Closing the loop: Integrated approaches to studying past climates

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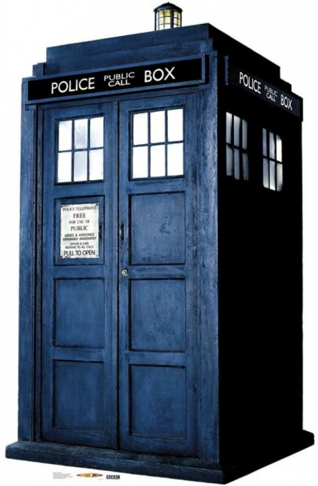
Understanding past climates

What we really want...



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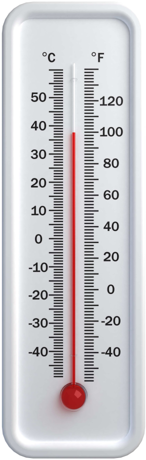
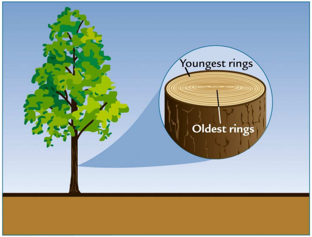


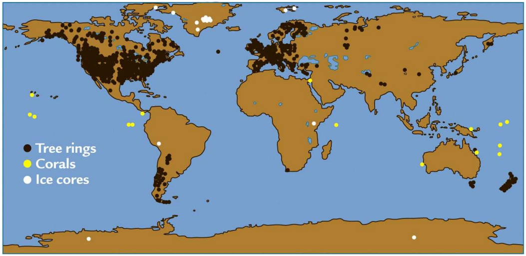
What I really want...

Sources of information: tree rings

- Tree rings provide information about changes in temperature and precipitation over the past tens to thousands of years.
- Annual resolution; precise dating possible.
- Widely distributed throughout mid-latitudes.

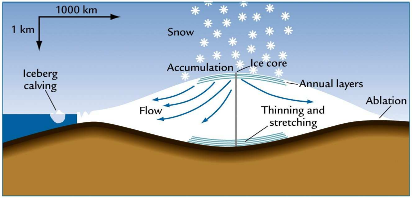


C Annual tree rings



Sources of information: ice cores

- Annual snowfalls deposit continuous sequences of ice.
- Provide information about climate drivers (e.g. greenhouse gases) as well as information about past changes in the climate (e.g. temperature).



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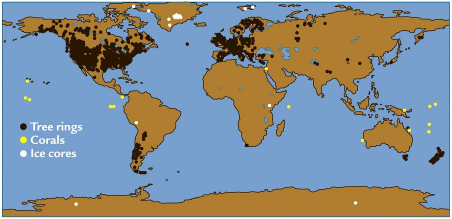
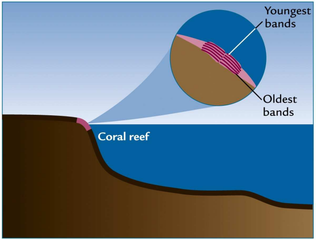
Continental ice sheets

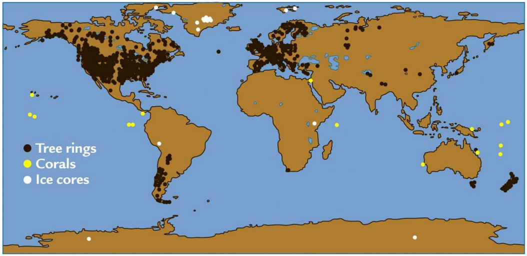


Sources of information: coral reefs

- Corals in tropical and subtropical oceans form annual bands of calcite ($CaCO_3$) that record information about the climate.
- Individual corals can live for hundreds of years.
- Very high (e.g. monthly) resolution possible.



D Annual coral bands



Coral $\delta^{18}O$ versus local sea surface temperature

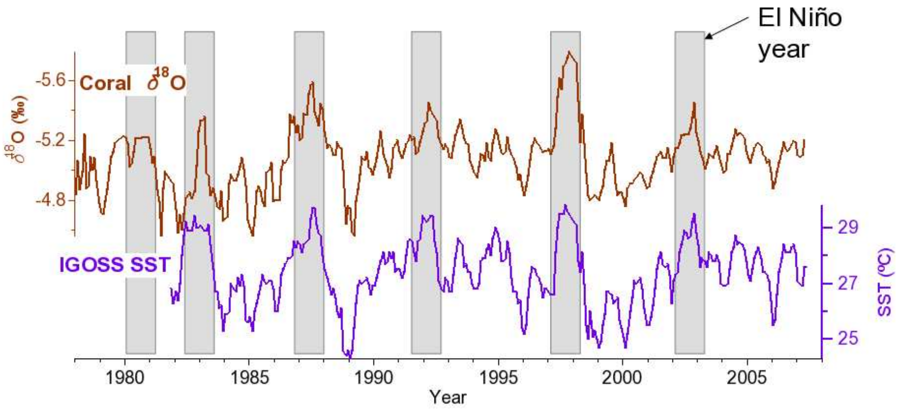


Figure courtesy of Helen McGregor

Even wine can provide valuable information!

brief communications

Grape ripening as a past climate indicator

Summer temperature variations are reconstructed from harvest dates since 1370.

French records of grape-harvest dates in Burgundy were used to reconstruct spring–summer temperatures from 1370 to 2003 using a process-based phenology model developed for the Pinot Noir grape. Our results reveal that temperatures as high as those reached in the 1990s have occurred several times in Burgundy since 1370. However, the summer of 2003 appears to have been extraordinary, with temperatures that were probably higher than in any other year since 1370.

Biological and documentary proxy records have been widely used to reconstruct temperature variations to assess the exceptional character of recent climate fluctuations[1–3]. Grape-harvest dates, which are tightly related to temperature, have been recorded locally for centuries in many European countries. These dates may therefore provide one of the longest uninterrupted series of regional temperature anomalies (highs and lows) without chronological uncertainties[1].

In Burgundy, these officially decreed dates have been carefully registered in parish and municipal archives since at least the early thirteenth century. We used a corrected and updated harvest-date series[4] from Burgundy, covering the years from 1370 to 2003, to reconstruct spring–summer temperature anomalies that had occurred in eastern France. To convert historical observations into temperature anomalies, we used a process-based phenology model for Pinot Noir, the main variety of grape that has been continuously grown in Burgundy since at least the fourteenth century[5] (for details, see supplementary information).

