CLIVAR Ocean and Climate: Variability, Predictability and change is the World Climate Research Programme's core project on the Ocean-Atmosphere System.
Editorial

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The interaction among the tropical ocean basins has received increased attention in recent years. While El Niño Southern Oscillation (ENSO) in the tropical Pacific has long been understood to have global impacts, there has been growing recognition that the Atlantic and Indian Ocean basins feature variability patterns and feedbacks, some of which are partially independent of ENSO, that have the potential to influence ENSO.

While progress has been made in understanding and quantifying the interaction among the tropical basins, much remains to be learned. This was the motivation for forming the CLIVAR Research Focus (RF) on Tropical Basin Interaction (TBI) in March 2020. One of the first agenda items of the RF TBI was to hold a workshop to energize the community, consolidate knowledge and chart the way forward. The emerging pandemic delayed the workshop planning, and eventually the decision was made to move to an online format. While this allowed a wider pool of researchers to participate in the workshop, it also brought many logistic challenges, including how to accommodate an audience that spanned essentially all time zones. The workshop was held February 24-26 and received a lot of positive feedback (see the article by Jose Santos for details about the participants’ feedback). The present Special Edition of CLIVAR Exchanges summarizes the outcomes of the workshop (Richter and Keenlyside), describes the logistic challenges and lessons learned from the workshop (Santos and Li), and highlights eleven research contributions that were presented at the workshop.

In holding this workshop, we received generous financial support from NOAA and NSF, and logistical support from the US CLIVAR Project Office and the University Corporation for Atmospheric Research (UCAR). We (Noel and I) would particularly like to thank Mike Patterson (US CLIVAR) for coordinating the planning efforts and keeping us all on track, Tammy Kepple (UCAR) and Heidi Allen (UCAR) for their tireless support in the planning and holding of the event, Paul Martinez (UCAR) and Brett Batterman (UCAR) for their excellent technical support, and Jennie Zhu (US CLIVAR) for taking care of many important details, including housekeeping information at the beginning of each day. And, of course, we would like to thank Jose Santos as well as his assistants, Jing Li, Liping Yin and Qian Zhao, for their excellent support of the RF in general and their tremendous effort to make this workshop happen. Finally, we would like to thank all the members of the workshop organizing committee (Michael McPhaden, Yuko Okumura, Chunzai Wang, Ping Chang, Malte Stuecker, and Andrea Taschetto) and all the members of the RF TBI for helping with the organization of the workshop and for chairing many of the discussion sessions.

The CLIVAR RF on Tropical Basin Interaction is still in its early days. We hope the workshop made a useful contribution to invigorating research on tropical basin interaction, and are looking forward to further contributing to this exciting research topic.

Ingo and Noel
1. Introduction

The CLIVAR Research Focus (RF) on Tropical Basin Interaction (TBI) was launched in March 2020. Its goals are to stimulate and foster research activities that elucidate the mechanisms and pathways by which the tropical ocean basins influence each other, with a focus on interannual variability. In the 1970s and 1980s many research efforts focused on El Niño Southern Oscillation (ENSO) and its global impacts (e.g. McCreary 1976; Held et al. 1989). From the 1990s, there was a growing recognition that the tropical Atlantic and Indian Ocean were home to interannual variability patterns that were at least partially independent of ENSO. Examples of such variability patterns are the Atlantic meridional mode (e.g. Chang et al. 1997; Amaya et al. 2017), the Atlantic zonal mode (e.g. Zebiak 1993; Keenlyside and Latif 2007; Richter and Tokinaga 2021), the Indian Ocean basin mode (e.g. Xie et al. 2002), and the Indian Ocean dipole (e.g. Saji et al. 1999). From the 2000s onward there was increasing interest in how these modes of variability might impact other regions of the world, including ENSO (e.g., Chang et al. 2006; Kug and Kang 2006; Rodriguez-Fonseca et al. 2009; Luo et al. 2010; Ham et al. 2013). While our understanding of the interaction among the tropical basins has improved, much work remains to be done to understand the ocean and atmospheric pathways of TBI, to quantify the impacts of individual pathways, and to evaluate the importance of TBI for sub-seasonal-to-decadal prediction (Cai et al. 2019; Wang et al. 2019; Keenlyside et al. 2020). This was the motivation behind the inception of RF TBI.

One of the first goals of RF TBI was to hold a workshop that would summarize the current understanding of TBI and chart the way forward. This workshop was held in February 2021 and is the focus of this special edition of CLIVAR Exchanges. The first two days of the workshop were devoted to summarizing current understanding of TBI, while on day three, key future research areas were discussed in four working groups (WGs) with the following themes:

1) Design of global climate model (GCM) sensitivity experiments to elucidate the pathways of TBI and its importance to seasonal prediction (WG1)
2) Theoretical approaches and intermediate complexity models (WG2)
3) Optimal use of existing observations and identification of new observations crucial to the understanding of TBI (WG3)
4) Role of paleo proxies in understanding TBI (WG4)

In sections 2-5 we summarize the outcomes of the workshop, following the themes outlined above. In section 6 we present an overall summary and concluding remarks.

2. Results from Working Group 1: GCM experiments

2.1 Background

While recent decades have seen progress in understanding the importance of basin interaction to the climate system, there remains much to be understood. This includes an evaluation of the importance of TBI to seasonal forecasts. Of vital interest in its own right, such an evaluation would also allow quantifying the impacts of TBI and could shed new light on the pathways and directions of remote linkages. A few studies have addressed the role of TBI in seasonal forecasts (Luo et al. 2010; Keenlyside et al. 2013; Zhou et al. 2019; Exarchou et al. 2021; see also Exarchou et al. in this special edition). These, however, have focused on sensitivity experiments with a single model and used different experimental protocols. The disparity of experimental approaches makes it difficult to compare results. Moreover, experiments using a single model do not allow assessing the robustness of the outcomes and to evaluate the influence of model biases on the simulated remote linkages. Recognizing these difficulties, the RF TBI has made coordinated multi-model experiments one of its main targets. Such coordinated experiments would facilitate intercomparison across models and help build a consensus on the mechanisms and importance of TBI. In particular, hindcast experiments with sea surface temperature (SST) restoring to observations in selected tropical ocean basins (pacemaker hindcasts, hereafter) were identified as a central tool for examining the benefit of remote influences on prediction skill. More details on the experiments and their rationale can be found in the full proposal of the RF TBI, downloadable from http://www.clivar.org/
2.2 Outcomes from the workshop

Discussions during the workshop again highlighted the need for a better understanding and quantification of TBI influences on seasonal prediction. Results in the published literature disagree on the patterns and strength of TBI, which could be due to differences in experiment design, model biases, study period, or any combination of these factors. Thus, there is a need to conduct sensitivity experiments with diverse GCMs following the same experimental protocol.

The relatively poor prediction of the 2015/2016 El Niño event (McPhaden 2015) was brought up as one particular case in which a deeper understanding of TBI might have led to better prediction outcomes. While there is no consensus on whether TBI was crucial to the unexpected evolution of the event, it might serve as an important test case for prediction sensitivity experiments.

Discussions during the workshop identified several considerations and caveats regarding the planned coordinated experiments. First, there was some disagreement on which experiments to prioritize. While the original plan of the RF TBI was to prioritize pacemaker hindcasts, some participants suggested that standard pacemaker experiments should be conducted first. In addition to being more easily coordinated and conducted, these pacemaker experiments, it was argued, would allow to better understand the basic mechanisms and formulate specific hypotheses to be addressed by pacemaker hindcasts. More discussion will be needed to agree on the priority of experiments. The success of the coordinated experiments depends on the participation of a sufficiently large number of modeling groups. It is therefore important to ensure a low entry threshold by identifying a limited number of mandatory core experiments with relatively small computational burden. To this end, a three-tiered structure is desirable, with the core experiments as tier 1, and further experiments in tiers 2 and 3 (Fig. 1). In addition, it would be desirable to allow some flexibility in the experimental protocol so that participating groups could, for example, use existing hindcasts as their control experiment, as opposed to insisting on a specific initialization procedure that would probably necessitate rerunning hindcast experiments. Obviously, there is a fine balance between this kind of flexibility and the intercomparability of the model output.

Even though we will strive to minimize the computational burden for participating in the intercomparison project, it is clear that substantial resources will be needed. To ensure efficient use of these resources it will be prudent to thoroughly assess the feasibility and usefulness of the proposed experiments before the start of the project. This could be achieved through a pilot project, in which one group completes the proposed experiments to identify potential problems. Having a completed set of experiments would also be instrumental in promoting the coordinated experiments to modeling groups and centers, and to increase “buy-in”.

Figure 1. Basic structure of the three-tiered experiment design. Tier 1 contains the core experiments that all participating groups are expected to perform. These experiments serve to understand the basic mechanisms of TBI, their robustness across models, and the potential benefits of TBI to seasonal prediction. Tier 2 features additional experiments that address specific questions, such as the influence of model biases on the simulation of TBI. Tier 3 will be used for experiments that will address additional questions that emerge from the experiments in tiers 1 and 2. The specific examples are only meant to illustrate the 3-tiered approach. The exact content of each tier will be decided after consultation with participating groups.

3. Results from Working Group 2: Theoretical approaches and intermediate complexity models

The development of a model hierarchy is an essential aspect to understanding the climate system (Held 2005). At the top are the high-resolution Earth system models that aim to represent as realistically as possible the climate system, while at the bottom are conceptual models that distill aspects of complex dynamics to an understandable level. Intermediate complexity models (ICM) provide a seamless and necessary transition from complex models to conceptual understanding.

Currently there exists a very limited model hierarchy for TBI. While GCMs have been extensively used to study TBI, only a few studies have employed conceptual or intermediate complexity models. For example, a conceptual model with three connected recharge-oscillators representing the three tropical basins has shown key differences between Atlantic and Indian Ocean influences on ENSO (Jansen et al. 2008). Examples of ICMs include a reduced complexity atmospheric GCM coupled to a reduced gravity ocean model that first identified the dynamics underlying the impact of the Atlantic Niño on ENSO (Rodriguez-Fonseca et al. 2009); or an AGCM coupled to a slab ocean model augmented with a recharge-oscillator representation of ENSO in the Pacific, which was used to show how the tropical Atlantic and Indian Ocean can act as delayed negative feedbacks to ENSO (Dommenget and Yu, 2017).
A clear outcome of the workshop has been identifying the need for building a model hierarchy to understand TBI. The need to develop conceptual models and ICMs that are largely missing in the hierarchy was stressed. These models can provide theoretical understanding for the pathways, predictability and modulation of TBI, as well as its sensitivity to the background state and its role in climate change.

While Jansen et al.’s (2009) conceptual model provides a good starting point, it should be extended by adding other patterns of climate variability. For example, the Central Pacific Niño, Indian Ocean Basin Mode, Atlantic Meridional Mode, and extra-tropical patterns could be included. Key atmospheric and oceanic pathway linking these patterns should be represented, as should be dynamic and thermodynamic ocean-atmosphere interactions. It will also be useful to account for the possible modulation of TBI by longer-term patterns of climate variability, such as the Atlantic Multidecadal Variability, or climate change. Here, modern data analysis techniques provide a powerful means to disentangle interactions (Di Capua et al. 2020). Lack of data can be mitigated through learning from GCM output (Ham et al. 2019). Filter techniques and EOF analysis are needed to identify modes.

It was argued that a new class of ICM is needed that is an extension of the Cane and Zebiak (CZ) model (Zebiak and Cane, 1987) for the tropical Pacific to include all three tropical ocean basins. The ocean component could be based on a reduced gravity model to represent the dynamics and simplified SST equations to represent the thermodynamics, as in the original CZ model. The atmospheric model could be a moist linear baroclinic model that would extend the Gill-Matsuno formulation of the CZ model to include moist dynamics (Hayashi and Watanabe, 2017), or a Quasi-equilibrium Tropical Circulation Model (Neelin and Zeng 2000). This class of ICM is essential for developing conceptual models and for building a theory of TBI. It will allow to explore several poorly understood aspects (Fig. 2): the atmospheric bridge, the atmospheric sensitivity to the ocean, and the oceanic sensitivity to the atmosphere. It will allow to pick apart the atmospheric and oceanic pathways, the role of dynamic versus thermodynamic coupling, the impact of model biases, as well as the influence of the background state and therefore the modulation of TBI by low frequency variability and climate change.

**Figure 2.** Schematic of the three tropical ocean basins and the processes linking them.

In addition, developing models with more complex ocean or atmospheric components would help bridge the gap between CZ-type ICMs and GCMs. For example, the SPEEDY-AGCM has been coupled to a variety of ocean models and provides a computationally efficient alternative to full GCMs while offering many of their features (Rodriguez-Fonseca et al. 2009; Kucharski et al. 2016). This model could be used to perform large ensembles of pacemaker experiments to better assess signal-to-noise issues. It would be particularly useful in understanding extra-tropical influences on TBI.

### 4. Results from Working Group 3: Observations

The discussions of WG3 examined various issues regarding the role of observations in understanding TBI.

The limitations of currently available observations were discussed. Considering that TBI includes decadal and longer time scales, the roughly 150-year instrumental record is relatively short. Moreover, data quality is relatively low before the 1950s, due to data sparsity and changes in measurement techniques, among others. Records of the subsurface ocean are even shorter, with many long-term measurements limited to surface variables like SST. Several regions remain under-observed, including the Southern Ocean, the Indonesian Through Flow (ITF), and coastal upwelling zones. Century-long reanalyses can help extend the data records but are ultimately also limited by insufficient observational constraints. Several international observing systems exist (e.g. TPOS, TAOS, AtlantOS, IndOOS) and provide valuable services but do not consider transbasin interactions. Therefore, more communication between observing groups, modelers, and reanalysis groups would be desirable. Several actions items were recommended:

(i) An assessment of the decadal reviews of the tropical observing systems (TPOS review, TAOS review, IndOOS review) from a TBI perspective could identify opportunities for cooperation and potential gaps that need to be addressed. This could be a first step toward an integrated pan-tropical (or global) observing system and data archive. Such ideas should be presented at the upcoming CLIVAR Workshop on Ocean Observing Systems.

