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To cite this article: Chris Kent *et al* 2025 *Environ. Res. Lett.* **20** 064014

ENVIRONMENTAL RESEARCH
LETTERS

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OPEN ACCESS

RECEIVED
31 January 2025

REVISED
27 March 2025

ACCEPTED FOR PUBLICATION
2 May 2025

PUBLISHED
13 May 2025

LETTER

Transition of El Niño to La Niña can be driven by regional perturbations a year ahead

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Keywords: transition, El Niño, Niña, driven, regional, perturbations

Abstract

Interannual forecasts provide skilful predictions of El Niño-Southern oscillation (ENSO) up to a year in advance, however our understanding of what drives the ensemble skill and diversity of outcomes across members is limited. Using a fully coupled ocean–atmosphere ensemble forecasting system, we investigate the causality of regional perturbations on the evolution of ENSO at interannual timescales. Using forecasts initialised on 1 November 2009, transplanting more realistic cooler conditions in the South Pacific across ensemble members on 1 January 2010 significantly cools the resulting 2010/2011 winter ENSO one year later. The imposed perturbations migrate equatorward via wind–evaporation–sea surface temperature feedback and significantly alter tropical zonal gradients during late spring and summer. This drives the ensemble towards La Niña conditions, in line with observations. Repeating the experiment with warmer South Pacific conditions, results in the reverse signal and warms ENSO one year later. Across the experiments we find an almost four-fold increase in probability of La Niña and a three-fold decrease in probability of El Niño, demonstrating that long lead regional perturbations can systematically tip the climate system between ENSO states. Predicted surface conditions are significantly impacted across many parts of the world and the forecast global annual mean surface temperature for 2010 is significantly cooled, resulting in better agreement with observations. Our results demonstrate sensitivity of ENSO evolution and the global climate system to specific regional perturbations and provide new insights for interannual climate prediction.

1. Introduction

The El Niño-Southern oscillation (ENSO) is the primary mode of interannual variability within the climate system and whether El Niño (warm) or La Niña (cool) conditions develop each year is of significant scientific and societal interest. As a strongly coupled air–sea phenomenon which peaks in boreal winter, ENSO events drive a large-scale reorganisation of the entire tropical climate and influence the mid-latitudes through extratropical teleconnections (Horel and Wallace 1981, McPhaden *et al* 2006, Deser *et al* 2017, Ayarzagüena *et al* 2018, Timmermann *et al* 2018, Scaife *et al* 2024). In addition to affecting the climate in many regions (e.g. Taschetto *et al* 2020), its influence even extends to the global annual mean surface temperature (Tippett and Becker 2024).

ENSO is highly predictable months in advance (Barnston *et al* 2012, Kumar *et al* 2017, Ineson *et al* 2018), but skill decreases considerably around the boreal springtime, a critical transition period of the tropical Pacific state (McPhaden 2003, Ren *et al* 2016). At interannual timescales (i.e. >12 months) skilful ENSO forecasts are possible (Luo *et al* 2008, Knight *et al* 2014, Dunstone *et al* 2020, Weisheimer *et al* 2022, Sharmila *et al* 2023) partly due to its oscillatory nature (Lenssen *et al* 2024, Wu *et al* 2024), however higher frequency stochastic processes still play an important role for individual events (e.g. Ineson *et al* 2018). Understanding the drivers of interannual forecast skill remains a key area of research.

Several precursors of ENSO at such long lead times have been identified. These include the North Pacific meridional mode (NPMM, Vimont *et al* 2003) via the seasonal footprinting mechanism (Vimont *et al* 2003) driven by the North Pacific oscillation (Yu and Kim 2011, Ding *et al* 2022), as well as the corresponding South Pacific meridional mode (SPMM, Zhang *et al* 2014), associated with the South Pacific oscillation (SPO) and South Pacific quadrupole (SPQ, Terray 2011, Ding *et al* 2015, 2020, You and Furtado 2017). Outside the Pacific, precursors include Atlantic Niños and Niñas (Hounsou-Gbo *et al* 2020, Zhang *et al* 2025) and the South Atlantic subtropical dipole (SASD, Ham *et al* 2021) as well as conditions across the Indian ocean (Izumo *et al* 2010, Ohba and Watanabe 2012, Jo *et al* 2022, Jin *et al* 2023). The role of these precursors in driving ENSO events is often assessed through empirical analyses (Zhang *et al* 2019, Iwakiri and Watanabe 2021, Hasan *et al* 2022,) or idealised model experiments (Izumo *et al* 2010, Imada *et al* 2016, Ding *et al* 2022), with some evidence of their predictive use (Larson and Kirtman 2014, Chen *et al* 2020). To date however, their *causality* has not been demonstrated within ensemble forecasting systems.

In this study we aim to address this and demonstrate ENSO sensitivity to regional conditions which can develop naturally within a few months of the forecast initialisation. We focus on a case study of the transition from a strong El Niño to a strong La Niña during 2010 and employ a newly developed transplanting technique (Kent *et al* 2023) to exchange regional conditions between forecast members. By inserting conditions from one ensemble member into all others at a specific time within the forecast, the method allowed the direct causality of a sudden stratospheric warming to regional perturbations 10 days prior to be established (Kent *et al* 2023). Here we apply the same methodology but to interannual (16 month) ENSO forecasts from a coupled ocean–atmosphere climate model.

The datasets and experimental design are detailed in section 2. In section 3 we identify regional ensemble conditions associated with the correct transition to La Niña. In section 4 we perform new interannual forecasts with these conditions transplanted across ensemble members and assess their impact. We the discuss the outcomes of this work, and its potential impact on long-range predictions in section 5.

2. Methodology

2.1. Datasets

Historical atmospheric and surface temperature conditions for the period 1991–2020 were extracted from the ERA5 reanalysis dataset (Hersbach *et al* 2020). Monthly anomalies were generated at each grid cell by removing the climatological mean and all fields were bilinearly interpolated to the DePreSys model grid.