Our yearly reconstruction is significantly correlated (Table 1) with summer temperatures deduced from tree rings in central

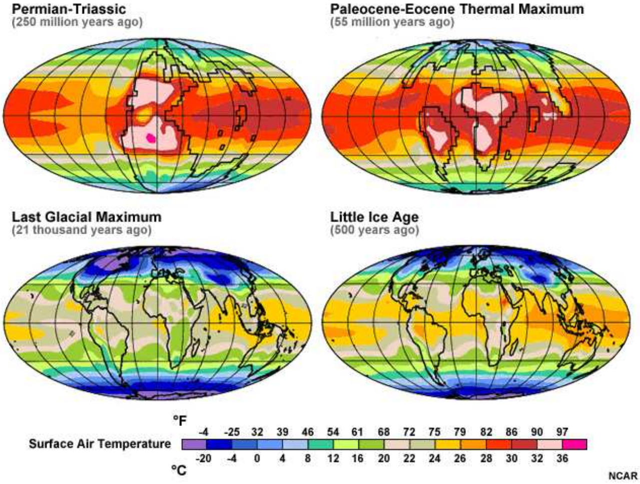
A fifteenth-century depiction of the grape harvest from *Les Très Riches Heures du Duc de Berry*, a medieval book of hours.

V&A MUSEUM/WWW.BRIDGEMAN.CO.UK

France[6] (correlation coefficient, $r = 0.53$), the Burgundy part of a spatial multi-proxy recon-

Chuine et al. (2004), *Nature*

Sources of information: climate modelling



Closing the loop: towards integrated approaches

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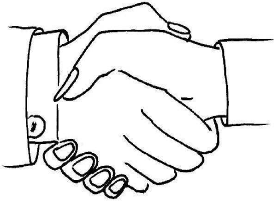
$\delta^{18}O$
Sr/Ca

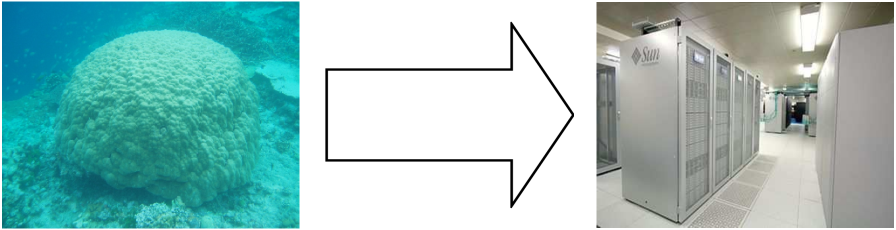
Temperature
Precipitation

The "handshake" question



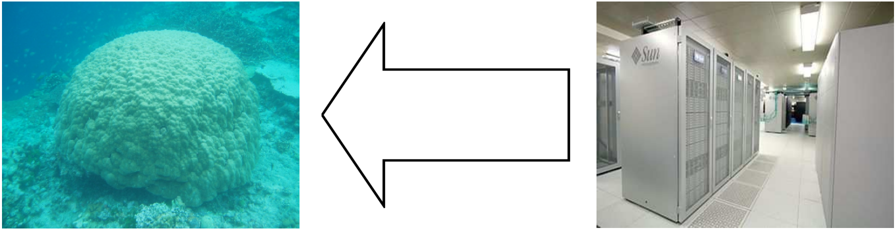
How do we integrate data from natural archives with climate models in a way that extracts the maximum possible information about the dynamics of the climate system?

The inverse approach



- Translate proxy variables into physical climate variables.
- Achieved by calibrating proxy variables against local or remote climatic variables, typically using observational data.
- Involves the necessary but usually implicit assumption of stationarity.
- Proxies can integrate multiple environmental variables, so information is lost when only reconstructing a single variable.

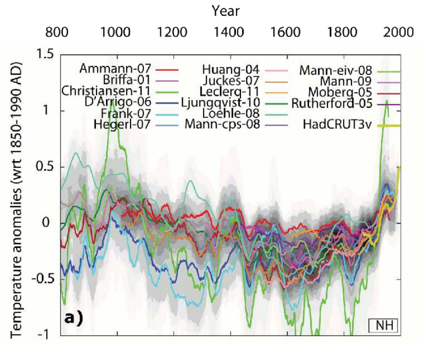
The forward approach

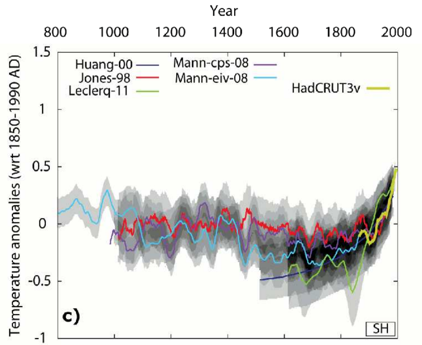


- Translate model variables into proxy variables.
- Achieved by using physical and biological principles to simulate the evolution of proxy variables within a modelling framework.
- Capable of avoiding the assumption of stationarity.
- Can account for the fact that proxies integrate multiple variables.
- Require a complete description of all the relevant processes.

The climate of the past 2000 years

Past changes in hemispheric temperature





Fernández-Donado et al. (2013), *Climate of the Past*

The Mediaeval Warm Period (∼950–1250 CE)

The Little Ice Age (~1400–1700 CE)

A regional perspective on the past 2000 years

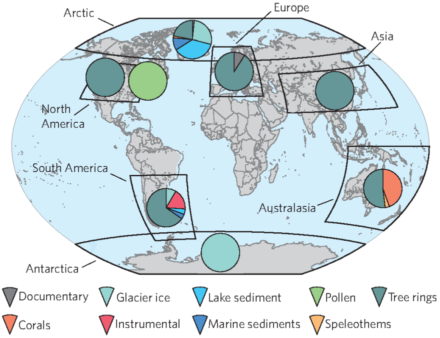


Figure 1 | The PAGES 2k Network. Boxes show the continental-scale regions used in this study. The pie charts represent the fraction of proxy data types used for each regional reconstruction. Supplementary Database S1 includes information about each study site and the proxy data for all time series used in the regional reconstructions.

