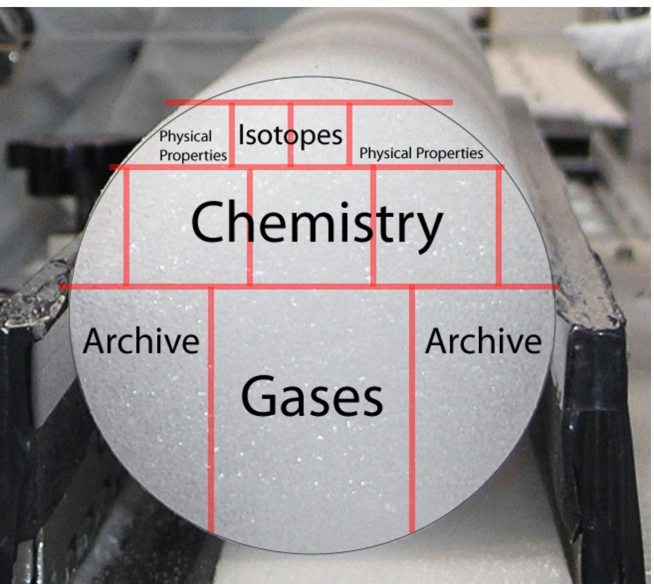
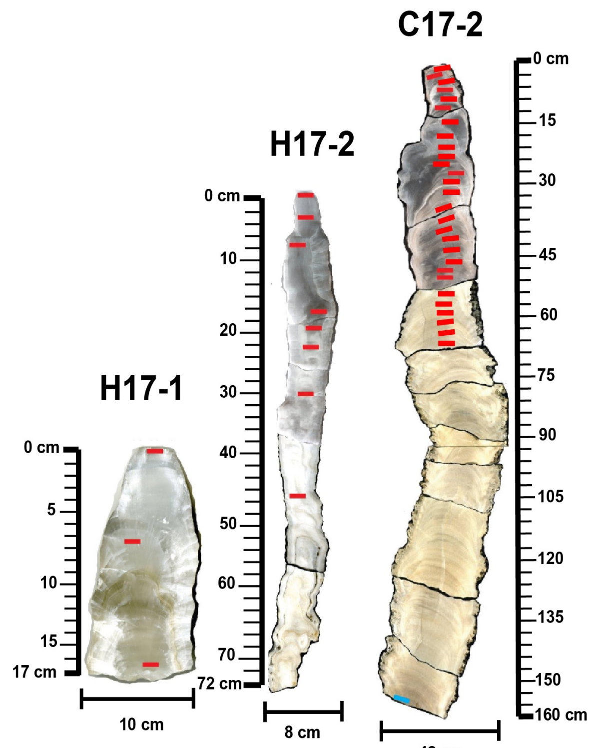
Glacial Climate Dynamics: Information Measurements in Ice-cores and Stalagmites

Juan Romero - Computational Physics Class Project

Spring 2022





Paleo-climate and climate change:

- Reconstructing past climate is beneficial for researchers to understand the mechanism of past climate change, recognize the context of modern climate change and predict scenarios of future climate change

Limitations

- Earth scientists commonly rely in methods that can not capture all the dynamics of complex systems and don't infer causality. Many causal inference methods are still only known within a small community of methodological developers and rarely adopted in applied fields like Earth system sciences.

Approach to overcome limitations

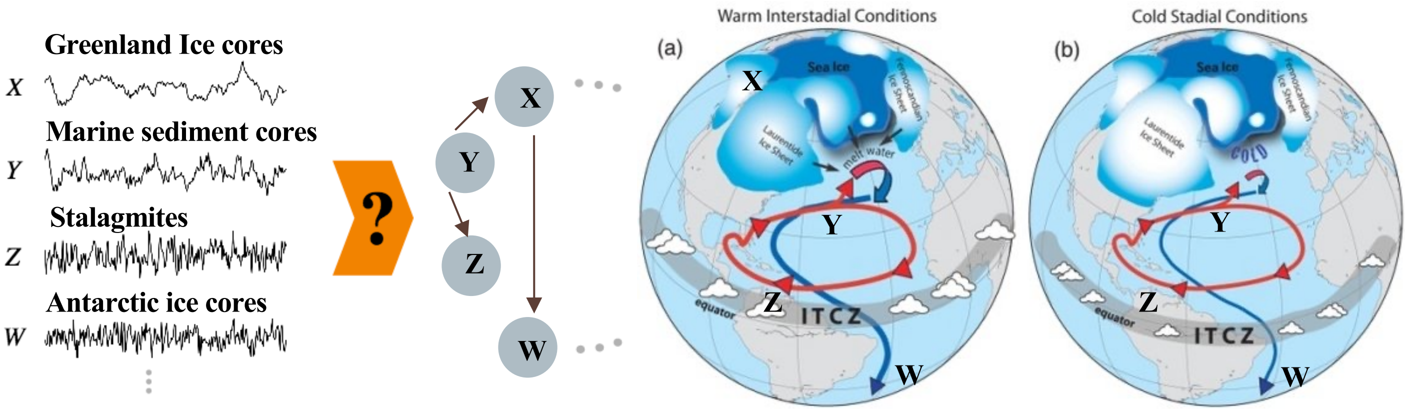
- Methods to infer causality: Data-driven causality analyses need to be designed carefully. They should be guided by expert knowledge of the system (requiring expertise from the relevant field) and interpreted based on the assumptions and limitations of the causality method used (requiring expertise from the causal inference method).

e.g. Granger causality in Multivariate time series

e.g. Entropy transfer in Multivariate time series

The Big Picture - Information flow in past-periods of climate change:

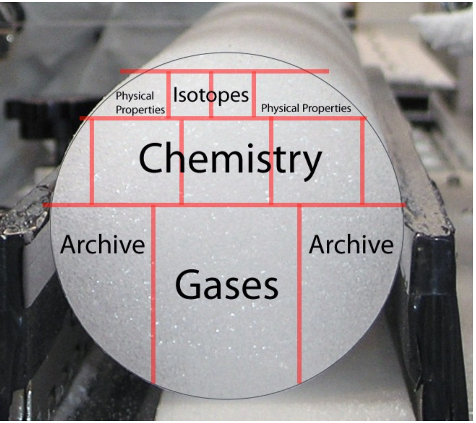
S={Stadials, Interstadials}



- Input of meltwater in the North Atlantic - Cold Conditions high latitudes of the Northern hemisphere (X)& (Y)
- Thermohaline circulation weakened – Warm water from the tropics stop reaching northern hemisphere
- ITCZ moves down to balance energy budget of the planet(Z)
- warm water pile up in the south Atlantic –High latitudes of the southern hemisphere warm up (W)

Proxy-records time-series construction and data limitations:

Age-depth models & climatic variables reconstruction



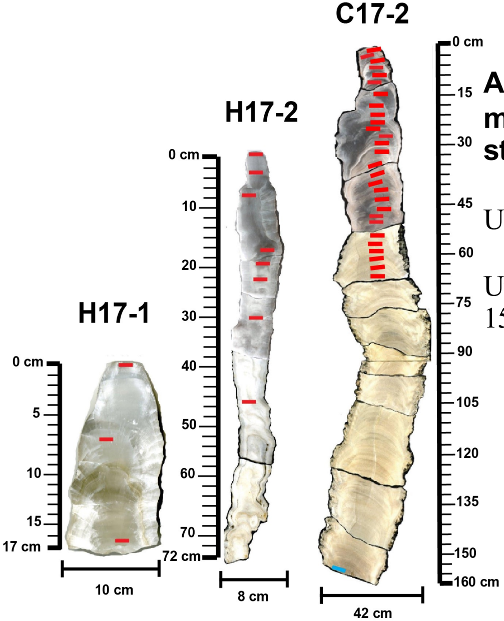
Age-depth models in ice cores

Layer counting + U-Th in Dust

Volcanic markers

Uncertanty +/- 5-10 yrs

$\delta^{18}O$ Directly correlated with temperature



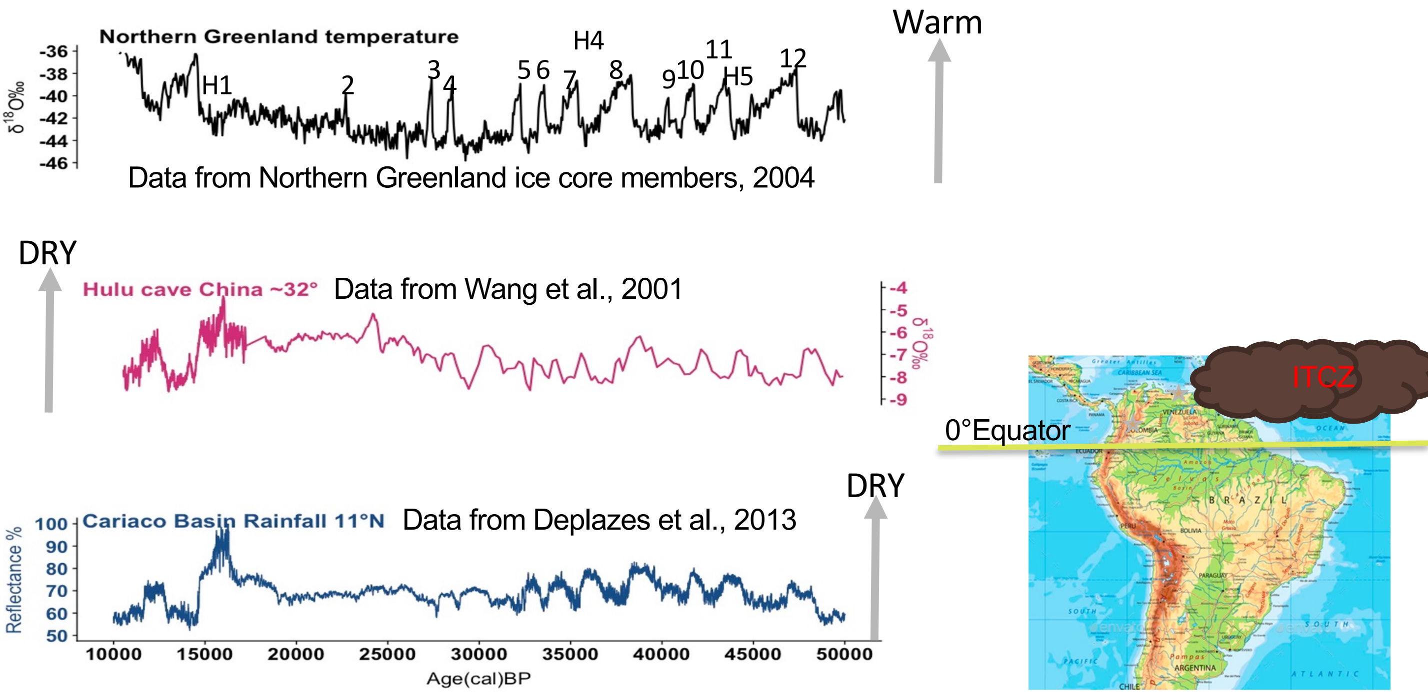
Age-depth models in stalagmites

U-Th in calcite

Uncertanty +/- 10-150 yrs

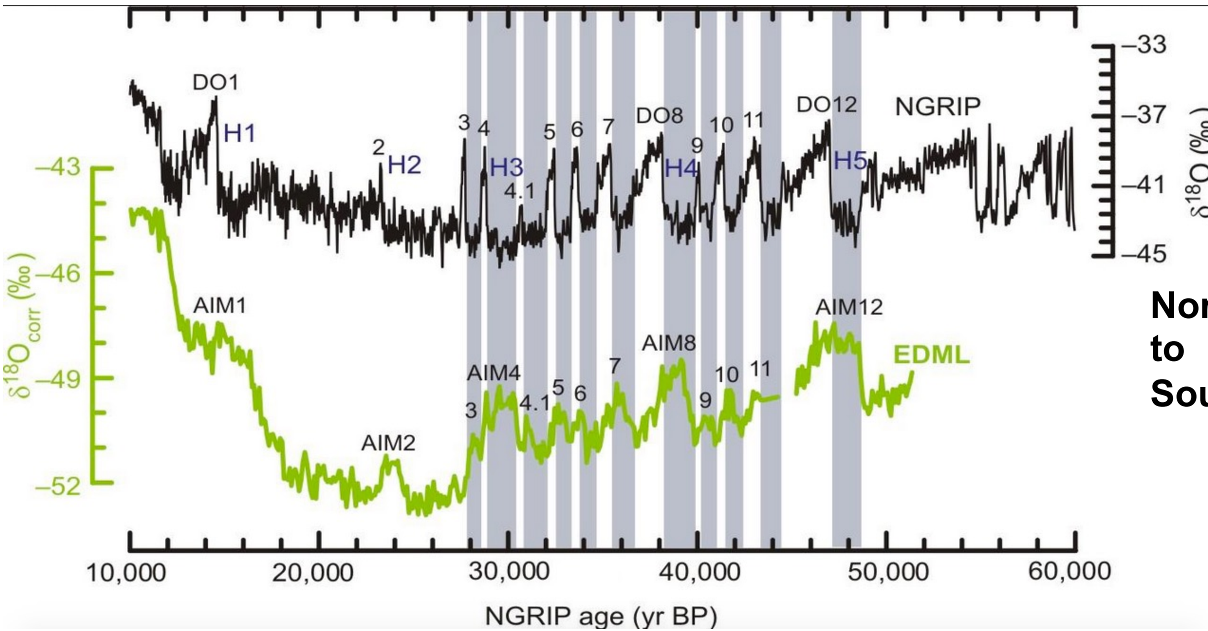
$\delta^{18}O$ Inversely correlated with amount of rain

Directionality of the climatic signal – North- South



- For every warming event there is a response of tropical and subtropical rainfall indicating the ITCZ moved north causing increased rainfall over these places

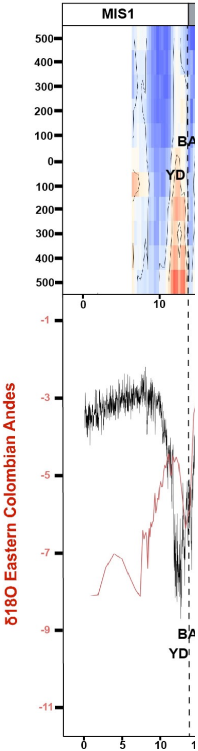
Directionality of the Climatic signal –Bipolar seesaw

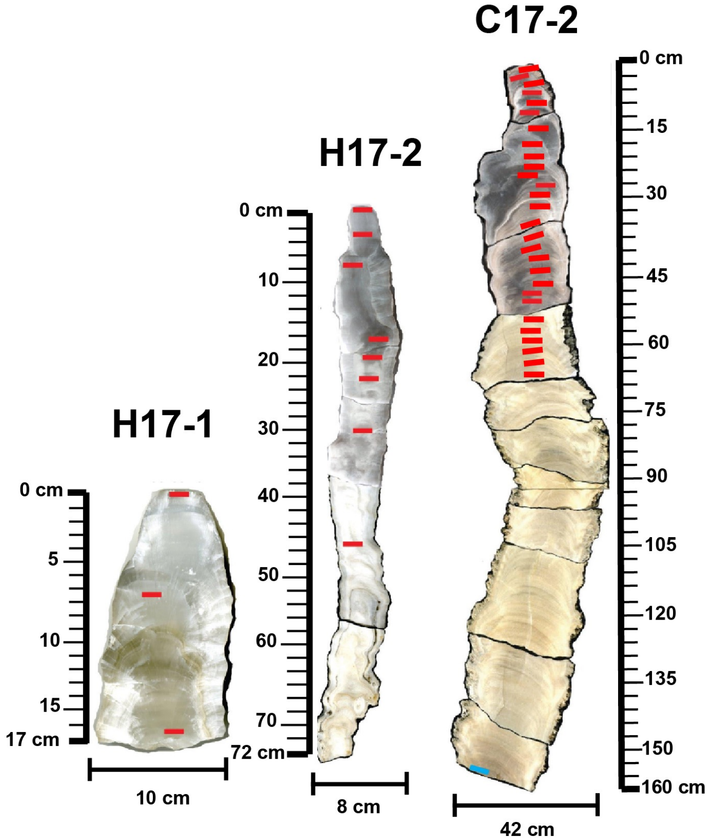


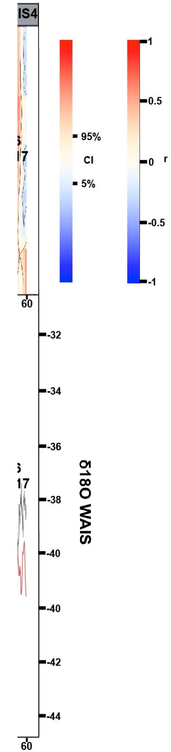
North to South

https://gpm.nasa.gov/education/sites/default/files/videos/thermohaline_conveyor_30fps.mp4