Interannual climate forecasts are taken from the fully coupled ocean–atmosphere operational decadal prediction system DePreSys4 (Hermanson *et al* 2024) which is based on the HadGEM3-GC3.1 climate model (Andrews *et al* 2020). This has a spatial resolution of 60 km in the atmosphere, 0.25° in the ocean, and initial conditions taken from a data assimilation scheme which is been nudged towards observed analyses in the atmosphere and ocean (Hermanson *et al* 2024). A 150-member ensemble initialised from the first member on 1 November 2009 forms the control ensemble for this analysis. All 150 members are initialised from identical climate states and the ensemble spread is generated by atmospheric stochastic parameterisations (Tennant *et al* 2011). The model's monthly climatology as a function of lead time is calculated for the period 1991–2020 and removed from all members.

2.2. Experimental design

To investigate causality, we employ a 'transplanting' methodology (Kent *et al* 2023) in which regional conditions are taken from a selected ensemble member and placed into other ensemble members at a specific lead time. The modified ensemble members are then restarted and continue for the rest of the forecast period without further adjustment. For a given experiment, we transplant atmospheric and ocean conditions and include a linear smoothing (extending out 15° in each direction) to prevent model instabilities developing. We extend the methodology and transplant all 85 atmospheric model levels for zonal, meridional and vertical velocities, air density, potential temperature and humidity, and all 75 ocean model levels for zonal and meridional velocities (and wind surface stress), temperature, salinity, density, and sea surface height. The experiments consist of an ensemble of 50 members and the same members are used in all experiments to allow comparison. The model is bit-reproducible and so differences between experiments are solely due to the regional conditions transplanted.

3. Regional perturbations associated with the transition to La Niña during 2010

Interannual forecasts initialised on 1 November 2009 from the DePreSys4 operational prediction system (Hermanson *et al* 2024) successfully capture the El Niño conditions during winter 2009/2010 (DJF1) and then tend towards a neutral Niño3.4 index (170° W–120° W, 5° S–5° N) during 2010. In reality, the tropical Pacific continued to cool and strong La Niña conditions were established by winter 2010/2011 (DJF2),

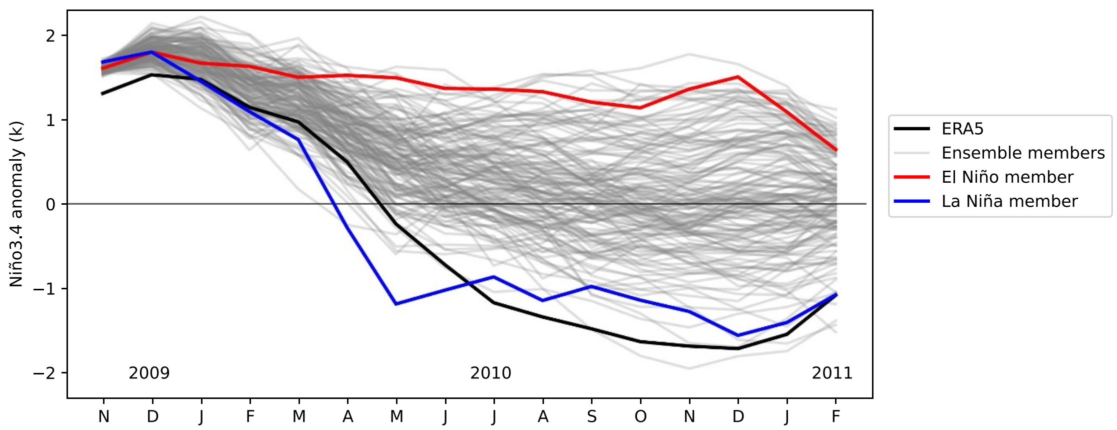

Figure 1. Interannual Niño3.4 forecasts initialised on 1 November 2009 from the DePreSys4 system. Individual ensemble members (150) are shown in grey and the ERA5 observed anomaly is in black. The El Niño and La Niña members selected for this study are shown in red and blue respectively. All anomalies are relative to 1991–2020.

reaching an anomaly of −1.45 K (relative to 1991–2020). Within the control ensemble (figure 1) 17% of members successfully forecast the transition to La Niña during 2010 (−0.5 K threshold), 54% predict neutral conditions and 29% remain in an El Niño state (+0.5 K threshold). In this study we want to understand the causality of regional conditions which develop within DJF1 on the ENSO state during DJF2.

To identify potential perturbations which can drive members towards La Niña, we first compare DJF1 surface temperature conditions between the strongest 25 La Niña and El Niño members (figure 2 figure 1(a), shading). Secondly, we condition in the opposite manner and assess where the difference in DJF1 surface temperatures are associated with a greater than ±0.5 K DJF2 Niño3.4 change (figure 1 figure 2(a), pink contours). These two constraints indicate that cooler conditions across the subtropical North and South Pacific as well as warmer conditions across the subtropical South Atlantic are associated with the successful transition towards La Niña during 2010. Furthermore, La Niña members also better reflect the observed conditions (i.e. reduced error to ERA5) across these regions (not shown).

Focusing on the large-scale signals present across the South Pacific, we find patterns resembling previously identified precursors such as the SPMM (Zhang *et al* 2014, Ding *et al* 2020) which grow during DJF1 and into the springtime and appear to reach the equator in early summer (not shown). The corresponding differences in the northeast subtropical Pacific, which resemble the NPMM, show a weaker relationship with the DJF2 Niño3.4 conditions (fewer pink contours in figure 2(a)) and the subtropical Atlantic differences do not persist beyond the winter (as proposed for the Atlantic Niño or SASD mechanism). We therefore focus our experiments on the South Pacific to investigate the causality of these regional conditions on interannual forecasts.