PAGES 2k Consortium (2013), *Nature Geoscience*

A regional perspective on the past 2000 years

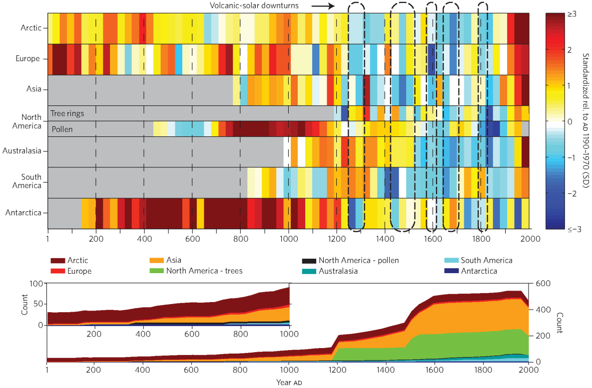
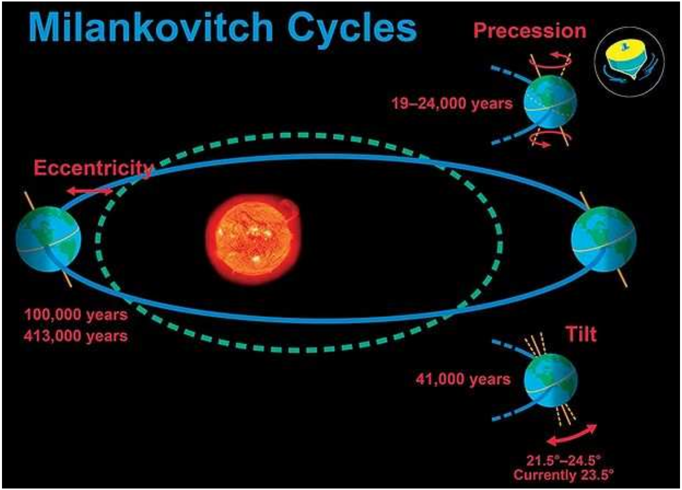


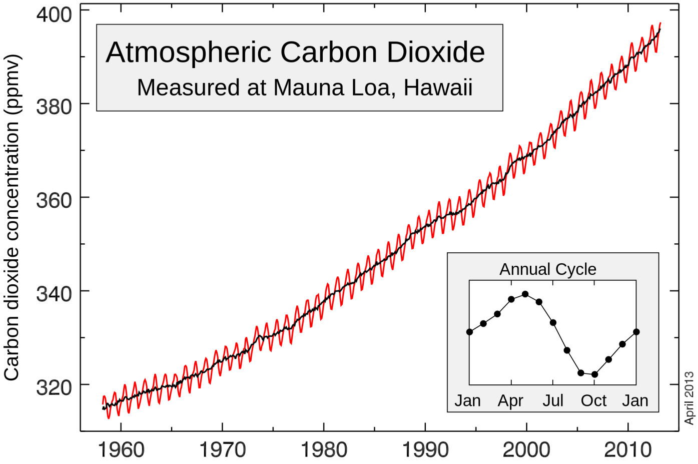
Figure 2 | Continental-scale temperature reconstructions. 30-year-mean temperatures for the seven PAGES 2k Network regions, standardized to have the same mean (0) and standard deviation (1) over the period of overlap among records (AD 1190–1970). North America includes a shorter tree-ring-based and a longer pollen-based reconstruction. Dashed outlines enclose intervals of pronounced volcanic and solar negative forcing since AD 850 (see Methods). The lower panel shows the running count of number of individual proxy records by region. Data are listed in Supplementary Database S2.

PAGES 2k Consortium (2013), *Nature Geoscience*

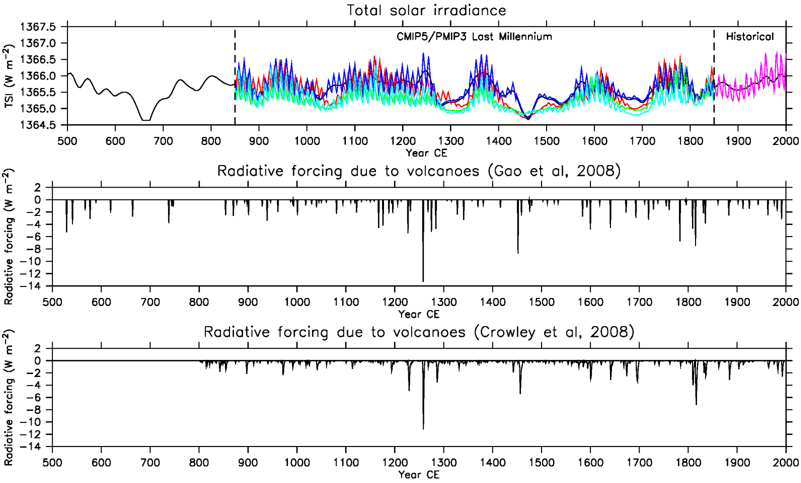
External drivers: the Earth's orbital cycle



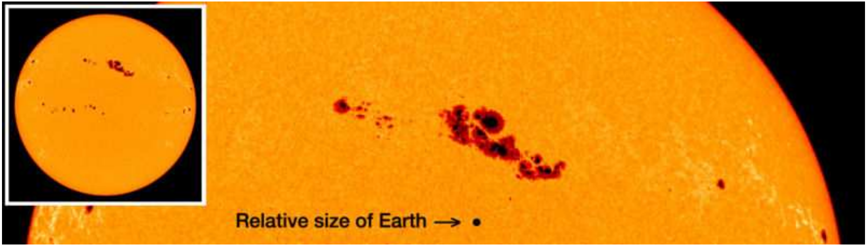
External drivers: anthropogenic greenhouse gases

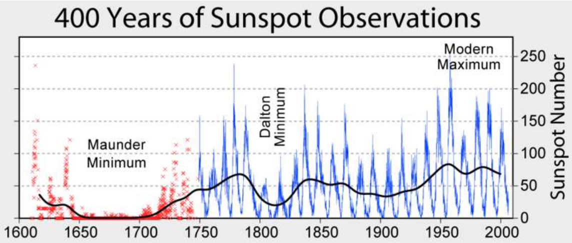


External drivers: the sun and volcanoes

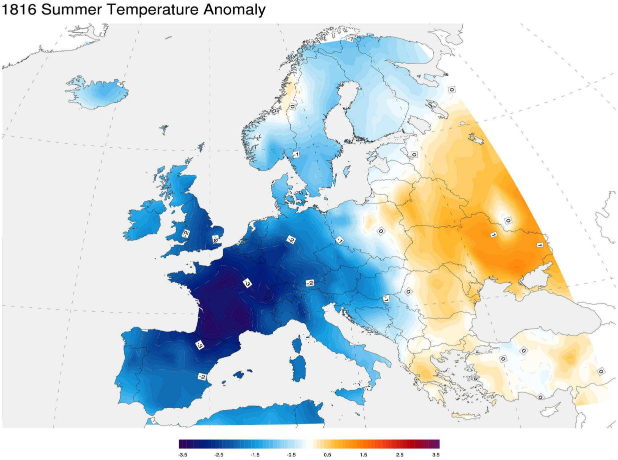


External drivers: solar irradiance





The "Year Without a Summer"



