The Teleconnections of the El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) in the Mid-Pliocene Warm Period (mPWP) (3Ma) – Can they be used as a Utility to Predict the Dynamics of Climate Oscillations in a Warmer World?

Thomas Olsen, Prof. Alan Haywood, Dr. Julia Tindall and Prof. Dominick Flietmann.

Abstract: The anthropogenic enhancement of the greenhouse gas effect has, and will continue to, impact on planetary systems including the ENSO and NAO. However, considerable uncertainties surround their future projections. A good opportunity to improve future predictions is to analyse previous warm climates, such as the mPWP (3Ma), to examine the dynamics of a warmer-than-modern world. This study will use the HadCM3 to simulate mPWP, pre-industrial and doubled-CO$_2$ climatic states of the Atlantic and Pacific, which will be validated against geological proxies. This project aims to better understanding of ENSO and NAO teleconnections in these three time periods and to infer more accurate future projections from simulated mPWP activity.

1. Scientific Rationale

The Earth’s current concentrations of atmospheric NO$_2$, CH$_4$ and CO$_2$ have reached unprecedented levels, relative to the last 800ka (IPCC, 2014). The excessive anthropogenic input of pollutants has amplified the natural greenhouse effect and caused an unequivocal increase in temperature (Hu and Wu, 2004; Haywood et al., 2016). Since the pre-industrial era atmospheric CO$_2$ concentrations have risen from 280ppmv to 404ppmv, which resulted in a 0.85$^\circ$C average temperature increase during 1750-2012 (IPCC, 2014; Haywood et al., 2016). This global warming has, and will continue to, impact on large-scale atmospheric and oceanic systems including the El Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO). These two phenomena have vast spatial teleconnections. ENSO can induce hurricanes, drought and flooding (Latif and Keenlyside, 2009; Bonham et al., 2016), whilst the NAO contributes to weather systems experienced across an area spanning Siberia, Eastern United States and Turkey (Visbeck et al., 2001; McIvor, 2010; Dong et al., 2011). In regard of their socioeconomic importance, it’s imperative that the future responses of ENSO and NAO are understood. Unfortunately, for both systems model discrepancies within simulations are common and a conclusive consensus of their future activity within a warming world remains undetermined (Hu and Wu, 2004; Tindall et al., 2017).

A good opportunity to improve confidence in future projections is to analyse past climates (Haywood et al., 2016). The mid-Pliocene warm period (mPWP) that occurred 3.264-3.025Ma ago is a useful tool for understanding a warmer-than-modern climate. The mPWP had atmospheric CO$_2$ levels of 400ppmv, temperatures 1-2$^\circ$C greater than today and similar continental configurations (Haywood et al., 2013; Tindall and Haywood, 2015; Bonham et al., 2016). Of all pre-Quaternary periods, it is argued that the mPWP has the greatest correlation of numerical simulations and geological proxies (Haywood et al., 2016). By verifying mPWP simulations with localised proxies, scientists can accurately determine how ENSO and NAO behaved in a warmer-than-current climate (Haywood et al., 2016). So, mPWP reconstructions can give insight into near-future behaviour of these two systems, as temperatures continue towards those of the mPWP.

2. Background Information

2.1. The El Nino Southern Oscillation

The ENSO originates in the equatorial Pacific, whereby atmospheric-oceanic coupling cause semi-periodic alterations between warm and cold sea-surface temperature (SST) extremes, defined as El Ninos and La Ninas respectively (Latif and Keenlyside, 2009; Bonham et al., 2016).
oscillation between these extremes is driven by alterations in the Pacific’s zonal SST gradient which induces interactions between the depth of the thermocline, SSTs and the atmospheric Walker Circulation (WC) cell (Figure 1) (Latif and Keenlyside, 2009). It has been recently accepted that two El Nino flavours exist: the Central Pacific El Nino (CP-EN) and Eastern Pacific El Nino (EP-EN) (Sung et al., 2012; Tindall et al., 2016). The CP-EN and EP-EN have their anomalous SST increases in the Central and Eastern equatorial Pacific respectively (Sung et al., 2012).