We now need to select an ensemble member to transplant conditions from with the aim of forcing the ensemble into cooler DJF2 Niño3.4 conditions. We select the ensemble member with the coolest surface temperature conditions during DJF1 averaged over the southeast Pacific (black boxes in figure 2(a)). This is a strong La Niña member with a DJF2 Niño3.4 anomaly of −1.35 K (figure 1, blue line). Transplanting conditions from this member are hereafter termed ‘La Niña’ experiments.

An opposing member is selected based on the warmest DJF1 conditions (figure 2(a), black boxes). This member exhibits a regional spatial correlation across the southeast Pacific with the La Niña member of −0.74, confirming it exhibits an opposing signal across the region of interest. This is a member with a DJF2 Niño3.4 anomaly of +1.08 K (figure 1, red line) and transplanting from it are hereafter termed ‘El Niño’ experiments.

Assessing monthly conditions (not shown) indicates that spatially coherent perturbations first appear during January 2010. We therefore perform transplanting on 1 January 2010 00:00z, two months after the forecast initialisation. Comparison of the selected La Niña and El Niño members during January 2010 (figure 2(b)) highlights cooler sea surface temperatures (SSTs) across the southeast and sub-tropical South Pacific by design. In terms of magnitude, the differences in many regions are larger than the model’s interannual variability. Whilst all members exhibit El Niño conditions during this time (DJF1), the two selected members contain a range of potential signals not only in the South Pacific.

The primary experiments involve transplanting conditions across the South Pacific (150° E–300° E, 60° S–0° N, figure 2(b)) from the selected La Niña or El Niño member into all other members on 1 January 2010. Given the large anomalies in

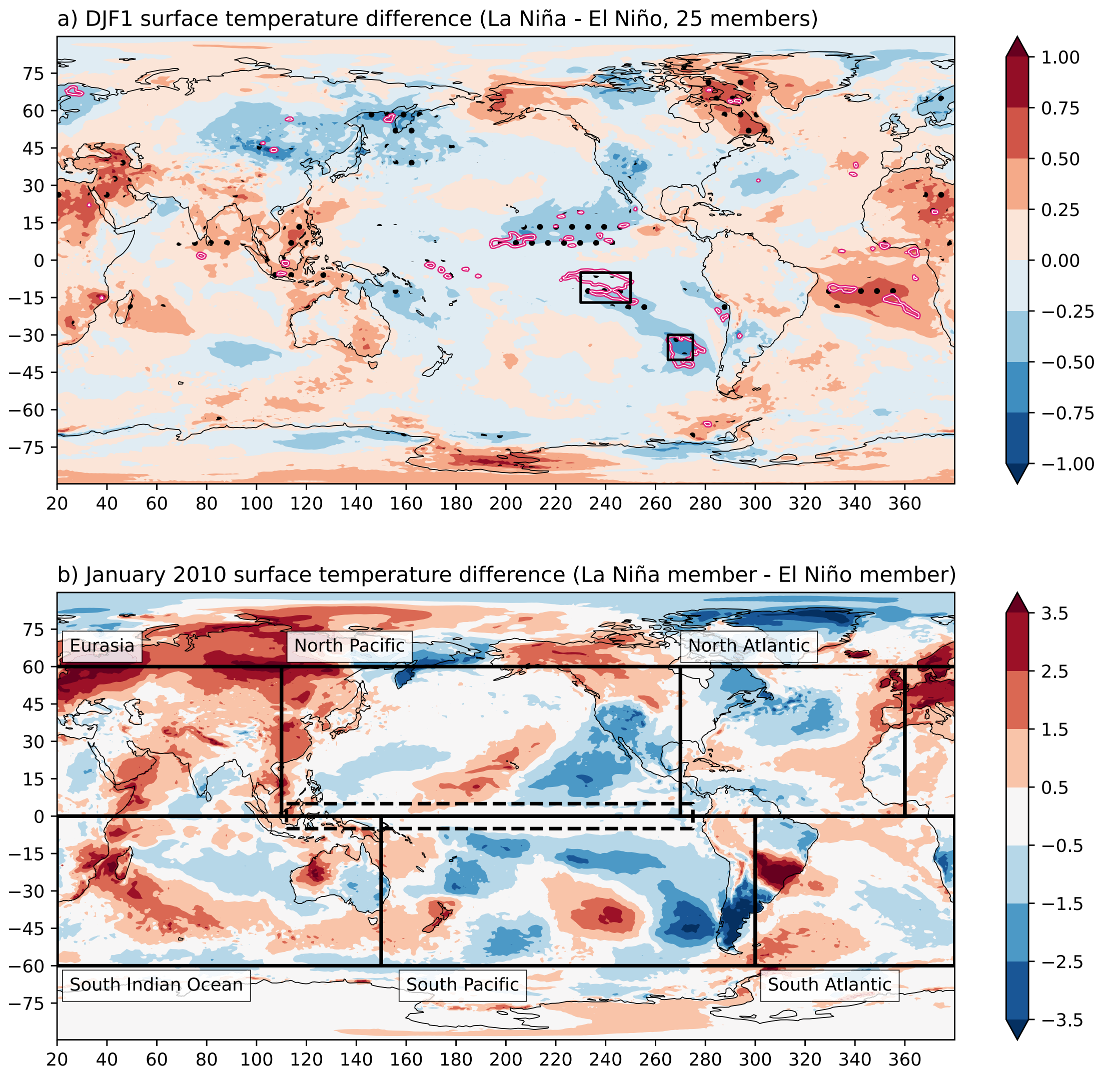

Figure 2. Surface temperature differences between members producing El Niño and La Niña one year later. (a) First winter (DJF1) surface temperature difference between 25 coolest and 25 warmest second winter (DJF2) Niño3.4 members (stippling, two-tailed T-test 95% confidence level). Units are DJF1 standard deviations (calculated across 1991–2020). Pink contours indicate where subsetting the 25 coolest and warmest DJF1 members at each location is associated with a greater than |0.5| K difference in DJF2. Black boxes show regions used to select La Niña member. (b) January 2010 surface temperature difference between the two selected members (La Niña—El Niño) in units of monthly standard deviations (calculated across all DJF1 months, 1991–2020). Regions selected for transplanting experiments are shown in black (Tropical Pacific in dashed).

