Indian Ocean Dipole

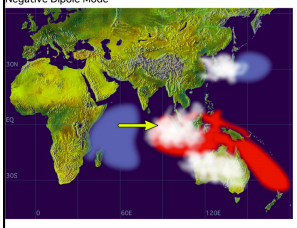
Present, past and future

Indian Ocean Dipole

Present, past and future

Normal Indian Ocean Circulation

Negative Dipole Mode



Mean conditions:

- close proximity to the Asian continent and strong seasonal Asian monsoon

→ ***the equatorial Indian Ocean lacks steady easterly winds***
→ long-term mean winds along the equatorial Indian Ocean are ***westerlies***

Saji et al. (1999) Nature

Normal Indian Ocean Circulation

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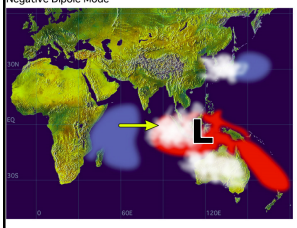

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Normal Indian Ocean Circulation

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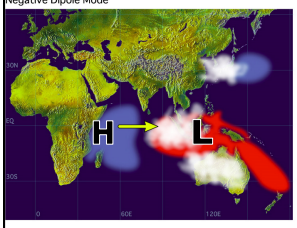

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Saji et al. (1999) Nature

Indian Ocean Dipole

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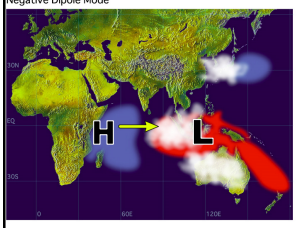
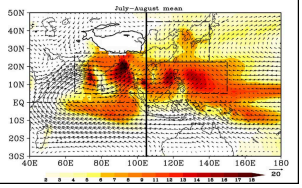


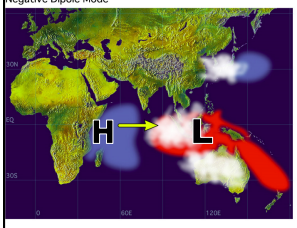
June to November
→ westerlies weakest & east-to-southeasterly winds prevail off the Sumatra–Java coast (associated with the Asian monsoon)
→ lifts the thermocline

Saji et al. (1999) Nature



Indian Ocean Dipole

Negative Dipole Mode



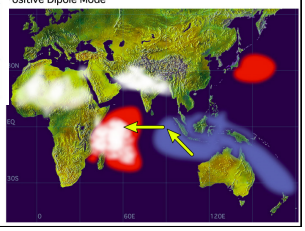
June to November
→ westerlies weakest & east-to-southeasterly winds prevail off the Sumatra–Java coast (associated with the Asian monsoon)
→ lifts the thermocline

Saji et al. (1999) Nature

→ When the anomalous easterlies are strong enough, the thermocline is lifted shallow enough to influence SST

→ development of a positive IOD event

Positive Dipole Mode



Indian Ocean Dipole

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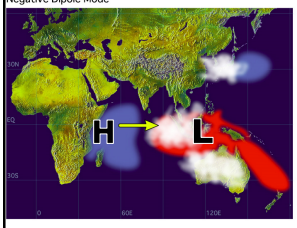
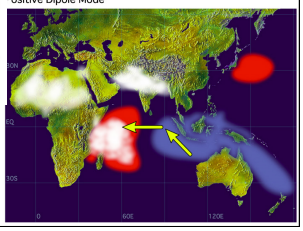


Saji et al. (1999) Nature

Explains ~12% of SST variance (Saji et al. 1999)

Positive Dipole Mode



Seasonal Evolution

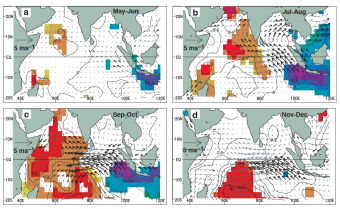


Figure 2 A composite dipole mode event. **a**–**d**, Evolution of composite SST and surface wind anomalies from May–June (**a**) to Nov–Dec (**d**). The statistical significance of the analysed anomalies were estimated by the two-tailed *t*-test. Anomalies of SSTs and winds exceeding 90% significance are indicated by shading and bold arrows, respectively.

Saji et al. (1999)

Indian Ocean Dipole Precipitation

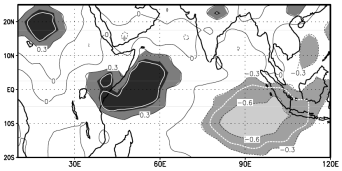
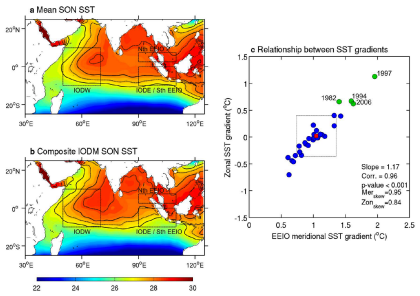


Figure 4 Rainfall shifts northwest of the OTCZ during dipole mode events. The map correlates the DMI and rainfall to illustrate these shifts. The areas within the white curve exceed the 90% level of confidence for non-zero correlation (using a two-tailed *t*-test).