Directionality of the climatic signal-Bimodal Forcing?
Last 60 Kyrs high latitudes- tropics

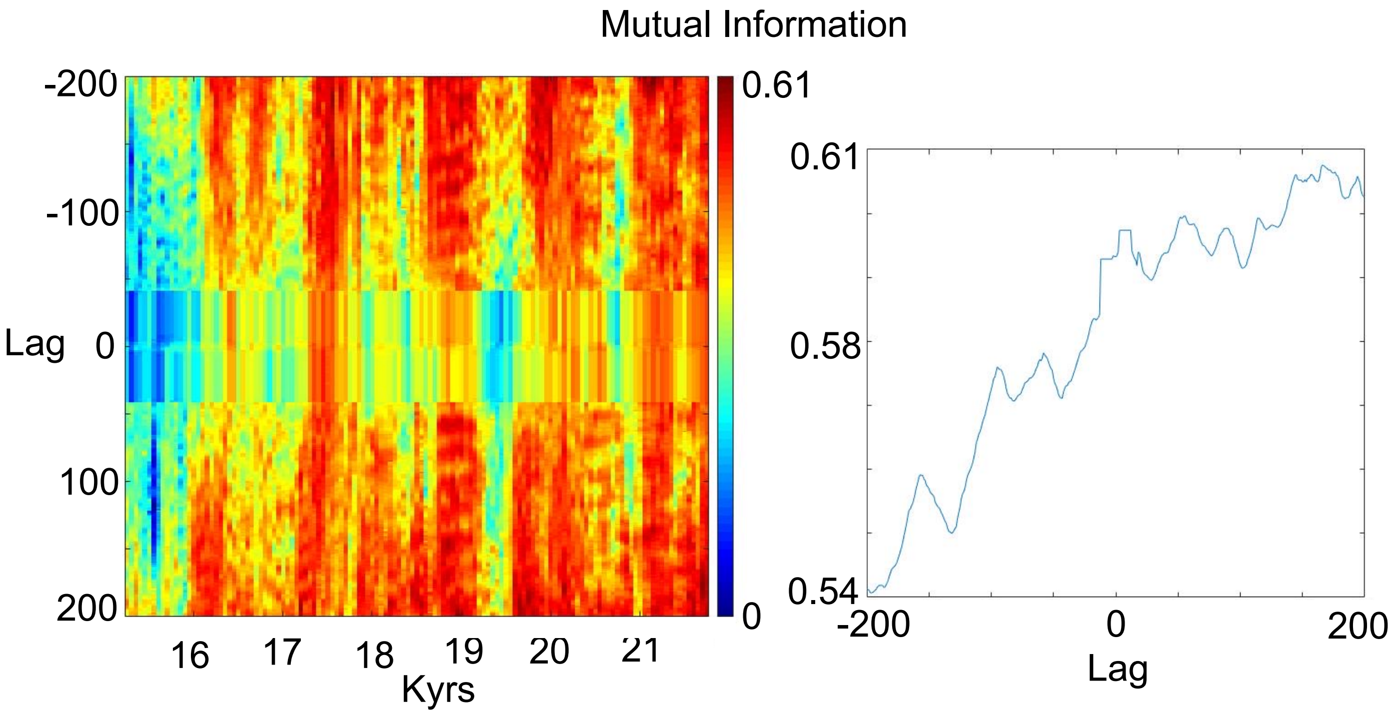




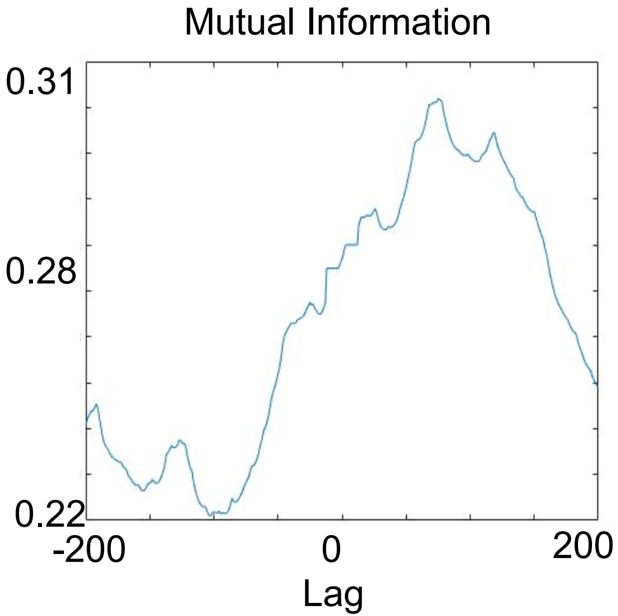


To test the hypothesis that some of these periods of climate change originated in the Southern Hemisphere, I evaluated MI and transfer entropies between Antarctic temperatures, rainfall in the tropics and Greenland temperatures.

Information measures Antarctica – ITCZ rainfall during deglaciation (15-22 Kyrs)



Information measures Greenland – ITCZ rainfall during deglaciation (15-22 Kyrs)



X=Antarctica Temperatures Y=ITCZ rainfall

Shannon Transfer Entropy Results:

Direction	TE	Eff. TE	Std.Err.	p-value	sig
X->Y	0.0001	0.0000	0.0004	1.0000	
Y->X	0.0017	0.0008	0.0003	0.0100	*

Bootstrapped TE Quantiles (100 replications):

Direction	0%	25%	50%	75%	100%
X->Y	0.0000	0.0001	0.0002	0.0004	0.0021
Y->X	0.0002	0.0005	0.0007	0.0011	

Number of Observations:

p-values: < 0.001 '***', < 0.01 '**', < 0.05 '*', < 0.1 '.'

X=Greenland Temperatures Y=ITCZ rainfall

Shannon Transfer Entropy Results:

Direction	TE	Eff. TE	Std.Err.	p-value	
X->Y	0.0010	0.0005	0.0003	0.1100	
Y->X	0.0013	0.0006	0.0003	0.0100	*

Bootstrapped TE Quantiles (100 replications):

Direction	0%	25%	50%	75%	100%
X->Y	0.0000	0.0001	0.0003	0.0005	0.0017
Y->X	0.0001	0.0003	0.0005	0.0007	

Number of Observations: 7000

p-values: < 0.001 '***', < 0.01 '**', < 0.05 '*', < 0.1 '.'

Discussion

- Mutual information seems to show strong link between ITCZ rainfall and Southern Hemisphere temperatures as Pearson correlation estimates.
- Entropy transfer shows only significant information transfer from tropical to extratropical regions.

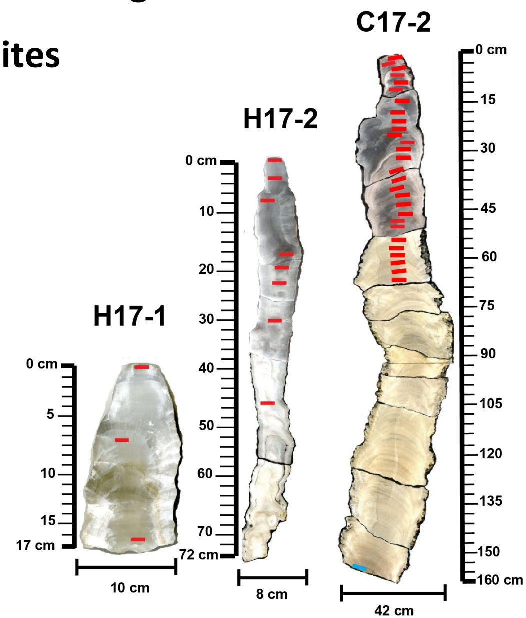
Future Work

- Compare results from NEST to DIT
- Include e-machine into analysis
- Multivariate information measures?

Multiproxy Hydroclimate Reconstruction of Intertropical Convergence Zone (ITCZ) Migrations Through the Last Glacial Period Using Northern South American Stalagmites

Did Antartic Warming Force ITCZ Migrations During the Last Deglaciation?

How Far Can The ITCZ Shift in response to extratropical warming?