(ii) More interactions between instrumental, paleo, and modeling communities would allow identifying targets for rapid improvement. Modelers, e.g., can point to specific regions that are crucial for TBI and should be targeted by measurement campaigns.

(iii) Enhanced data sharing was seen as an essential tool. This would be particularly valuable in coastal regions, where extensive data records often exist but are not accessible to the scientific community. The United Nations (UN) Ocean Decade may provide opportunities for increasing data sharing.

(iv) The Global Ocean Observing System (GOOS)
must be continued and, if possible, expanded. GOOS is essential for extending coordinated observational activities into the future.

(v) Artificial Intelligence and Machine Learning may open new avenues for extracting additional information from existing data sets (see section 3 of this article).

(vi) Data archaeology may be useful in enhancing and extending existing data records.

(vii) One could envision future field campaigns to address key hypotheses and processes in TBI hotspots. On the atmospheric side, an example of a potential candidate would be the Central American isthmus, as it is a key region that regulates the export of atmospheric moisture from the Atlantic toward the Pacific region. On the oceanic side, the ITF is vital in regulating water mass exchanges between the tropical Pacific and Indian Oceans.

While the RF TBI certainly does not have the resources to address all the above action items, it should endeavor to raise awareness of these issues and to foster activities that address them.

5. Results from Working Group 4:
Paleo data

Paleo climate data are essential to understanding TBI, complementing models and instrumental observations to provide key information on past TBI. Such information is important as models suffer from biases and sensitivity tests are always subject to some degree of inconsistency, while instrumental data are too short to disentangle factors modulating TBI. In particular, long-lived marine biota, such as tropical corals, bivalve mollusks, and coralline algae, provide annually resolved, well-dated climate reconstructions of SST prior to the instrumental era (e.g., Tierney et al. 2015; Black et al., 2019; Gillikin et al., 2019). Many of these data are available through the PAGES2K archive (Emile-Geay et al., 2017). Seasonally resolved corals from the Pacific have been shown to capture ENSO diversity (Freund et al. 2019). Corals have also been used to study interactions between ENSO and the Indian Ocean (Timm et al. 2005), and have shown that a tight IOD-ENSO coupling has existed during the last millennium (Abram et al. 2020). Multi-proxy reconstructions of Atlantic multi-decadal variability could similarly be used to study interannual variability and its modulation (Svendsen et al. 2014; Martín-Rey et al. 2014; Yu et al. 2014).

Paleo climate data can help address many key science questions regarding TBI. These include understanding longer timescales of TBI, such as AMV interactions with Pacific Decadal Variability (PDV), and the role of slowly evolving oceanic processes, such as the Indonesian Throughflow. A crucial question is also how AMV, PDV and other low-frequency climate variations modulate TBI on shorter time scales (Martín-Rey et al., 2014; Yu et al., 2014). Paleo data can help understand how climate change will influence TBI (Jia et al. 2019), through better quantification of external influences on TBI. It can also help assess uncertainties in early observations (before the 1950s).

The workshop identified several key gaps and challenges. There is a lack of communication between climate dynamics and paleo communities. The climate dynamics community needs to know the strengths and limitations of paleo proxies, while the paleo community needs to know the most pressing TBI science questions/hypotheses. The geographic coverage of proxies is very limited in the tropical Atlantic and in the eastern and central IO. For example, there are no paleo-proxies of the Atlantic Niño. There is also limited temporal coverage of proxies, particularly tropical corals, before ~1800. There are issues with data archiving and accessibility that are being addressed by PAGES 2k, but overall, there is a lack of funding and institutional support for data management. Isotope observations needed for better understanding and calibration of proxies are lacking. There are also some important challenges with proxy data, including the non-stationarity of teleconnections and the signal-to-noise ratio.

Several actions were recommended by the workshop. (1) Collaboration and communication must be improved between climate dynamics and paleo communities. This could be achieved through WCRP by creating incentives, by formulating key questions and hypotheses for TBI research, by raising awareness of the availability and interpretation of paleo climate data, and by curating centralized information sources (e.g., data guides, intro videos, blogs, discussion fora). (2) Observations, data archiving, and research tools are needed to link existing paleo databases and increase accessibility to the climate dynamics community. (3) There is a need to identify unexplored “supersites” (key locations) relevant to the key science questions, and to explore untapped potential (e.g., individual foram analyses, bivalves, fossil corals). However, there must be funding for dedicated data stewards (rather than relying on volunteers) and isotope observing networks (TPOS2020) and the development of isotope-enabled models (as pursued by the US CLIVAR Water isotopes WG). (4) In terms of research, there should be greater use of existing paleo data and data assimilation products, as well as analysis tools; models should be used to identify locations for new samples, taking into consideration model biases and site accessibility; proxy data should be used in combination with models, observations, and machine learning; and there should be joint data assimilation of early instrumental and paleo data to produce improved paleo climate reanalyses.

6. Overall summary and concluding remarks

The WCRP-CLIVAR Workshop on Climate Interactions among the Tropical Basins summarized the current understanding of TBI and provided an update on recent research efforts, some of which
are featured in this Special Edition. The discussions among participants identified knowledge gaps and potential avenues of addressing them. Some of the key challenges that lie ahead are:

1) coordinated GCM experiments to obtain a consensus on the strength and pathways of TBI, and to assess the influence of model biases

2) a hierarchy of numerical models, from conceptual to Earth system models, to gain a deeper understanding of the processes and pathways of TBI, and to obtain statistical robustness at a high significance level

3) strengthened communication between the climate dynamics and paleo proxy communities to ensure optimal use of existing proxy data and to identify key geographic reasons for future paleo reconstructions

The above are just a few examples of the challenges and issues identified at the workshop. While the RF TBI certainly cannot address all of them, it will endeavor to pursue some of them. One of the key issues identified was bridging the gap between communities. Addressing this issue will be a high priority, and future activities of the RF, such as summer schools and workshops, will strive to facilitate communication across disciplines.

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Overview
The WCRP-CLIVAR Workshop on “Climate Interactions Among the Tropical Basins”, held from 24th to 26th February 2021, was the first major scientific event organized by CLIVAR that was completely online. After the face-to-face meeting was postponed by several months due to the COVID-19 pandemic, the organizers felt that it was necessary to move on and adapt to the new situation.

One of the key activities of the ICPO is the organization of workshops, meetings, training courses, conferences and other events, which are held not only in Qingdao but in many places around the world. These events aim to help build teams, formulate projects, engage stakeholders, share information, launch initiatives, synthesize lessons, coordinate and plan activities, etc.

When the pandemic led to lockdowns around the world, it was apparent that the difficulties of international travel would persist for quite some time. Thus, it was necessary to test some new approaches, including migration toward digital formats. This required not only testing new digital tools and platforms, but also opening our minds to a whole new way of working. Since online formats help reduce the carbon footprint of travel and allow for wider international participation, they will most likely continue long after the pandemic restrictions end.

Even with face-to-face meetings, it is important to organize events such that they are engaging and facilitate attaining the meeting objectives. This becomes even more crucial for online events. Thus, the planning process should consider many factors, such as ensuring that the planned activities attract and energize the participants, and that the agenda combines information sharing with interaction among participants, thereby encouraging contributions from everyone and fostering relationships among participants through joint conversations and activities. Meeting these objectives requires a mix of formats.

Challenges and lessons learned
For the TBI workshop, the first challenge was to set up meeting times that were workable for everybody involved. The over 200 registered participants came from 30 countries around the world, thus covering practically all time zones (see Figure 1).

The workshop was conducted over a three-day period. The first two days consisted of four plenary talks, using webex (www.webex.com) as the main platform, two poster sessions (using app.virtualpostersession.org) and a 90-minute discussion each day (using webex and slack.com). Recordings of the plenary talks are available online, and the poster gallery will remain accessible for one year after the workshop. While the first two days were open to all registered participants (registration was free of charge), day three was by invitation only. On this day, participants were divided into four working groups (WGs) according to the discussion topics (WG1: GCM experiments; WG2: Theoretical approaches and intermediate complexity models; WG3: Observations; WG4: Paleo data). Two time slots were provided to accommodate different time zones.

We had a good gender and professional experience distribution, as roughly half of the participants were female and/or Early Career Scientists (ECS). After the workshop, we set up an online feed-back form, which received responses from 52 participants. Some of these responses are shown in Figure 2.
The online form included two open-ended questions: “How could the workshop have been improved?” and “Are there any other comments, ideas or suggestions you would like to share with us?” Analysis has been done for different formats (i.e. plenary talks, poster sessions, breakout sessions) as well as the feedback on meeting logistics, platforms and general feedback to the workshop.

(1) General Comments
Participants were satisfied with the workshop content and its organization, and appreciated the organizers’ effort at organizing an event during the difficult circumstances brought on by the pandemic. Participants found the workshop topic to be timely and very important, and thought that it provided a good platform for bringing the community together, listening to excellent scientific presentations, and having interactive discussions. Many responses mentioned that the workshop has increased their understanding and enabled them to keep up-to-date on the latest developments in TBI research and to appreciate current knowledge gaps. In addition, respondents thought the workshop increased the interaction and engagement with scientists around the world, which is a particularly important aspect for ECSs and postgraduate students.

Despite missing informal face-to-face discussions, people thought that having such workshops online was a great chance to get a larger variety and diversity of people participating. Maybe it is a lesson to be learned for the post-COVID era. However, participants suggested that in-person meetings should still be held where possible, because online meetings do not offer opportunities for social interaction, impromptu chats, exchanges on other scientific topics, and for discussion about scientific perspectives.

One participant suggested that in the future it would be important to bridge some remaining hurdles of understanding between the proxy and climate science/modeling communities. One concrete example cited was to solicit perspective talks from scientists engaged in cross-cutting climate-paleo research. This is in line with one of the workshop recommendations that greater collaboration is needed between climate dynamics and paleo-climate communities to advance TBI research. We agree that this is an excellent suggestion and will consider it for future workshops.

(2) Plenary talks
The feedback received for the plenary talks was very positive (e.g., “excellent”, “brilliant”). There were requests to have more oral presentations and to schedule those between the plenary talks and poster sessions. There were also calls for more time for Q&A and more engaging discussions. We note that having a limited number of presentations was a deliberate decision that was meant to leave more time for interactive discussions at the posters. We may explore different formats for future workshops.

One suggestion was to find a better way for informing the speakers about their remaining time without interrupting them, and more flexibility about the length of the plenary talks.

(3) Poster Sessions
There were many calls for longer poster sessions (e.g., two hours), as one hour was not enough for discussing with several presenters. Specific suggestions were to allow those interested to continue discussing during the break; or to hold each poster session twice for two time zones. Furthermore, it could have been more efficient if there had been a better way to interact with poster presenters. By putting each poster presenter into a separate virtual room, the conference missed common discussions on poster presentations. Respondents complained that it was frustrating for poster presenters not to be able to attend other posters during their session, even though those were closely related to their own research. This might have been alleviated if the posters had been made available well before the meeting. In addition, making the poster presentations available only one day before the workshop was seen as inadequate and preventing full engagement prior to the workshop. Lightning presentations (one-minute intros) of posters could have been held within the plenary sessions before moving into the poster session.

We fully agree that the time at the posters was too short and will strive to have longer or additional poster sessions. This would also allow presenters to visit other posters.

There were also many constructive comments regarding the poster platform used for this workshop.
(i.e., virtualpostersession.org): i) The provided instructions did not match what was required: instructions noted that the abstract, recording and presentation could be uploaded. In fact, the abstract needed to be cut and pasted into the submission, and the recording needed to be put on a third-party platform and then the link to the presentation had to be uploaded (rather than the recorded presentation itself). ii) After uploading a poster there was no confirmation. Nevertheless, the poster platform layout itself was widely praised as very intuitive and informative. iii) Participants found that some requirements for the poster presentations were unnecessary, such as the need to make a quick-intro PPT with recorded narration. A large size classical poster PDF was also requested, but never used apart from being displayed in the poster app. iv) Some participants would have liked to have their posters not available for download since the content was unpublished and not ready for widespread dissemination. v) The chat room/discussion function of the poster session was not easy to use. Participants did not know whether the presenter was available or not and how many participants were there until they logged into the web chat platform. The poster session may need a rethinking to increase the audience and a better option for the platform to enable an effective chat group and interaction with poster presenters.

In addition, there were also requests for more timely information to presenters.

All these comments will be very useful for guiding the planning of future workshops and will hopefully lead to a more streamlined experience the next time around.

(4) Breakout Session

We received many constructive suggestions regarding the organization of the breakout and working group (WG) sessions. Respondents remarked that it would have been useful if organizers had provided abstracts or descriptions with clear goals outlined for the breakout sessions well in advance. Also, the note takers should have been determined earlier.

Some participants, on the other hand, were disappointed in the discussion groups because it seemed the organizers had already fixed the key discussion topics and was only seeking input on those. Allowing the participants to steer the direction of the discussions a bit more might have helped to bring in more challenges and ideas. It was also suggested to mix the paleo-climate and climate dynamics communities in the breakout groups to enhance interdisciplinary exchange.

This diversity of opinions, with calls for more as well as less structured discussion groups, illustrates the challenge of finding a compromise. Unmoderated discussion may drift off into unrelated topics, while a too heavily moderated discussion may stifle creativity.

We believe, however, to have struck a decent balance with our approach, though some adjustments might have to be made for future meetings.

Regarding logistics it was suggested to integrate the signing up for breakout sessions and WGs with the registration process, rather than arranging it by email during the meeting. In addition, it seems there were some isolated problems, with some participants complaining that their day one discussion group was not well-structured and unclear, as participants waited for nearly 15 minutes until the discussion really got going and there did not seem to be a clear direction of the discussion for some of the time. Also, one of the breakout groups seemed to have too many participants and a few loud voices drowned out everyone else. There was a suggestion to limit groups to 12 participants in the future.

The time for the breakout sessions on day one and two might not be convenient for participants in some time zones, and it was suggested to schedule the same breakout discussion twice. Summaries of the breakout sessions could then be shared with all registrants.