other regions between these members, to test the geographic sensitivity of our results we perform additional regional experiments (figure 2(b)), defined as: North Pacific (110° E–270° E, 0° N–60° N), Tropical Pacific (5° S–5° N, 110° E–270° E), South Atlantic (60° W–20° E, 60° S–0° N), North Atlantic (90° W–0° E, 0° N–60° N), South Indian Ocean (20° E–150° E, 60° S–0° N) and Eurasia (0° E–110° E, 0° N–60° N). A 15° linear smoothing is applied to all regions to ensure stability and ensure equatorial areas are included within the transplanted conditions. All experiments are identical except for the transplanted area, allowing a direct assessment of causality. For some regional experiments, instabilities prevented one or two members (out of 50) from completing and this is accounted for within the statistical testing.

4. Results

4.1. The causality of DJF1 conditions on DJF2 ENSO forecasts

We find that transplanting South Pacific conditions from the La Niña member on 1 January 2010 significantly cools the resulting 2010/2011 winter Niño3.4 index by −0.25 K compared to the control ensemble mean (figures 3, 95% confidence level, one-tailed *T*-test). Importantly, repeating the experiment but with the El Niño member, significantly warms the forecast Niño3.4 index by 0.37 K. This demonstrates that conditions across the South Pacific prior to the spring predictability barrier can systematically impact the forecast DJF2 Niño3.4 ensemble mean index by over 0.6 K. This is very close to the model's interannual variability of 0.64 K for this lead time.

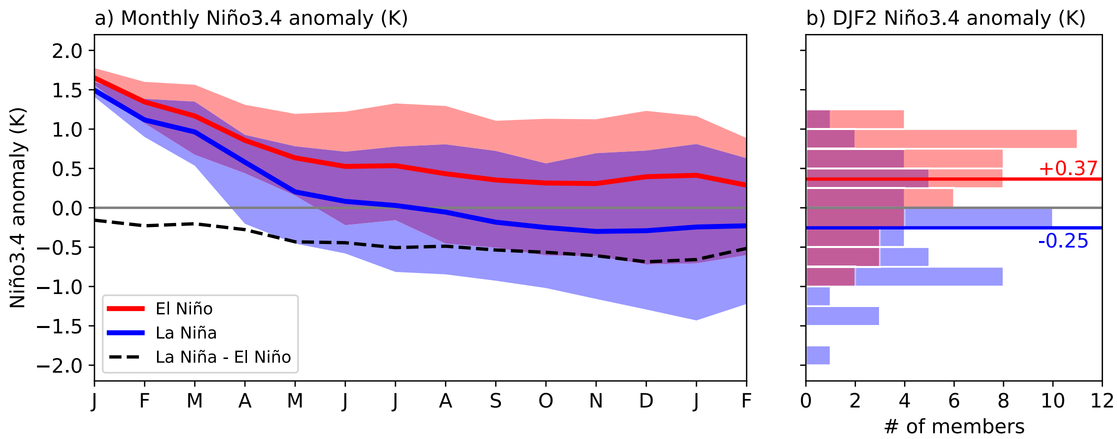

Figure 3. South Pacific conditions systematically shift the probability of El Nino and La Nina. (a) Monthly ensemble mean (solid), ensemble range (shading, 5%–95% percentile), and difference (black dash) throughout the forecast period. (b) Distribution of ensemble member DJF2 Niño3.4 anomalies within the experiments. Solid lines and numbers show the ensemble mean anomalies. The ensemble mean values are significantly different to each other (95% confidence level, two-tailed T-test) for all forecast months.

Both transplanting experiments exhibit the decay of the DJF1 El Niño conditions, however whilst the El Niño experiment's Niño3.4 ensemble mean remains positive throughout the forecast, the La Niña experiment reaches zero in early summer and continues to cool into the second half of 2010 (figure 3(a)). An initial difference of approximately −0.15 K occurs between the experiments in January 2010 and this almost doubles in magnitude during March–April–May, before continuing to increase to over −0.6 K throughout the summer and autumn (figure 3(a)). Comparing ensemble members between the experiments (figure 3(b)), we find an almost four-fold increase in the probability of DJF2 La Niña from 10% up to 38%, as well as a three-fold decrease in probability of El Niño from 47% to 15%, both of which are highly significant ($p \ll 0.001$, two proportion Z-test). These results demonstrate that the perturbations applied prior to the spring predictability barrier can drive a systematic shift between ENSO states a year in advance.

Composite analysis between these two South Pacific experiments (La Niña–El Niño) highlights the physical mechanism for this regional influence. Firstly, the transplanted ocean and atmospheric states impose a dipole of SSTs across the South Pacific, associated with an enhanced South Pacific High, and strengthened south-easterly trade winds (figure 4(a)). This pattern aligns with cool SPMM and SPQ patterns (Ding *et al* 2020), and an enhanced northern node of the SPO (You and Furtado 2017). The cool SST anomalies within the subtropics migrate north-westward into the equatorial region via the wind–evaporation–SST feedback, as proposed for the SPMM (Zhang *et al* 2014). A transect between the central equatorial Pacific and the southeast Pacific (0° N, 161° W to 30° S, 80° W, figure 4(b)) demonstrates this migration (towards the bottom left) in which strengthened winds (red contour) lead enhanced latent heat fluxes (cooling, solid grey contour) ahead of the cool SST anomalies (blue shading). The signal of cooler SSTs and enhanced south-easterly winds reach the equatorial region in late spring 2010 (figure 4(c)) where it affects the tropical zonal gradients. The 20 ° C thermocline deepens in the western tropical Pacific and shoals in the east, and easterly wind anomalies develop over the central Pacific (figures 4(c) and (d)). The easterly wind anomalies appear to initiate Rossby waves (figure 4(d), red shading, line B) which travel westward with a phase speed of approximately 0.3 m s^{-1}, in line with observations (Chelton and Schlax 1996), providing a positive feedback on the transplanted signal. These changes in the tropical Pacific drive the ensemble away from an El Niño state and towards La Niña for winter 2010/2011.