UCDAVIS

Motivation

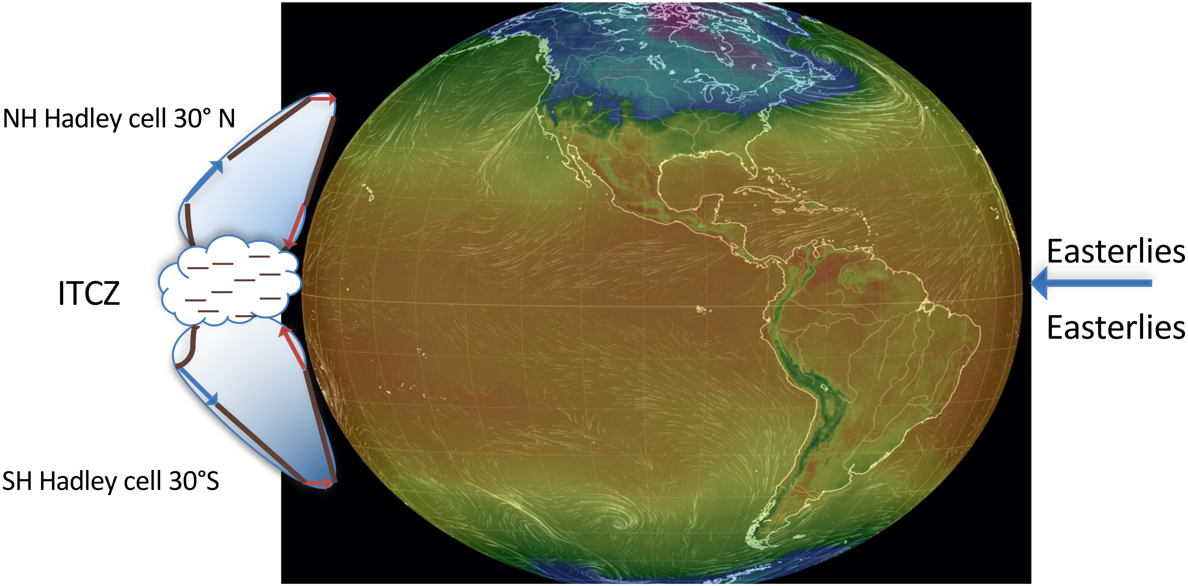
- The ITCZ accounts for 32% of global precipitation.

- The ITCZ has narrowed over recent decades yet its location has remained approximately constant.

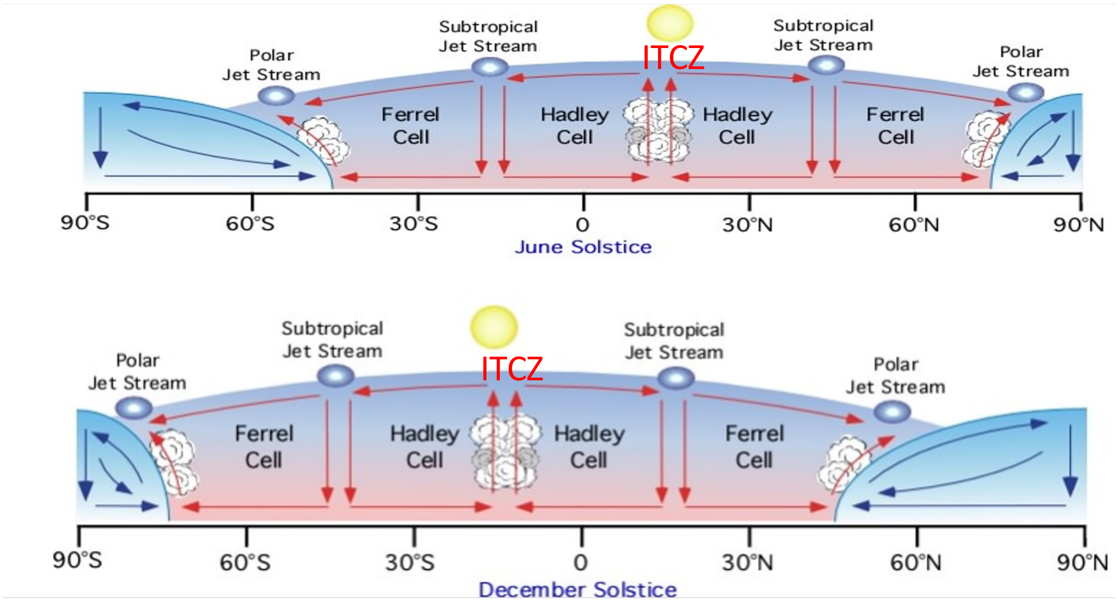
Where we can look for hints of past behavior of the ITCZ to climate change?

Paleorecords

ITCZ - Intertropical Convergence Zone

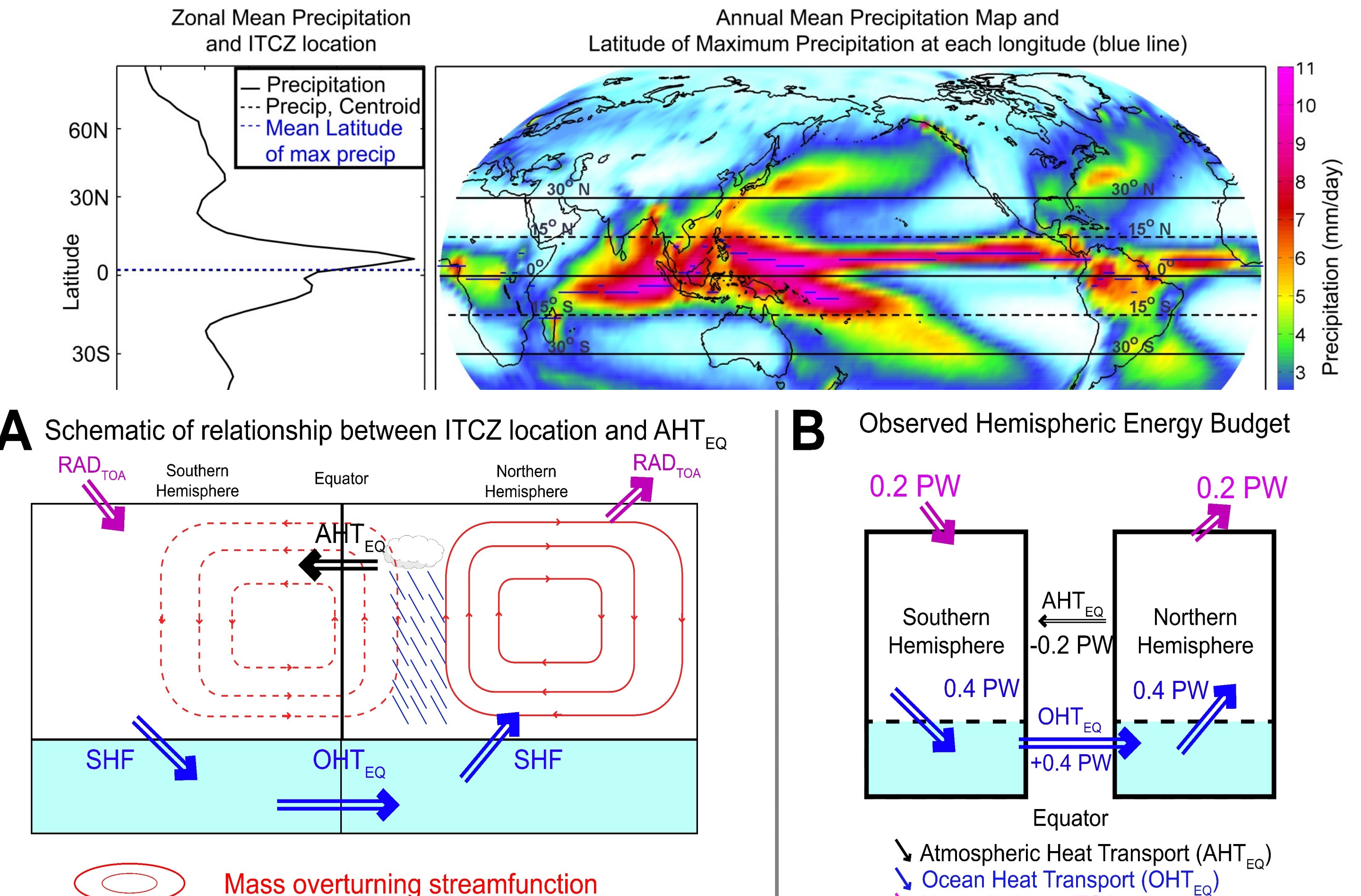


- Differential heating of the earth induces flow from high pressure (Cooler) areas in the subtropics to low pressure (Warmer) areas in the tropics.
- Warm air is less dense so it rises at the equator forming a low pressure rainy cloud belt. The ITCZ.