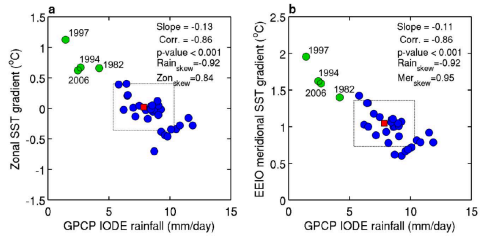
Saji et al. (1999)

Zonal & Meridional SST gradients



Weller and Cai 2014

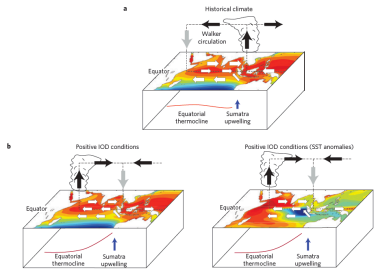
SST gradients vs rainfall



IODE: 90E–110E, 10S–Equator

Weller and Cai 2014

Indian Ocean Dipole



Cai et al. 2013

Ocean-atmosphere coupling

Winds and SST are mutually reinforcing:

Strong monsoon circulation

Bjerknes feedback

Strong SST gradient

Strong trades

Cai et al. 2013

Ocean-atmosphere coupling

What causes the demise of IOD events?

Strong Asian monsoon circulation

Boreal summer: Sumatra–Java south-easterlies

Wind-evaporation feedback

Cool SST Eastern IO

Enhanced heat loss

\+ feedback

Cai et al. 2013

Ocean-atmosphere coupling

What causes the demise of IOD events?

Strong Australian monsoon circulation

Boreal winter: Australian monsoon westerlies

Wind-evaporation feedback

Warm SST Eastern IO

Reduced heat loss

\- feedback

Cai et al. 2013

Ocean-atmosphere coupling

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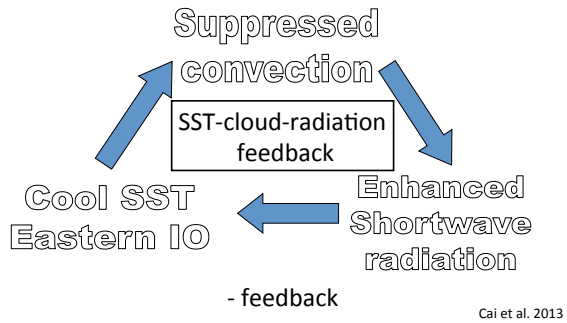


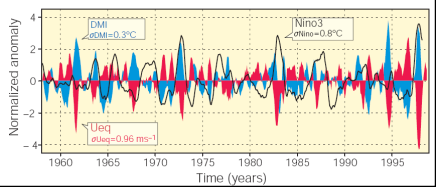
Cai et al. 2013

Independent mode?

Blue: Dipole Mode Index (west-east SST anomaly)

Black: Nino3 SST anomaly

Red: Equatorial wind anomaly



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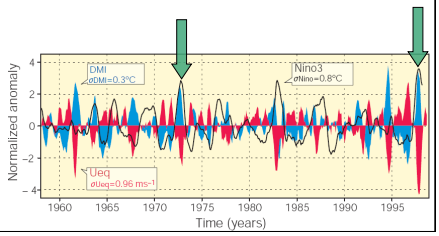

Saji et al. (1999)

Independent mode?

- Only 56% of IOD events coincide with El Niños (Abram et al. 2008)

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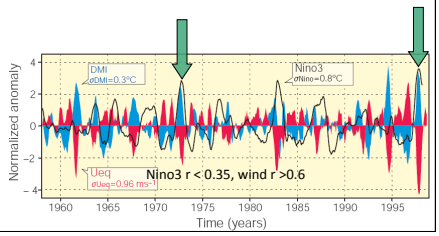

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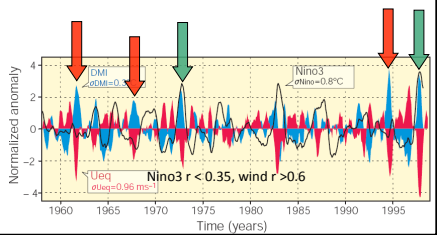

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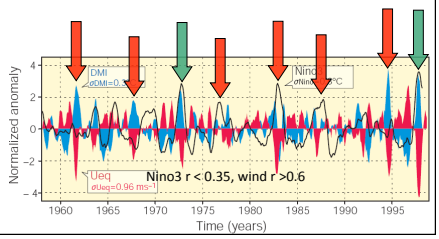
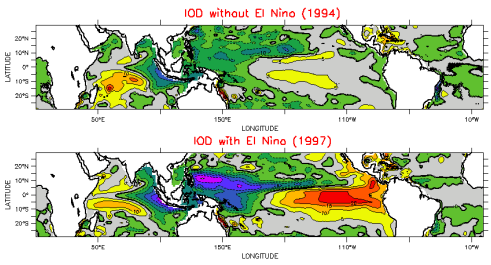