The tropical time-longitude profiles (figures 4(c) and (d)) exhibit significant wind and thermocline differences during January to March 2010. These resemble eastward propagating Kelvin waves driven by strong wind anomalies in the central Pacific (figure 4(c), line A), which potentially reflect off the eastern boundary and contribute to the signal. In addition, the Niño3.4 index is found to be persistently cooler from January 2010 within the La Niña experiment (figure 3(a)). Perhaps therefore, it is the transplanted January 2010 equatorial state which is driving the DJF2 interannual response? This does not appear to be the case because transplanting the Tropical Pacific region does not significantly change the DJF2 Niño3.4 (figure 5). This regional sensitivity provides evidence that the key signal within our results, which were selected based on conditions across the South Pacific, originates in the extratropical South

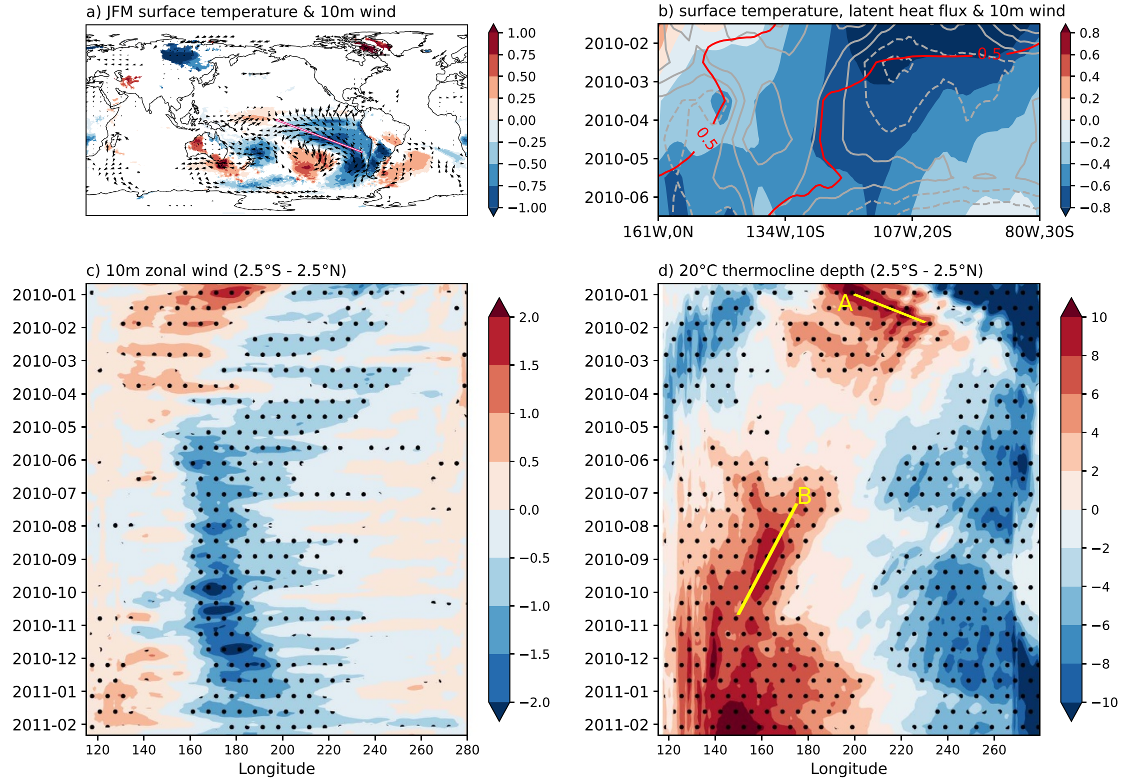

Figure 4. Impact of transplanting South Pacific regional climate on interannual forecasts (La Niña–El Niño experiments). (a) Significant differences (95% level, two-tailed T-test) in surface temperature (k, shading) and wind speed (arrows), January–March 2010. (b) Differences in monthly surface temperature (k, shading), wind speed (0.5 ms^{-1}, red contour) and latent heat flux (units of 5 Wm^{-2}, grey contours) as a function of time along a transect between 30° S, 80° W and 0° N, 161° W (pink line in a). (c) Rolling 10 d tropical (2.5° S to 2.5° N) differences in 10 m zonal wind speed (ms^{-1}, stippling indicates significance at 95% confidence level, two-tailed T-test). (d) as (c) but for 20 ° C thermocline depth (m). Note that time increases downwards. Line A is representative of an eastward traveling wave at 2 ms^{-1}, and line B a westward travelling wave at 0.3 ms^{-1}.

Pacific and has minimal dependence on the equatorial state in January 2010.

Repeating the South Pacific experiments but transplanting only ocean conditions provides very similar response in the ensemble to when the atmosphere is also transplanted. The DJF2 Niño3.4 difference is greater than 0.5 K (significant at the 95% confidence level, two-tailed T-test), however the El Niño experiment is no longer significantly warmer than the control. Comparison of the composite differences (not shown) indicates very similar spatial anomalies to those seen when also transplanting the atmosphere, but of slightly smaller magnitudes. This indicates that the ocean is the primary source of the important perturbations, but with the atmospheric perturbation also amplifying the signal.