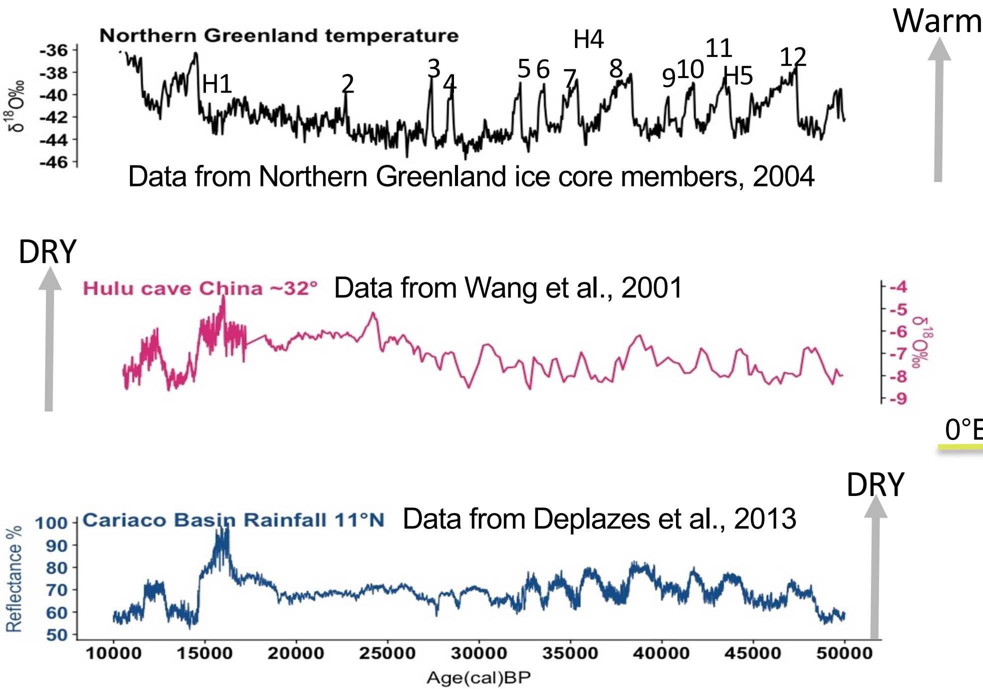
- ITCZ follows seasonal insolation maxima

warmer northern hemisphere → ITCZ north of equator
warmer southern hemisphere → ITCZ south of equator



Zonal Mean Precipitation and ITCZ location
Precipitation
Precip, Centroid
Mean Latitude of max precip
60N
30N
0
30S
Latitude
Annual Mean Precipitation Map and Latitude of Maximum Precipitation at each longitude (blue line)
30° N
15° N
0°
15° S
30° S
Precipitation (mm/day)
3
4
5
6
7
8
9
10
11
A
Schematic of relationship between ITCZ location and AHT_EQ
RAD_TOA
Southern Hemisphere
Equator
Northern Hemisphere
AHT_EQ
SHF
OHT_EQ
Mass overturning streamfunction
B
Observed Hemispheric Energy Budget
0.2 PW
Southern Hemisphere
Northern Hemisphere
AHT_EQ
-0.2 PW
0.4 PW
OHT_EQ
+0.4 PW
Equator
Atmospheric Heat Transport (AHT_EQ)
Ocean Heat Transport (OHT_EQ)

Current information about the past behavior of the ITCZ



- Dansgaard–Oeschger (DO) and Heinrich (H) events effect on tropical rainfall.

Glacial inter-glacial: > 4º Southward shift

nature COMMUNICATIONS

ARTICLE

Received 5 Aug 2015 | Accepted 11 Dec 2015 | Published 22 Jan 2016

DOI: 10.1038/ncomms10449 OPEN

Large deglacial shifts of the Pacific Intertropical Convergence Zone

A.W. Jacobel[1,2], J.F. McManus[1,2], R.F. Anderson[1,2] & G. Winckler[1,2]

Last glacial maximum: 7º Southward shift

nature geoscience

LETTERS

PUBLISHED ONLINE: 13 OCTOBER 2013 | DOI: 10.1038/NGEO1961

Meridional shifts of the Atlantic intertropical convergence zone since the Last Glacial Maximum

Jennifer A. Arbuszewski[1*†], Peter B. deMenocal[1], Caroline Cléroux[1†], Louisa Bradtmiller[2] and Alan Mix[3]

Little Ice Age (1400-1850): 5º Southward shift

nature geoscience

ARTICLES

PUBLISHED ONLINE: 28 JUNE 2009 | DOI: 10.1038/NGEO554

Southward movement of the Pacific intertropical convergence zone AD 1400–1850

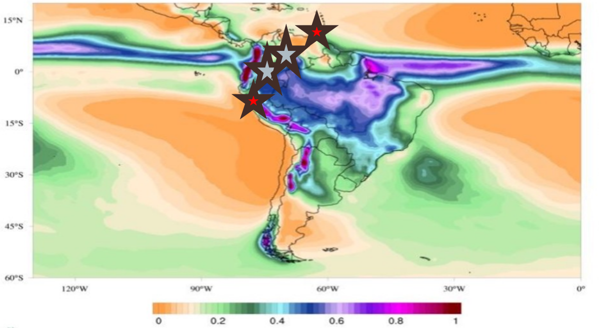
Julian P. Sachs[1*], Dirk Sachse[1†], Rienk H. Smittenberg[1†], Zhaohui Zhang[1†], David S. Battisti[2] and Stjepko Golubic[3]

Climate models predict less than 1°

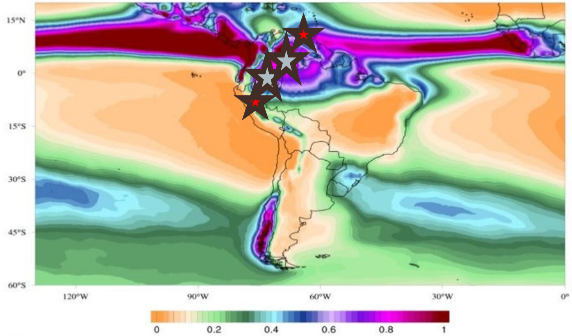
Study Areas and Modern Climatology

- The study areas are located ~6° and 3° N
- Two rainy seasons, (Mar-May) and (Sep-Nov), in response to ITCZ seasonal migrations.

