El Niño/Southern Oscillation



Curtesy: William M. Connolley, https://commons.wikimedia.org/w/index.php?curid=8010087



Two different types of El Niño

Vol 461 | 24 September 2009 | doi:10.1038/nature08316

nature

LETTERS

El Niño in a changing climate

Sang-Wook Yeh[1], Jong-Seong Kug[1], Boris Dewitte[2], Min-Ho Kwon[3], Ben P. Kirtman[4] & Fei-Fei Jin[3]

Two Types of El Niño Events: Cold Tongue El Niño and Warm Pool El Niño

JONG-SEONG KUG* AND FEI-FEI JIN
School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu,
SOON-IL AN
Department of Atmospheric Sciences, Yonsei University, Seoul, South Korea

(Manuscript received 13 May 2008, in final form 20 August 2008)

Asia-Pac. J. Atmos. Sci., 50(1), 69-81, 2014
DOI:10.1007/s13143-014-0028-3

REVIEW

Recent Progress on Two Types of El Niño: Observations, Dynamics, and Future Changes

Sang-Wook Yeh[1], Jong-Seong Kug[2], and Soon-Il An[3]
[1]*Department of Marine Sciences and Convergent Technology, Hanyang University, Ansan, Korea*
[2]*Korea Institute of Ocean Science and Technology, Ansan, Korea*
[3]*Department of Atmospheric Sciences, Yonsei University, Seoul, Korea*

(Manuscript received 26 November 2013; accepted 8 January 2014)

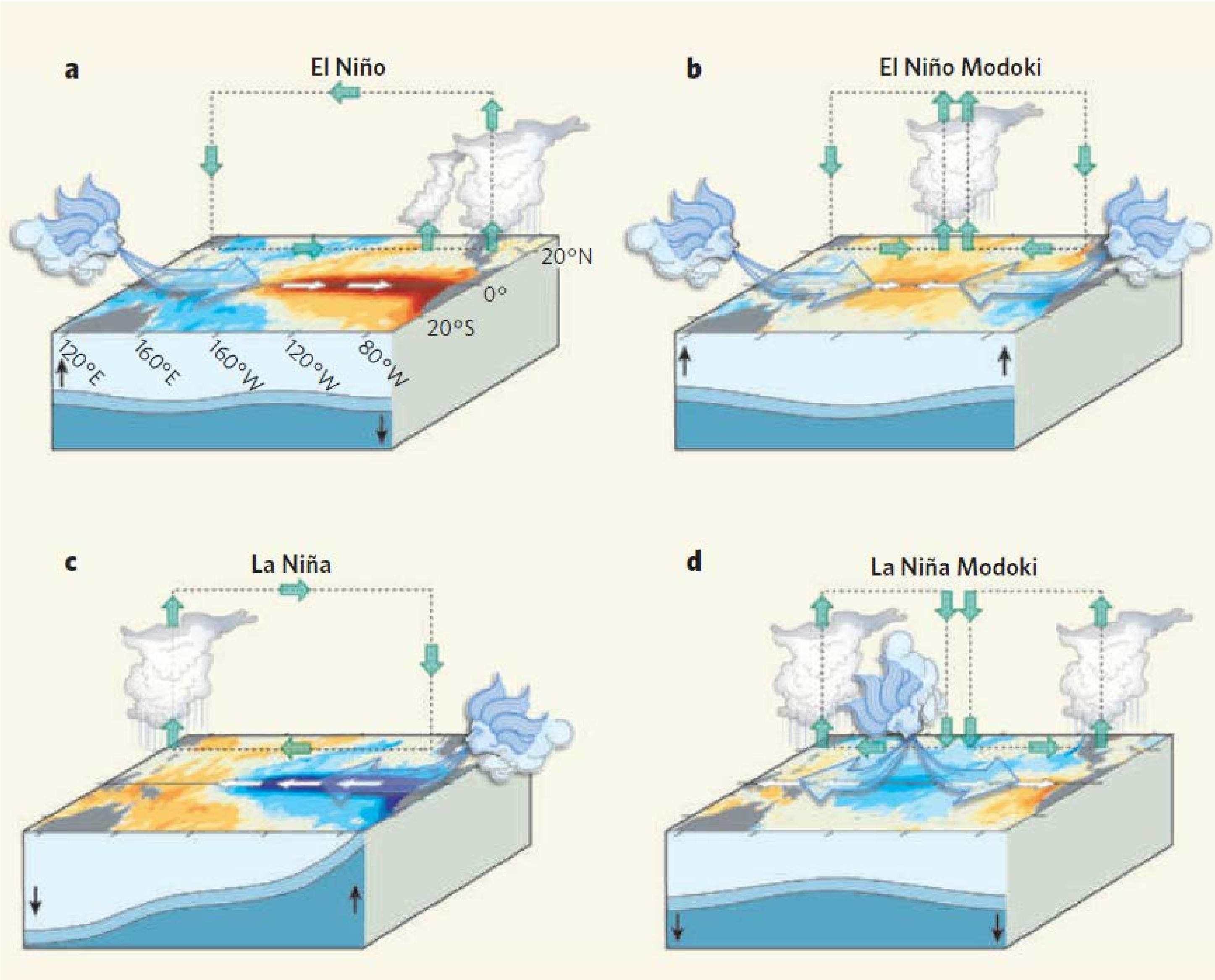
Click Here for Full Article

GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L14603, doi:10.1029/2010GL044007, 2010