Luterbacher et al. (2004), *Science*

CLIMATIC AND DEMOGRAPHIC CONSEQUENCES OF THE MASSIVE VOLCANIC ERUPTION OF 1258

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Abstract. Somewhere in the tropics, a volcano exploded violently during the year 1258, producing a massive stratospheric aerosol veil that eventually blanketed the globe. Arctic and Antarctic ice cores suggest that this was the world's largest volcanic eruption of the past millennium. According to contemporary chronicles, the stratospheric dry fog possibly manifested itself in Europe as a persistently cloudy aspect of the sky and also through an apparently total darkening of the eclipsed Moon. Based on a sudden temperature drop for several months in England, the eruption's initiation date can be inferred to have been probably January 1258. The frequent cold and rain that year led to severe crop damage and famine throughout much of Europe. Pestilence repeatedly broke out in 1258 and 1259; it occurred also in the Middle East, reportedly there as plague. Another very cold winter followed in 1260–1261. The troubled period's wars, famines, pestilences, and earthquakes appear to have contributed in part to the rise of the European flagellant movement of 1260, one of the most bizarre social phenomena of the Middle Ages. Analogies can be drawn with the climatic aftereffects and European social unrest following another great tropical eruption, Tambora in 1815. Some generalizations about the climatic impacts of tropical eruptions are made from these and other data.

Stothers (2000), *Climatic Change*

Makīn, 1260; Bar-Hebraeus, 1286). Because the Middle East has been historically prone to epidemics of bubonic plague, possibly that is what it was.

6. The Flagellants

Flagellation, or scourging, had long been practiced as an occasional form of discipline or penance within Christian monastic communities. In the spring of 1260, however, a popular penitential movement of self-flagellation arose in Perugia, central Italy, and spread south, in the autumn, to Rome and north toward central Europe. Wholly orthodox at first, it attracted not only members of the clergy but all ranks and ages of pious lay people. Early in the following year, though, it degenerated into a heterodox movement of peasants and malcontents, which was put down finally by the ecclesiastical and civil authorities. In its typical manifestation, bands of unshirted male flagellants marched through the streets in double file, uttering hymns and religious slogans and flogging their backs with whips until blood began to flow. Troops of flagellants traveled from town to town. It was one of the oddest mass social phenomena of the Middle Ages.

Stothers (2000), *Climatic Change*

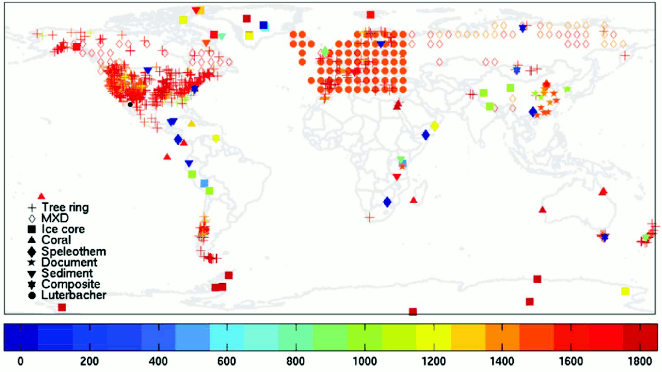
Extreme weather events of 535–536 CE

- *The sun was dark and its darkness lasted for eighteen months; each day it shone for about four hours; and still this light was only a feeble shadow; the fruits did not ripen and the wine tasted like sour grapes.* - Michael the Syrian
- *During this year [536 CE] a most dread portent took place. For the sun gave forth its light without brightness ... and it seemed exceedingly like the sun in eclipse, for the beams it shed were not clear.* - Procopius of Caesarea
- Crop failures and famine worldwide
- Low temperatures, including summer snowfall, in China
- A “dense, dry fog” in the Middle East, China and Europe
- Drought in Central and Southern America; fall of the city of Teotihuacán
- Scandinavian elites sacrificed large amounts of gold, possibly to appease the angry gods and get the sunlight back
- Probably caused by a volcanic eruption in around 533 CE

The drivers of large-scale temperature

Temperature reconstructions

- Hemispheric-mean temperature reconstructions (Mann et al., 2008)
- Global network of 1209 annually- and decadally-resolved proxies
- Decadal temperature for 300–2006 CE (NH) and 400–2006 CE (SH)

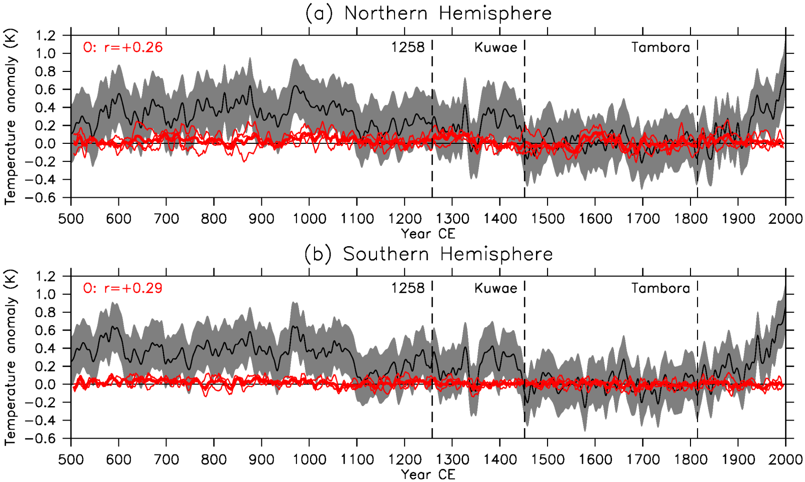


Climate model simulations

- The CSIRO Mk3L climate system model (Phipps et al., 2011, 2012)
  - Atmospheric general circulation model (5.6° × 3.2°, 18 levels)
  - Ocean general circulation model (2.8° × 1.6°, 21 levels)
  - Dynamic-thermodynamic sea ice model
  - Land surface scheme
- 10,000-year pre-industrial control simulation
- Multiple transient simulations using three-member ensembles:

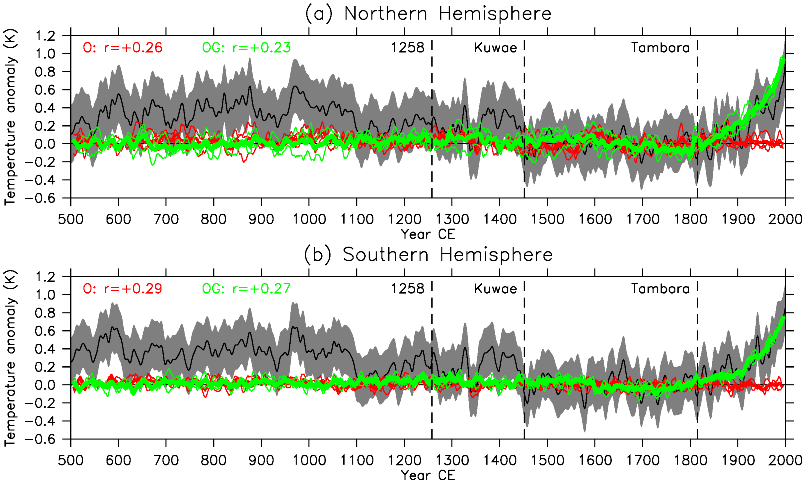
Ensemble	Years (CE)	Forcing(s)
O	1–2000	Orbital (Berger, 1978)
OG	1–2000	O + GHGs (MacFarling Meure et al., 2006)
OGS	1–2000	OG + solar irradiance (Steinhilber et al., 2009)
OGSV	501–2000	OGS + volcanic aerosols (Gao et al., 2008)

Simulated annual-mean temperature



Phipps et al. (2013), *Journal of Climate*

Simulated annual-mean temperature



Phipps et al. (2013), *Journal of Climate*

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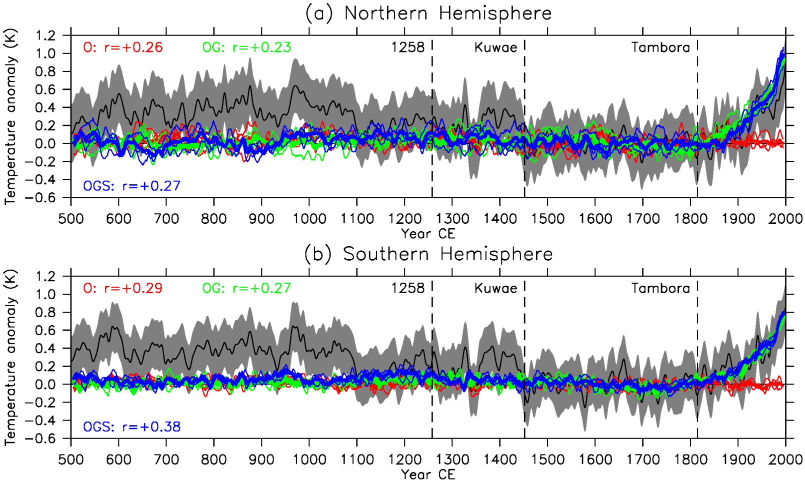
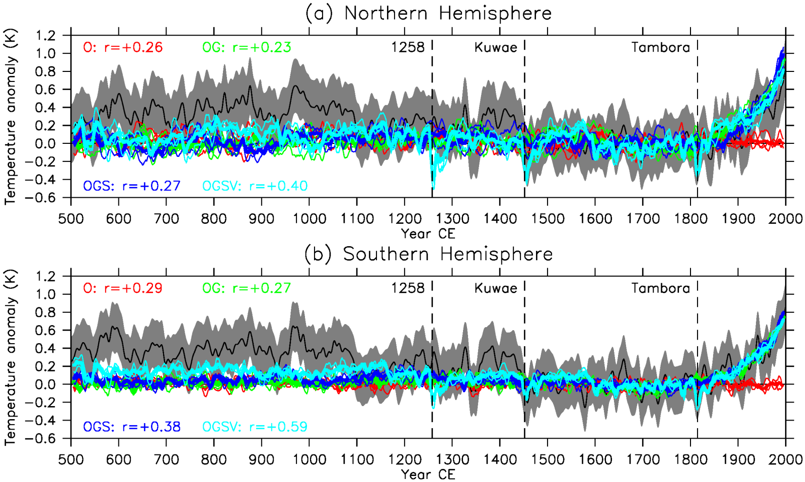


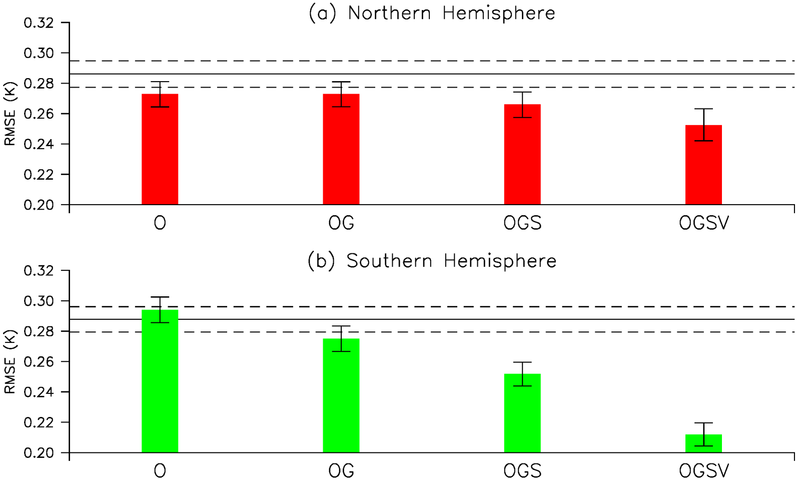
Phipps et al. (2013), *Journal of Climate*

Simulated annual-mean temperature



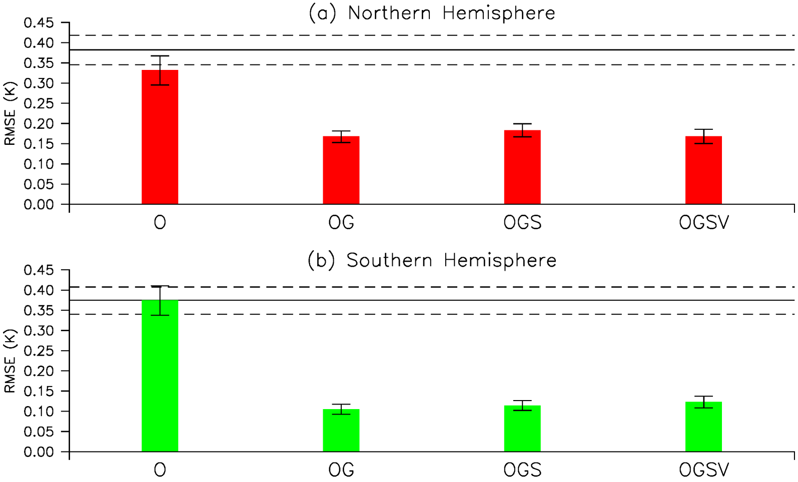
Phipps et al. (2013), *Journal of Climate*