The above comments highlight the important issue of discussion group size. Having two separate groups discussing the same topic at different time slots, as suggested, could be one way to alleviate this problem. This was actually the approach taken on day three. Nevertheless, since workshop registration was open to anyone, as was the signup to discussion groups on days one and two, it was challenging to determine the right number of discussion groups beforehand. The decision to leave both registration and signup open was made to ensure inclusivity and freedom of choice for the participants.

The communication of the outcomes of the breakout discussions was also commented on by participants, with some complaining that the outcomes of the first time slot on day three were not available before the second time slot of the WGs. It was suggested to use Slack channel for sharing the outcomes, as it would have allowed for further discussions and thereby improved the workshop outcomes.

The last comment brings up the important issue of Slack and its utilization during the meeting. While we encouraged participants to make use of this tool, the uptake was only limited.

The decision not to make the outcomes of the first time slot available before the second was intended to give participants a “clean slate”, rather than constrain them by the outcomes of the previous discussion. One can of course debate whether this approach was optimal.

(5) Meeting Logistics

The time zone differences might be the biggest challenge for both organizers and participants. Some would have preferred no breaks or shorter breaks,
to avoid having to stay up late into the night. Others suggested holding the meeting over one week instead of three days. This would have decreased the daily burden and encouraged more in the audience to attend not just the oral sessions. Nonetheless, the effort of the organizers in accommodating the different time zones was recognized.

In hindsight, it indeed would have been better to hold the meeting over a one-week period and we will likely take this approach next time. Nevertheless, accommodating participants spread all over the globe remains a challenge.

Participants suggested circulating the meeting information (program/schedule, meeting links, poster app, etc.) earlier to participants, and bundling this information in only one or two emails. Additionally, this information should have been published on the webpage well in advance.

An ice- breaker session at the beginning might have some value, although not everyone is favorably disposed to virtual socializing, particularly when the meeting schedule is demanding as was the case here.

(6) Meeting Platforms

The meeting used several platforms, including a website for general information, email notifications, Slack for informal discussion, Webex for the plenary and breakout sessions, the Webex chat box for Q&A, a virtual poster gallery, YouTube videos for the poster summaries, additional platforms for the poster presentations (as chosen by the presenters), and Google Docs for the breakout session discussion notes. Some respondents complained that it was hard to keep up with all these platforms. Respondents suggested that this should have been managed at a central point on the webpage, along with the agenda. Furthermore, it should have been explained in advance how the whole system worked.

Respondents suggested using zoom or google meet instead of Webex, as these offer more functionality. Also, some respondents complained about issues with the Webex platform, such echoes and poor internet connections, which they did not experience with Webex in the past.

Concluding remarks

In this next section we discuss the lessons we have learned from holding this workshop. Our experience is not entirely different from that of Ballantyne et al. (2020).

Virtual meetings can be surprisingly efficient. They tend to be more focused and stick to the planned agenda. There is growing realization that many meetings that used to require travel can be held virtually.

One of the positive effects of the COVID19 pandemic is that online interaction “literacy” has considerably improved. People around the world are increasingly familiar with video conferencing and ways to better facilitate discussion. Necessity has encouraged the ICPO to be more flexible and willing to experiment with new online tools, taking into account that virtual meetings will become a “new normal” and can be very efficient and provide several advantages compared to face-to-face meetings.

On the other hand, however, there are fewer or no spontaneous exchanges. “Icebreaker” moments, side conversations and networking opportunities are mostly lost online. We have yet to find a way to replace the impromptu post-workshop gatherings or afternoon coffee breaks that help us build trust and new relationships.

While we have found that virtual meetings broaden participation (and have a much smaller carbon footprint than flying), new blockages have to be addressed. Inclusion/participation/hidden biases are just as (if not more) pronounced in virtual events. Individual participants may be marginalized. People with poor internet connectivity, unstable electricity supply, or stretched home “offices” can be excluded. Thus we have to make sure EVERYONE can get online and access resources; build in spaces and opportunities, such as group work, where everyone can contribute; when bandwidth permits, encourage participants to use their video.

In addition, it’s difficult to measure people’s attention and engagement. Social aspects of face-to-face–facial expressions, body language–are harder to detect, especially when videos are off. This is another area where we would be keen to find new solutions.

Last but not least, virtual events can be organized at lower cost, can be held more frequently, and are easier to attend, compared to traditional face-to-face meetings. This encourages researchers to attend more meetings and shoulder more responsibilities than they used to, which can easily lead to overcommitment. Thus, organizers need to consider carefully how to assign action items and tasks at meetings, to avoid over commitment by participants and to ensure productive outcomes.

Reference:

1. Introduction
The El Niño Southern Oscillation (ENSO) has broad impacts on global climate variability, including the tropical Atlantic Ocean through atmospheric teleconnections (Timmermann et al. 2018; Chikamoto and Tanimoto 2006; Chikamoto et al. 2013). However, the opposite pathway also exists: the tropical Atlantic Ocean also affects ENSO (Cai et al. 2019). Previous research has proposed three tropical Atlantic precursors in different seasons that affect the ENSO evolution: the Atlantic Niño during the boreal summer (Ding et al. 2012; Keenlyside et al. 2013; Martín-Rey et al. 2014; Polo et al. 2015; Rodríguez-Fonseca et al. 2009), the North tropical Atlantic during the boreal spring (Ham et al. 2013b, a; Wang et al. 2017), and the entire tropical Atlantic on decadal timescales (Chikamoto et al. 2015; Kucharski et al. 2011, 2016; Li et al. 2016; McGregor et al. 2014; Ruprich-Robert et al. 2017). However, relative contributions of these Atlantic precursors to ENSO are still unknown because of the seasonally locked relationship and a lack of appropriate model experiments. A question remains: what Atlantic pathway effectively modulates the interannual ENSO evolution?

This article highlights the Atlantic modulation on the ENSO evolution based on Chikamoto et al. (2020). This study applies a unique approach called partial ocean data assimilation experiments, which can isolate the ENSO response to the Atlantic forcings. The partial ocean assimilation approach incorporates observed three-dimensional ocean temperature and salinity fields in the Atlantic region into the ocean components of MIROC and CESM by using an Incremental Analysis Update scheme (Bloom et al. 1996; Huang et al. 2002). By assimilating the three-dimensional oceanic fields, the models can simulate ocean variability in the mixed layer and thermocline more appropriately than an SST-only assimilation (Chikamoto et al. 2019). During the assimilation process, we utilize the “anomaly” field observation while maintaining the model climatology in the MIROC ATL anomaly and the CESM ATL anomaly runs but used the ‘full’ field observations (i.e., observed anomaly plus observed climatology) in the CESM ATL full run. The anomaly run minimizes the unrealistic model artificial drift, whereas the full run suppresses model mean-state biases in the assimilated region. Observations were derived from the objective analysis of ProjD (Ishii and Kimoto 2009) for 1950-2010 in MIROC and the ECMWF ocean reanalysis product version 4 (Balmaseda et al. 2013) for 1960-2014 in CESM. These runs consist of 10 ensemble members with time-varying observed external forcings (solar, aerosols, land-use change, and greenhouse gases) before 2005. After 2005, we prescribed the A1B-type emission scenario for MIROC and the RCP4.5 scenario for CESM. Our Atlantic partial assimilation run shows less seasonality of Niño 3.4 index than the observations, suggesting that the Atlantic impact on ENSO can occur in any season even though the Atlantic Niño is prominent during the boreal summer (Chikamoto et al. 2020). Details of the technique and the model performance can be found in previous studies (Chikamoto et al. 2013, 2012; Mochizuki et al. 2010; Johnson et al. 2018, 2020).

For validation, we combine several gridded observation datasets. Observed sea level pressure (SLP) is obtained from NCEP-NCAR (Kalnay et al. 1996) and JRA55 atmospheric reanalyses (Kobayashi et al. 2015). SST datasets include ERSST version 4 (Huang et al. 2014) and an objective ocean analysis compiled by the Japan Meteorological Agency (Ishii and Kimoto 2009). Anomalies are defined as deviations from the climatological mean for the 50 years 1960–2009 in each

2. Methods
We conducted three sets of Atlantic Ocean partial assimilation runs using two global climate models, MIROC3.2 (Nozawa et al. 2007) and CESM1.0 (Shields et al. 2012). These three experiments are the MIROC ATL anomaly, the CESM ATL anomaly, and the CESM ATL full runs. To capture the climate response to the Atlantic Ocean forcing, we assimilated the observed 3-dimensional ocean temperature and salinity fields in the Atlantic Ocean only into the ocean components of MIROC and CESM by using an Incremental Analysis Update scheme (Bloom et al. 1996; Huang et al. 2002). By assimilating the 3-dimensional oceanic fields, the models can simulate ocean variability in the mixed layer and thermocline more appropriately than an SST-only assimilation (Chikamoto et al. 2019). During the assimilation process, we utilize the “anomaly” field observation while maintaining the model climatology in the MIROC ATL anomaly and the CESM ATL anomaly runs but used the ‘full’ field observations (i.e., observed anomaly plus observed climatology) in the CESM ATL full run. The anomaly run minimizes the unrealistic model artificial drift, whereas the full run suppresses model mean-state biases in the assimilated region. Observations were derived from the objective analysis of ProjD (Ishii and Kimoto 2009) for 1950-2010 in MIROC and the ECMWF ocean reanalysis product version 4 (Balmaseda et al. 2013) for 1960-2014 in CESM. These runs consist of 10 ensemble members with time-varying observed external forcings (solar, aerosols, land-use change, and greenhouse gases) before 2005. After 2005, we prescribed the A1B-type emission scenario for MIROC and the RCP4.5 scenario for CESM. Our Atlantic partial assimilation run shows less seasonality of Niño 3.4 index than the observations, suggesting that the Atlantic impact on ENSO can occur in any season even though the Atlantic Niño is prominent during the boreal summer (Chikamoto et al. 2020). Details of the technique and the model performance can be found in previous studies (Chikamoto et al. 2013, 2012; Mochizuki et al. 2010; Johnson et al. 2018, 2020).

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El Niño-Southern Oscillation Evolution Modulated by Atlantic Forcing

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model experiment and observations. All anomalies are detrended using a least-squares quadratic trend and are re-gridded into a 2.5° x 2.5° latitude-longitude grid. We applied a 12-month running mean to all anomalies, which filtered the effect of seasonality. We also took the multi-model ensemble mean after taking the mean of 10 ensemble members for each model experiment during the 1960–2009 period. Observational estimates are based on the average of the two reanalysis products during the same period.

3. Results
To depict the ENSO precursors, we made SST and SLP correlation maps with the Niño 3.4 index at −12, −6, and 0-month lags in the observation and the multi-model ensemble mean of the three Atlantic partial assimilation runs (Figure 1). Consistent with previous studies (Cai et al. 2019), colder SSTs emerge in the tropical Atlantic 6 and 12 months before the mature stage of El Niño (left panels in Figure 1). These colder SSTs disappear at a 0-month lag (Fig 1e). The multi-model ensemble mean of our Atlantic partial assimilation runs emphasizes the negative SST anomalies in the tropical Atlantic with an equatorial maximum (right panels in Figure 1), indicating that the equatorial Atlantic is a prominent ENSO precursor. In the multi-model ensemble mean, colder equatorial Atlantic SSTs appear at least 12 months before the mature stage, which accompanies the overlying higher SLP anomalies. This colder SST and associated higher SLP persist during the ENSO developing stage. At the same time, we can find enhanced SLP in the Indian Ocean and reduced SLP in the tropical Pacific. This SLP contrast between the Indian Ocean and the Pacific accompanies the weakened trade winds, which energize the subsequent El Niño development by activating the Bjerknes feedback. Since the multi-model ensemble mean only includes the observed temperature and salinity in the Atlantic Ocean but not the atmospheric observations, the simulated SLP anomalies in the tropics indicate the climate responses to the Atlantic forcing.

To describe the equatorial climate response to the Atlantic forcing, we produce Hovmöller diagrams for the lead-lag correlations of SST and SLP anomalies at the equator with the Niño 3.4 index (Figure 2). The multi-model ensemble mean shows the colder equatorial Atlantic SST around seven months before the mature phase (Figure 2b). At the same time, we can find higher SLP in the equatorial Atlantic and lower SLP in the central and eastern Pacific. The positive SLP anomaly propagates eastward from the Atlantic to the western Pacific across the Indian Ocean, inducing a large zonal SLP gradient over the western Pacific. This zonal gradient emerges around 14 months before the El Niño mature stage and then strengthens during the ENSO developing phase. Since this zonal SLP gradient corresponds to the weakened trade winds, we can find the weakening trade wind and the SST warming in the tropical Pacific until 0-month lag due to the activated Bjerknes feedback. This feature is prominent in the multi-model ensemble mean rather than the observation because the observation includes the two-way inter-basin interaction between the Pacific and the Atlantic Oceans.

4. Discussion and Summary
Based on the three sets of Atlantic partial ocean assimilation runs, this study found that SST anomalies in the equatorial Atlantic are a prominent precursor in the ENSO evolution for several seasons ahead. This happens through a two-step process. First, tropical Atlantic SST warming induces a lower SLP response. These lower SLP anomalies propagate eastward toward the western Pacific across the Indian Ocean and strengthen surface trade winds over the western Pacific, although the mechanism of eastward SLP propagation is still unknown. Next, these strengthened trade winds activate the Bjerknes...
feedback in the tropical Pacific and energize the La Niña development. Opposite tendencies occur for a colder equatorial Atlantic. Whereas this article identified the Atlantic impact on ENSO, the trade wind responses to the Atlantic forcing exhibit a large sensitivity among the assimilation systems (Chikamoto et al. 2020). Further studies using the various ocean assimilation techniques and climate models are beneficial for quantifying the effects of model sensitivity and improving model performance in simulating inter-basin climate interactions.

References


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Northern Europe and the UK experienced an exceptionally mild and wet winter in 2019/20. Europe as a whole experienced its warmest winter on record, and February 2020 was the wettest UK February on record. This weather was due to an anomalously positive North Atlantic Oscillation (NAO), which strengthened the north Atlantic storm track, and moved it further poleward, bringing the warm, moist air from the Atlantic across the UK and northern Europe (Figure 1(a)). This circulation anomaly was accurately forecast in November 2019 by several climate centres, suggesting that it was highly predictable at long lead times. Furthermore, such a strong level of agreement across different dynamical seasonal forecasting systems on the circulation over the Atlantic and European sector is unusual and suggests that some common strong forcing from outside of the North Atlantic-European domain drove this circulation anomaly. Strong tropical forcing is known to exist via teleconnections between the El Niño Southern Oscillation (ENSO) and the NAO, but ENSO was in a neutral state during winter 2019/20. However, in November 2019 the observed sea surface temperatures in the west/east parts of the Indian Ocean basin were anomalously warm/cold, leading to the second strongest recorded positive Indian Ocean Dipole (IOD) since 1972.