Increasing intensity of El Niño in the central-equatorial Pacific

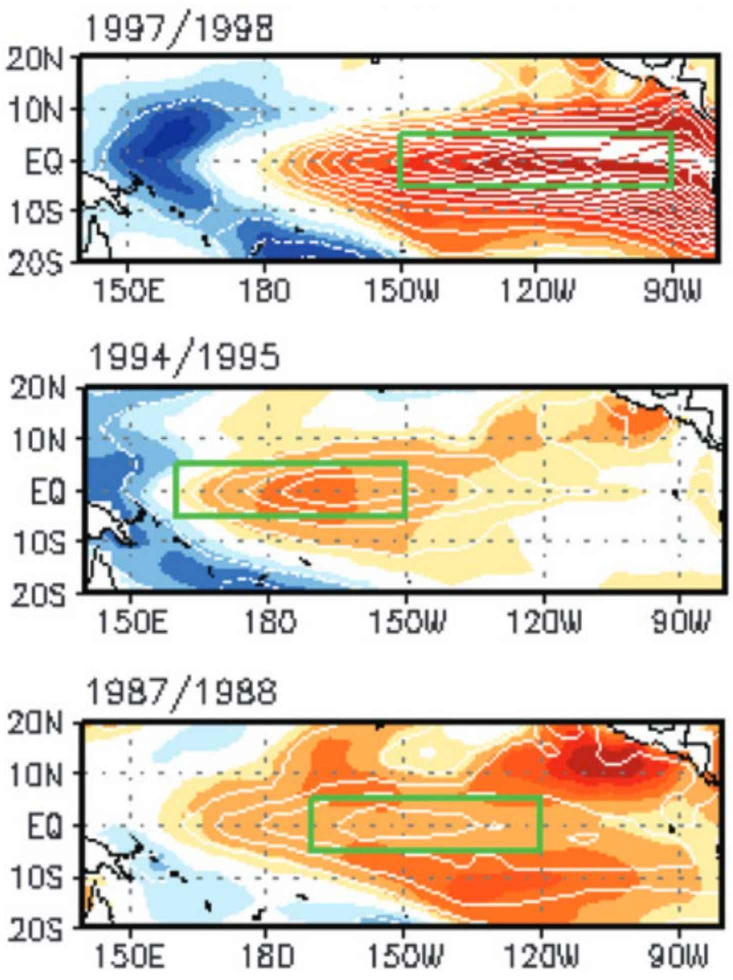
Tong Lee[1] and Michael J. McPhaden[2]

Received 15 May 2010; revised 7 June 2010; accepted 17 June 2010; published 24 July 2010.



(Ashok & Yamagata, Nature, 2009)

Discriminating El Niño flavors



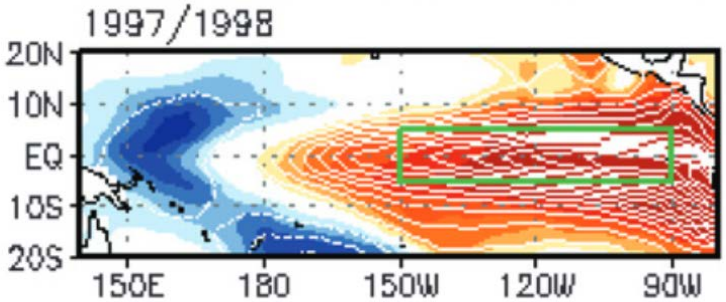
Canonical (East Pacific) El Niño

Dateline (Central Pacific) El Niño
(El Niño Modoki)

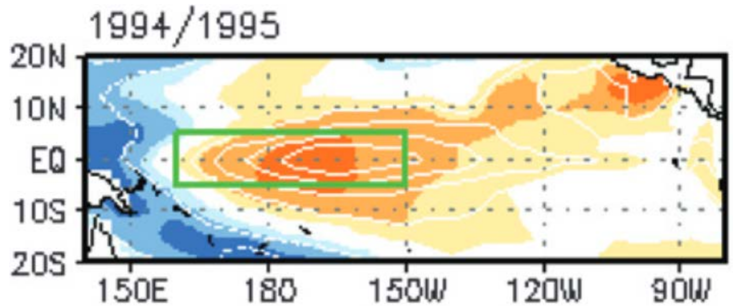
?

(Kug et al., J. Clim., 2009)

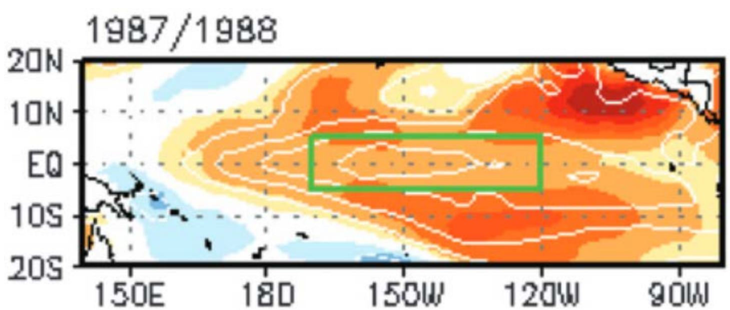
Discriminating El Niño flavors



Canonical (East Pacific) El Niño



Dateline (Central Pacific) El Niño
(El Niño Modoki)



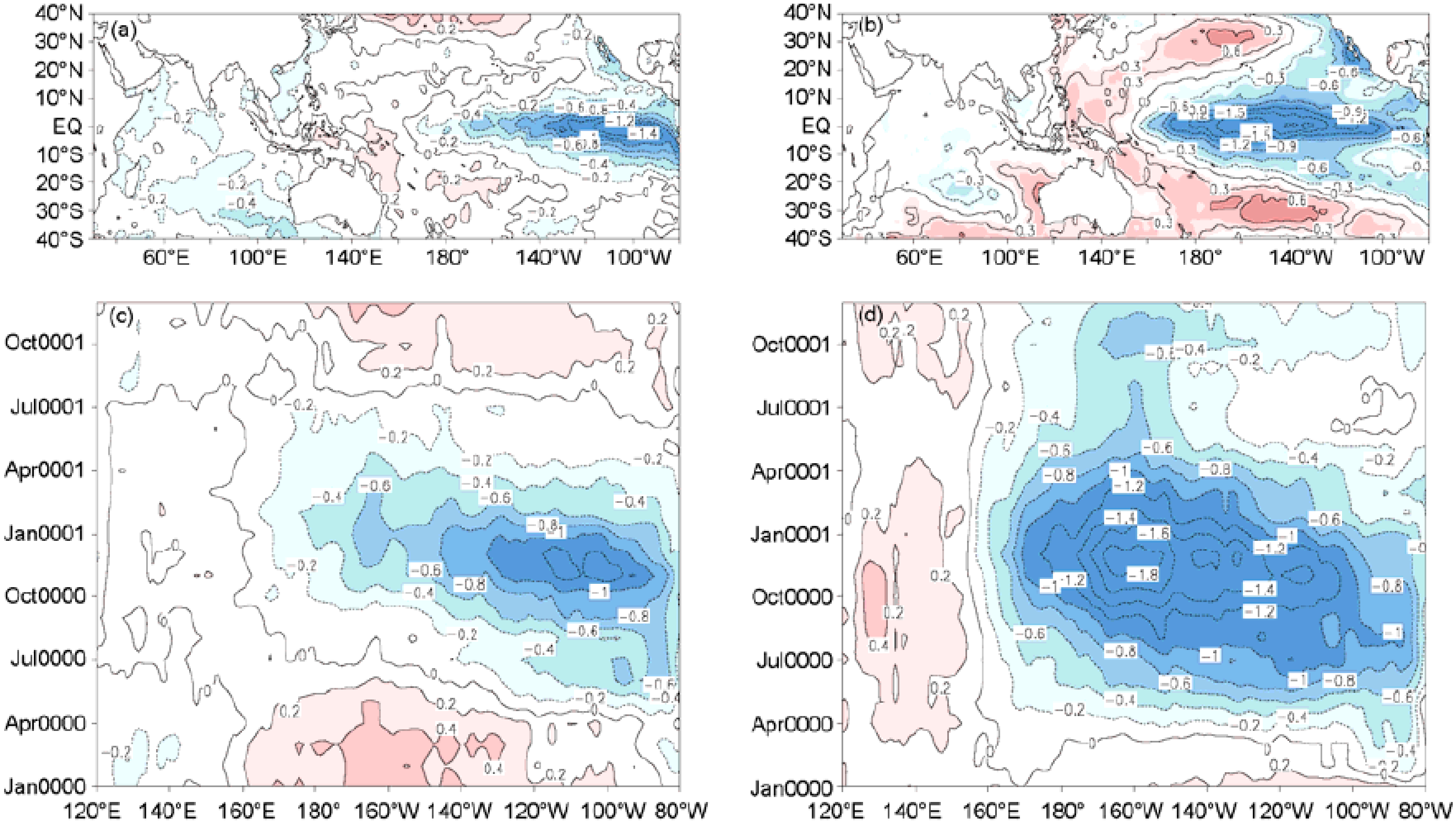
(Kug et al., J. Clim., 2009)