RMS errors in model simulations (501–2000 CE)

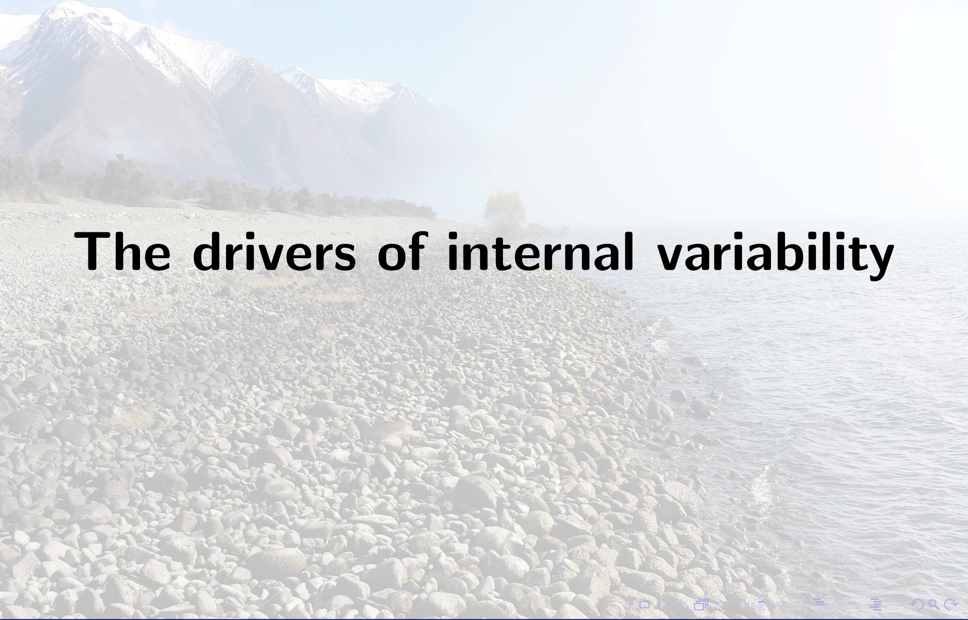


Phipps et al. (2013), *Journal of Climate*

RMS errors in model simulations (1851–2000 CE)

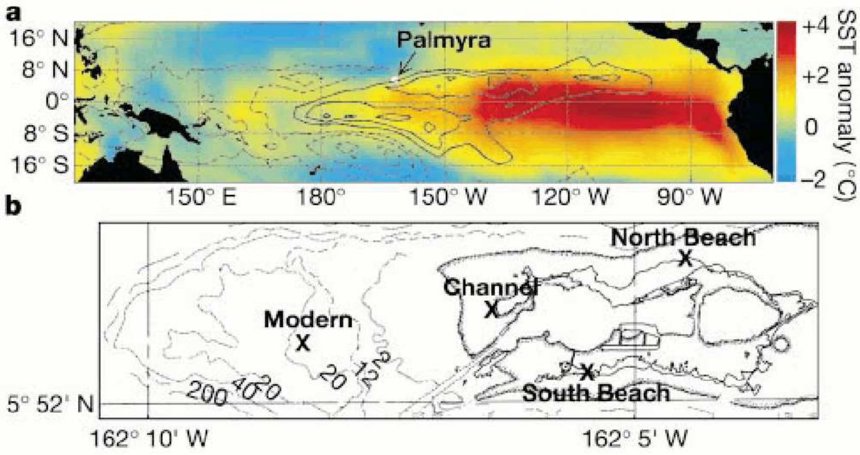


Phipps et al. (2013), *Journal of Climate*



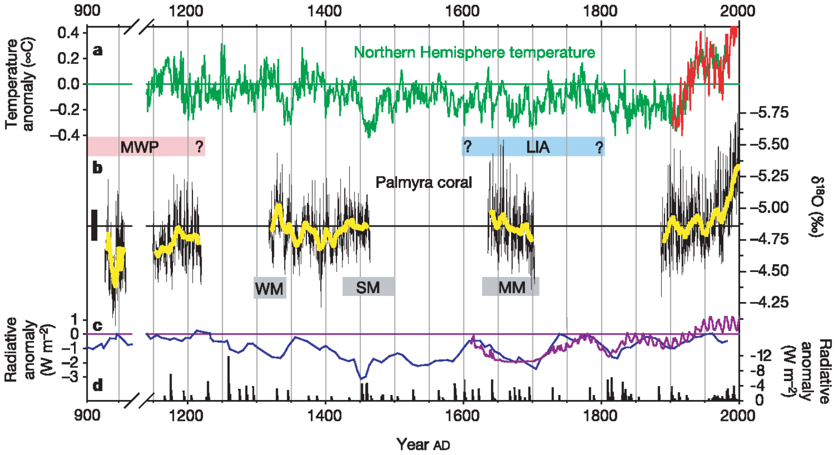
The drivers of internal variability

Past changes in El Niño-Southern Oscillation



Cobb et al. (2003), *Nature*

Past changes in El Niño-Southern Oscillation



Cobb et al. (2003), *Nature*

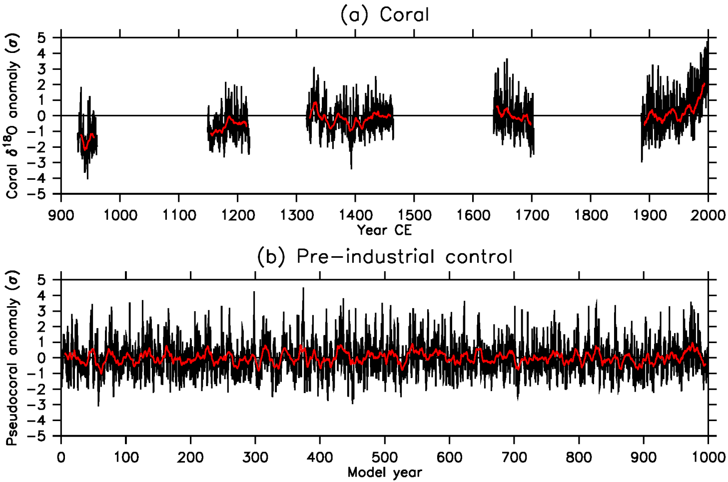
Deriving a pseudocoral

- Corals provide a single chemical variable: δ^{18}O.
- The climate model simulates physical variables: SST, SSS, P, E...
- These variables are not directly comparable.
- The solution is to construct a "pseudocoral" (Brown et al., 2008).
- Using the pre-industrial control simulation, we regress a set of potential predictors (SST, SSS, P, E) onto the simulated Niño 3.4 SST anomaly.
- We obtain the following pseudocoral:

$$C = \underset{(\pm 0.015)}{0.692}\,\Delta SST - \underset{(\pm 0.056)}{0.708}\,\Delta SSS + \underset{(\pm 0.002)}{0.023}\,\Delta P + \underset{(\pm 0.013)}{0.248}\,\Delta E$$

- This indicator describes 70% of the simulated ENSO variance.