In Hardiman et al. (2020), composites are formed over extreme positive/negative values of the November IOD Dipole Mode Index (DMI) in the years 1978-2018 using the ERA-5 reanalysis dataset, with the effects of ENSO removed by linear regression on the Niño 3.4 index. These composites show that a very strongly positive November IOD event leads, on average, to a positive NAO in the following December-January-February (DJF), and correspondingly anomalously high rainfall over the UK and northern Europe, consistent with that forecast and experienced in winter 2019/20 (Figure 1(b, c)). The paper goes on to demonstrate causality by repeating a set of 40-member winter forecasts made with the Met Office decadal prediction system, with the top 1000m of the Indian Ocean perturbed to reverse the 2019 anomalies to negative IOD. The ensemble mean difference between the original forecast members and these perturbed forecast members (referred to below as the “IOD experiment”) then shows twice the impact of a positive IOD (assuming linearity) on the dynamical fields over the following winter. The impact on the Atlantic jet stream and associated precipitation anomalies, in this ensemble mean difference, is to double the anomalies in the original forecast, suggesting both a linear response in the Atlantic and one that, in 2019, is largely driven by the IOD (see Figure 5 of Hardiman et al., 2020). In what follows, this suite of simulations (the “IOD experiment”) is used to diagnose clear and convincing dynamical mechanisms and teleconnection pathways.

Two teleconnection pathways of the IOD to the North Atlantic emerge from the analysis of the IOD experiment. The first is a tropospheric pathway via a Rossby wave train travelling from the Indian Ocean over the Pacific and into the Atlantic diagnosed using anomalous meridional velocity at 250 hPa (v250). Figure 2(a) shows the December mean wave train. By design, this is the signal due only to changes in the Indian Ocean. The wave train propagates poleward and eastward from the Indian Ocean, reaching extratropical latitudes across North America, before propagating equatorward again. As the wave train crosses North America it splits into two paths. Once in the Atlantic, the high latitude branch of this wave train projects directly onto the NAO. The DJF mean is similar, but the wave train for DJF is weaker than that for December (Figure 2(b)). Although it originates in a different location, this IOD tropospheric teleconnection pathway is similar to that already documented for ENSO, consisting of a trans-Pacific-Atlantic wave train, the high latitude branch of which projects onto the NAO.

The second teleconnection pathway is a stratospheric pathway via the Aleutian region and the stratospheric polar vortex, which then influences the troposphere over the North Atlantic. The wave train discussed above also passes over the location occupied by the
climatological Aleutian cyclone in the North Pacific (Figure 2(a)) leading to poleward flow in the North Pacific near the dateline, and equatorward flow to the east of this. These two responses combine to give anomalously positive mean sea level pressure (MSLP) just south of Alaska and the Aleutian Islands, reducing the strength of the climatological Aleutian cyclone. This is very similar to the already documented stratospheric teleconnection pathway of ENSO when in its La Niña phase. The mean amplitude of planetary waves propagating upwards into the stratosphere is thus reduced (Figure 2(c)), leading to an anomalously strong stratospheric polar vortex, the signal from which propagates downwards into the troposphere, resulting in a positive NAO at the surface approximately 1 month later (Figure 2(d)).

The link between the IOD and European winter weather is not widely recognised, as few large IOD events have occurred without the simultaneous presence of ENSO. This important new knowledge of the teleconnection pathways between the Indian Ocean and the North Atlantic offers greater understanding and hence confidence in future seasonal forecasts, not least because the frequency and intensity of positive IOD events is expected to continue to increase. Such connections could, therefore, become increasingly important in the future.

Figure 1: Observed 2019/20 conditions and observed IOD composites
(a) DJF 2019/20 observations (ERA-5 anomalies, plotted relative to recent (2014–2018) climatology to avoid the complications of climate change trends) of anomalous total precipitation (mm/day), plotted in coloured shading, and anomalous zonal wind, U (250 hPa; m/s), shown by contours. The U contours are in intervals ±2, and the zero contour is not plotted.

Composite patterns for the IOD Dipole Mode Index [DMI > 1σ – DMI < −1σ, where σ = standard deviation] over the last 40 years (1979/80–2018/19) of the ERA-5 dataset on (b) Mean Sea Level Pressure (MSLP; hPa) and (c) Precipitation (mm/day), with ENSO signal removed and stippling denoting statistical significance at the 90% level.
Figure 2: IOD teleconnection pathways to the North Atlantic
Tropospheric pathway: Anomalous meridional wind at 250 hPa (v250; m/s) is plotted in coloured shading and anomalous MSLP (hPa) is shown by contours for (a) December 2019 and (b) DJF 2019/20, for the IOD experiment (Original forecast ensemble mean – IOD negative forecast ensemble mean). Stippling denotes statistical significance at the 95% level. Positive/negative MSLP contours are shown by solid/dashed lines. The zero MSLP contour is not plotted. MSLP contours (hPa) have the same numerical values as the v250 contours (m/s). The contour values are doubled (2m/s) since the IOD forcing is doubled (Original – IOD negative).

Stratospheric pathway: (c) Planetary wave number 1 amplitude (m) diagnosed using geopotential height (40–80°N, 100 hPa), and (d) anomalous zonal mean zonal wind at 60°N (U(60N)), for the IOD experiment (Original forecast ensemble mean – IOD negative forecast ensemble mean). The filled circle in (c) denotes statistical significance at the 95% level. Stippling in (d) represents statistical significance at the 95% level.

Reference
Synthesizing corals and ocean models to study Pacific to Indian Ocean heat and freshwater exchange

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Introduction
The Indonesian Throughflow (ITF) serves as an important oceanic teleconnection for Indo-Pacific climate through modulating heat and freshwater transport from the Pacific to the Indian Ocean. Yet, sparse observational data networks that only cover the most recent few decades throughout the Indonesian Seas limit examination of past changes in ITF variability as well as the resulting implications for Indo-Pacific climate. Corals are a unique paleoclimate tool that not only resolve seasonal and interannual variability, but also allow insights into variability on decadal to multi-decadal timescales prior to satellite observations. In Murty et al. (2021), we synthesize coral δ\textsuperscript{18}O records, instrumental indices (Interdecadal Pacific Oscillation (IPO), Asian Monsoon), and simulated ocean variability (sea surface salinity (SSS), temperature, heat content, thermocline depth) from NEMO ocean model simulations to explore drivers of seasonal to multi-decadal variability. The Makassar Strait coral site is located within main ITF pathways and is influenced by monsoon-driven, buoyant South China Sea surface waters during boreal winter that obstruct surface ITF flow and reduce heat transport to the Indian Ocean. We show that Makassar Strait coral δ\textsuperscript{18}O co-varies with simulated SSS and thermocline depth at the coral site. Sensitivity experiments additionally indicate that the site is dominantly influenced by wind forcing at multi-decadal timescales. Notably, the variability in these coral and model responses reveals sensitivity to the IPO. These results collectively suggest that the paleoproxy record is capturing important features of regional hydrography and Indo-Pacific heat and freshwater exchange. Such a proxy-model comparison is critical for understanding the drivers of variability related to changes in ITF oceanic teleconnections over the recent centuries.

Ocean model simulations
A series of global ocean model simulations were analyzed, building on the ocean/sea ice numerical Nucleus for European Modeling of the Ocean (NEMO; Madec, 2007). ORCA025 is an established eddy-active configuration at 0.25° nominal resolution based on the NEMO framework. The simulations include 46 discretized vertical levels, with 10 levels in the upper 100 meters and increasing to a thickness of 150 meters at depth. These simulations employ the Coordinated Ocean-Ice Reference Experiment phase 2 (CORE-II; Griffies et al. 2009) atmospheric forcing fields of wind and thermohaline fluxes, building on the analysis products ofLarge and Yeager (2004) that combine reanalysis fields by the National Centers for Environmental Prediction and National Center for Atmospheric Research and correct for biases. The ocean model is spun up over the period 1978-2007 and hindcast integrations were performed over the full 1948-2007 period. Throughout all simulations interannual wind forcing spans the full model run 1948-2007, while interannual buoyancy forcing begins after 1980, prior to which only climatological freshwater forcing is imposed.

The simulations contain very weak SSS restoring at a 1-yr time scale (Behrens et al. 2013), ensuring an almost free evolution of surface quantities. An analogous simulation with global climatological (the “normal year” CORE product) forcing was used to correct for spurious model drift by subtracting the linear trends for the analysis period 1952-2007 in the climatological simulation from all interannually forced simulations. For further details on the model simulations, see Ummenhofer et al. (2017).

In addition to the reference simulation, a set of sensitivity experiments were conducted where interannual atmospheric forcing was restricted to only buoyancy or wind stress. These experiments thus allow us to isolate the variability driven by each of these two atmospheric forcing components and determine to what degree each forcing factor contributes to the variability of the reference simulation.

Coral δ\textsuperscript{18}O record
A previously published coral δ\textsuperscript{18}O record from the southern Makassar Strait (5.38°S, 117.91°E; Murty et al., 2017; Figure 1) was compared to the NEMO
ocean model simulations. This record has been used to document SSS variability related to monsoon-driven surface ocean circulation from seasonal to decadal timescales. The site is located within the main ITF pathway and is influenced by monsoon-driven, buoyant South China Sea surface waters during boreal winter that obstruct surface ITF flow and reduce heat transport to the Indian Ocean. Description of coral sampling and analytical methods can be found in the original publication that presents this record (Murty et al. 2017). Here, the coral record has been detrended and a 5-year smoothing has been imposed to focus on low-frequency variability.

Multi-decadal variability in coral $\delta^{18}O$ and reference simulations

To examine co-variability between the model simulations and coral proxy record, we compared coral $\delta^{18}O$ from the southern Makassar Strait (MAK) site with the reference simulation encompassing both the wind and buoyancy-forced components. MAK coral $\delta^{18}O$ (reflecting SSS) exhibits strong multi-decadal variability from 1950-2010, revealing freshwater “pulses” in the 1950s/60s as well as the early 2000s (figure 2a). A comparison of the southern Makassar Strait coral proxy data with the reference simulation when averaged for the MAK region (4-5.5°S, 116-118.5°E) indicates co-variance with SSS, which is particularly strong during both the 1950s/60s and early 2000s freshwater pulses (figure 2a). Notably, the lack of interannual freshwater forcing prior to 1980 limits examination of the role of interannual buoyancy forcing during the 1950s/60s freshwater pulse, though it hints at an anomalous advective, rather than a local buoyancy-forced signal. Yet, the co-variation between the proxy data and reference simulation during the freshwater pulse in the early 2000s, when both interannual wind and buoyancy forcing is imposed, suggests that the model is overall capturing the SSS variability recorded by the coral $\delta^{18}O$ proxy.

Constraining past changes in thermocline depth is also critical for understanding past changes in ITF variability and its interactions with the South China Sea buoyancy plug that is modified at seasonal (Gordon et al., 2003) and interannual (Ffield et al. 2000; Gordon et al. 2012; Hu et al. 2015) timescales in the southern Makassar Strait and Sulawesi Sea (north of the Makassar Strait), respectively. At MAK, variability in the depth of the 20°C isotherm from the reference simulation co-varies with coral $\delta^{18}O$ from the 1980s to early 2000s, albeit with temporal offsets. In particular, the freshwater pulse of the early 2000s that is evident in both the coral $\delta^{18}O$ and simulated SSS reference records (figure 2a) coincides with a shoaling thermocline, as represented by the 20°C isotherm (figure 2b). A shoaling thermocline during the early 2000s freshwater pulses may be related to the mechanisms that modify surface and subsurface ITF variability, where freshwater advection into the western Indonesian Seas co-occurs with changes in thermocline depth. Previous work has indeed
documented that at interannual timescales ocean circulation changes during sustained El Niño events result in the advection of buoyant South China Sea surface waters into the Sulawesi Sea and northern Makassar Strait, a main ITF pathway (Gordon et al. 2012; Hu et al. 2015). These buoyant waters act as a “plug” that limits the southward advection of the ITF in the surface layer, leading to a deepening of the ITF velocity maximum and coinciding with a shoaling thermocline (Gordon et al. 2012; Gruenburg et al. 2018). The similarity of the coral δ¹⁸O, and simulated SSS and thermocline depth variability suggests that a similar mechanism may be at play on decadal to multi-decadal timescales.

Contributions of buoyancy forcing and wind stress

The strong covariance of coral δ¹⁸O with simulated SSS and 20°C isotherm depth from the reference simulation at multi-decadal timescales highlights the strength of a proxy-model approach in understanding past drivers of upper-ocean variability reflected in the coral proxy records. Yet, SSS and the 20°C isotherm depth from the reference simulation reveal more pronounced interannual to decadal variability from the 1970s to 1990s compared to that of MAK coral δ¹⁸O, suggesting that either the coral might not be fully resolving southern Makassar Strait variability through time, or that the model is overly sensitive to buoyancy forcing during periods of the mid- to late-20th century. To better constrain the drivers of Indo-Pacific oceanic exchange and elucidate their respective temporal evolution, we therefore utilized sensitivity experiments that isolate the variability from buoyancy forcing and wind stress. From the mid- to late-20th century, the variability captured in the coral δ¹⁸O record in the southern Makassar Strait is dominantly influenced by wind stress at multi-decadal timescales (figure 2).