Mixed form? (Kug et al., J. Clim., 2009)
Canonical? (Kim et al., GRL, 2011;
Hu et al., Clim. Dyn., 2012)
Central Pacific? (Larkin & Harrison, GRL, 2005)

	Kug et al. [2009]	*Kim et al.* [2011]	*Hu et al.* [2011]	*Larkin et al.* [2005]	*Hendon et al.* [2009]	*Graf et al.* [2012]	*Yeh et al.* [2009]	*Kim et al.* [2009]	Literature Synthesis
1953/1954	-	-	-	-	-	-	-	-	-
1957/1958	-	-	**EP**	**EP**	-	**EP**	**EP**	**EP**	**EP**
1958/1959	-	-	-	-	-	-	-	-	-
1963/1964	-	-	-	**CP**	-	**CP**	EP	EP	-
1965/1966	-	-	**EP**	**EP**	-	**EP**	**EP**	**EP**	**EP**
1968/1969	-	-	**CP**	**CP**	-	**CP**	**CP**	-	**CP**
1969/1970	-	-	EP	EP	-	-	EP	**CP**	-
1972/1973	**EP**	**EP**	**EP**	**EP**	-	**EP**	**EP**	**EP**	**EP**
1976/1977	**EP**	**EP**	-	**EP**	-	**EP**	**EP**	**EP**	**EP**
1977/1978	**CP**	**CP**	-	**CP**	-	**CP**	**CP**	-	**CP**
1979/1980	-	-	-	-	-	-	b	-	-
1982/1983	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**
1986/1987	b	EP	EP	**CP**	**CP**	**CP**	EP	-	-
1987/1988	b	-	**CP**	EP	EP	-	EP	EP	-
1991/1992	b	EP	EP	EP	**CP**	**CP**	EP	**CP**	-
1994/1995	**CP**	**CP**	**CP**	**CP**	**CP**	**CP**	**CP**	**CP**	**CP**
1997/1998	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**
2002/2003	**CP**	**CP**	**CP**	EP	**CP**	**CP**	b	**CP**	-
2004/2005	**CP**	**CP**	-	-	**CP**	**CP**	**CP**	**CP**	**CP**
2006/2007	-	EP	**CP**	**CP**	-	-	EP	-	-
2009/2010	-	**CP**	-	-	-	**CP**	-	-	**CP**

What about La Nina?

(Yuan & Yan, Chin. Sci. Bull., 2013)



What about La Nina?

Possible criteria suggested in literature:

- **Location of strongest negative SST anomaly**
- **Sign of difference between normalized Nino3 and Nino4 indices**

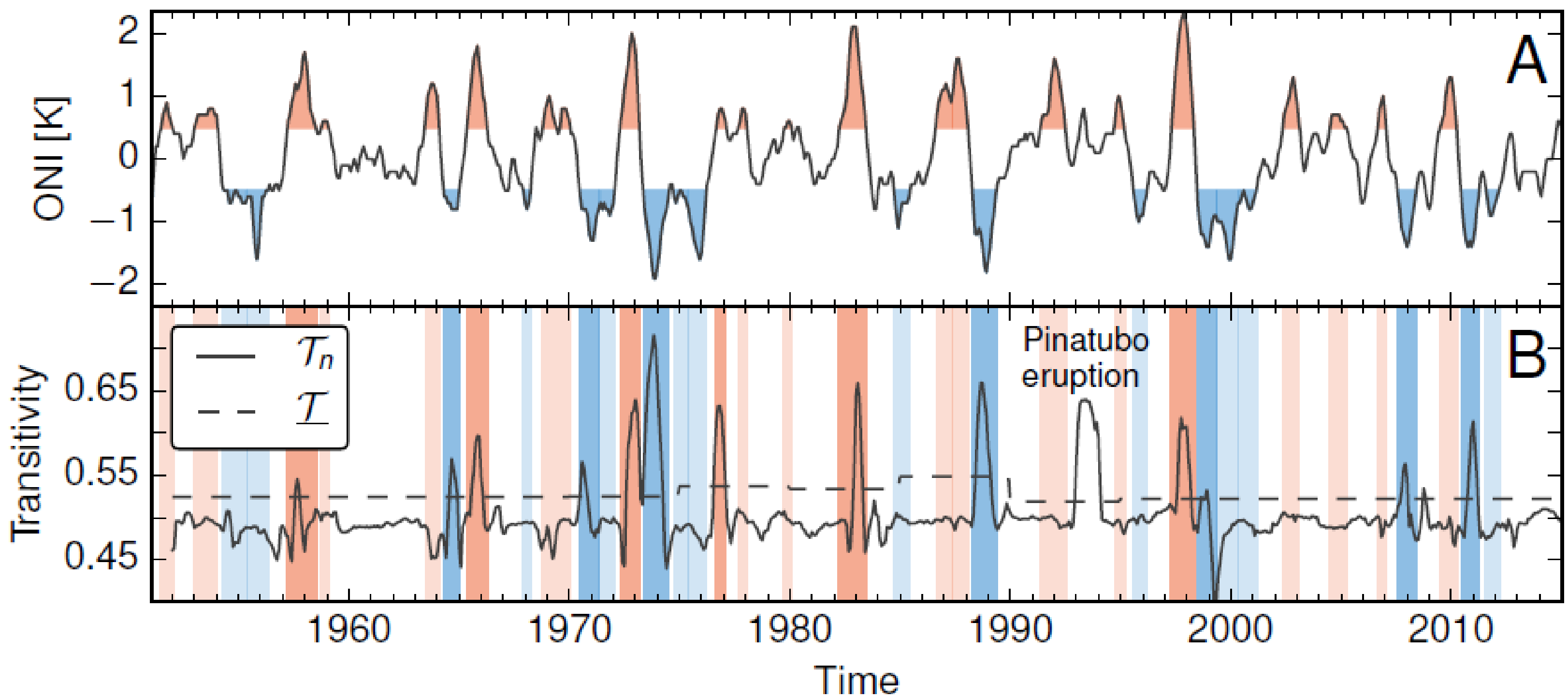
⇒ Objective classification?