Reconstructed and simulated mean state



Phipps et al. (2013), *Journal of Climate*

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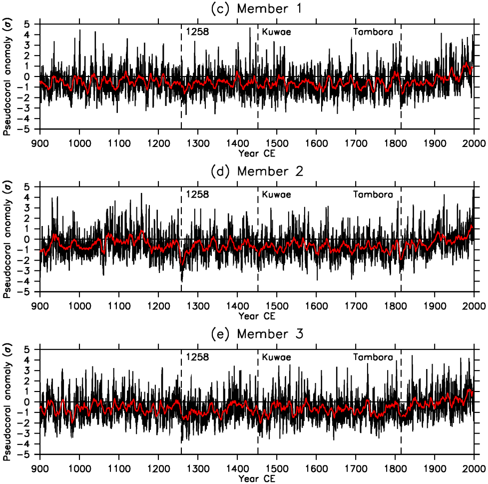


Phipps et al. (2013), *Journal of Climate*

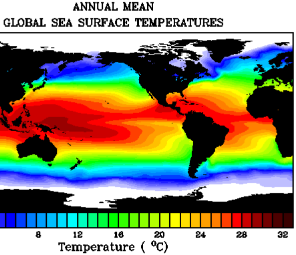
Mean state versus individual forcings

Ensemble member	Greenhouse gases	Solar irradiance	Volcanic eruptions
(a) Annual mean			
1	**+0.31**	+0.11	0.00
2	**+0.28**	**+0.17**	+0.04
3	**+0.31**	**+0.19**	+0.05
Mean	**+0.47**	**+0.25**	+0.04
(b) Decadal mean			
1	**+0.59**	+0.22	+0.12
2	**+0.50**	**+0.29**	**+0.33**
3	**+0.59**	**+0.35**	**+0.23**
Mean	**+0.71**	**+0.37**	**+0.29**

Phipps et al. (2013), *Journal of Climate*

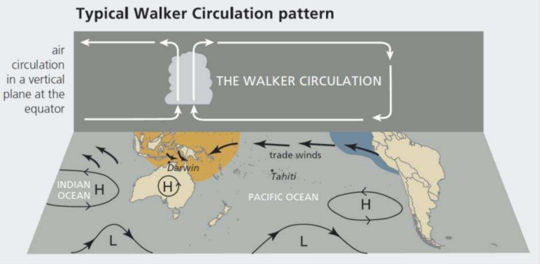
Possible dynamical mechanisms

- The ocean dynamical thermostat (Clement et al. 1996):
  - Warming in the tropics causes enhanced upwelling in the eastern Pacific.
  - This increases the magnitude of the zonal sea surface temperature (SST) gradient.
  - Predicts a positive relationship between the SST gradient and radiative forcing.

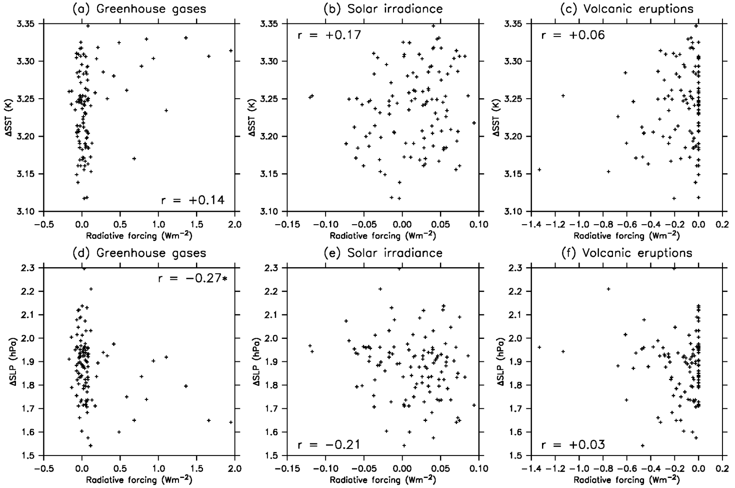


Possible dynamical mechanisms

- The "Weaker Walker" mechanism (Held and Soden 2006):
  - Global-scale warming causes a weakening of the Walker Circulation.
  - Manifested in a reduction in the zonal sea level pressure (SLP) gradient across the equatorial Pacific.
  - Predicts a negative relationship between the SLP gradient and radiative forcing.

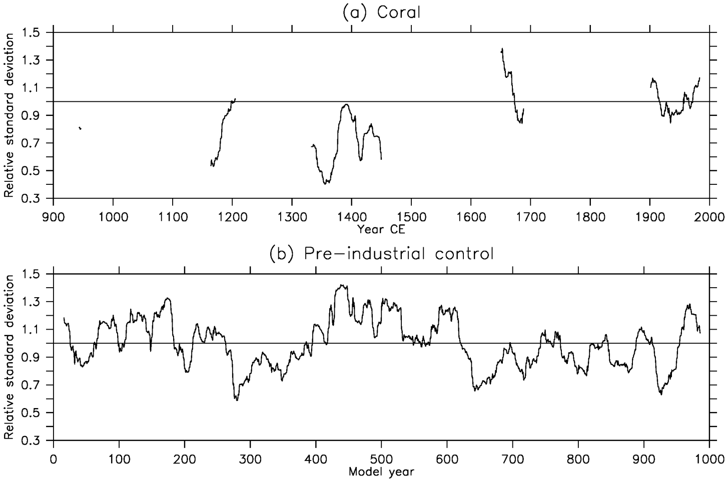


Testing possible dynamical mechanisms



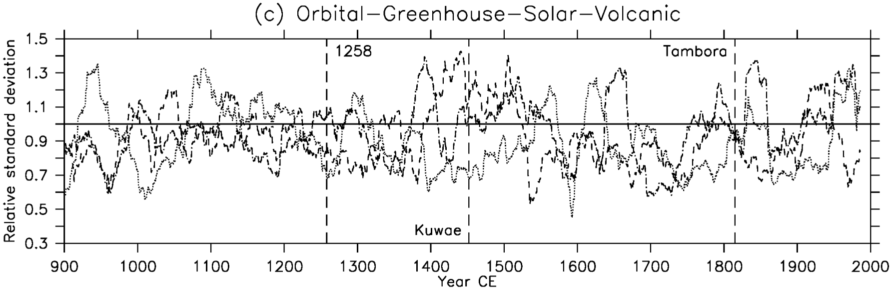
Phipps et al. (2013), *Journal of Climate*