To additionally demonstrate the importance of the South Pacific we assess the geographic sensitivity of the transplanting results with the regions shown in figure 2. Repeating the experiments for other areas (figure 5) found that no other regional perturbations could drive significant cooling or warming of the ensemble when using the selected La Niña or El Niño member respectively. This provides further evidence that the South Pacific is the key source of the signal for our results. Interestingly, transplanting the global conditions (60° S–60° N) provides an additional cooling compared to the South Pacific region for the La Niña case, but no warming when transplanting from the El Niño member. Regional conditions may therefore act constructively or destructively within the forecasts, highlighting the need for dynamical model experiments.

4.2. Impacts on the global climate during 2010

ENSO is a driver of the global climate, influencing the global mean annual temperature by up to ±0.2 K (Trenberth *et al* 2002) with strong El Niño events often followed by new temperature records (Dunstone *et al* 2024, Raghuraman *et al* 2024). In our experiments we find that transplanting the South Pacific region on 1st January can cool the predicted global annual mean surface temperature for 2010 by 0.067 K, which is highly significant ($p \ll 0.001$, two-tailed T-test) and larger than the control ensemble's standard deviation of 0.05 K. This relative cooling also reflects a more accurate prediction for 2010, bringing the predicted anomaly down from 0.21 K to 0.15 K and closer to the ERA5 anomaly of 0.13 K. The regional perturbations identified therefore not

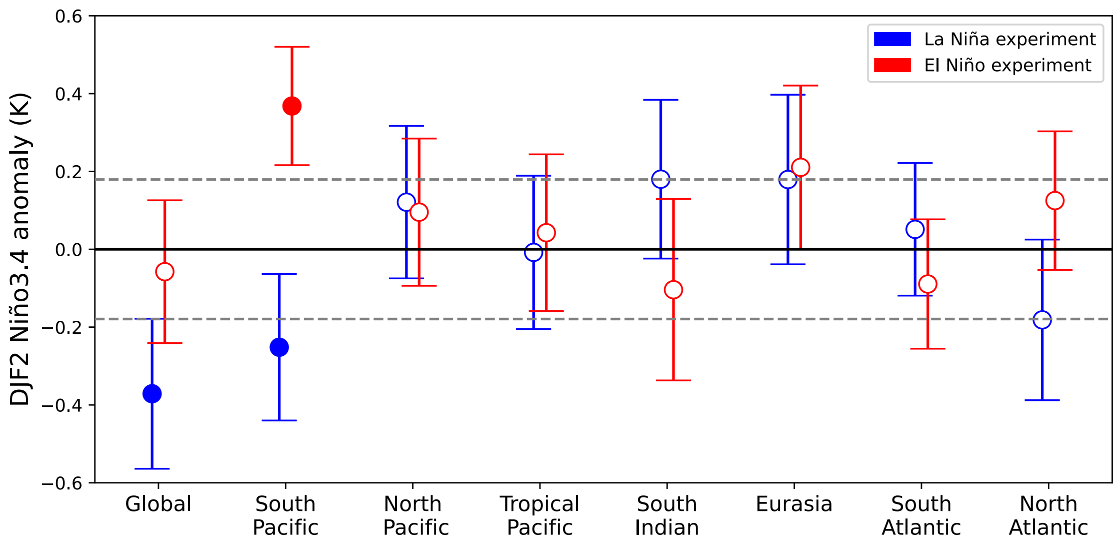

Figure 5. Sensitivity of ENSO to conditions around the globe. Second winter (DJF2) ensemble mean Niño3.4 regional transplanting results are shown as anomalies from the control ensemble. Circles show the La Niña (blue) and El Niño (red) experiments and filled circles indicate significant cooling/warming (one-tailed T-test, 95% confidence). Error bars and dashed grey lines show ±1.96 standard error. Note that only the South Pacific experiment significantly warms and cools the DJF2 Niño3.4 index.

only influence the transition of the tropical Pacific throughout 2010 but also affect the forecast of a key metric for monitoring and informing international climate policy (Smith *et al* 2018, Betts *et al* 2023).

At the regional scale, ENSO variability exerts a significant influence on the climate across many parts of the world. Within our South Pacific experiments, composite differences of the La Niña–El Niño DJF2 surface temperature and precipitation (figure 6) also exhibit significant regional differences. In particular, the shift towards La Niña is associated with wetter conditions across the western Pacific, southern Africa and the Amazon basin, and much drier conditions across eastern Africa, southern South America and the Caribbean. There is also a large-scale cooling signal across much of the tropics and southern hemisphere land. These differences align well with canonical ENSO teleconnections (Taschetto *et al* 2020) and are generally closer to the observed ERA5 anomalies for DJF2 (figure 7), representing a widespread improvement of the forecast. Weaker signals are found across the northern hemisphere, possibly due to the smaller change in Niño3.4 between our experiments (∼0.6 K) compared to observed ENSO events (typically >2 K). Nevertheless, by increasing the probability of tipping the tropical Pacific into a La Niña state, the regional perturbations in the South Pacific are able to influence the chances of regional climate conditions across many parts of the world over a year in advance.

As a final part of understanding the impact of the identified regional perturbations we assess the change in ensemble mean forecast skill between the La Niña and El Niño South Pacific experiments. Comparison of the absolute error for surface temperature to ERA5 (figure 7) highlights a persistent improvement in forecast skill for the South Pacific. This is partly due to the experimental design in that the selected La Niña member exhibits reduced error for the South Pacific, however it is encouraging to see that this signal persists throughout the entire period. Forecast skill is largely unchanged for other regions during summer 2010 (figure 7(a)). By DJF2 (figure 7(b)) the forecast is found to have improved across many regions including central and southern Africa, South America and Eurasia. The relative decrease in skill in the western tropical Pacific around 160E is due to the developing La Niña not extending as far westwards as it does ERA5. Nevertheless, tipping more members into La Niña conditions drives improved long-range predictions across the globe for this case study.