Type	La Niña	Mature phase	SSTA propagating direction
EP	1954–1957	Nov 1955–Jan 1956	east to west
	1964–1965	Oct–Dec 1964	east to west
	1967–1968	Jan–Mar 1968	east to west
	1970–1971	Jul–Sep 1970	east to west
	1978	Jun–Aug 1978	east to west
	1995–1996	Sep–Nov 1995	east to west
	2005–2006	Nov 2005–Jan 2006	east to west
CP	1973–1974	Nov 1973–Jan 1974	east to west
	1975–1976	Sep–Nov 1975	west to east
	1983–1985	Nov 1984–Jan 1985	west to east
	1988–1989	Nov 1988–Jan 1989	east to west
	1998–2001	Jan–Mar 2000	west to east
	2007–2009	Jan–Mar 2008	east to west
	2010–2012	Nov 2010–Jan 2011	west to east

(Yuan & Yan, Chin. Sci. Bull., 2013)

Evolving global surface air temperature network

New index for El Nino / La Nina flavor based on transitivity of weighted climate networks (weights = absolute correlations)



(Wiedermann et al., Geophys. Res. Lett., 2016)

	Kug et al. [2009]	*Kim et al.* [2011]	*Hu et al.* [2011]	*Larkin et al.* [2005]	*Hendon et al.* [2009]	*Graf et al.* [2012]	*Yeh et al.* [2009]	*Kim et al.* [2009]	Literature Synthesis	This study
1953/1954	-	-	-	-	-	-	-	-	-	CP
1957/1958	-	-	**EP**	**EP**	-	**EP**	**EP**	**EP**	**EP**	EP
1958/1959	-	-	-	-	-	-	-	-	-	CP
1963/1964	-	-	-	**CP**	-	**CP**	EP	EP	-	CP
1965/1966	-	-	**EP**	**EP**	-	**EP**	**EP**	**EP**	**EP**	EP
1968/1969	-	-	**CP**	**CP**	-	**CP**	**CP**	-	**CP**	CP
1969/1970	-	-	EP	EP	-	-	EP	**CP**	-	CP
1972/1973	**EP**	**EP**	**EP**	**EP**	-	**EP**	**EP**	**EP**	**EP**	EP
1976/1977	**EP**	**EP**	-	**EP**	-	**EP**	**EP**	**EP**	**EP**	EP
1977/1978	**CP**	**CP**	-	**CP**	-	**CP**	**CP**	-	**CP**	CP
1979/1980	-	-	-	-	-	-	[b]	-	-	CP
1982/1983	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	EP
1986/1987	[b]	EP	EP	**CP**	**CP**	**CP**	EP	-	-	CP
1987/1988	[b]	-	**CP**	EP	EP	-	EP	EP	-	CP
1991/1992	[b]	EP	EP	EP	**CP**	**CP**	EP	**CP**	-	CP
1994/1995	**CP**	**CP**	**CP**	**CP**	**CP**	**CP**	**CP**	**CP**	**CP**	CP
1997/1998	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	**EP**	EP
2002/2003	**CP**	**CP**	**CP**	EP	**CP**	**CP**	[b]	**CP**	-	CP
2004/2005	**CP**	**CP**	-	-	**CP**	**CP**	**CP**	**CP**	**CP**	CP
2006/2007	-	EP	**CP**	**CP**	-	-	EP	-	-	CP
2009/2010	-	**CP**	-	-	-	**CP**	-	-	**CP**	CP
TPR	1.0	0.57	0.62	0.6	0.67	1.0	0.5	0.75	1.0	