At MAK, SSS from the wind-only forced simulation strongly co-varies with coral δ¹⁸O throughout nearly the entire 1950s-2000s period, capturing both the 1950/60s and early 2000s freshwater pulses (figure 2a; red line). Only a brief period in the 1960s/early 1970s reveals a discrepancy between the records, when coral δ¹⁸O reflects more saline waters compared with the simulated SSS variability. Most notably, the covariance between MAK coral δ¹⁸O and simulated SSS is even stronger by isolating the wind forcing than when compared with the reference simulation (black line). The muted interannual response of the coral δ¹⁸O and earlier timing of the early 2000s freshwater pulse is better reflected in the muted variability of the wind-forced simulation from the 1970s to 1990s (figure 2a; red line) in contrast with the greater variability and later freshwater pulse evident in the reference simulation (figure 2a; black line). In fact, during the periods of greatest departure between MAK coral δ¹⁸O and the SSS in the reference simulation (e.g., late 1970s-1990s; figure 2a), the reference simulation instead more strongly co-varies with the buoyancy-forced sensitivity experiment (figure 2a; blue line). This disagreement between the MAK coral δ¹⁸O variability and the buoyancy and reference simulations from the 1970s to 1990s suggests that the coral proxy record either is not influenced by or does not resolve the buoyancy-driven variability reflected in the reference simulation.

The dominance of wind forcing on coral δ¹⁸O and SSS highlights the importance of wind-driven advection in influencing surface ocean variability. However, an examination of the drivers of thermocline depth variability is crucial to understand whether this wind-driven surface freshwater layer induces a buoyancy plug mechanism on decadal timescales. Sensitivity experiments indicate that MAK thermocline depth is consistently dominated by wind forcing throughout the mid- to late-20th century, with minimal contribution from buoyancy forcing. The buoyancy-forced simulation exhibits low interannual to decadal variability after 1980, when interannual buoyancy forcing is imposed (figure 2b, blue line), contributing only ~5% of the variability in the reference simulation from 1980 to 2007. Isolated wind-forced variability instead shows ~94% agreement with the reference simulation during this same period, suggesting that thermocline depth in the southern Makassar Strait is dominantly influenced by wind stress. When
compared to the MAK coral δ¹⁸O record, both the wind-forced and reference simulations of thermocline depth exhibit similar interannual to multi-decadal variability, particularly after the 1970s and albeit with temporal offsets throughout much of the record. Prior to the 1970s, however, variability in both the reference and wind-forced simulations of thermocline depth do not coincide well with coral δ¹⁸O, suggesting a potential non-stationary relationship.

**Links to subsurface IPWP variability in response to IPO phase changes**

The comparison of the coral proxy data with the reference and sensitivity experiments documents strong decadal to multi-decadal variability and often co-variance, suggesting that lower-frequency climate drivers may play an important role in both surface and subsurface upper ocean variability throughout the Maritime Continent. To further examine the climate drivers on multi-decadal timescales and links to subsurface variability, we assessed temporal and spatial responses to IPO phase changes through the Indo-Pacific Warm Pool region. Coral δ¹⁸O reveals significant coherence (at the 90% confidence level) with the Tripole Index for the IPO (Henley et al. 2015) at 16-20 year timescales (not shown), suggesting a response in coral-based SSS to IPO variability. Similarly, spatial patterns evident in the model simulations reveal clear responses to IPO phase changes. Throughout the Maritime Continent, a positive IPO phase spanning 1978 to 1998 is characterized by a shallower thermocline (figure 3a-c), and lower heat content anomalies (figure 3d-f). These patterns are in agreement with recent studies using observational data that identify the influence of the IPO on recent upper ocean variability (Ummenhofer et al. 2021). Notably, a comparison of the reference simulation to the sensitivity experiments indicates that wind forcing dominantly influences the region on multi-decadal timescales. The response to the IPO in the coral proxy record as well as the model simulations suggests that the IPO may serve as an important driver that links surface and subsurface ocean variability within the Indonesian Seas. Even more importantly, however, these linkages indicate that corals may be useful for examining the drivers of past surface and subsurface ocean variability, underscoring the importance of proxy-model syntheses in this region.

In summary, we have demonstrated that the coral δ¹⁸O record and ocean model simulations co-vary on interannual to multi-decadal timescale, suggesting that surface ocean signals recorded in corals can likely reconstruct low-frequency subsurface ocean variability. Sensitivity experiments indicate that wind forcing dominantly influences multi-decadal variability, with contributions from buoyancy forcing occurring during periods of the late 20th century. In addition, both coral δ¹⁸O and the ocean model simulations reveal sensitivity to the IPO over the late-20th century and thus a linkage between the surface and subsurface ocean. Ongoing expansions of this proxy-model synthesis work will incorporate evaluation of additional coral sites throughout the region and comparison of the spatial patterns between phases of major climate modes, including the IPO (e.g., Murty et al. 2021). These comprehensive proxy-model comparisons will provide a broader spatial and temporal understanding of the drivers of upper ocean variability, filling in existing gaps in data and understanding related to limited regional observations beyond the last few decades.

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References


Using linear inverse modelling to assess tropical interbasin interaction

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1. Introduction

By modulating large-scale atmospheric circulation, sea surface temperature (SST) variability in the tropics exerts significant influence on regional and global climate variability. In particular, the El Niño - Southern Oscillation (ENSO) in the tropical Pacific is the most prominent climate signal on interannual timescales, and tremendous efforts have been devoted to understand its characteristics, governing mechanisms, and predictability (Philander 1990; Neelin et al. 1998; McPhaden et al. 2006, 2020).

A large body of observational and modelling studies has pointed out that two-way interaction of the Pacific Ocean (PO) with regions outside of the PO, such as the tropical Atlantic (AO) and Indian Ocean (IO), plays an important role in the growth and decay of ENSO (see recent reviews by Cai et al. 2019; Wang 2019; and references therein). For instance, El Niño causes significant SST warming over the AO and IO (Enfield and Mayer 1997; Klein et al. 1999), and these SST anomalies, in turn, modulate the PO variability by changing the zonal atmospheric Walker circulation (Annamalai et al. 2005; Dommengnet et al. 2006; Kug et al. 2006; Jansen et al. 2009). Additionally, intrinsic SST variability in the AO and IO, such as the Atlantic zonal mode and Indian Ocean Dipole, also affects the temporal evolution of ENSO (Keenlyside and Latif 2007; Rodriguez-Fonseca et al. 2009; Luo et al. 2010; Izumo et al. 2010; Ding et al. 2012; Polo et al. 2015). Such interactive coupling among the three tropical oceans has been shown to have significant impacts upon the seasonal prediction of ENSO and related variability (Luo et al. 2010, 2017; Frauen and Dommengnet 2012; Keenlyside et al. 2013). However, due to the short observational record and the systematic biases of general circulation models (GCMs), our understanding of tropical basin interaction (TBI) is still incomplete, and the relative importance of each coupling component has not been carefully evaluated. To shed further light on this issue, here we adopt a new approach that relies on linear inverse modelling (LIM; Penland and Sardeshmukh 1995). Our focus is on the impact of TBI on ENSO forecast skill.

2. Data and methods

Since the basic concept of LIM has been comprehensively discussed in the literature (e.g. Penland 1989; Penland and Sardeshmukh 1995; Penland and Matrosova 1998), here we only present a brief summary and the unique aspects of our approach. In this study, we use the cyclostationary LIM (OrtizBéviá 1997; Johnson et al. 2000; Shin et al. 2020), which can incorporate the effects of the seasonal cycle. Its governing equation can be written as follows:

\[
\frac{dx}{dt} = L^{(0)}x(t) + S^{(0)}\xi(t),
\]

where \(x(t)\) is the state vector (e.g., SST, sea surface height etc.), \(L^{(0)}\) is the linear system matrix, \(S^{(0)}\) denotes the forcing amplitude matrix, \(\xi\) is a vector with time-independent unit-variance white noise, and \(j=1,2,3...12\) denotes the calendar month. Here, we estimate \(L^{(0)}\) for each calendar month using the fixed-phase approach (OrtizBéviá 1997; Shin et al. 2020):

\[
L^{(0)} = \frac{1}{\tau_0} \ln[C^{(0)}(1)C^{(0)}(0)^{-1}], j = 1, 2, \ldots, 12;
\]

where \(C^{(0)}(0) = \langle x(t)x^T(t) \rangle\), and \(C^{(0)}(1) = \langle x(t+1)x^T(t) \rangle\) are the lag-0 and lag-1 covariance matrices for month \(j\), respectively, and the square brackets indicate time averaging with \(\langle \cdot \rangle^T\) denotes the transpose. A 3-month running mean filter is applied to these covariance matrices prior to estimation of \(L^{(0)}\), following Shin et al. (2020). Optimal predictions are then obtained by successively multiplying the system matrices of the corresponding months, \(G^{(0)} = \exp(L^{(0)})\); for instance, an optimal prediction of March state \((x(3))\) predicted from the January initial condition \((x(1))\) is given by \(x(3)=G^{(0)}G^{(0)}X(1)\).

To reduce the dimensionality of the problem, the state vector is expressed in terms of the leading principal components (PCs) of an empirical orthogonal function (EOF) analysis of SST anomalies. Since we are interested in separating the influences of individual ocean basins, we perform the EOF analysis separately for each of the three tropical basins. The total state
vector is formed by concatenating the PCs as follows:

\[
\mathbf{x}(t) = [\mathbf{x}_{PO}, \mathbf{x}_{AO}, \mathbf{x}_{IO}],
\]

where \(N_{PO}, N_{AO}, \) and \(N_{IO}\) are the truncation numbers of PO, AO, and IO PCs, and \(\mathbf{x}_{PO}, \mathbf{x}_{AO}, \) and \(\mathbf{x}_{IO}\) denote submatrices representing the PO, AO, and IO PCs, respectively. Here, the SST data is taken from the Extended Reconstructed Sea Surface Temperature, Version 5 (ERSSTv5) (Huang et al. 2017) and cross-validated retrospective forecasts are made from January 1959 to December 2019, using a jackknife procedure similar to Richter et al. (2020). The longitudinal range of the PO, AO, and IO are 120°E-70°W, 75°W-20°E, and 40°-115°E, respectively. To ensure the robustness of our results, we have tested three meridional domains (20°S-20°N, 25°S-25°N, and 30°S-30°N) and three EOF truncation numbers (determined by calculating the minimum number that explains 70%, 80%, or 90% of total variance). This results in 9 different versions of LIM, and the ensemble mean of these LIMs is used as our baseline forecast (referred to as the LIM_CTL). We note that qualitatively similar results are obtained even when we use the Met Office Hadley Centre Sea Ice and Sea Surface Temperature version 1.1 (HadISST) (Rayner et al. 2003) instead of ERSST_v5.

The advantage of our LIM formulation is that it allows to separate out the influence of individual basins. To illustrate this point, we substitute Eq. (3) into Eq. (1) and obtain

\[
\frac{d}{dt} \begin{bmatrix} \mathbf{x}_{PO} \\ \mathbf{x}_{AO} \\ \mathbf{x}_{IO} \end{bmatrix} = \begin{bmatrix} \mathbf{L}_{PP}^{(i)} & \mathbf{L}_{PA}^{(i)} & \mathbf{L}_{PI}^{(i)} \\ \mathbf{L}_{AP}^{(i)} & \mathbf{L}_{AA}^{(i)} & \mathbf{L}_{AI}^{(i)} \\ \mathbf{L}_{IP}^{(i)} & \mathbf{L}_{IA}^{(i)} & \mathbf{L}_{II}^{(i)} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{PO} \\ \mathbf{x}_{AO} \\ \mathbf{x}_{IO} \end{bmatrix} + \mathbf{S}^{(i)} \xi(t)
\]

where \(\mathbf{L}_{PP}, \mathbf{L}_{AA}, \) and \(\mathbf{L}_{II}\) represent coupling processes intrinsic to each basin, whereas the off-diagonal submatrices \(\mathbf{L}_{PA}, \mathbf{L}_{AI}, \) and \(\mathbf{L}_{IP}\) represent the influence of the AO and IO, respectively, upon the time evolution of the PO. Thus, the coupling between the three basins can be artificially removed by setting all off-diagonal submatrices to zero in the original dynamical operator (Newman et al. 2011; Vimont et al. 2014). This new operator is referred to as \(\mathbf{L}_{\text{decpl}}\), and other “partially decoupled” operators, \(\mathbf{L}_{\text{noPI}}, \mathbf{L}_{\text{noPA}}\) and \(\mathbf{L}_{\text{noAI}}\) are also obtained by zeroing out specific components of TBI (e.g. \(\mathbf{L}_{\text{noPI}}\) is obtained by setting \(\mathbf{L}_{\text{IP}}^{(i)}=\mathbf{L}_{\text{IP}}^{(i)}=0\)). Using these modified linear operators, we have conducted additional LIM forecast experiments with the same initial conditions as the LIM_CTL. These experiments are labeled as LIM_decpl, LIM_noPI, LIM_noPA, and LIM_noAI. We will assess the impacts of individual coupling components by examining their departures from the baseline experiment (LIM_CTL).

### 3. Results

To assess the validity of our LIM approach, we first evaluate the skill of the baseline forecast. For this purpose, we calculate the anomaly correlation coefficient (ACC) between LIM_CTL and observations at lead times of 6 and 12 months (Figs. 1a-d). In most regions, the ACC of LIM_CTL is higher than that of persistence, especially in the tropical Pacific (Figs. 1c, d). LIM_CTL also beats persistence in terms of the root-mean-square error (RMSE) in most areas (figures not shown), suggesting that our LIM-based forecast is reasonably skillful at predicting the tropical SST variability at seasonal to interannual timescales. The skill of LIM_CTL is comparable to that of “standard” LIMs used in previous studies (Penland and Matrosova 1998; Newman et al. 2011; Newman and Sardeshmukh 2017).