Many inconsistencies exist within climate simulations of ENSO activity and long-term patterns of variability are unquantifiable as the instrumental record only extends back to the mid-19th Century (Tindall et al., 2016). Nevertheless, studies have attempted to simulate future variations of El Nino activity, relative to this record. Large uncertainties surround predictions of future El Nino frequency. Timmerman et al. (1999) inconclusively predicted an increase, whilst Cai et al. (2014) simulated a 4% frequency reduction in El Ninos during 1991-2091, relative to 1891-1990. Recently, EP-ENs have decreased in frequency, whilst CP-ENs have increased. McPhaden et al. (2011) reported 75% and 33% of El Ninos during 2000-2010 and 1980-1999 respectively were central-Pacific based. But, it still remains uncertain whether this flavour shift is attributed to global warming (Yeh et al., 2009) or natural variability (McPhaden et al., 2011). It is believed that anthropogenic-induced global warming has intensified El Nino events, and this trend is expected to continue. Cai et al. (2014) simulated intense El Ninos to increase in recurrence from once every 20 years in 1891-1990 to once every 10 years in 1991-2090, as increasing CO₂ emissions induce a weakened WC overturning. Furthermore, Latif et al. (2015) concluded a 0.37°C temperature increase above today’s global average has the potential to induce Super-El Ninos, whereby anomalous SST increases exceed 6°C. However the reliability of these aforementioned studies is questionable, as the instrumental record is of insufficient length to ensure statistical significance of results. So, any future predictions based from it must be accepted with caution.

In contrast, the use of the mPWP to examine the dynamics of a warmer-world holds more reliability. This approach been widely adopted recently, as will be implemented in this present study. However, mPWP El Nino activity is debated with differing simulations and geological proxies suggesting varied frequencies and amplitudes (e.g. Brierley, 2015; Tindall et al., 2016), a permanent El Nino-like climate named El Padre (e.g. Wara et al., 2005), and clear oscillatory nature between ENSO extremes (e.g. Haywood et al., 2013; Bonham et al., 2016). From their respective datasets, Wara et al. (2005) and Seki et al. (2012) suggested an El Padre condition whereby El Nino to La Nina fluctuations were absent and the zonal SST gradient was considerably weakened, relative to modern. However, the majority of studies disregard El Padre for various reasons. For instance, numerous authors (e.g. Tindall et al., 2016; Bonham et al., 2016) have identified SST fluctuations in simulations, proxies used by Wara et al. (2005) had minimal resolutions, and El Padre conditions are likely a result of equifinality, and not permanent El Nino-like conditions (Bonham et al., 2016). Hence, it is generally agreed that mPWP ENSO variability was apparent, but the extent of the variability remains undetermined.
Via an analysis of a 9-model ensemble of the NINO3.4 region, Brierly (2015) concluded the mPWP demonstrated reduced ENSO variability, weaker El Ninos and minimal variance in El Nino ‘flavour’, relative to a pre-industrial control run. These characteristics were inconclusively attributed to Andean Uplift by Brierly (2015). In contrast, Tindall et al. (2016) found from a 2500-year simulation that mPWP El Ninos demonstrated increased amplitudes and CP-ENs were apparent in NINO4 regions, which were not simulated by Brierly (2015). Tindall et al. (2017) developed this further in stating that El Nino temperature, precipitation, $\delta^{18}O_s$ and $\delta^{18}O_{sw}$ (stable water isotope tracers of precipitation and seawater, respectively) magnitude anomalies were respectively 28%, 32%, 29% and 37% larger than those in the pre-industrial. Unfortunately, spatial variability was evident for these quantities, especially the former (Tindall et al., 2017). Overall, significant ambiguity still surrounds mPWP El Nino activity and solving this uncertainty is imperative to understand warmer-world ENSO variability (Tindall et al., 2016).

2.2. The North Atlantic Oscillation

The NAO operates in the Atlantic basin and involves meridional re-distributions of atmospheric mass between two pressure centres-of-action: the Icelandic Low (IL: 65-68°N, 17-20°W) and the Azores High (AH: 40-43°N, 11-14°W) (Santos and Corte-Real, 2006; McIvor, 2010). Shifts in pressure-system governance control NAO phase activity. A positive phase is characterised by anomalous low and high pressures over the IL and AH respectively (McIvor, 2010), whereby the simultaneous strengthening of the pressure gradient force induces faster-than-average Westerlies (Dong et al., 2011). A less pronounced gradient, and subsequently mirrored teleconnections, are evident during negative phases (McIvor, 2010).