All times

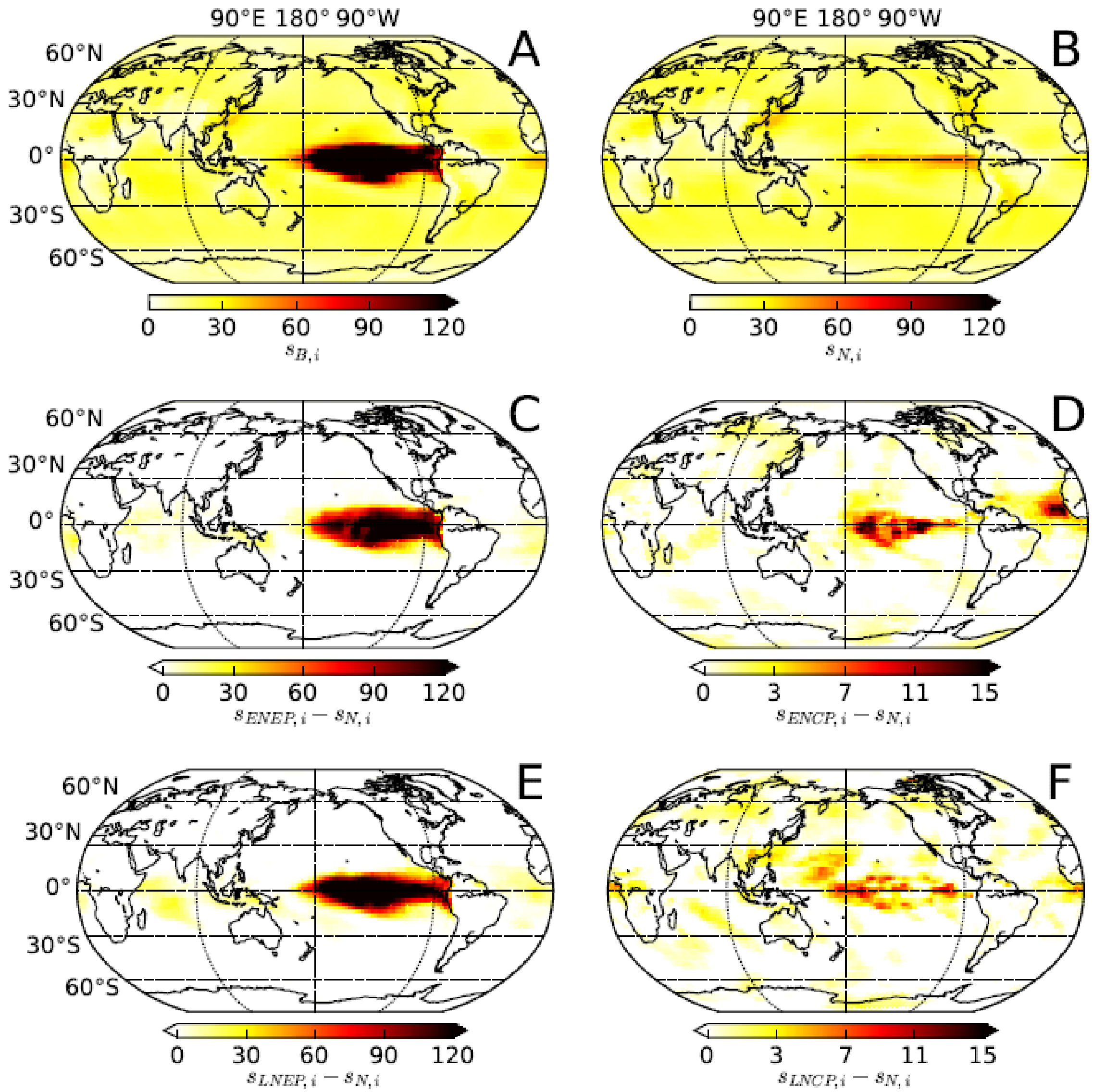
All “normal“ times

Classical El Nino

El Nino Modoki

Classical La Nina

La Nina Modoki



(Wiedermann et al., Geophys. Res. Lett., 2016)

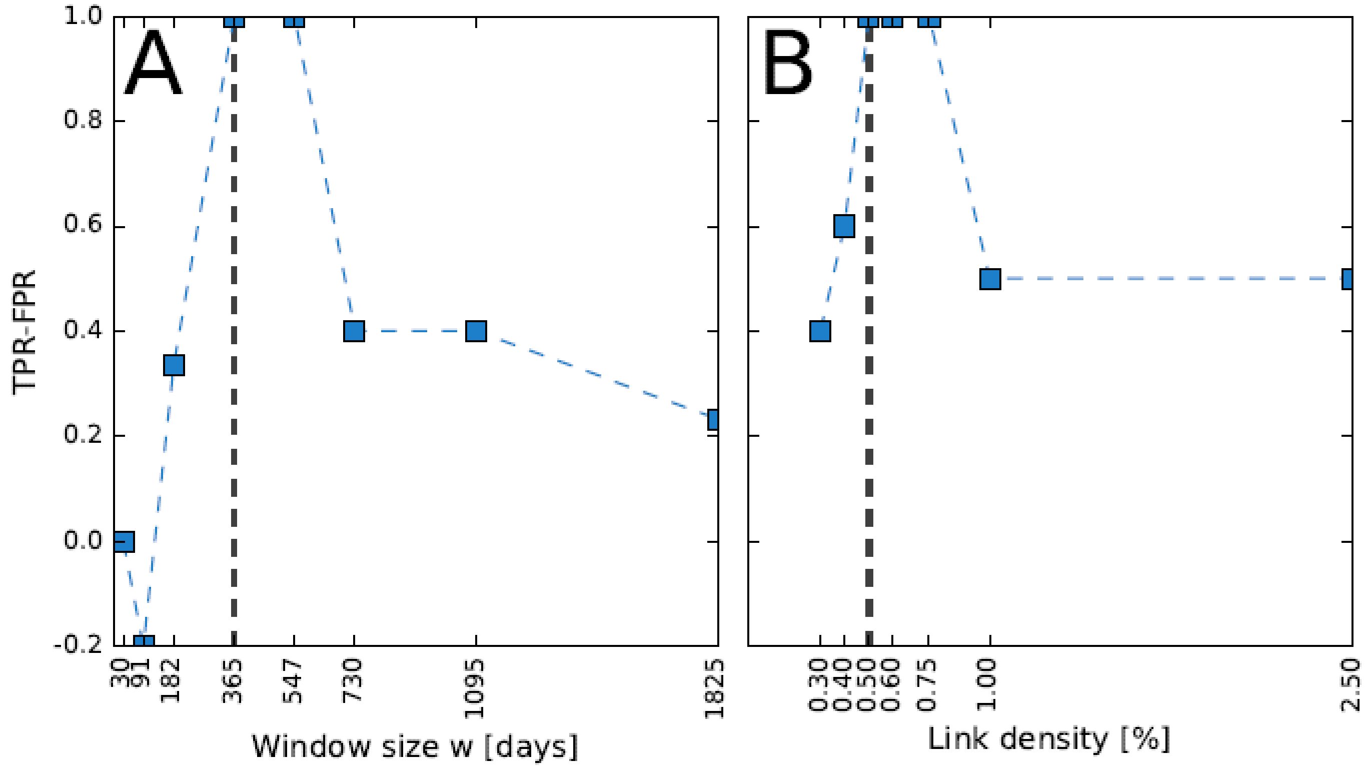
Evolving global surface air temperature network