We next compare the forecast skills of each sensitivity experiment. ACC differences between the LIM_CTL and LIM_decpl (Figs. 1e and f) clearly demonstrate that the removal of TBI substantially deteriorates the forecast skills of tropical SST anomalies, particularly in the equatorial Pacific and at longer lead times. The relative role played by each coupling component can be evaluated by results from partial decoupling experiments (Figs. 1g-l). They suggest that the PO-IO coupling has the largest impact in the Indo-Pacific sector, though the PO-AO and AO-IO coupling also have a non-negligible contribution to the forecast skill of the PO SST variability for the lead time of 12 months. Similar features are also found in maps of the RMSE difference (figures not shown). Such improvements in ENSO forecast skill due to coupling with other tropical basins have also been reported by several previous studies (Frauen and Dommenget 2012; Keenlyside et al. 2013); those studies, however, did not explicitly separate contributions from individual coupling components. For example, the impact of AO coupling depicted by these works contains both impacts from PO-AO and AO-IO coupling. Our results imply that the AO-IO coupling may also have important impacts upon the forecast skill of ENSO, in addition to the relatively well-studied PO-IO and PO-AO connections. Further observational and modelling studies are required to clarify the significance of this link and related physical processes.
Figure 1: Cross-validated forecast skill of sea surface temperature (SST) anomalies, measured by the anomaly correlation coefficient (ACC) for lead times of (a) 6 months and (b) 12 months for the LIM_CTL. ACC differences between LIM_CTL and persistence forecast are shown in (c) and (d). ACC differences between LIM_CTL and each sensitivity experiment are shown in (e-l). (e and f: LIM_CTL-LIM_decpl; g and h; LIM_CTL-LIM_noPI; i and j: LIM_CTL-LIM_noPA ; k and l; LIM_CTL-LIM_noAI)

An illustrative case demonstrating the importance of TBI is the 2010 La Niña event (Fig. 2b), which has also been investigated by other studies from the viewpoint of tropical interbasin coupling (Kim et al. 2011; Luo et al. 2017). In agreement with observations, the LIM_CTL forecast initialized in March 2010 successfully predicts the emergence of a La Niña event during late 2010, although its magnitude is somewhat underestimated (Figs. 2d, e). In contrast, the LIM_decpl erroneously predicts reemergence of El Niño-like conditions (Fig. 2e), suggesting that TBI plays a crucial role in the phase transition from El Niño to La Niña. During early 2010, both the AO and IO experienced anomalous warming (Figs. 2a, c), and these SST anomalies may have acted to strengthen the easterly wind in the western tropical Pacific by modulating the Walker circulation (Annamalai et al. 2005; Kug et al. 2006; Kim et al. 2011; Luo et al. 2017). The LIM implicitly incorporates such dynamical links in a statistical manner and provides information of their relative importance. Indeed, partial decoupling experiments again demonstrate that the PO-IO coupling has the largest impact, while the PO-AO and PO-AO also play an important role (Fig. 2e), in agreement with GCM sensitivity experiments by Luo et al. (2017).

4. Conclusions and discussions
LIM-based forecasts trained on observed SST anomalies in the three tropical oceans offer a new way to isolate the relative impacts of each component of TBI upon the prediction skill of ENSO and other tropical SST variability patterns. It is found that the PO-IO coupling has the largest impacts on ENSO forecasts, while the PO-AO and AO-IO coupling also play an important role. A typical case demonstrating such features is the 2010-2011 La Niña: LIM forecasts suggest that all the components of TBI are crucial to the rapid phase transition from an El Niño to La Niña event.

Our results show that LIM serves as a powerful tool for investigating the nature and significance of TBI. Since LIM is much simpler and computationally cheaper than GCMs, it is easy to perform various sensitivity experiments that help us to interpret complicated GCM results. In addition, a more detailed mathematical analysis of the linear operator, such as calculations of the optimal initial conditions (Penland and Sardeshmukh 1995; Newman et al. 2011; Vimont et al. 2014) can provide further insights into the dynamics of TBI. LIM may be also useful to elucidate the origin of decadal changes in the strength of individual coupling components (Rodríguez-Fonseca et al. 2009; Martin-Rey et al. 2014).

A caveat of this study is the lack of explicit subsurface ocean memory, which may potentially boosts the forecast skill of the ENSO (Newman et al. 2011). Although some aspects of these elements are implicitly incorporated in the SST-only LIM, it may be interesting to investigate how these variables affect the strength and features of TBI by incorporating more variables (e.g., sea surface height, thermocline depth, and wind stress anomalies) into our LIM.
Figure 2: (a) and (b): SST anomalies in (avv) March 2010 and (b) December 2010 from the ERSST_v5. (c) and (d): As in (a) and (b), but from LIM_CTL initialized in March 2010. (e) Observed and LIM-predicted time series of the Niño 3.4 index (in °C). Note that all LIM experiments are initialized from the same initial conditions in March 2010 (Fig. 2c).

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References


Furthermore, Dominguez et al. (2020) found that the rainfall produced by EWs over Northern South America decreases (increases) when the TC activity over the Main Developing Region (MDR) increases (decreases) but only during neutral El Niño-Southern Oscillation (ENSO) conditions and after the year of 2000. Anomalies in seasonal precipitation (defined as the accumulated precipitation from May to November), anomalies in TC density, and anomalies of integrated moisture flux were analyzed during years of active and inactive TC seasons to prove the proposed hypothesis (figure 2). The findings revealed that EWs produced less precipitation over the tropics during years of high TC activity (i.e., 2005, 2011 and 2012), and most of the moisture is transported into the subtropics, as more TC recurving tracks affect...
the east coast of the USA. In other words, a decrease in seasonal accumulated precipitation in the tropical landmass is caused by fewer EWs that reach the continent (e.g., over NAS) and the drying effect associated with TC circulation, whose tracks affect the east coast of the USA. By contrast, EWs produced more rainfall in Tropical North America during years of low TC activity (i.e., 2006, 2008 & 2013). Consequently, more moisture is transported into NAS as EWs reach the landmass and take a more relevant role in the tropics while TCs are absent (figure 2).

Interestingly, this signal was only present during the most recent decades, which leads to the next question: can the AMO conditions modulate the EW-TC relationship? It was found that AMO+ conditions induce low vertical wind shear and warm sea surface temperature in the tropics. These environmental conditions are favorable for tropical cyclogenesis so that more EWs can become TCs under AMO+ conditions. On the contrary, under AMO- conditions, vertical wind shear is more intense, and the sea surface temperatures are colder, which prevents EWs from initiating TCs over the North Atlantic Ocean. Therefore, the EW-TC relationship is only valid under neutral ENSO conditions and the AMO+ phase.

3. Concluding remarks and future work
EWs and TCs are key tropical phenomena for transporting moisture in the tropics and subtropics. An EW-TC relationship was found during neutral ENSO conditions and AMO+: more (fewer) EWs reach the continental landmass of NSA when fewer (more) TCs form over the MDR. This increase in EW activity causes tropical moisture flux to affect the NAS, but the opposite occurs when the EW activity decreases, as more TCs originate from EWs and tropical moisture is transported towards the subtropics.

Further research should focus on exploring how the different phases of decadal oscillations, as IPO- and AMO+, or other combinations, can influence the behavior of tropical phenomena in frequency, rainfall, and their role in transporting moisture.

Tropical phenomena are key elements to define if certain regions will experience wet or dry years and, consequently, impact water availability and socioeconomic activities.

References


1. Introduction

El Niño-Southern Oscillation (ENSO) generates perturbations in temperature, precipitation and winds that alter the large-scale atmospheric circulation and trigger a cascade of weather patterns affecting the weather and climate throughout the world (Davey et al., 2014). Given the widespread impacts of ENSO, its skillful prediction at seasonal timescales has paramount importance in accurately predicting temperature and precipitation at different regions of the world. Despite the recent progress in predicting ENSO, not all systems remain equally skillful, as demonstrated by the large spread in ENSO predictions across a selection of prediction systems from the multi-model ensembles NMME, EUROSIP and the in-house EC-Earth (figure 1a; the prediction systems are described in Exarchou et al. (2021)).

There is important potential for improving seasonal predictions of ENSO through increased understanding of the dynamical connections among the tropical basins. While the effects of ENSO on other tropical oceans, like the Tropical Atlantic and Indian Oceans, are well studied, the feedbacks of other tropical basins back onto the Pacific are less known and under an ongoing debate (Cai et al., 2019). A center of such an interbasin connection is the equatorial Atlantic, where a variability similar to ENSO takes place in the boreal summer. The equatorial Atlantic variability is commonly described by the SST anomalies over the ATL3 region in the East Atlantic (20°W–0, 3°S–3°N). ATL3 exhibits an interannual variability that, similar to ENSO variability, creates warm and cold events, also known as Atlantic Niños and Niñas. Recent studies based on observations have demonstrated that summer Atlantic Niños (Niñas) favor the development of Pacific Niños (Niñas) the following winter (Rodríguez-Fonseca et al., 2009; Ding et al., 2012). Anomalous heating during an Atlantic Niño leads to local wind convergence, altering the Walker circulation and increasing subsidence over the central Pacific. The latter leads to anomalous divergence at the surface that enhances easterly winds on the western Pacific. These in turn trigger an equatorial upwelling oceanic Kelvin wave that propagates eastward, cooling the surface and thus promoting the occurrence of a Pacific Niña event. A positive Bjerknes feedback mechanism further maintains this ENSO phase. Opposite changes occur during the Atlantic Niñas. The Atlantic-Pacific connection has been shown to be compromised by the long standing systematic biases in the tropical regions (Richter et al., 2016). However, despite the recent evidence that errors in tropical mean state and variability can deteriorate the Atlantic-Pacific connection and the Pacific mean state and seasonality (Dippe et al., 2018; Prodhomme et al., 2019; Li et al., 2020), the impact of the equatorial Atlantic, and specifically of its mean state biases and erroneous variability, on the prediction skill of ENSO, remains an open question. This impact on ENSO prediction skill at seasonal timescales is the main research question addressed in this study. The results of this analysis have recently been published by the authors of the present article in Exarchou et al. (2021). Here we summarize the main results.

2. Tropical prediction skill and Atlantic-Pacific connection in a multi-model ensemble

Here we assess the prediction skill of the Atlantic and Pacific Niños and their sensitivity to the Atlantic-Pacific connection in a multi-model ensemble. The en-semble consists of 11 prediction systems from NMME (Kirtman et al., 2014), 3 systems from
EUROSIP and the in-house model EC-Earth (version v3.1, an older version is described in Hazeleger et al. (2012)), amounting up to 15 models in total. The prediction systems are initialized in June, when the teleconnection starts developing. The June initialization also ensures that the Atlantic variability in the predictions is decoupled from the previous winter ENSO event, allowing us to focus exclusively on the Atlantic-Pacific teleconnection pathway without the influence of the Pacific/Atlantic one.

The prediction skill in Niño3, evaluated with the Anomaly Correlation Coefficient (ACC), is shown in figure 1a. The Niño3 skill is relatively high, demonstrating that recent developments in climate models dynamics and their initialization techniques in recent years have resulted in improvements in the initialized sub-surface anomalies and in the representations of the dynamical aspects of the Bjerknes feedback loop (McPhaden, 2003; Rashid, 2020; Barnston et al., 2019). Despite the high skill in Niño3, there is an appreciable inter-model spread which grows larger with forecast time (0.5 − 0.9 by March). With this study we are exploring the part of this spread that can be explained by a different representation of the teleconnection mechanisms with the equatorial Atlantic and the inter-model spread in the equatorial Atlantic prediction skill. The latter is shown in figure 1b, evaluated with the ACC in the ATL3 region, which is the centre of equatorial Atlantic variability. ATL3 has comparatively low skill and a large inter-model spread (0.2 − 0.7 by September).

The relation between the spread in the boreal summer (JJA) ATL3 skill and the following boreal autumn (SON) and winter (NDJ) Niño3 skill is strong and significant, with correlation values 0.78 and 0.82, respectively (not shown). To assess how the ENSO skill is related to the Atlantic-Pacific connection, we evaluate the latter as the correlation between the boreal summer ATL3 and boreal summer, autumn and winter Niño3. The corresponding correlations from observations are -0.45, -0.46 and -0.49, which are negative as expected by the link between warm (cold) summer ATL3 phases with the latter occurrence of cold (warm) winter ENSO events (Rodríguez-Fonseca et al., 2009; Ding et al., 2012). All models underestimate the magnitude of the correlations and show a large spread, from −0.07 to −0.41 in the autumn, and from −0.06 to −0.42 in the winter. The large model spread, is indicative of the models’ inability to properly represent the teleconnection. Interestingly, the spread in the teleconnection strength also correlates significantly with the skill of Niño3 in the corresponding season (-0.56 and -0.62, respectively for autumn and winter), verifying that the uncertainty in the teleconnection plays a role in the spread in Niño3 skill (not shown).

3. EC-Earth experiments

The above analysis points at a significant role of both the Atlantic-Pacific connection and the ATL3 variability in achieving higher levels of skill in Niño3. To show further evidence for the causal link between ATL3 variability and the Niño3 skill, we use EC-Earth to perform a sensitivity analysis using seasonal predictions. The analysis comprises two sets of seasonal forecasts for the period 1981-2018. First, a baseline prediction ‘CTR’ (already included in the multi-model analysis and in figures 1 discussed above, but for the shorter period 1981-2011). Second, a pre-
SST nudging increases, as expected, the prediction skill of ATL3, according to both the ACC and the root mean square error (RMSE metrics (Fig. 2a, b), with values significantly better in the nudged experiments than in CTR at all forecast times. In Niño3, both nudged experiments start to show significant improvements in ACC with respect to CTR in early autumn (ASO) and the subsequent months, both for Niño3 and Niño3.4 indices (results for Niño3.4 not shown). RMSE improvements are also seen, starting in early autumn.

The improvements in the nudged experiments are not limited to the skill, but also to the representation of the Atlantic-Pacific connection. This is illustrated by the improvements in the spatial correlations of the JJA ATL3 index and the lower and upper part of the JAS Walker circulation, as described by the velocity potential at 200 hPa (figure 3a). For the positive JJA ATL3 phases, observations suggest that one month later (i.e. JAS) there is an increase in convection over the Tropical Atlantic accompanied by enhanced subsidence over the central Tropical Pacific. Qualitatively, both CTR and NUD are able to represent this response in Root Mean Square Error RatioAnomaly Correlation Coefficient ATL3 Anomaly Correlation Coefficient NINO3 Root Mean Square Error Ratio the Walker circulation. But while the CTR forecast system clearly underestimates the magnitude of the correlations, these are visibly higher, and therefore closer to the observed ones in NUD (figure 3d, h). This improvement manifests clearly at the surface, where the ATL3-nudged experiment also develops a more realistic response in SST and winds (figure 3i-l).