Surprisingly, relative to ENSO, little emphasis has been placed on mPWP NAO activity meaning a literature imbalance exists. However, this does provide a good opportunity for this present study to advance the field. One of the few studies, by Haywood et al. (2000), modelled mPWP European climate using HadCM3. Simulations demonstrated landmasses experienced 400-1000mm/yr$^{-1}$ precipitation, temperatures 5°C warmer than current and subdued seasonality, whilst Northern Atlantic SSTs exceeded today’s by 6-8°C (Haywood et al., 2000). These conditions are highly indicative of a prevailing positive NAO phase. McIvor (2010) supported this as their simulations indicated minimal variability around the equilibrium mPWP state, whereby re-distribution of atmospheric mass accounted for 53.17% of pressure gradient variation. Hill et al. (2011) reached similar conclusions when verifying HadCM3 simulations with fossilised tree-ring data. The intensified mPWP IL and AH (that characterise positive NAOs) have been predominantly attributed to reductions in Northern Hemisphere ice volumes and partially to the reduced elevation of the Rocky Mountains, relative to modern (Haywood et al., 2000; Hill et al., 2011). Apart from these aforementioned studies, substantial scope still exists for filling a research gap.

When considering future NAO, significantly more analysis has been completed. Various studies demonstrate that model responses are directionally consistent, but varied in magnitude (Hill et al., 2011). Since 1970, the NAO has demonstrated highly positively phased activity at a magnitude that has been previously unobserved (Visbeck et al., 2001). Simulations by Hu and Wu (2004), Santos and Corte-Real (2006) and Gillett and Fyfe (2013), among others, have all predicted this positive trend to continue in the near-future. From HadCM3 simulations, Santos and Corte-Real (2006) stated a CO$_2$ increase to 850ppmv by 2100 would induce NAO behaviour capable of warming North-Eastern Europe by >8°C during winter. Santos and Corte-Real (2006) also suggest a modification of NAO structure is possible during 2070-2099 whereby the AH would extend East to incorporate areas of the Mediterranean Basin. Currently no consensus has yet to conclusively explain post-1970 (and predicted 2017-2100) NAO activity. Suggested theories include increased SSTs,
which would forcibly deepen the IL (more positive NAO), and stratosphere-troposphere interactions (Hu and Wu, 2004). Stratospheric-tropospheric coupling may have recently been influenced by a stronger stratospheric polar vortex which can propagate below the tropopause and interact with Northern Hemisphere oscillatory patterns (Hu and Wu, 2004; Dong et al., 2011). These theories are yet to be confirmed and should be accepted cautiously.

3. Aims and Objectives

Overall, this project aims to build upon the current foundation of knowledge of the warmer-world teleconnections of the ENSO and NAO, both past and present, and to hopefully contribute to the existing NAO mPWP literature gap. At our current level of understanding various mPWP and doubled-CO$_2$ simulations have demonstrated shared commonalities, but variance still exists between outputs forced with matching boundary conditions (Haywood et al., 2013). For instance, Haywood et al. (2013) reported a 1.76°C global mean temperature range between 8 models of Pliocene climate forced with identical conditions. Collectively, as the scientific community undertakes increasing amounts of research, modelling uncertainties will hopefully be reduced.

The specific objectives of this project are as follows:

1) Using new and existing simulations, identify and analyse alterations of ENSO structure between simulations of mPWP and pre-industrial, doubled-CO$_2$ and pre-industrial, and mPWP and doubled-CO$_2$ climatic states in the Pacific Ocean.

2) Using new and existing simulations, identify and analyse alterations of NAO structure between simulations of mPWP and pre-industrial, doubled-CO$_2$ and pre-industrial, and mPWP and doubled-CO$_2$ climatic states in the Atlantic Ocean.

3) Compare simulated model outputs with proxy datasets (for mPWP and pre-industrial) to determine the existence of ENSO and/or NAO teleconnections within the data.