Given this relationship between reduced errors during DJF1 and DJF2 we briefly explored weighting members within the control ensemble by their regional RMSE over the South Pacific during DJF1. This did not however improve the forecast skill at longer lead times or significantly alter the DJF2 Niño3.4. The enhanced skill over the wider South Pacific therefore appears to be a characteristic, and not a driver, of the improved ENSO forecasts.

5. Discussion and conclusions

Focusing on the transition from El Niño to La Niña during 2010, we identified important perturbations across the South Pacific and demonstrated how they can systematically impact the ensemble forecast one year later. To the best of our knowledge this is the first

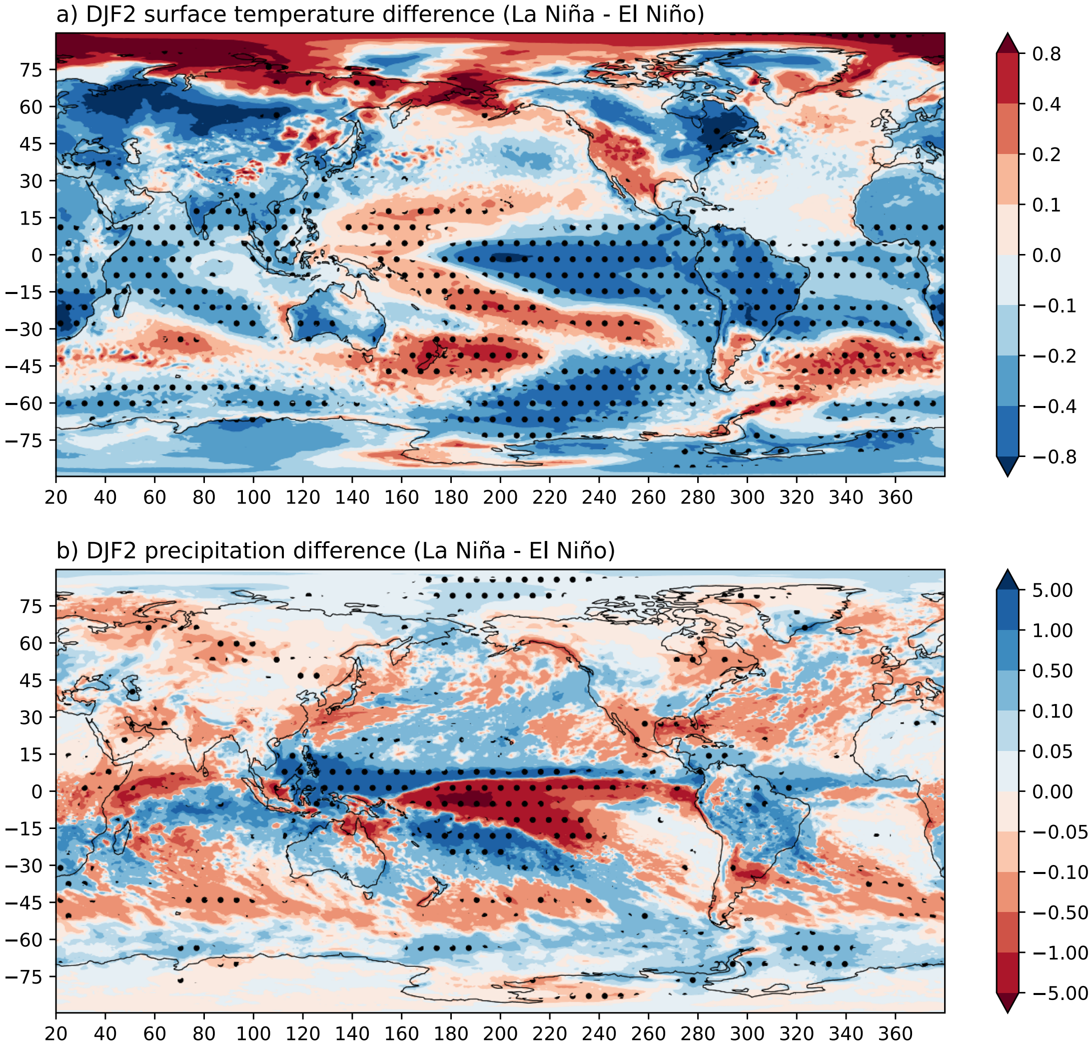

Figure 6. Impacts of South Pacific perturbations on global climate one year later. Change in DJF2 surface temperature (a) and precipitation (b) between the South Pacific transplanting experiments (La Niña–El Niño). Stippling indicates a significant difference based on a two-tailed t-test (95% confidence level). Units are (a) K and (b) mm. Note that both colour scales are nonlinear.

demonstration of the causality of regional perturbations within an ensemble forecasting system at interannual timescales.

Resembling an SPMM-like pattern (Zhang *et al* 2014), extratropical anomalies reach the equatorial region during the early summer months, altering tropical zonal gradients and increasing the chances of tipping the tropical Pacific into a La Niña state almost four-fold. A series of experiments confirms the important perturbations originate in the South Pacific, however it is important to note that these are based on ensemble members selected for their differences found across the South Pacific. We do not specifically assess potential perturbations across other regions in relation to this La Niña event, such as the Indian and Atlantic basins as highlighted within our ensemble (figure 2(a)) and idealised experiments (Luo *et al* 2017). Due to the global influence of ENSO, the transplanted South Pacific perturbations are found to drive significantly different climate conditions across multiple regions in better agreement with observations and even modify the global mean annual surface temperature. This reveals a high sensitivity of the global climate to regional conditions a year in advance.