4. Concluding remarks

Here we have investigated the impact of the equatorial Atlantic on ENSO predictive skill and demonstrated that a good representation of ATL3 (as the centre of action in equatorial Atlantic) and its teleconnection over the Tropical Pacific boost the predictive skill of ENSO. With a multi-model analysis of 15 state-of-the-art prediction systems we show here that there is a strong and significant relation between the ENSO predictive skill and both the ATL3 skill and the Atlantic-Pacific connection. With an additional set of sensitivity experiments, where we apply SST nudging over the equatorial Atlantic (thus allowing us to single out the influence of the equatorial Atlantic while excluding other neighboring areas), we demonstrate that improvements in the equatorial Atlantic result in improvements in the prediction skill of ENSO according to both the ACC and the root mean square error, but also in improvements in the teleconnection.

The general improvements after SST corrections on the equatorial Atlantic, which involve a better teleconnection, offer interesting prospects for dynamical seasonal predictions of ENSO. Unfortunately, the tropical Atlantic is a region of key uncertainty in the climate system: state-of-the-art climate models exhibit large systematic errors (Richter et al., 2018). Correcting these errors can thus be beneficial not only in the Atlantic but worldwide, by improving the prediction skill of ENSO, and through it of the prediction of ENSO’s most important widespread climate impacts.

Recent studies also suggest an important influence of the equatorial Atlantic variability on the Indian summer monsoon rainfall (ISMF) by enhancing the Kelvin wave response into the Indian Ocean (Sabeerali et al., 2019). By inspecting our sensitivity experiments with EC-Earth we can see that improving
the equatorial Atlantic results also in significant skill increase in the SST over the West Indian Ocean (WIO) and Indian Ocean Basin (IOB) (figure 4a, b). However, there is no significant change for precipitation neither for the ISMR nor for the Extended Indian Monsoon Rainfall (EIMR) (figure 4c, d). Our current setup does not exclude the ENSO influence over the Indian Ocean. Further analysis exploring the Atlantic-Indian connection (excluding ENSO’s influence) could offer possibilities of enhancing the predictive skill over the Indian region and provide further motivation for modeling groups towards reducing tropical Atlantic biases and improving its seasonal and interannual variability.

Figure 4: Prediction skill for CTR and NUD (evaluated by the Anomaly Correlation Coefficient; ACC) of a) West Indian Ocean (WIO, 60°E 80°E–10°S 10°N) SST, b) Indian Ocean Basin(40°E 110°E–20°S 20°N) SST, c) Indian summer monsoon rainfall (ISMR, precipitation averaged over land in the region 70°E 95°E–5°N 30°N), d) Extended Indian Monsoon Rainfall (EIMR precipitation averaged in the region 70°E 110°E–10°N 30°N). Skill in SST is evaluated against HadISSTv1.1, in land rainfall against GPCC, and in land and ocean rainfall against GPCPv2.3. The period is 1981-2018. Empty circles indicate when the prediction skill is statistically significant (p < 0.05); full circles and full rhombuses when NUD has significantly higher skill than CTR (p < 0.05 and p < 0.1, respectively).

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The statistical analysis of climate variability commonly exploits cross-correlations to characterize the mutual relationships between (one-dimensional) time series. However, correlation measures by definition do not imply causality and suffer from several drawbacks. For example, the presence of autocorrelation in one of the two time series can be enough to inflate the correlation between them and indicate an actually spurious statistical relationship. Similarly, two time series may fluctuate in synchrony (and thus potentially exhibit a statistically significant correlation) because they are both driven by the same third variable (common driver) or because a third variable communicates the signal between them (indirect link).

Causal discovery tools, such as the Peter and Clark Momentary Conditional Independence (PCMCI) algorithm (Runge et al., 2019), can help to disentangle spurious from actual causal links among a set of time series by applying a sequence of iterative operations. In this framework, the concept of “causality” depends on several assumptions, relating to the theoretical conditions of causal Markov property, faithfulness, causal sufficiency, and stationarity of the causal links, and the term causal is always meant as “causal with respect to the set of analyzed variables” (Runge, 2018). With the PCMCI algorithm, causality can be quantified based on different association measures, and it can be directly applied to produce “causal effect networks” (CEN) (Kretschmer et al., 2016). Such CEN provide abstract representations of the causal links among a set of dynamical variables (time series), which can be visualized (see figure 1 for an example) by arrows (indicating the strength and the direction of the causal links) and circles (representing each time series - or actor - used in the CEN). In the most common linear framework, the PCMCI algorithm is based on iteratively calculating partial correlations between pairs of variables conditional on sets of third variables, while a (more data-demanding) nonlinear version replaces the partial correlations by the so-called conditional mutual information. The concept is also readily applicable to full (two-dimensional) fields of climate variability by either iterating on each grid point or by identifying potential precursor regions (Di Capua et al., 2020a; Kretschmer et al., 2017), leading to the concept of causal maps (figure 2) and the Response-Guided Causal Precursors Detection (RGCPD) scheme.

Causal effect networks have already been successfully applied in several recent studies to problems such as stratospheric polar vortex dynamics (Kretschmer et al., 2016, 2017), forecasting of crop yields (Lehmann et al., 2020), Indian summer monsoon (ISM) dynamics (Di Capua et al., 2019, 2020b) and, more general, tropical – extratropical teleconnections (Di Capua et al., 2020a). For example, studying the interactions between the ISM circulation system and tropical precipitation patterns can provide insights into the predictability of extreme weather events.
the extratropical circumglobal teleconnection (CGT) pattern at intraseasonal time scales during boreal summer (Di Capua et al., 2020b) revealed not only the causal nature of the ISM–CGT coupling (previously hypothesised based on simple correlation). Moreover, it also allowed quantifying the respective magnitudes of causal effects exerted by different tropical and extratropical drivers on ISM intraseasonal variability (figure 1). Those results demonstrate the importance of mid-latitude wave trains originating in the North Atlantic in driving changes in the weekly amount of ISM rainfall. The underlying two-way causal interaction between ISM and mid-latitude circulation is also found when causal maps are calculated starting from the dominant modes of covariability between tropical convective activity and extratropical circulation (Di Capua et al., 2020a). Figure 2 shows how the South Asian monsoon (SAM) and the circumglobal teleconnection (here defined as the first mode of covariability identified using maximum covariance analysis (MCA) between weekly geopotential height at 200 hPa (Z200) in the mid-latitudes and outgoing longwave radiation (OLR) in the tropics) affect circulation and surface conditions in the Northern Hemisphere during boreal summer at one-week lag. Comparing panels 2a and 2b (showing correlation maps) with panels 2c and 2d (showing the respective causal maps), it is possible to distinguish which regions are directly influenced by either SAM or CGT and which show spurious links (e.g. North Africa). Finally, RGCPD has been successfully employed to identify the causal precursors of interannual variability of ISM rainfall (Di Capua et al., 2019).

At present, remaining practical challenges of the aforementioned methods include the length of the datasets, the integration of variability at different time scales and the effect of choosing a specific (linear or nonlinear) framework. Moreover, CEN assume stationarity of the dataset, hence making it difficult to study climate change related effects or nonstationarity intrinsic to the data. This problem can however be addressed, when enough data are available to allow for the time series to be split in several subsets (Di Capua et al., 2019).

Despite the need for further theoretical work, causal discovery tools like those described here represent a promising tool to help empirically identifying new mechanisms linking climate variability among regions and challenging the causality of links already reported in the literature. Especially tropical basin interactions present a topic for which CEN, RGCPD and causal maps have great potential to contribute important new insights. For example, they could prove useful in answering questions like: Where does the influence of the El Niño–Southern Oscillation reach in the other basins (and vice versa), and which pathways contribute how strongly? Is it possible to identify large-scale drivers of ENSO variability at different time scales? Or, more specifically, how does the connection between the tropical Atlantic and Pacific Ocean influence especially the development phase of La Niña events, as suggested in recent studies (e.g. Exarchou et al., 2021, and references therein)? These are just a few examples for ongoing research problems in the field of tropical basin interactions that could be further addressed by applying PCMCI-based tools.

Figure 2: Influence of the leading coupled pattern from MCA of tropical OLR and Northern Hemisphere mid-latitude Z200 fields on Northern Hemisphere circulation (reproduced from ref. [5]). (a) Correlation map between the weekly South Asian Monsoon (SAM) time series and the Z200 field. (b) Same as panel (a) but for the dependency between weekly CGT time series and the Z200 field. (c) Path coefficient β for link SAM,τ = −1→Z200,τ = 0 for a 3-actors CEN built with SAM, CGT and Z200. Here, the ”1” denotes the conditioned-out actor (CGT). (d) Same as (c) but for the link CGT,τ = 1→Z200,τ = 0. The ”1” again denotes the conditioned-out actor (SAM). Panels (e) and (g): Same as panel (c) but for the influence of SAM on OLR and 2m air temperature (T2m) fields, respectively. Panels (f) and (h): Same as panel (d) but for the influence of CGT on OLR and T2m fields, respectively. Only path coefficients β with p < 0.05 are shown. The dashed black line located at 30° N shows the border between the tropical and the mid-latitude belt that separates the considered OLR and Z200 data domains.

References


There exist at least three main possibilities for improving our understanding of tropical climate variability and inter-regional coupled processes. (i) Expanding the available observational record with longer and more reliable data sources. (ii) Further developing state of the art climate models and applying them to systematically studying the phenomena of interest. (iii) Utilizing advanced methodological approaches for uncovering statistical and dynamical information on essential space-time variability patterns contained in both types of datasets. Since the first option is very limited practically, recent progress has mainly focused on the second one. However, also ongoing methodological developments at the interface between statistics, theoretical physics and computer science provide new empirical perspectives on climate variability.

Climate scientists are commonly well-trained in applying standard techniques of spatiotemporal data analysis such as empirical orthogonal function (EOF), canonical correlation or maximum covariance analysis. One common feature of those methods is that they are based on linear correlations between time series and inherit some linear matrix manipulation technique (e.g., eigen or singular value decompositions). This twofold linearity (i.e., orthogonality) assumption puts strong constraints on the spatiotemporal variability modes identified by those traditional methods, which may not necessarily be uniquely attributable to specific climate mechanisms. In the last two decades, several approaches have been developed to address this issue. On one hand, nonlinear dimensionality reduction techniques have relaxed both assumptions and paved the way for machine learning techniques to enter climate science. On the other hand, complex system tools like causal inference and complex network techniques have proven their utility to complement classical statistical climate analysis. In what follows, I will briefly elaborate on functional climate network analysis (Tsionis et al. 2006; Donner et al. 2017; Dijkstra et al. 2019) as an important representative of the latter class of methods and its achievements and prospects in the context of research on tropical basin interactions.

The general idea of functional climate networks can be easily understood when drawing upon similarities with the established EOF analysis (Donges et al. 2015). Let us suppose that as soon as we have computed the correlation matrix based on some climate variable, EOFs are identified by means of an eigenvalue decomposition and return spatial patterns of strong co-variability (the empirical orthogonal functions) along with their associated temporal variability (the principal component scores). Notably, this mathematical transform utilizes all pairwise correlations (also the very weak ones) and provides patterns that do not allow directly assessing the specific relevance of each single grid point (for which one would commonly study single-point correlation/regression maps). By contrast, functional climate networks filter the strongest mutual associations among all time series and retain explicit information on the spatial placement of those “links”, hence reflecting functional relationships between different points in space (“nodes”) by taking strong statistical linkages as a corresponding proxy.

However, the functional climate network approach is far more than just a kind of “filtered EOF analysis”. In addition to choosing different climate variables for analysis (step 1 in figure 1), it is possible to utilize different similarity measures for establishing information on statistical associations (step 2). For example, instead of linear lag-zero correlation, alternative concepts previously employed include nonlinear mutual information or association measures between sequences of (extreme) events identified in each time series, such as event synchronization strength or event coincidence rate (Wolf et al. 2020).

Moreover, there exist different ways for filtering the obtained fully populated similarity matrix by selecting thresholds to the pairwise similarity measure in a global or local way (step 3). Finally, we are not restricted to the analysis of eigenvalues and eigenvectors within the EOF framework, but can exploit a vast toolbox of topological as well as...
geographical characteristics of the resulting complex, geographically embedded network representations (step 4). Even more, extensions of this methodology include multi-layer and coupled climate networks for studying interdependence patterns among two or more climate fields, or scale-specific climate networks to highlight spatial co-variability patterns associated with specific time scales.

In the context of tropical climate variability, climate network based studies on ENSO variability have provided deep insights into global surface air temperature co-variability reorganization associated with different flavors and successions of ENSO phases (Wiedermann et al. 2016; Kittel et al. in review). Specifically, the network transitivity index consistently discriminates between East and Central Pacific flavors of both El Niño and La Niña. Conceptually related approaches have provided skillful forecasts for El Niño occurrence and magnitude (Ludescher et al. 2013, Meng et al. 2020). Even more, exploiting the local connectivity properties of global surface air temperature based climate networks further allows identifying regions that are teleconnected with ENSO variability during El Niño or La Niña phases. While previous studies have focused primarily on instantaneous co-variability, a straightforward generalization to lagged correlations allows for an improved detection of relevant tropical basin interactions.

A second important recent research line addresses linkages between different regions and/or climate variables in terms of coupled network representations (Donges et al. 2011). Prominent examples include studies on the co-variability of sea surface temperature (SST) and continental precipitation at global and regional scales (e.g., Ekhtiari et al. 2019, 2021). By exploiting the resulting network connectivity properties, Ciemer et al. (2020) recently identified skillful SST predictors of Amazon basin rainfall deficits in both the tropical Pacific and Atlantic oceans. Notably, these predictors go beyond the long known influence of the Atlantic Meridional Mode on rainfall in Northeast Brazil (Hastenrath and Heller 1977, Nobre and Shukla 1996) and emphasize that the coordination between northern and southern tropical Atlantic SST anomalies is key for the emergence of strong drought conditions. More specifically, the time-dependent correlation between SST anomalies in both regions serves as a reliable early warning indicator at lead times of up to 18 months. A similar inter-regional coupled network analysis based on event synchrony allows for studying the linkages between heavy rainfall occurrences in different monsoon regions. For example, heavy rainfall patterns during the East Asian monsoon season have been found to exhibit synchronous occurrences in two characteristic regions north and south of the main Baiu-Meiyu front due to the constructive yet episodic interplay between lower and upper level winds associated with the South Asian anticyclone and Northwest Pacific subtropical high, respectively (Wolf et al. 2021). Taking such analysis one step further allows also studying interrelationships between, e.g., the South and East Asian monsoon branches based on synchronous (or systematically time-lagged) occurrences of heavy rainfall events (figure 2).