- Discrimination of El Nino and La Nina episodes into two types each
- Transitivity characterizing the spatial localization of links in climate network and, hence, provides a global impact-based perspective on ENSO patterns
- High transitivity values: classical El Nino / La Nina pattern (strongly localized structure)
- Low transitivity values: El Nino / La Nina Modoki pattern (more spatially diffuse teleconnections)

Advantages:

- Objective classification coinciding with the consensus among previous studies
- Moderate computational efforts comparable with classical EOF analysis
- Only two parameters to be chosen (link density and window width), results are robust over climatologically reasonable range of both parameters

Robustness of classification

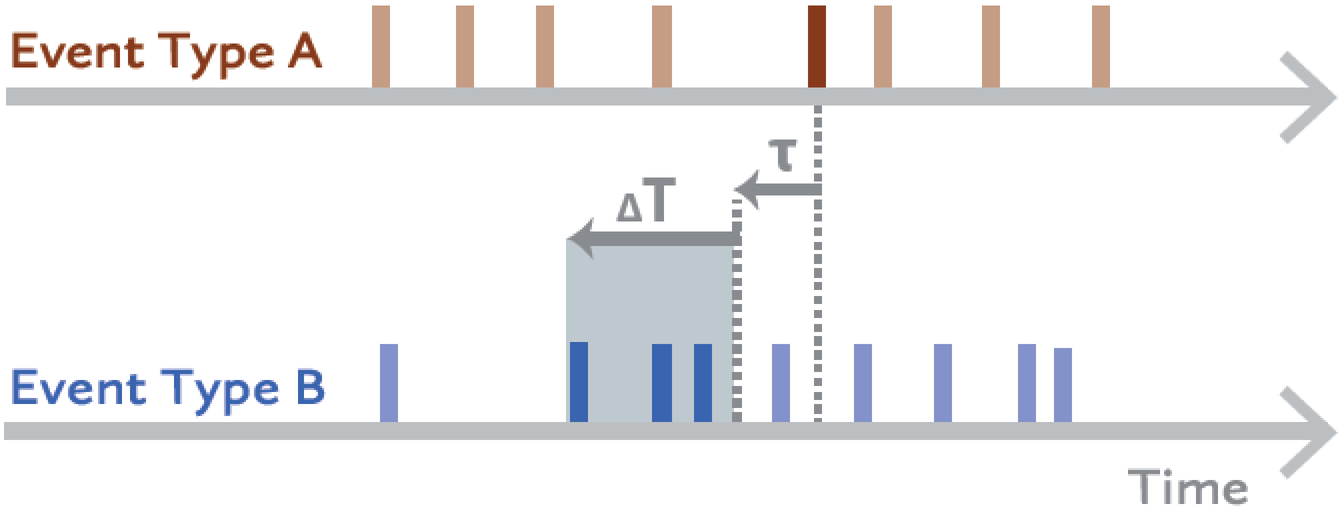


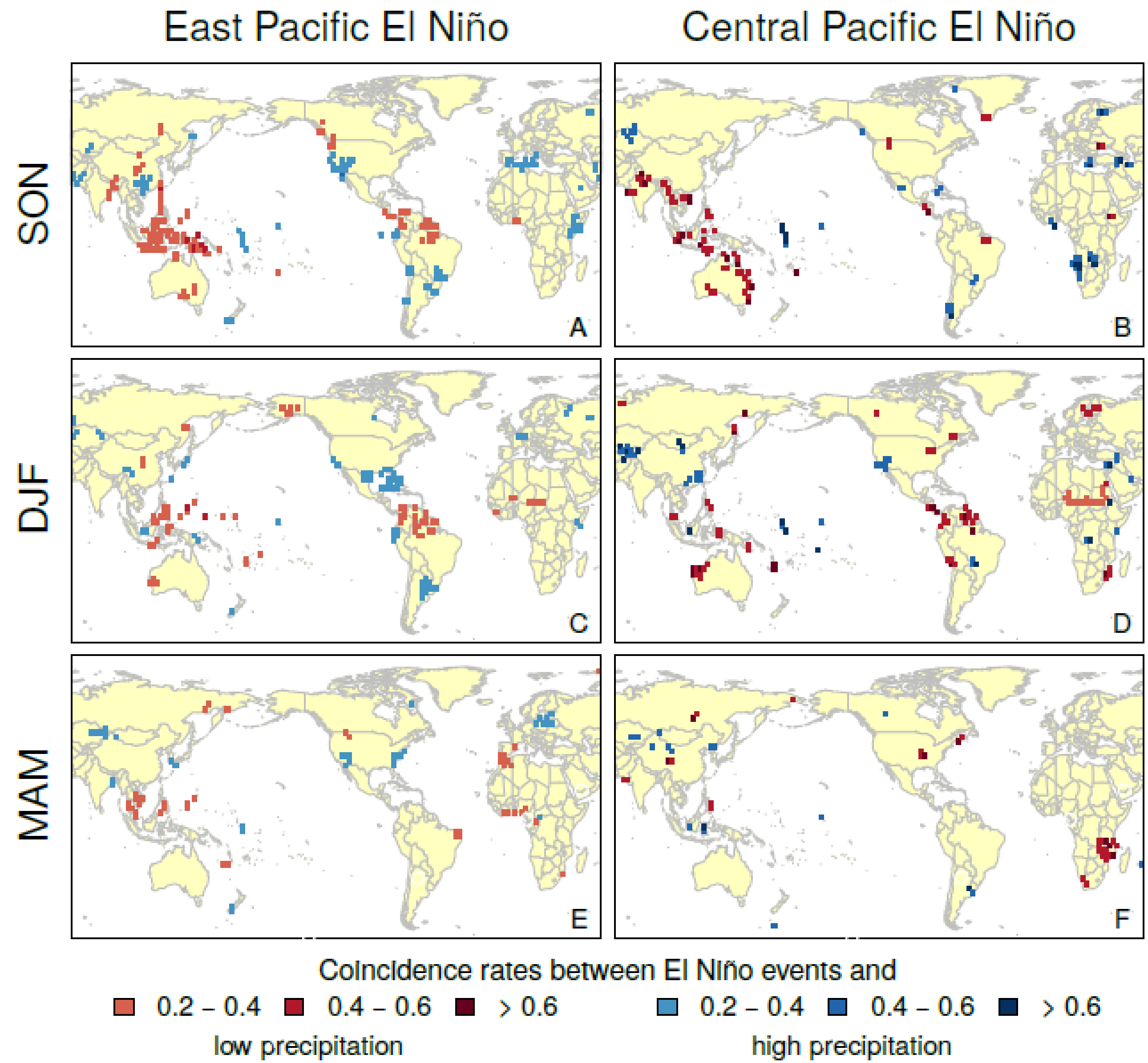
(Wiedermann et al., Geophys. Res. Lett., 2016)