Saji et al. (1999)

IOD, with and without ENSO



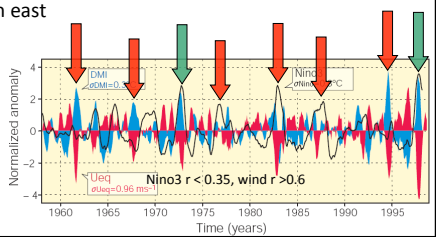
Independent mode?

- Only 56% of IOD events coincide with El Niños (Abram et al. 2008)
- Asian-Australian monsoon
  - Intensified Hadley circulation → strong SE tradewinds
  - Upwelling in east

Blue: Dipole Mode Index (west-east SST anomaly)

Black: Nino3 SST anomaly

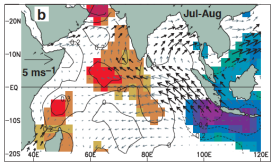
Red: Equatorial wind anomaly



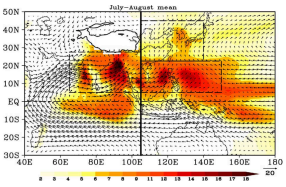
Saji et al. (1999)

Relationship to monsoons

IOD SST & Wind



Monsoon precip & Wind



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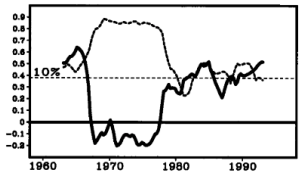
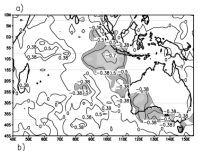


Correlation coefficients:
Dashed: ENSO vs Indian summer monsoon
Solid: IOD vs Indian summer monsoon

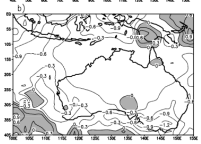
- IOD and ENSO both affect the ISMR (sometimes in opposing ways!)
- Whenever the ENSO-ISMR correlation is low(high), the IOD-ISMR correlation is high(low).
- IOD is a key modulator of the Indian monsoon rainfall and influences the correlation between ISMR and ENSO

Ashok et al. 2001

Relationship to monsoons



All events 1979-1997

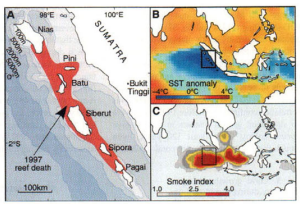


1994 (Non El Niño year)

Figure 3. (a) Partial correlations between the IODMI and the rainfall during JJAS (1979–1997). Negative correlations significant at 90% confidence level (<0.38) are shaded. (b) Normalized rainfall anomalies during JJAS, 1994. Positive values are shaded.

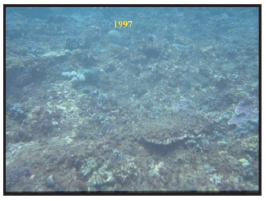
Ashok et al. 2003

Effects of the IOD



Abram et al. (2003)

- ~100% death of reef coral and fish
- Upwelling
- Fallout from wildfires
  - High [Iron]
  - Phytoplankton blooms



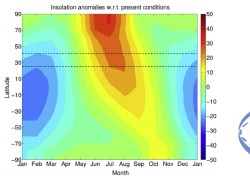
van Woesik (2004) *Science*

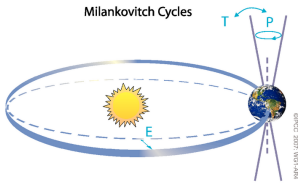
Indian Ocean Dipole

Present, **past** and future

Mid-Holocene Optimum

Insolation difference (W/m^2) between Mid-Holocene and present day (6 ka – 0 ka)





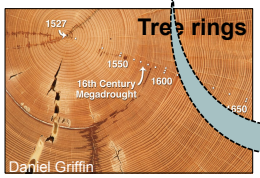
Orbital configeration, 6 ka vs today:

		control	6ka
Strongly elliptical orbit	eccentricity	0.016724	0.018682
Strong axial tilt	obliquity	23.446	24.105
Perihelion during boreal summer	precession	102.04	0.87

Mid-Holocene Optimum

- What were the conditions like during the mid-Holocene compared to today?
  - Monsoon?
  - ENSO?
  - IOD??