DJF ITCZ Seasonal migration



JJA ITCZ Seasonal migration

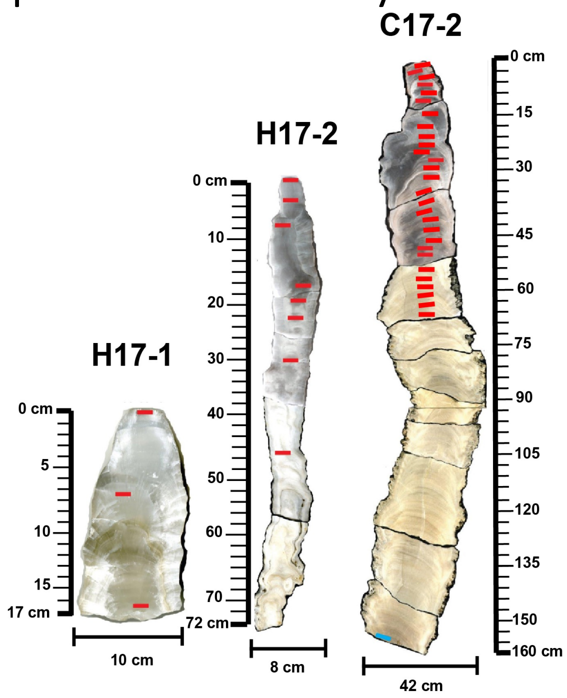


Step 1:Monitoring Study Sites

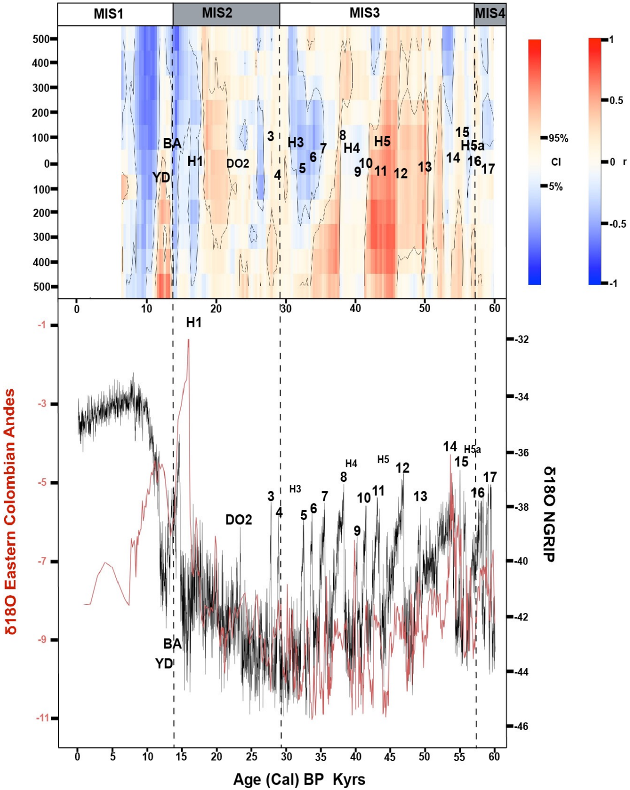
- 195 daily rain samples were collected in the study from 08/2017 to 09/2019
- Measurements binned by month and d18O weighted(R^2 =0.24)
- Measurements binned by 3 months and d18O weighted(R^2 =0.34)

ic values

Step 2:Construct Proxy Records



- Continuos 110 Kyrs stalagmite and replicates.
- Stable isotopes from calcite and fluid inclusion tied to U-Th radiometrical dating. Reconstructed precipitation
- Clumpled isotopes / Noble gases paleothemometry for temperature corrections

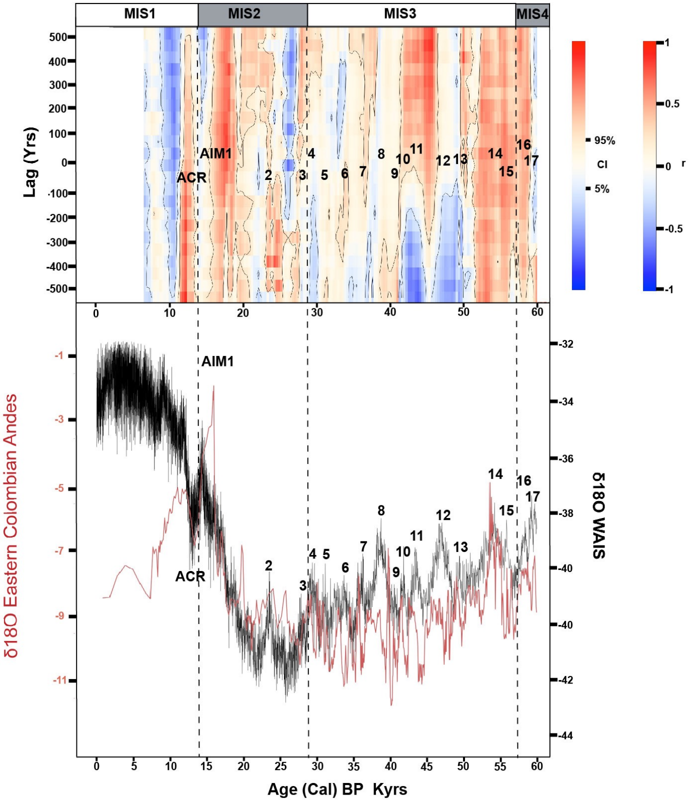


Step 3: Quantify the effect of past temperature variations on ITCZ migrations

- Different amount of warming=Larger ITCZ shifts?
- Quantifying similarity between time series is challenging. Different amount of observations between time series. No linear interpolation allowed
- Approach: Kernel based Pearson correlation and mutual information correlation.

Questions?

Cave ”La Tronera”, El Peñon, Eastern Colombian Andes

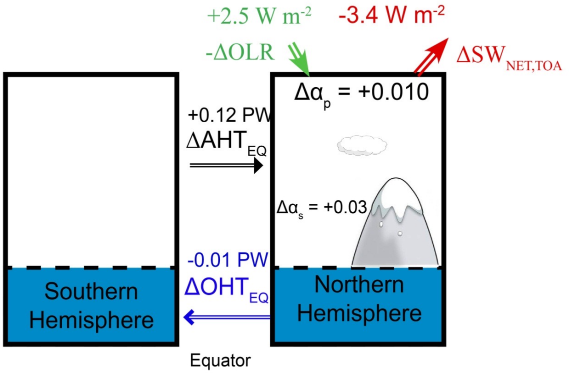


MIS1
MIS2
MIS3
MIS4
Lag (Yrs)
AIM1
ACR
95%
CI
5%
r
δ18O Eastern Colombian Andes
δ18O WAIS
Age (Cal) BP Kyrs

LGM Energetics

CLAIM: A 3 degree latitude shift in the ITCZ location requires 1 PW of atmospheric heat transport across the equator

→ 1 PW (10^{15} W) is a lot of energy– equivalent to simultaneous doubling of CO_2 in on hemisphere and halving in the other



What are the major controls on the oxygen isotopic signal in speleothems?

- Moisture sources
- Temperature
- Amount of precipitation


Collecting drip water, Cave “Hipocampo”

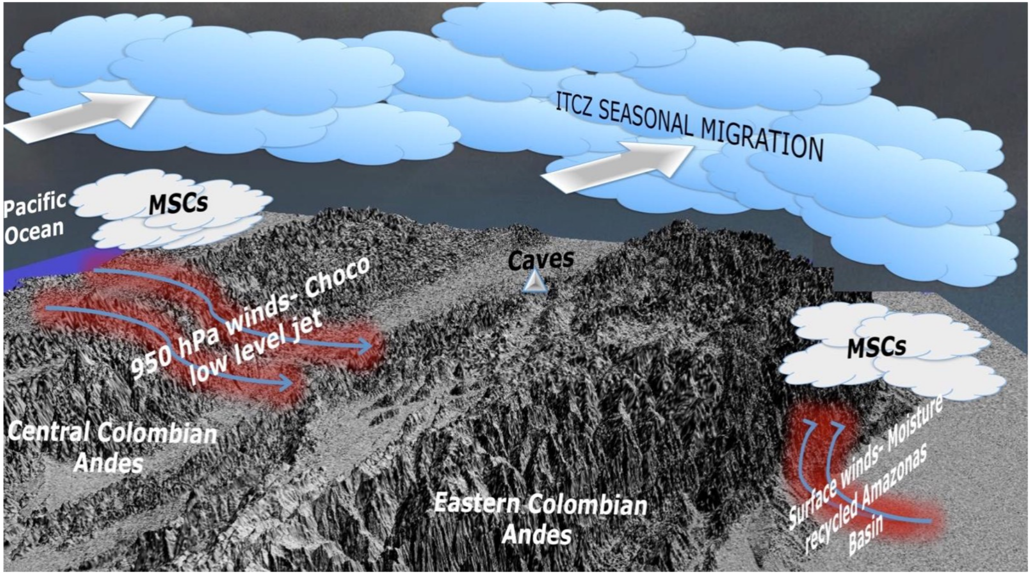
Fairchild and Baker, 2012

Leading Questions

Is there a Southern Ocean Control on the position of the ITCZ

Single or double forcing mechanism driving glacial period climatic variability?

Moisture sources at our study site



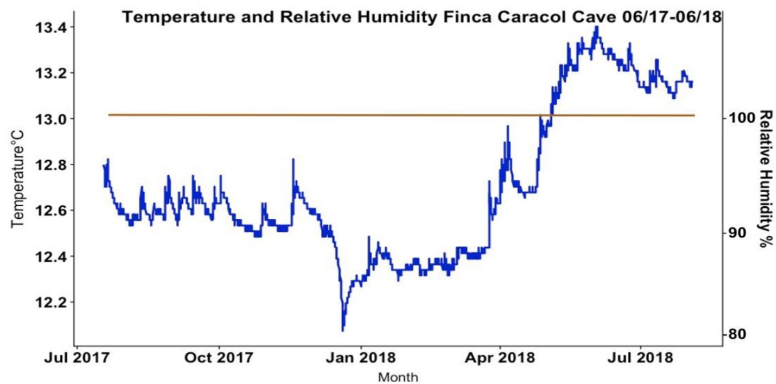
- 3 branches of the Andes act as topographic barriers for multiple moisture sources.