Regional impacts of El Niño and La Niña flavors

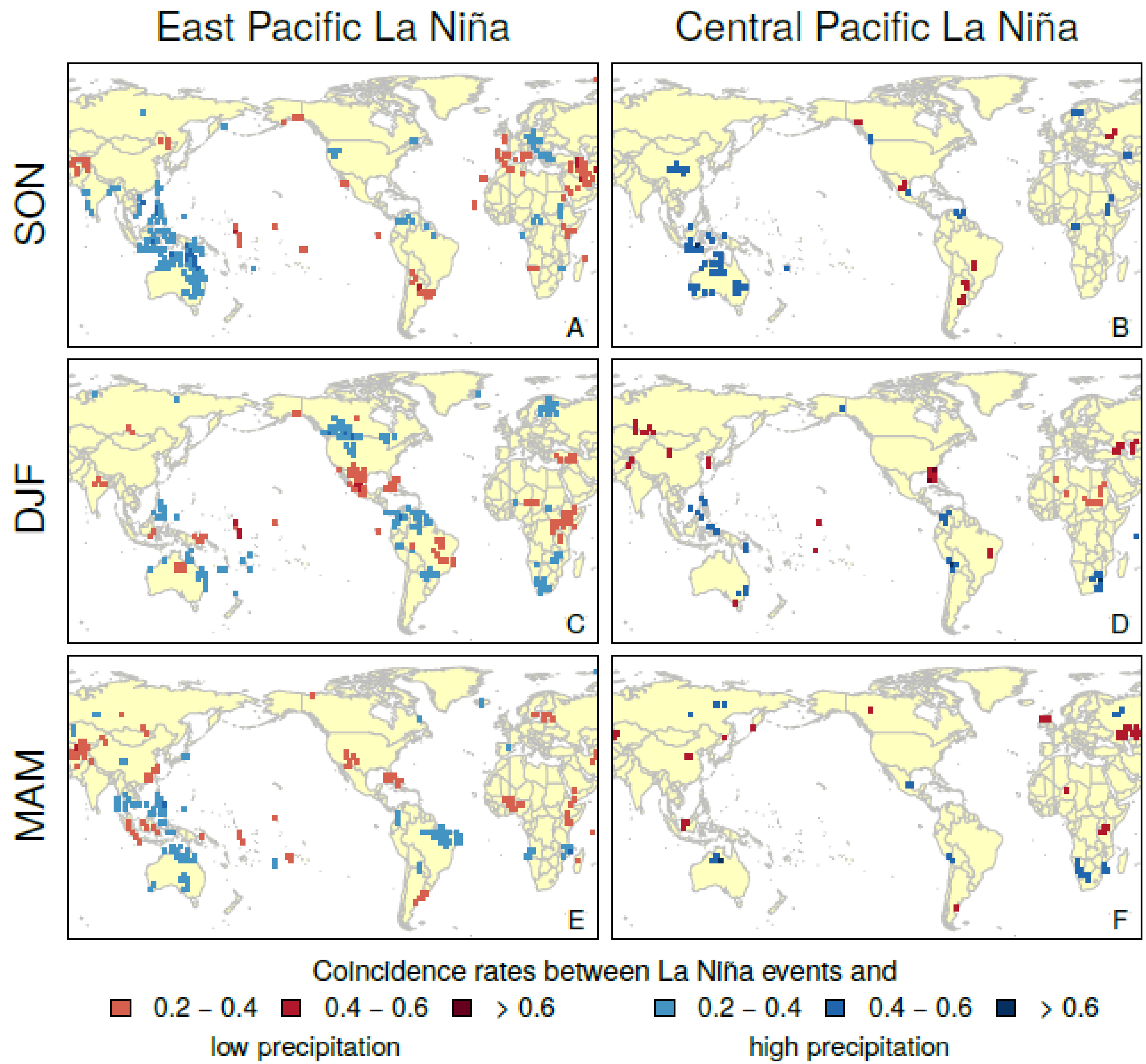
Problem: quantify the co-occurrence of different types of ENSO phases with extremal seasonal precipitation sums worldwide