Paleoclimate archives



Climate (e.g. rainfall, temperature)

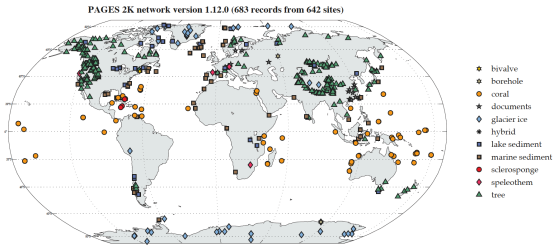
Sensor (e.g. ice, tree, lake, coral)

Archive (e.g. ice layer, tree rings, lamination, coral skeleton)

Observation (e.g. CO_2, ring width, $\delta^{15}N$, $\delta^{18}O$)

(Evans et al. 2013)

Spatial distribution of proxy records

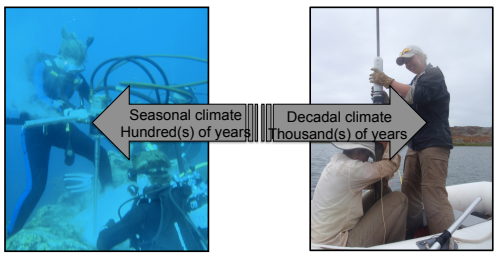


What proxies may you use to reconstruct…..
El Nino variability?
Thermohaline circulation?
Changes to the hydrological cycle?

Length vs. resolution tradeoff

Temporal resolution: the increment of time that can be measured in a proxy

Paleoclimate reconstructions

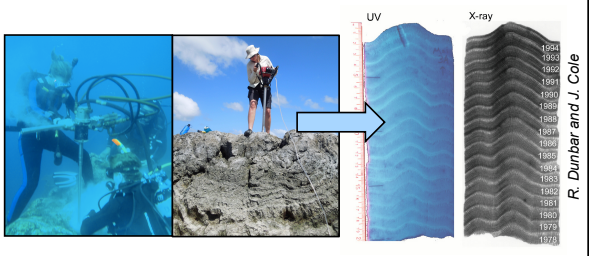


Drilling coral cores:
Wolf Island, Galapagos

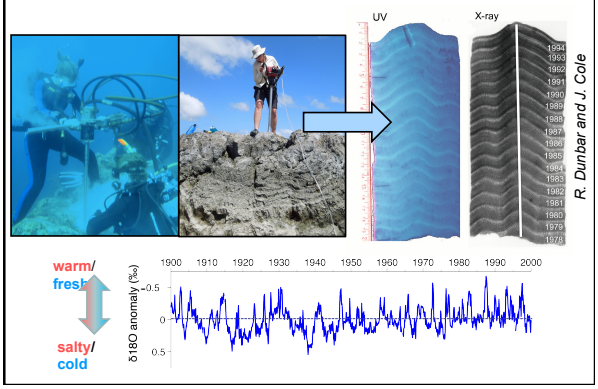
Drilling lake cores:
Rocas Bainbridge, Galapagos

Coral paleoclimate reconstructions

Coral paleoclimate reconstructions

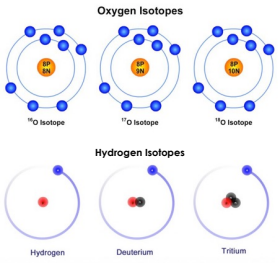


Coral paleoclimate reconstructions



Paleo-thermometers

- Many ways we can reconstruct past climates, but the most common is to use measured changes in isotope concentrations.
- Consider a single parcel of ocean water with 100,000 water molecules. **All but 274 are standard $^{1}H^{1}H^{16}O$**
- **205 / 274 are $^{1}H^{1}H^{18}O$**
- **39 / 274 are $^{1}H^{1}H^{17}O$**
- **30 / 274 are $^{2}H^{1}H^{16}O$**
- maybe 1/274 have 2 or 3 heavy atoms combined



Paleo-thermometers

- Rounding off: "Standard Ocean" would be about

$$\left(\frac{200}{100{,}000}\right) = \left(\frac{^{18}O}{^{16}O}\right)_{std} = \text{Standard Mean Ocean Water (SMOW)}$$

- When we measure a specific sample of water or ice, we measure how the heavy ^{18}O isotopes of the sample, compare to the Standard Mean Ocean Water (SMOW).
- The difference between the sample and the (SMOW) is expressed as a percentage (%)
- However, it is represented in parts per 1000 instead of per 100, so it is actually a "per-mille-age", or simply "permil" and is written as ‰. This is called the DELTA ^{18}O or just simply: $\delta^{18}O$.

$$\left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample} - \left(\frac{^{18}O}{^{16}O}\right)_{std}}{\left(\frac{^{18}O}{^{16}O}\right)_{std}}\right) * 1000 = \delta^{18}O \text{ (per mil)}$$

Paleo-thermometers

• Examples might be:

$$\delta^{18}O = \left(\frac{\left(\frac{199}{100{,}000}\right)_{sample} - \left(\frac{200}{100{,}000}\right)_{std}}{\left(\frac{200}{100{,}000}\right)_{std}} \right) * 1000 = -5 \text{ per mil}$$