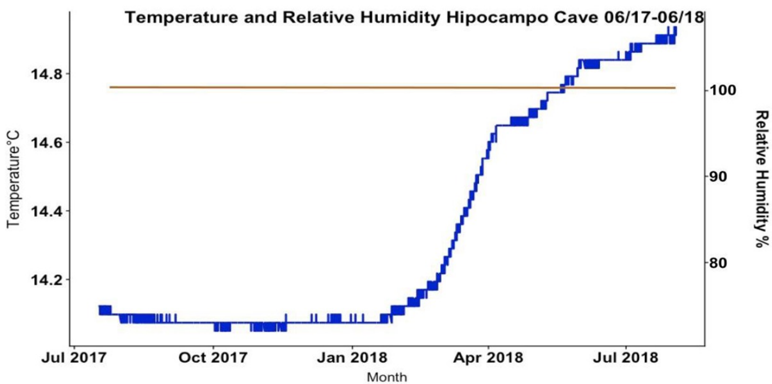
Conclusions

- We have reconstructed the isotopic variability from 3 Colombian stalagmites for the last 60 kyrs, which likely represent changes in precipitation in the area.
- Our results show different climatic drivers over tropical precipitation as boundary conditions change.
- Our results support a southern ocean control over the position of the ITCZ.
- Our results support a bimodal forcing mechanism in ice age dynamics.

Moving Forward

- Expand the record to cover 130 kyrs to see how this relationships behave under different boundary conditions. Especially during glacial inception.
- Develop more paleo-precipitation records north and south from the study area, explore PCA and nonlinear dynamics of the time series to evaluate further the bimodal forcing mechanism.
- Run Climate model experiments with fresh water housing/ changes in solar insolation in the southern ocean and evaluate northern south America precipitation response during selected intervals to test proposed mechanisms

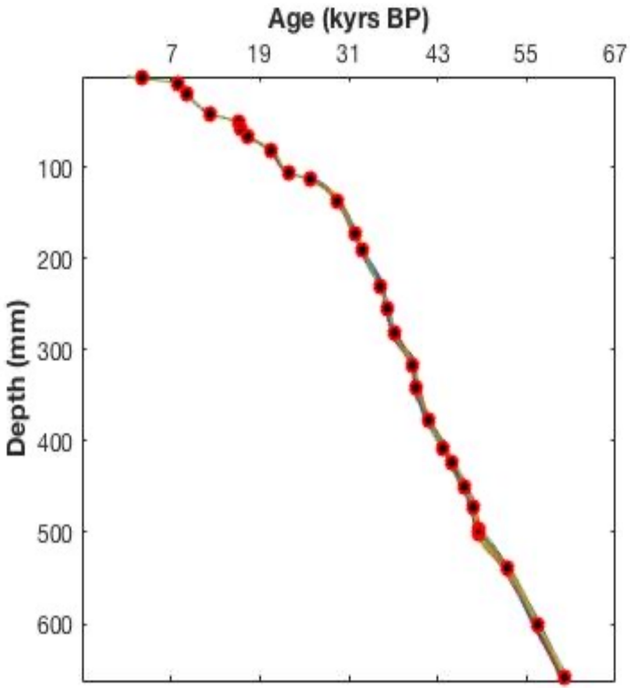

Temperature and Relative Humidity Finca Caracol Cave 06/17-06/18
13.4
13.2
13.0
12.8
12.6
12.4
12.2
Temperature°C
100
90
80
Relative Humidity %
Jul 2017
Oct 2017
Jan 2018
Apr 2018
Jul 2018
Month


Temperature and Relative Humidity Hipocampo Cave 06/17-06/18
14.8
14.6
14.4
14.2
Temperature°C
100
90
80
Relative Humidity %
Jul 2017
Oct 2017
Jan 2018
Apr 2018
Jul 2018
Month

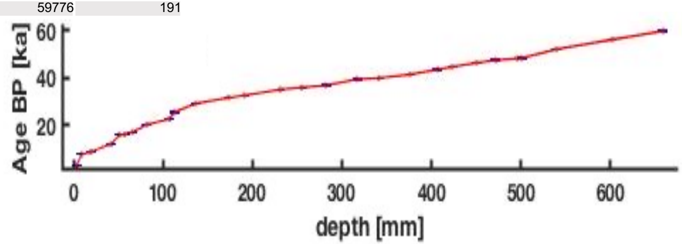
Methods

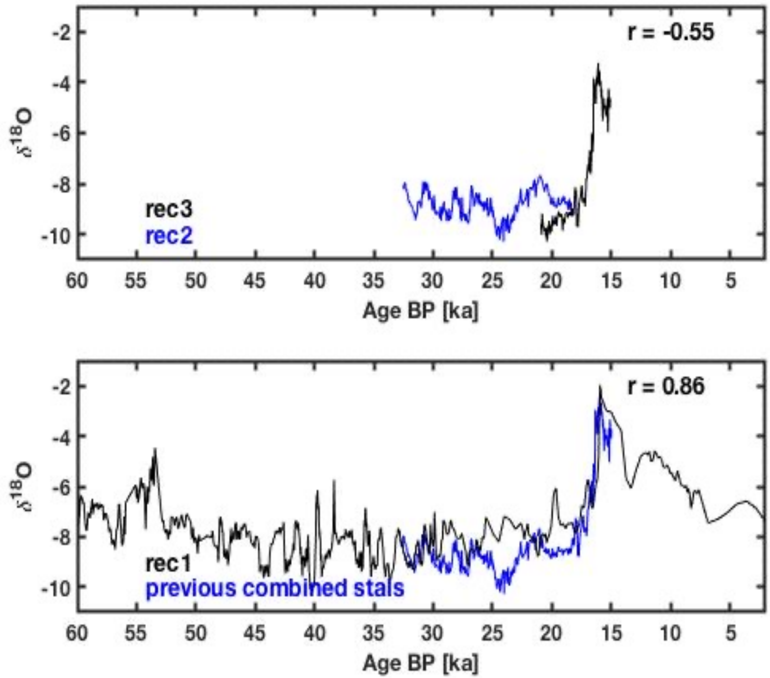
COPRA and ISCAM age models for C172.

- AR models with 2000 MC sim. to create 95 confident intervals.



Age(cal)BP	Uncertanty(years)
2791	22
3317	59
7678	22
8707	43
12119	43
15797	41
16121	59
17122	45
20308	90
22655	78
25634	142
29183	126
31569	91
32573	92
35043	100
35920	100
36802	125
39399	121
39878	113
41383	130
43507	141
44629	137
46282	144
47476	142
48157	150
48284	187
52097	158
56134	174
59776	191

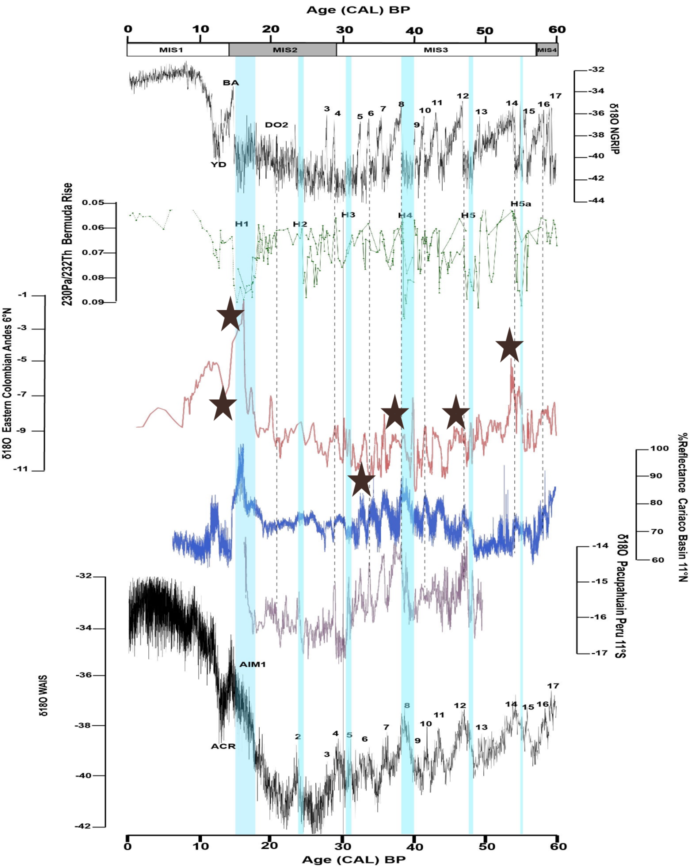




ISCAM Cross correlation with 2000 MC sim. 95% CI.