Reconstructed and simulated ENSO amplitude



Phipps et al. (2013), *Journal of Climate*

Reconstructed and simulated ENSO amplitude



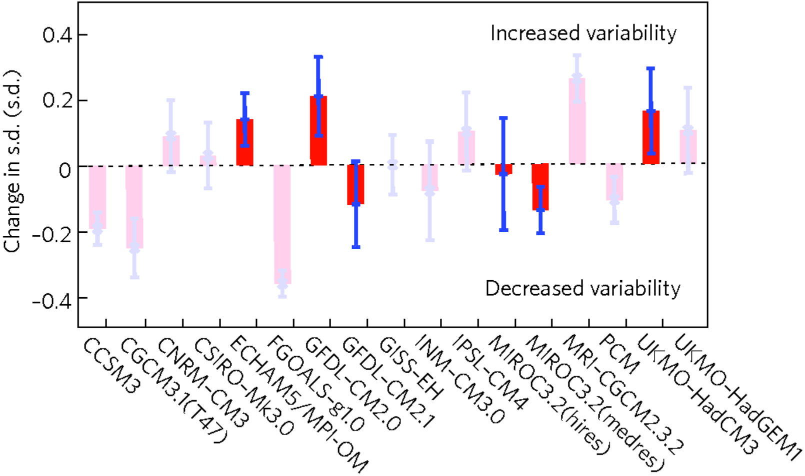
Phipps et al. (2013), *Journal of Climate*

ENSO amplitude versus individual forcings

Ensemble member	Greenhouse gases	Solar irradiance	Volcanic eruptions
1	+0.02	-0.24	0.00
2	+0.14	+0.27	+0.10
3	**+0.32**	-0.09	+0.03
Mean	+0.30	-0.04	+0.09

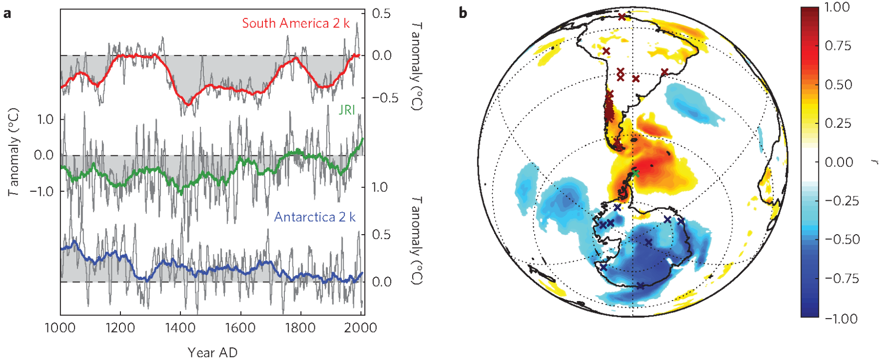
Phipps et al. (2013), *Journal of Climate*

Could this why be future projections disagree?



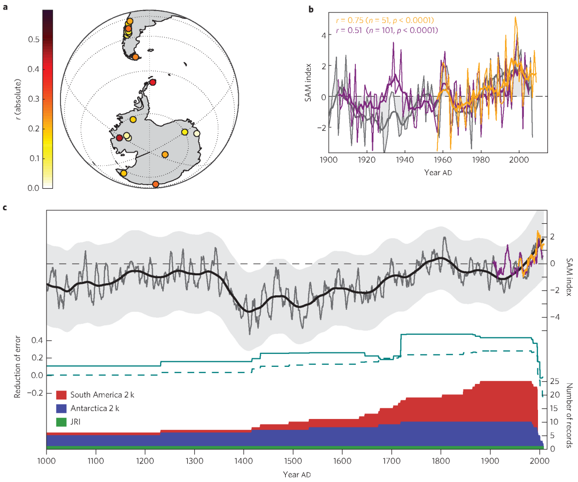
Collins et al. (2010), *Nature Geoscience*

Reconstructing the Southern Annular Mode (SAM)



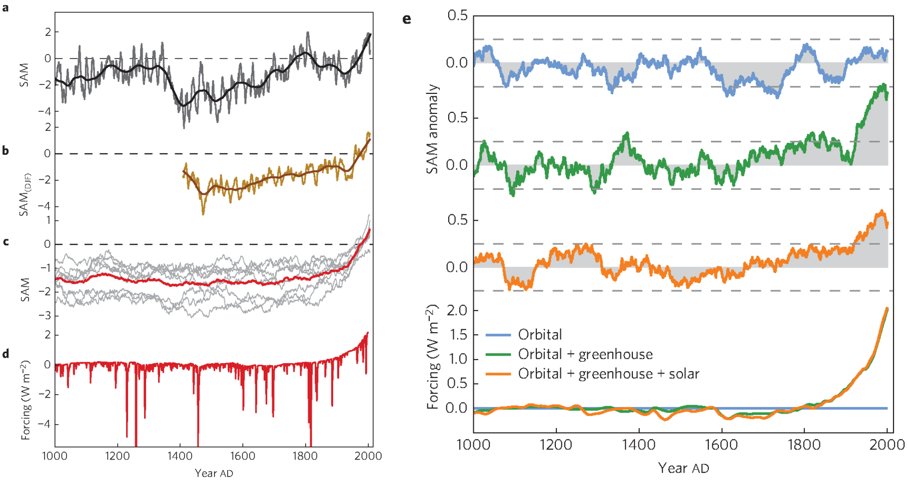
Abram et al. (2014), *Nature Climate Change*

Reconstruction of SAM over the last millennium



Abram et al. (2014), *Nature Climate Change*

Data–model comparison and role of external forcings



Abram et al. (2014), *Nature Climate Change*

Conclusions

Conclusions

- By "closing the loop" between palaeoclimate reconstructions and climate modelling, we can study the drivers of past changes and improve our understanding of climate dynamics.
- We find evidence of solar and volcanic influences on temperature, particularly in the Southern Hemisphere. However, after 1850 CE, anthropogenic greenhouse gases become increasingly dominant.
- We also find evidence of solar, volcanic and anthropogenic influences on the mean state of the central Pacific. However, we find no evidence of any natural or anthropogenic influences on ENSO. This supports the notion that ENSO variability arises from within the internal dynamics of the ENSO system itself.
- Similar conclusions apply for the SAM, although anthropogenic forcings cause a shift towards a more positive state during the late 20th century.