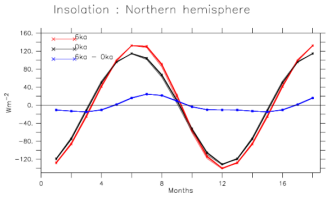
• Or…

$$\delta^{18}O = \left(\frac{\left(\frac{195}{100{,}000}\right)_{sample} - \left(\frac{200}{100{,}000}\right)_{std}}{\left(\frac{200}{100{,}000}\right)_{std}} \right) * 1000 = -25 \text{ per mil}$$

• You would say this 2nd example is ***more depleted*** in heavy ^{18}O isotopes….represented by a ***more negative $\delta^{18}O$ number***

Monsoon

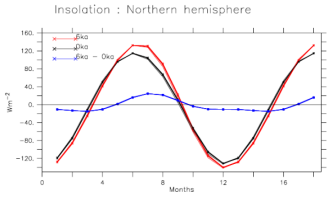
- High NH summer insolation



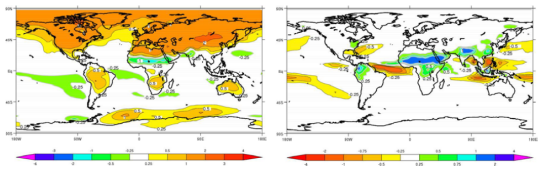
Braconnot et al. (2007)

Monsoon

- High NH summer insolation
- Strong monsoon
- Northward ITCZ (Fleitman et al. 2007)



(a) PMIP2 OA mean model

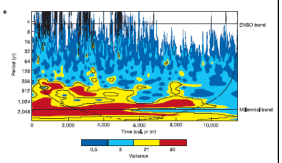


Braconnot et al. (2007)

Weak Early to mid-Holocene ENSO

La Niña-like climate state (Koutavas et al. 2006)

Laguna Pallcacocha, Ecuador



Moy et al. (2002) *Nature*

Weak Early to mid-Holocene ENSO

La Niña-like climate state
(Koutavas et al. 2006)

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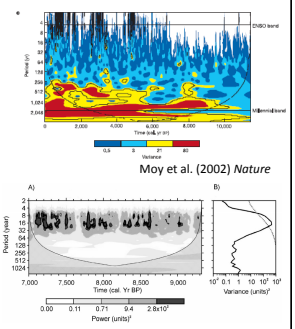

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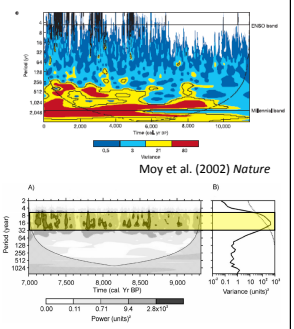

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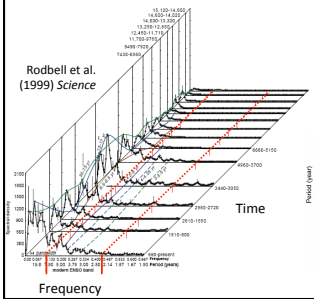
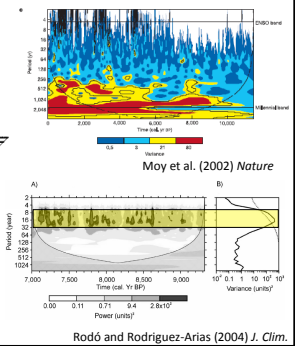
(1999) *Science*



Time

Frequency

Laguna Pallcacocha, Ecuador



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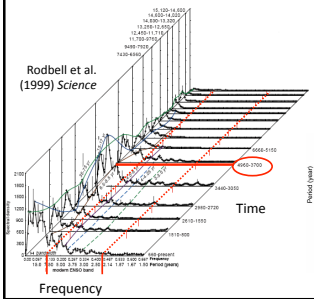
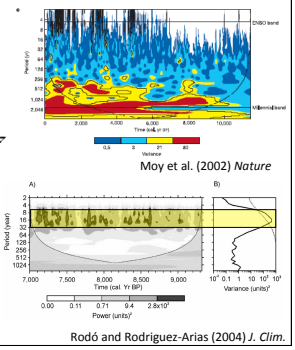