4. Methodology

Equal analysis will be done for the ENSO and NAO. In correspondence with the majority of literature, this study will analyse each system in isolation. Of course, ENSO-NAO synchronisations will be considered (e.g. Wu and Zhang, 2015) but, for clarity, they will be presented separately.

4.1. Objective 1

Simulations used throughout this project will be from the stable isotope derived version of the Hadley Centre General Circulation Model (HadCM3). HadCM3 has 19 vertical atmospheric levels with 3.75°x2.5° resolution and 20 vertical oceanic levels with 1.25°x1.25° resolution (Tindall et al., 2016). For atmospheric levels, this model employs Gregory and Rowntree’s (1990) convection scheme, Edwards and Slingo’s (1996) radiation scheme and a large-scale cloud scheme founded on Smith (1990). For oceanic levels, HadCM3 is comprised of a sea-ice scheme modified from Semtner (1976) which incorporates snow coverage and ice-drift. While HadCM3 has been recently superseded by the Hadley Centre Global Environment Model (HadGEM) ensemble (Hewitt et al., 2011), HadCM3 remains as the ideal instrument for this particular project. This project will predominantly concentrate on 2500-year simulations which would be unachievable using HadGEM models based on their complexity (Tindall and Haywood, 2015). Furthermore, HadCM3 accuracy is well established. Both Bonham et al. (2016) and Tindall et al. (2009) stated that HadCM3 simulations of modern day ENSO-induced sea-surface δ$^{18}$O anomalies match well with observational data. From 10 HadCM3 runs, Rodwell and Folland (2003) demonstrated the HadCM3 simulated North Atlantic Ocean responses that corresponded well with observational records. Santos and Corte-Real (2006) stated the HadCM3 skilfully reproduced atmospheric-
oceanic coupling within their study of future wintertime NAO activity, and HadCM3’s success was also well documented within the 4th IPCC Assessment Report (IPCC, 2007).

Model setup will differ for the three time-periods considered. For the mPWP, model design will be in correspondence with aforementioned Pliocene studies (Section 2) so boundary settings will be in accordance with the Pliocene, Research, Interpretation and Synoptic Mapping Project (PRISM). For the pre-industrial period, model setup will be similar to that done by Gordon et al. (2000), with pre-industrial CO₂ concentrations set at 280ppmv. The doubled-CO₂ world setup will be identical to pre-industrial, except concentrations will be set at 560ppmv. For the mPWP and pre-industrial climatic modes, existing 2500-year length simulations will be used. The doubled-CO₂ climatic state is intended to have a similar simulation length, and this HadCM3 simulation is currently in operation. Hence, this study will incorporate analysis of both existing and newly-generated HadCM3 model outputs. To analyse alterations in ENSO structure between the different time periods, El Nino indexes will be created within simulations after removing the annual cycle. Empirical Orthogonal Function analysis (EOFA) and Spectral Analysis (SA) will be performed. EOFA will be implemented to identify spatial variation in ENSO structure and is done by partitioning the simulated field into mathematically independent modes, from which atmospheric/oceanic signatures can be identified. SA will be done to determine the relative strength of independent frequencies within the specific period, so amplitudes can be inferred. Successful applications of these techniques for each time-period will accurately determine structure alterations, hence completing Objective 1. Additional unsupervised model runs may be implemented depending on the project progression at that particular stage.

4.2. Objective 2

For the completion of this objective, the same methodology will be applied as for Objective 1. However, simulations will focus on the Atlantic, NAO indexes will be instead created and EOFA and SA will concentrate on identification of structure differences of the IL and AH, not the El Nino.

4.3. Objective 3

To accurately determine the existence of ENSO and NAO teleconnections in the simulations, outputs will be extensively compared with proxy datasets. Particular emphasis will be placed on how teleconnections alter through different sampling within the model time series. These proxy datasets for the mPWP will be obtained from various published sources. A comprehensive list of all available Pliocene proxy data, and their respective references, is available in Bonham et al. (2009). Some of these data may be used, but this currently remains undecided. Proxy data that is confirmed to be used includes (identified on Figure 2): (1) Watanabe et al.’s (2011) 35-year long coral dataset, Philippines (2) Wang et al.’s (2015) meteoric Be-10 soil profiles, Atacama Desert, Chile (3) Winnick et al.’s (2013) pedogenic carbonate profiles, Southern California and Idaho (4) Scroxton et al.’s (2011) planktonic foraminifera, Eastern Pacific (5) Flietmann et al.’s (2004) speleotherm datasets, Saudi Arabia (from 13 caves in total). On the later dataset, Professor Flietmann completed fluid inclusion isotope analysis (to measure δ¹⁸Ohydr) in December 2016. Accurate δ¹⁸Ohydr data for the mPWP is extremely rare; hence, this new dataset is