We find an almost four-fold increase in the probability of La Niña as well as a three-fold decrease in the probability of El Niño, demonstrating the perturbations can tip the tropical Pacific between ENSO states. Importantly these perturbations are not idealised and develop naturally within the model, ensuring physical consistency, and they occur prior to the spring predictability barrier. These results show that the long-range predictability of ENSO is not merely due to the oscillatory nature of the tropical Pacific or the initial conditions (Lenssen *et al* 2024), and raises several interesting questions for further investigation: How often do such regional perturbations develop? Do they influence other ENSO events? How do they interact with each other? And,

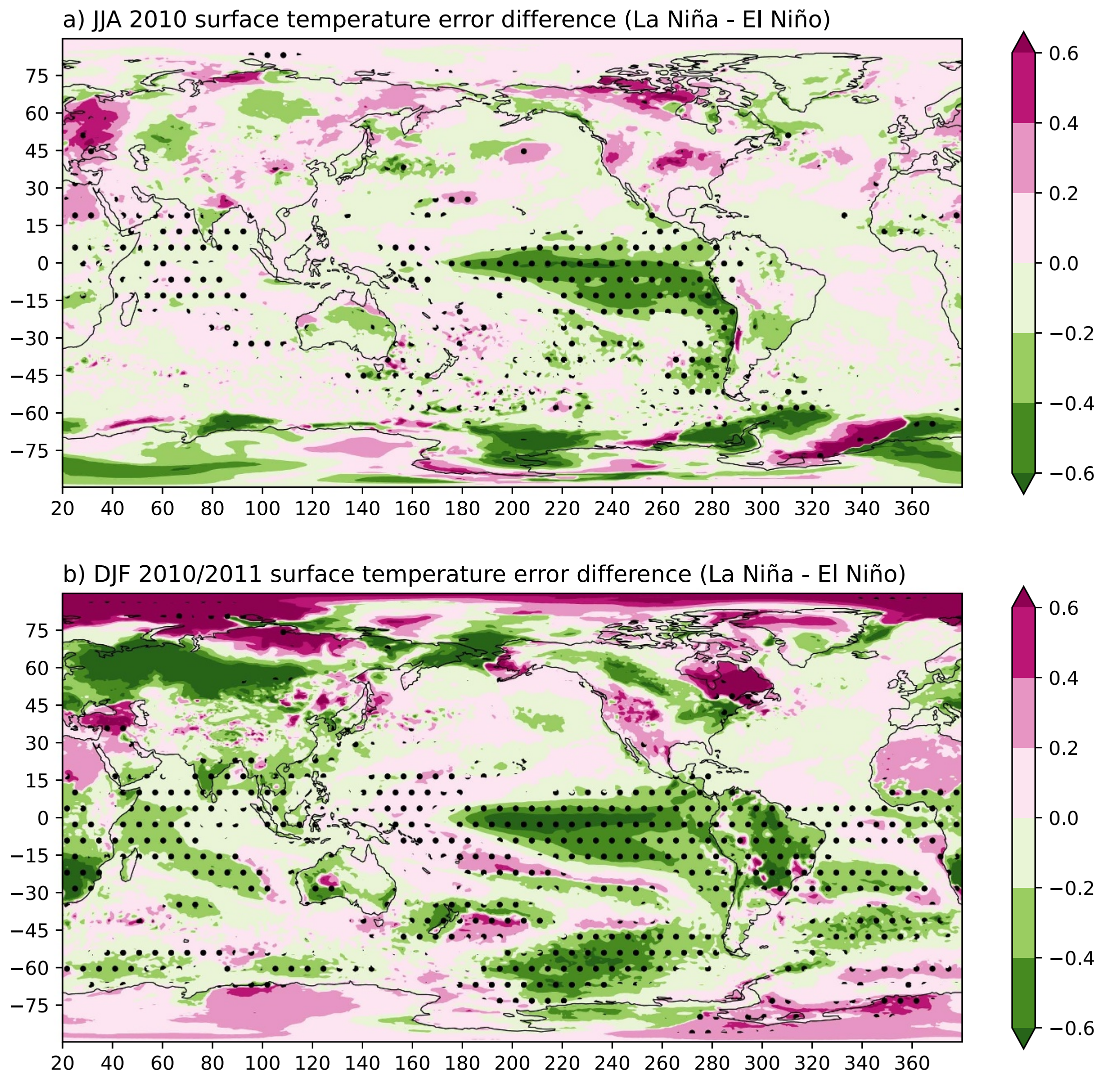

Figure 7. Improved interannual forecasts due to transplanting the South Pacific region in January 2010. Shading shows the difference in ensemble mean surface temperature absolute error to ERA5 for the La Niña minus El Niño experiments in JJA 2010 (a) and DJF 2010/2011 (b). Units are K. Stippling indicates where the ensemble mean surface temperatures are significantly different (95% level, two-tailed T-test). Green colours indicate improved forecasts when compared to ERA5.

at what lead times can they still exert a significant impact on the ensemble? Our initial assessment (figure 2) highlighted several regional signals that could be explored in further experiments. The methodology also raises the prospect for targeted observations, or focused model development, in regions identified as significant drivers of ENSO transition as well as driving ensemble forecasts to better explore extreme cases (e.g. 'ensemble boosting', Gessner *et al* 2021). In addition, experiments in which regionally modified observed conditions are transplanted could also enable improved understanding of the sensitivity of interannual forecasts to the strength of specific regional anomalies.

These new insights are of high relevance for interannual forecasting due to the infrequent initialization compared to seasonal or sub-seasonal systems. In line with previous studies on precursor signals (e.g. Larson and Kirtman 2014) our study highlights the importance of DJF1 conditions within interannual forecasts and opens potentially new avenues to explore including the identification and causality of important regional anomalies, as well as post-event analysis studies. Overall, this study has revealed the high sensitivity of the global climate to regional conditions on interannual timescales and highlights the need for future dynamical model experiments in understanding causality within the climate system.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/records/14779094 (Kent 2025).

Acknowledgment

This work was supported by the Met Office Academic Partnership (MOAP) and the Met Office Hadley Centre Climate Programme (HCCP), funded by the UK Department for Science, Innovation and Technology (DSIT).

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