Time

Frequency

Laguna Pallcacocha, Ecuador



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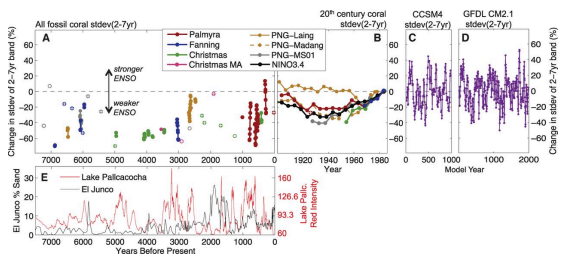
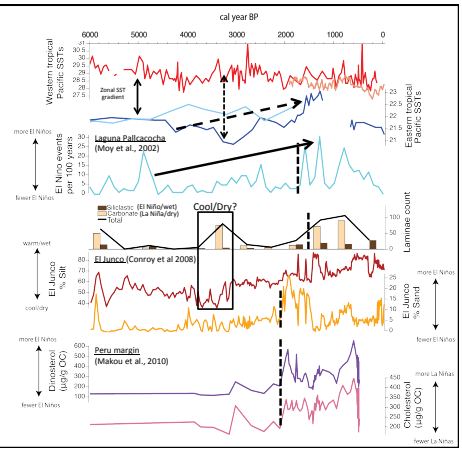
Weak Early to mid-Holocene ENSO



Cobb et al. (2013)

increase in ENSO **~1775 (± 190) cal. years BP**



Mid-Holocene Optimum

- What were the conditions like during the mid-Holocene compared to today?
  - Monsoon?
  - ENSO?
  - **IOD???**

Seasonal characteristics of the Indian Ocean Dipole during the Holocene epoch

Nerilie J. Abram[1]†, Michael K. Gagan[1], Zhengyu Liu[2,3,4], Wahyoe S. Hantoro[5], Malcolm T. McCulloch[1] & Bambang W. Suwargadi[5]

- Mid-Holocene vs. late Holocene IOD events
  - Effects of ENSO and monsoon on IOD

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- Mid-Holocene vs. late Holocene IOD events
  - Effects of ENSO and monsoon on IOD
- Determine how predicted increases in Asian monsoon will effect the IOD

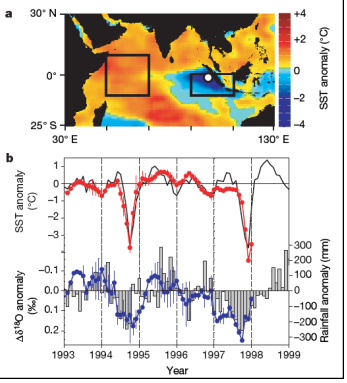
Mentawai Modern Coral

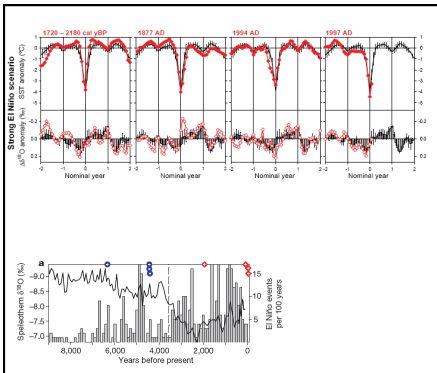
- Monthly resolution
- 1994 and 1997 IOD events:

Low Sr/Ca-SST

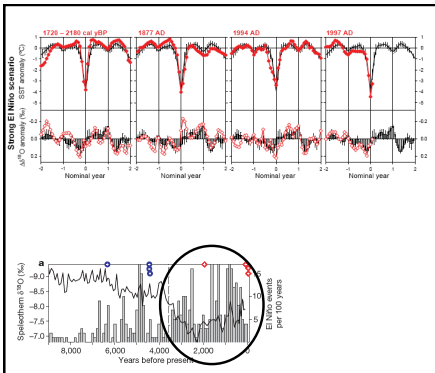
Low $\delta^{18}O_{sw}$ → dry

(temp component removed using Sr/Ca-SST)