Approach: Use event coincidence analysis





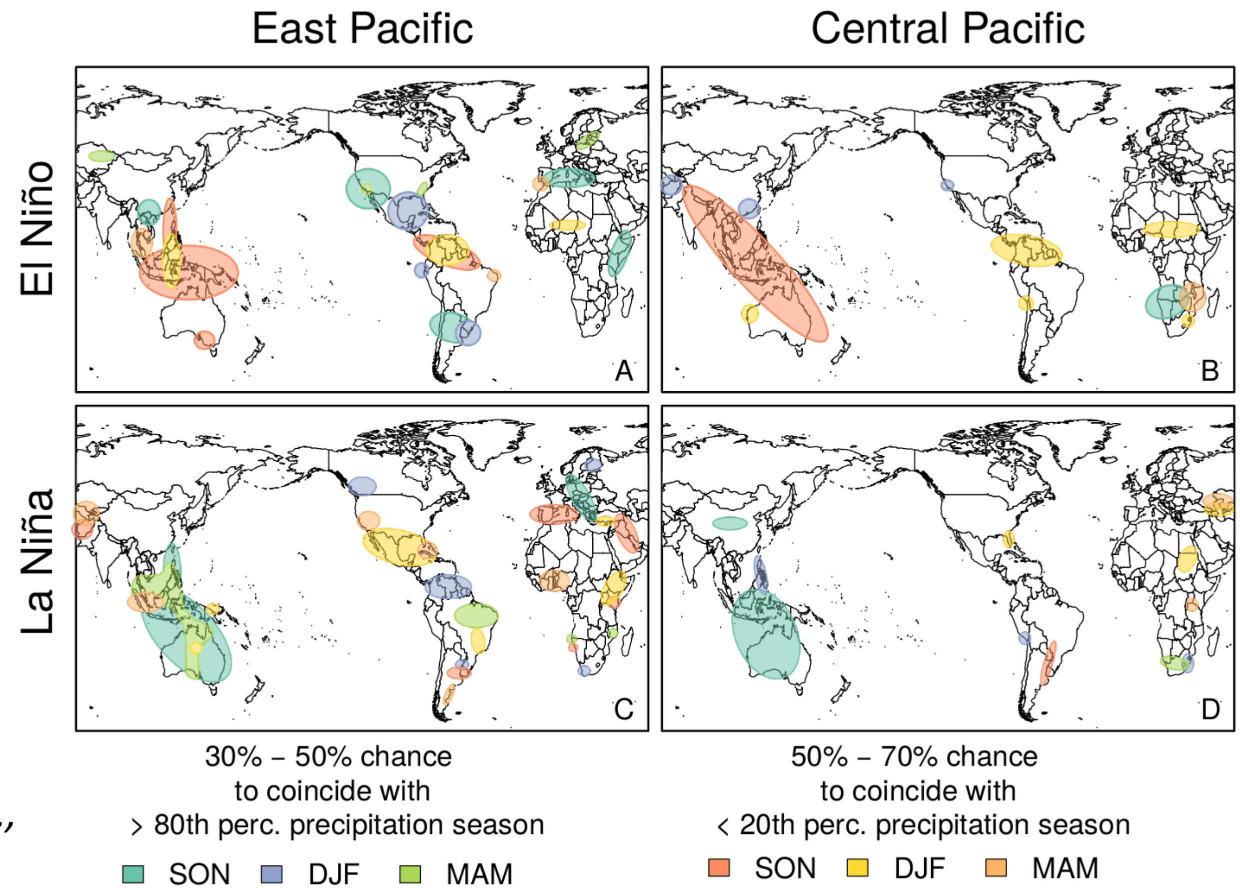
(Wiedermann et al., under review)



(Wiedermann et al., under review)

Regional impacts of El Niño and La Niña flavors

Simultaneous occurrence with extremely low/high seasonal precipitation sums



(Wiedermann et al., under review)

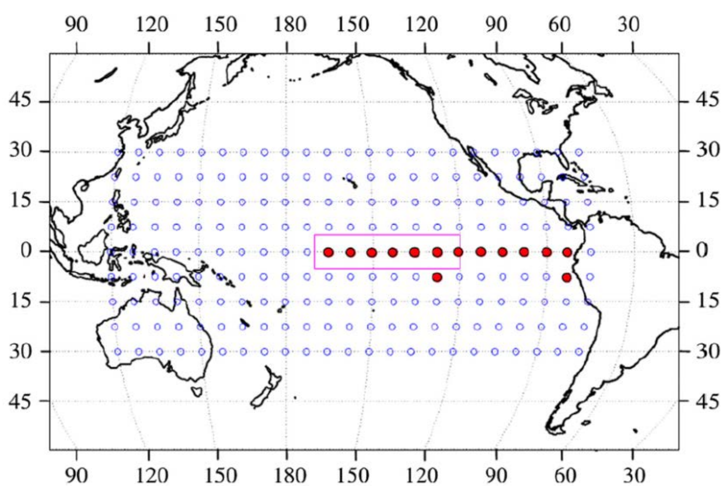
Forecasting El Nino?

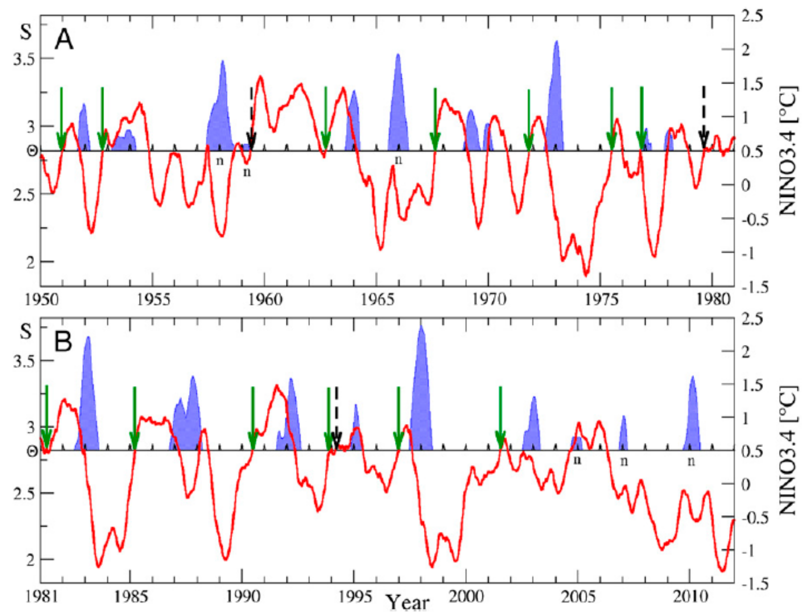
Idea: study emergence of ENSO teleconnections as predictor

(Ludescher et al., PNAS 2013)

Improved El Niño forecasting by cooperativity detection

Josef Ludescher[a], Avi Gozolchiani[b], Mikhail I. Bogachev[a,c], Armin Bunde[a], Shlomo Havlin[b], and Hans Joachim Schellnhuber[d,e,1]





Conclusions

- **Systematic discrimination between different flavors of El Niño and La Niña** *(Radebach et al., PRE, 2013; Wiedermann et al., GRL, 2016)*

- **Event coincidence analysis as new statistical analysis tool for quantifying interrelationships between distinct events – included in software packages `CoinCalc` (R) and `pyunicorn` (Python) [both available at GitHub]**

- **Distinct regional impact patterns of both flavors in terms of seasonal precipitation extremes around the globe** *(Wiedermann et al., under review, arXiv: 1702.00218)*

  Work in progress: obtain and interpret regional impact patterns for
  - **seasonal temperature extremes**
  - **occurrence of short-term extremes in precipitation / temperature**
  - **productivity of natural and managed terrestrial ecosystems (agriculture, forestry)**

- **Emergence of teleconnections: possible predictors for El Nino forecasting** *(Ludescher et al., PNAS, 2013 & 2014)*