Figure 2: Locations of proxy data used for this project. Numbers refer to the locations cited in text.
of high importance to this present study. Furthermore, as part of Objective 3, HadCM3 simulations of $\delta^{18}O_p$ can be directly compared to Professor Flietmann’s $\delta^{18}O_p$ proxy dataset. This high synergy between simulations and proxy-data (Tindall et al., 2017) means any identified teleconnections will hold higher accuracy relative to previous studies where $\delta^{18}O_p$ has only been inferred from alternate proxy datasets.

5. Resources

No funding is required for this project as data is already, or will shortly, be attained from various sources listed in Section 4.3. Access to HadCM3 simulations of mPWP, pre-industrial and doubled-CO$_2$ climates, and guidance on how to analyse them, will be provided by Professor Haywood and Dr Tindall. Access to library resources and online tutorials of Python programming language are imperative for the completion of this project. Both are supplied by the University of Leeds.

6. Programme of Research

The Gantt diagram presented in Table 1 demonstrates the idealised progression this project will take between mid-January and mid-September 2017. Computer project completion incorporates individual web-page preparation which must display well annotated code used in HadCM3 output analysis and associated graphical plots. For the scripts that will be used in this study, pre-existing code and that which has been individually modified will be clearly commented.

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Table 1: Gantt diagram demonstrating the stage-by-stage progression of this project.

7. Outcome

The idealised outcome of this research project would be its publication within a peer-reviewed scientific journal, which would allow the scientific community to build upon its conclusions. This project certainly has the scope to achieve this. Firstly, it is one of the first studies to look at both ENSO and NAO teleconnections within the mPWP and hence has the potential to fill the existing literature gap. Secondly, with the use of new and unseen proxy data, in terms of Professor Flietmann’s $\delta^{18}O_p$ dataset, there is potential for previously unobserved conclusions to be drawn. A direct comparison between $\delta^{18}O_p$ proxy data and HadCM3 simulated $\delta^{18}O_p$ has not previously been
done for the mPWP. This is what makes this project so unique, relative to previous literature. Hence, this high model-data synergy suggests previously unseen ENSO or NAO teleconnections may hopefully be identified.

8. Wider Applications

Conclusions drawn from this project will ideally increase the scientific awareness of mPWP, pre-industrial and doubled-CO₂ mean climatic states in the Atlantic and Pacific Oceans. A greater understanding of NAO and ENSO structures, frequencies, amplitudes and teleconnections in the warmer-than-present mPWP will hopefully give insight into the behaviour of large-scale oscillations that we are likely to expect within the coming centuries (Tindall et al., 2016). Increased knowledge of their future activity is of upmost importance due to the widespread socio-economic significance of these climatic patterns (discussed in Section 1). The extensive comparisons between model and proxy-data (particularly the use of δ¹⁸O_p), implemented for Objective 3, will have widespread applications for two reasons. Firstly, it will contribute to the ongoing validation of the HadCM3. Comparisons between site-specific proxy/instrumental data and globally modelled climatic patterns will further the scientific community’s knowledge of HadCM3 accuracy. Secondly, use of the new and unseen δ¹⁸O_p dataset will hopefully lead to previously unseen conclusions. A direct comparison between simulated δ¹⁸O_p and proxy δ¹⁸O_p mPWP data that will be done in this project has not yet been done within the literature. Previous studies have only inferred δ¹⁸O_p from other proxies which has meant agreements between model and data are limited in their reliability, due to uncertainties involved in inferring δ¹⁸O_p from other datasets. Hence, this project has a unique opportunity to analyse mPWP teleconnections which will hopefully advance the current understanding.

References