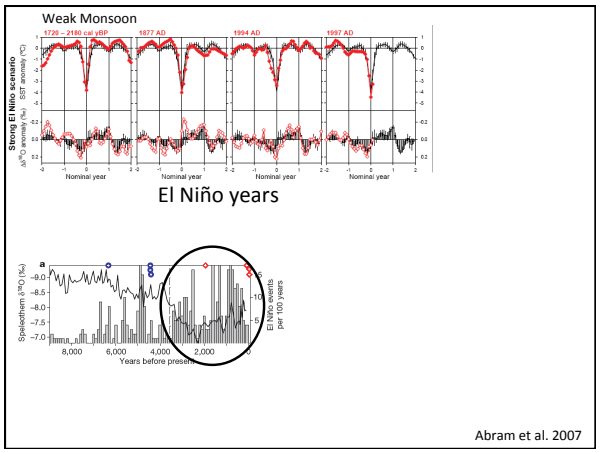


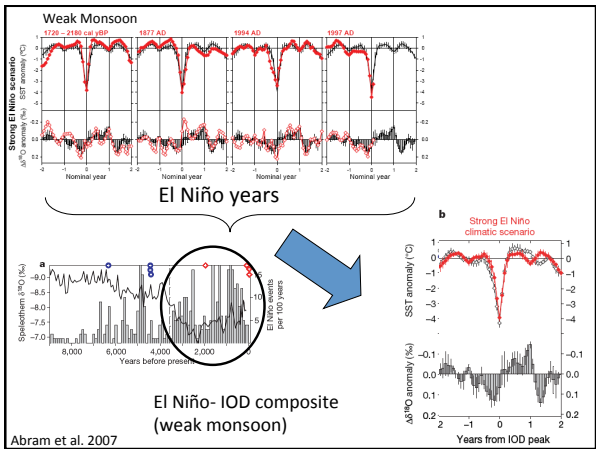


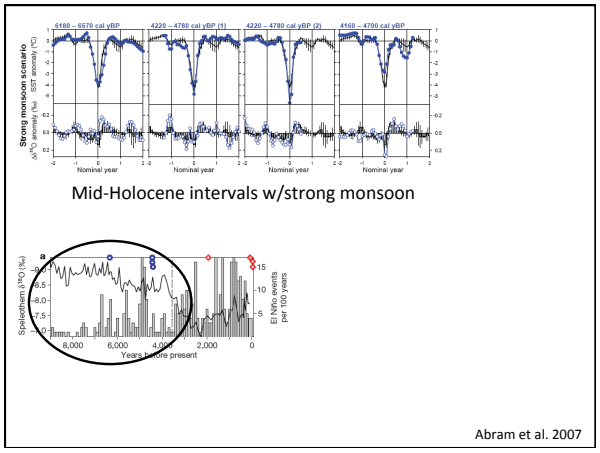
Abram et al. 2007

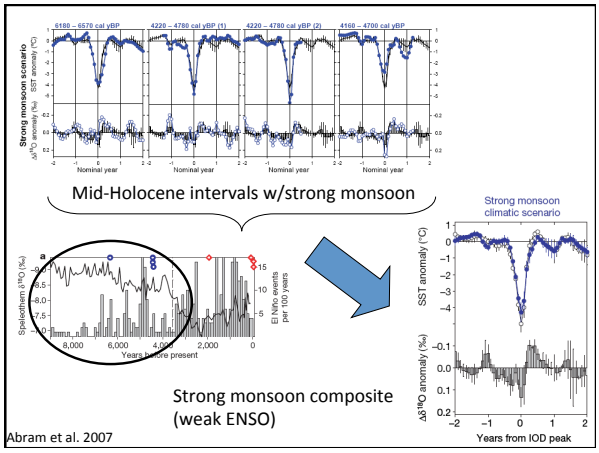


Abram et al. 2007

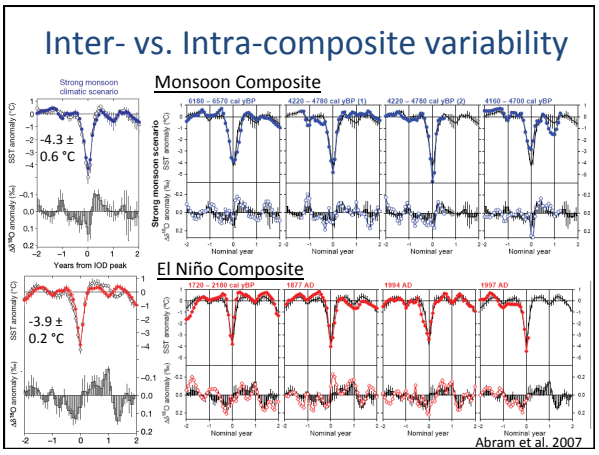

Weak Monsoon
1720 – 2180 cal yBP
1877 AD
1994 AD
1997 AD
Strong El Niño scenario
SST anomaly (°C)
Δδ18O anomaly (‰)
Nominal year
El Niño years
a
Speleothem δ18O (‰)
El Niño events per 100 years
Years before present
Abram et al. 2007


Weak Monsoon
El Niño years
El Niño- IOD composite
(weak monsoon)
b
Strong El Niño climatic scenario
SST anomaly (°C)
Δδ18O anomaly (‰)
Years from IOD peak
Abram et al. 2007

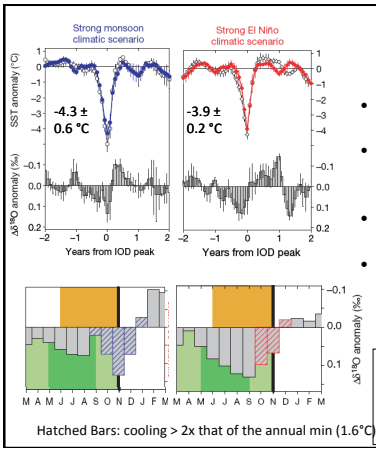

6180 – 6570 cal yBP
4220 – 4780 cal yBP (1)
4220 – 4780 cal yBP (2)
4160 – 4700 cal yBP
Strong monsoon scenario
Mid-Holocene intervals w/strong monsoon
Abram et al. 2007


Mid-Holocene intervals w/strong monsoon
Strong monsoon composite
(weak ENSO)
Strong monsoon climatic scenario
Years from IOD peak
Abram et al. 2007