- Stalagmites from different caves replicate the climatic signal, although discrepancies exist.

Results and Discussion

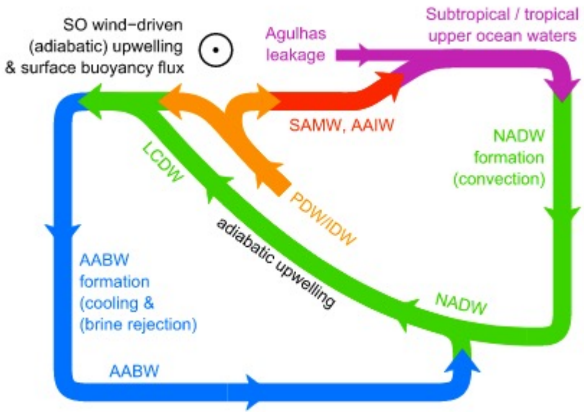


Is there a Southern Ocean Control over the position of the ITCZ?

Differential response from Colombian Hydroclimate to high latitude climate.

- DO events can be wet or dry in Colombia.
- DO events onset and Colombia hydroclimate response are time-aligned only during MIS 1 and 3.
- Heinrich Events can be dry/wet in Colombia under peak/low glacial conditions.
- HE events onset and Colombia hydroclimate response are time-aligned only during MIS 1 and 3.

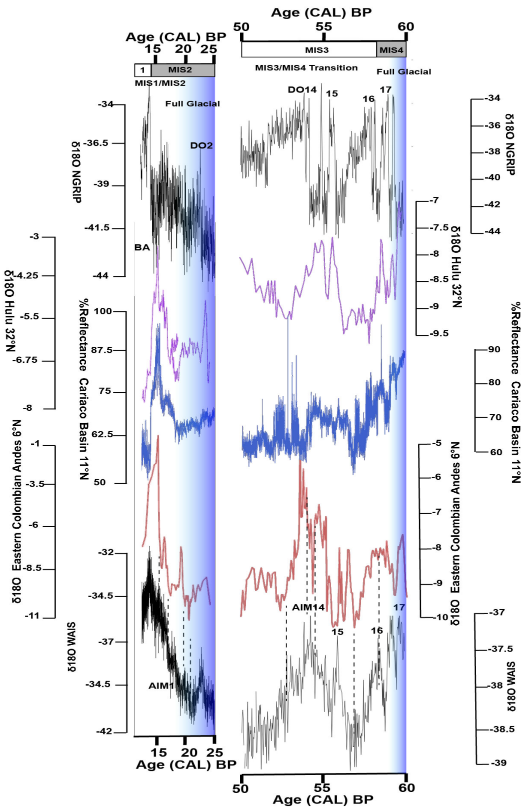
Under peak glacial conditions ITCZ response to high latitude climate change seems to be coeval to changes in the southern hemisphere. (e.g in response to warming in Antarctica).



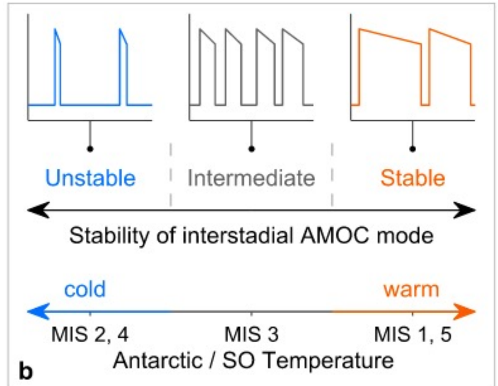
Is there a Southern Ocean Control on the position of the ITCZ?

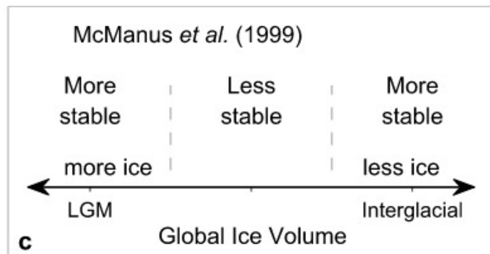
Differential response from Colombian Hydroclimate to high latitude climate.

- Decreasing densities of Antarctic Intermediate Water or Subantarctic Mode Water through either warming or freshening can increase the AMOC, either by changing the freshwater fluxes due to the overturning circulation in the South Atlantic associated with AAIW [Saenko et al., 2003] or by increasing the meridional pressure gradient between the South Atlantic and the North Atlantic [Hughes and Weaver, 1994], or both

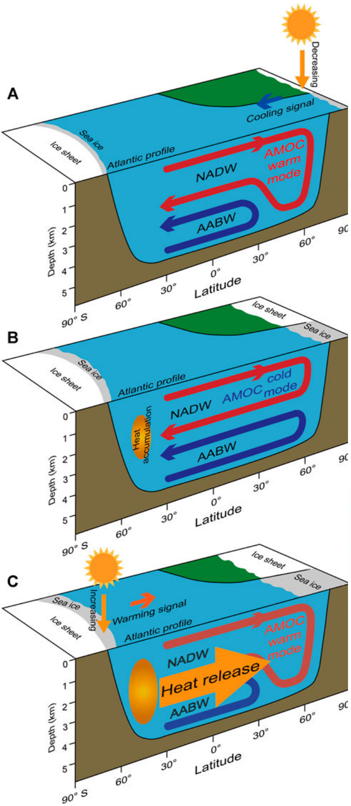


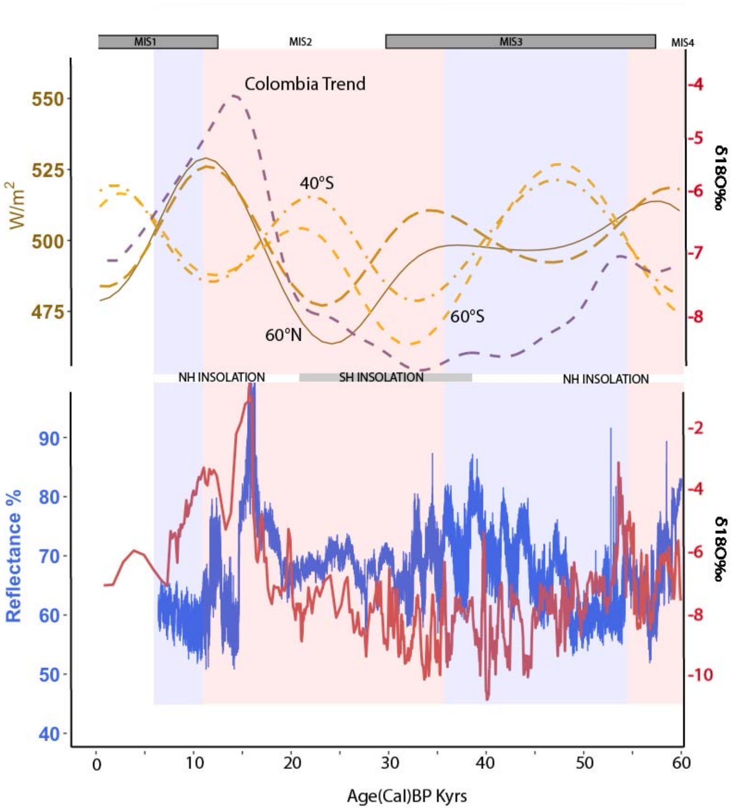
Is there a Southern Ocean Control over the position of the ITCZ?





- As peak glacial conditions develop. DO cycles are absent and ITCZ movements are highly dependent on SO temperatures.





chanism driving glacial

rst respond to decreasing deliver cooling signal to

vhen ice age is near its umulation in the SH.

ution cause the deglacial warming and associated conditions. Particularly, luring deglaciations, this and transported a huge