Inter- vs. Intra-composite variability



Cooling



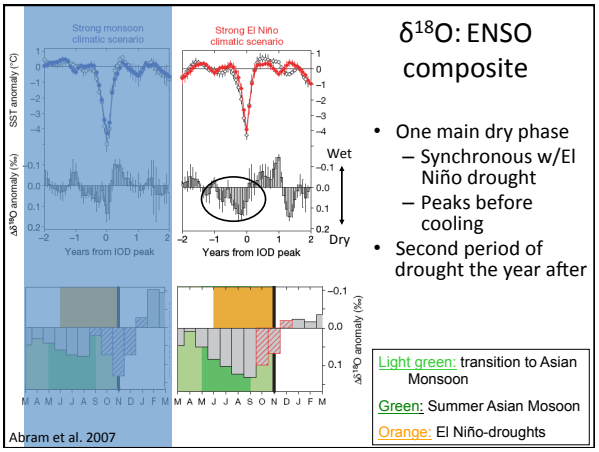
- Similar magnitude and timing
- Longer during strong monsoon (5 vs. 3 months)
- Cannot be attributed to coral growth
- Strong SE (summer) and NE (winter) winds → upwelling, cool E IO

Light green: transition to Asian Monsoon

Green: Summer Asian Mosoon

Orange: El Niño-droughts

$\delta^{18}O$: ENSO composite



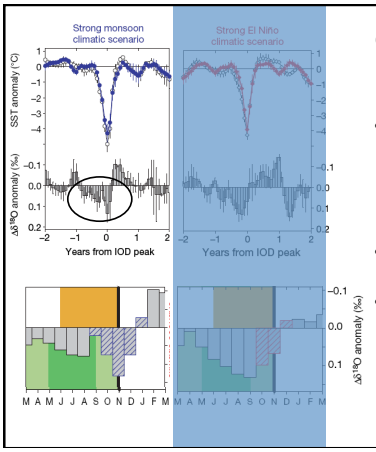
- One main dry phase
  - Synchronous w/El Niño drought
  - Peaks before cooling
- Second period of drought the year after

Light green: transition to Asian Monsoon

Green: Summer Asian Mosoon

Orange: El Niño-droughts

$\delta^{18}O$: Monsoon composite

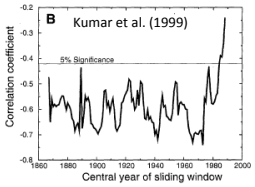


- Bimodal drought:
  1) During Asian monsoon
  2) During peak IOD cooling
- Peaks later during peak cooling
- Peak during month of annual precip maximum

Indian Ocean Dipole

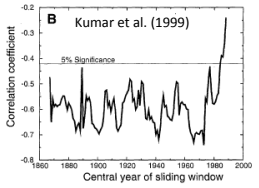
Present, past and **future**

Implications for the future?



ENSO-Monsoon relationship weakened → synergistic effects?

Implications for the future?



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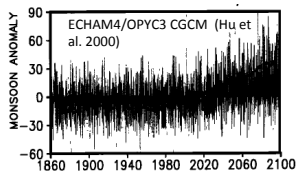
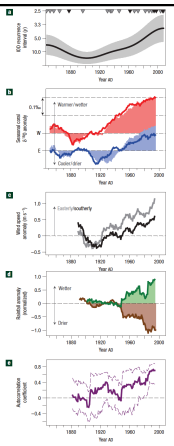


Monsoon strengthening → prolonged IOD droughts?

Trends

- More frequent IOD events
- Stronger SE winds
- IOD season wetter in west and drier in east
- Strengthened of IOD-monsoon relationship



Shading: non-IOD season

W. Africa

Indonesia

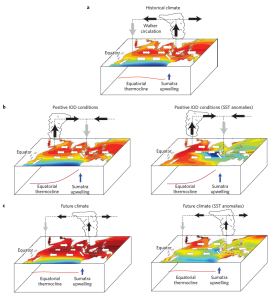
Abram et al. (2008)

Future IOD?

- Mean Indian Ocean climate state:
  - warming in austral
  - stronger easterly winds just south of the Equator
  - faster warming of SSTs in the western vs eastern Indian Ocean
  - shoaling equatorial thermocline.

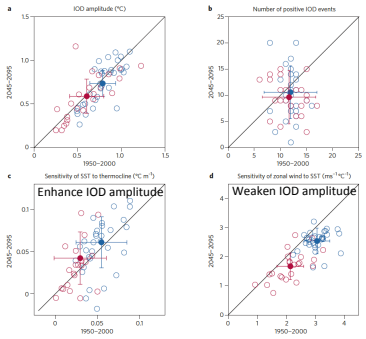
  → ***positive dipole-like state***

- Frequency of IOD events not projected to change
- Reduction in pos IOD vs neg IOD amplitude difference



Cai et al. 2013

Future IOD & mechanisms



Cai et al. 2013