In summary, recent work has opened new perspectives for employing complex network techniques for disentangling tropical climate variability among variables, regions, and time scales. For the latter purpose, existing examples for scale-specific climate network analyses (e.g., Ekhtiari et al. 2019) can be combined with new nonlinear statistical-dynamical approaches for quantifying cross-scale coupling that have been recently shown to allow disentangling ENSO variability (Jajcay et al. 2018). Taking all these exciting developments together, complex network applications to studying mutually delayed, scale-specific or even multi-scale coupling mechanisms between the tropical ocean basins (and relevant extratropical drivers) will provide an emerging topic of research in the upcoming years.

References


Introduction
Tropical central-to-eastern Pacific sea surface temperature (SSTs) experienced a notable cooling trend during ~1990-2013, together with the strengthening of Pacific trade winds (England et al. 2014). Pioneering studies have suggested this Pacific La Niña like change is the combined effect of internal variability (e.g., Interdecadal Pacific Oscillation, IPO) and external forcing (Meehl et al. 2013; Kosaka and Xie 2013; Marotzke and Forster 2015; Takahashi and Watanabe 2016; Smith et al. 2016). Nevertheless, the majority of Coupled Model Intercomparison Project phase 5 historical simulations (Taylor et al. 2012), which are generated by perturbed initial conditions and historical anthropogenic forcing, failed to reproduce this Pacific cooling trend (Meehl et al. 2014; Luo et al. 2017). Previous studies implied the failure of reproducing the Pacific cooling trend in the current climate models is partly due to the underrepresentation of trans-basin teleconnections (Luo et al. 2012; Han et al. 2013; McGregor et al. 2018; Luo et al. 2017).

Here we focus on the Atlantic-Pacific connection, due to the reported rising influence of the Atlantic Ocean on Pacific decadal variability in recent decades (Cai et al. 2019). A hierarchy of climate model simulations suggest that Atlantic warming accounts for a large part of the Pacific SST cooling and related Walker circulation changes (McGregor et al. 2014; Li et al. 2016). Thus, reproducing the trans-basin Atlantic-Pacific teleconnection is a key component for the models to capture the recent Pacific cooling trend. In this study, we investigate the roles of the model mean SSTs in capturing the atmospheric Atlantic-Pacific teleconnection.

Experimental design
We first conducted four sets of partially coupled (PARCP) UM7.3 (the Met Office Unified Model) experiments, with a slab mixed-layer ocean in the Pacific basin, to explore the Pacific SST response to the prescribed Atlantic warming forcing under different background SSTs, including: (1) the observational global monthly SST mean state; (2) with the CMIP5 multi-model ensemble monthly mean SST biases added into the Atlantic region; (3) with CMIP5 ensemble mean SST biases added to the Pacific region; and (4) with mean SST biases added to both the Atlantic and Pacific regions. To achieve these differing background SSTs, flux adjustment schemes are used to mimic the observed or the biased CMIP5-like mean state in the respective ocean basin. The fixed Atlantic warming pattern is obtained by multiplying the observed Atlantic SST trend during 1992-2011 by the total time period (figure 1a-d). For each set of experiments, we performed a pair of simulations: one control run where the Atlantic SST are prescribed to climatological SSTs, while the Atlantic warming run includes the observed Atlantic warming pattern superimposed on to the same climatology. Thus, the difference between them can be considered as the model’s response to the Atlantic warming forcing. Another four sets of atmosphere-only (AGCM) experiments (i.e., the SST-atmosphere coupling of the Pacific Ocean is turned off) are performed, which allows us to see the direct effect of the different background SSTs on the Pacific region’s atmospheric response to the prescribed Atlantic warming in the absence of coupled interactions in the Pacific.

Model results
Although the Pacific cooling response occurs in all experiments, the magnitude of Pacific cooling is significantly reduced in the simulations when background SSTs in either the Pacific or Atlantic region are nudged towards the biased CMIP5 mean SST (figure 1b-d), relative to the observed climatology simulation (figure 1a). The Atlantic mean state bias appears to have a somewhat stronger effect on the SST response of the eastern Pacific (figure 1e), while the SST and surface wind stress responses in the central Pacific tend to be more sensitive to the Pacific mean state bias (Figure 1f). In accordance with the reduced SST cooling response, the strengthening of central Pacific trade winds (6S-6N, 160E-140W) was also largely underestimated. Thus, background state biases in the Pacific and Atlantic Ocean individually both clearly act to supress the trans-basin induced Pacific cooling. Further to this, when combining the CMIP5-like background state biases in both Pacific and Atlantic Ocean basins, the simulated central-to-eastern Pacific cooling is further dampened. The combined impacts of these background state biases result in a simulated central-to-eastern Pacific cooling that is weakened by ~89% relative to the observed

Impacts of the model mean SST biases on the Atlantic-Pacific teleconnection

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climatology simulation. This result confirms the SST mean state biases in both regions play an imperative
and constructive role in reducing realistic trans-basin Atlantic-Pacific connections.

**Mechanisms**

Comparing the AGCM experiments with the partially coupled (PARCP) experiments shows significant differences to the simulated vertical velocity in response to the imposed Atlantic Ocean warming when this is superimposed over either the observed mean state (black lines in figure 2), or the CMIP5-like mean states (coloured lines in figure 2). McGregor et al. (2018) suggest that adding the CMIP5 Atlantic SST bias, with a warm SST bias in the southeastern tropical Atlantic along with a cold bias prevailing in the northwestern Atlantic, acts to alter the regions that are above or below the threshold for deep convection. This results in a weakening of the Atlantic atmospheric heating response to the prescribed tropical Atlantic warming trend along with reducing the ascending motion between 90W to 30W and a shift of the maximum ascending motion eastward. This weakening and eastward shift of the Atlantic heating response leads to a reduction in the descending motion of the central Pacific (180E to 135W), further reducing the anomalous easterly wind response in the central equatorial Pacific. Thus, an underestimated strengthening of the Pacific Walker circulation and a weakened Pacific cooling response is expected when Atlantic warming is imposed on top of common model background SSTs in the tropical Atlantic region.

**Results from our Atlantic bias experiment generally confirm those of the previous study, finding a similar eastward shift of the atmospheric circulation response (figure 2 a, c, d, f).**

**Figure 1:** SST and surface wind stress response in PARCP simulations. a, Simulated surface temperature (shading; °C) and wind stress (vectors; N m⁻²) response to the Atlantic warming forcing under the observed SST mean state. The Atlantic warming pattern is obtained by multiplying the observed Atlantic SST trend during 1992-2011 with 20 years. b-d, As in a, but with additional CMIP5 Atlantic mean state bias, Pacific bias, and the combined Atlantic/Pacific bias in the SST background, respectively. e, f, g, the response differences between b and a, c and a, and d and a, respectively. Stippling indicates the statistical significance at the 10% level for SST. Only the significant wind stress (zonal or meridional component reaches the 10% level) is shown in the plots.

**Figure 2:** Vertical velocity response in PARCP and AGCM simulations. a-c, The averaged equatorial (15S-15N) vertical velocity (1000-200hPa) response to the Atlantic warming in PARCP simulations. The black lines represent the response under observed mean state. The red, blue, and green lines represent the result from Atlantic bias, Pacific bias, and combined Atlantic and Pacific bias simulations, respectively. The grey shading indicates that the differences between the
bias and unbiased simulations are above 90% confidence level. d-f, As in a-c, but for the AGCM simulations. Note the positive vertical velocity (unit: mm/s) represents upward motion and vice versa.

The introduction of the Pacific region background SST bias leads to a significant reduction in upward motion over the tropical Atlantic region (figure 2e) in the Atmosphere-only simulations. The reduction in Atlantic ascending air along with weakened convection are also robust in the lower layer’s velocity potential and precipitation responses. This raises the question of how biased Pacific background SSTs affect the Atlantic heating response. The CMIP5 ensemble mean background SST shows a strong warm bias in the southeastern Pacific. This positive SST bias has been considered as a dominant driver of the so-called double intertropical convergence zone (ITCZ) problem in CMIP5 models (Queslati and Bellon 2015), which is presented as stronger than observed precipitation south of the equator in the Pacific. The strong convection tends to warm the upper troposphere, in particular, the warm effect is stronger and more expanded in the upper atmosphere than the near-surface, thus stabilizes the atmosphere and reaches into the tropical Atlantic. This enhanced Atlantic stability acts to weaken the Atlantic heating response and reduces the descending motion in the central Pacific (figure 2b, e). The change of vertical motion can further affect the Pacific surface heat flux dominated by the wind-evaporation-SST feedback: the weaker descending velocity leads to an undermined southwesterly surface wind response in the central Pacific. These surface wind changes reduce the anomalous surface wind speeds, restricting the surface latent heat flux, and therefore contributing to the underestimated Pacific SST cooling effect (Li et al. 2020).

In addition to modulating the Atlantic-Pacific ascending and descending motions, adding the CMIP5 Pacific background SST bias also tends to dampen the Pacific’s own amplifying wind-SST feedback (Li et al. 2020). This weakening feedback is manifested by a weakening relationship between the central Pacific (6S-6N, 160E-140W) zonal wind stress anomaly and the Niño3.4 SST anomaly (figure 3a). The weakened atmosphere positive feedback is also associated with a weakening and westward shift of the Walker circulation’s rising branch (figure 3b). In observations, the strong zonal wind feedback is caused by a convective response in the western to central equatorial Pacific. A cold SST mean state in this region, which is the most common equatorial bias in the current climate models, contributes to a westward shift of the Walker Circulation and a weaker convective response, and further determines the strength of zonal wind feedback.

![Figure 3: Pacific atmospheric zonal wind-SST feedback and mean Walker circulation in PARCP control simulations. (a) The linear regression of the monthly anomalous central Pacific zonal wind stress (6S-6N, 160E-140W) and Niño 3.4 SST (5S-5N, 170-120W) under different SST mean state background, (Unit: N m-2 °C-1). Vertical bars represent the standard error of the regression coefficient. (b) Averaged equatorial (15S-15N) vertical velocity (200-1000hPa) in the PARCP control run simulations (Unit: mm s-1). The solid colored lines indicate the vertical velocity differences between the biased simulations and unbiased simulation (the black line) are statistically above the 90% level.](image-url)
Summary
Targeted climate model experiment results suggested that common model SST biases in Atlantic and Pacific both help to explain the underestimated Pacific cooling in response to the rapid Atlantic Ocean warming that occurred between ~1990-2013. The Atlantic mean SST bias acts to reduce and shift eastward the atmospheric heating response to the tropical Atlantic warming forcing. On the other hand, the Pacific SST bias tends to weaken the trans-basin teleconnection by strengthening the Atlantic atmospheric stability. Besides, the Pacific SST bias also acts to substantially undermine the positive zonal wind-SST feedback in the tropical Pacific. Furthermore, when combined, the Pacific and Atlantic SST biases led to a Pacific cooling response that is almost non-existent (underestimated by 89%). Future efforts aimed at reducing the model mean state biases may significantly help to improve the simulation skills of trans-basin teleconnections.

It is important to note that although the use of slab ocean model allows us to adjust the Pacific SST mean state and focus on the atmospheric dynamics, the absence of oceanic dynamics (which can provide an amplification effect) may lead to an underestimated Pacific SST response to the Atlantic forcing. Moreover, the eastern Pacific SST variability in the slab ocean is halved, compared with that in the fully coupled model. Further studies are needed to address the role of SST mean state while including active ocean dynamics.

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Here we present results from three different kind of experiments designed to shed light on the problem of inter-basin connectivity. All experiments use as testbed the ECMWF seasonal forecasting system (SEAS5, Johnson et al. 2019). The first experiment is an initial value problem case study, targeting the impact of the Indian Ocean initial conditions in the unusual evolution of El Niño-Southern Oscillation (ENSO) during 2014-2016. The second experiment is a seasonal attribution case study conducted in uncoupled mode; it aims to attribute the source of the positive NAO predictability during DJF 2019-2020. The third experiment is a seasonal re-forecast ocean observing System Experiment (SF-OSE) and intends to quantify the impact of the ocean in-situ observations on the characteristics of the coupled forecast. The details of these three experiment types and the key results are illustrated and summarized below.

Case Study of Initial Value Problem: Role of the Indian Ocean Initial Conditions on the 2014-2016 ENSO events

After a false alert in the northern winter 2014/15, in 2015/16 one of the strongest El Niño events on record occurred in terms of the standard Niño 3.4 SST anomaly index (N3.4 in what follows). A study based on reanalyses revealed that the 2015/16 El Niño was also associated with unusual energy transfers (Mayer et al. 2018). Most notably, the Indonesian Throughflow (ITF) was exceptionally weak during 2015-2016, which led to the retention of warm waters in the Pacific Ocean. The weak ITF appeared related to the relatively high sea level in the Indian Ocean with respect to the Western Pacific. This result pointed toward the possibility of predicting the ITF and its impact on ENSO two years ahead.

To further explore this possibility, sets of 24-month coupled seasonal forecast have been conducted using the ECMWF SEAS5 seasonal forecasting system. Each experiment consists of 50 ensemble members. The reference experiments were initialized from ORAS5 (Zuo et al. 2019) in February 2014 and February 1997. In the perturbed experiments, the Indian Ocean initial conditions are swapped between 2014 and 1997. The results are discussed in Mayer and Balmaseda (2021) and confirm the hypothesis that the exceptionally warm Indian Ocean state in 2014 was responsible for the unprecedented reduction of observed ITF transports and retention of heat in the Pacific. The results also show that both ocean tunnel and atmospheric bridge contribute to the impact of the Indian Ocean on ENSO.

Figure 1 shows the array of probabilities for Cold events (N3.4 < -0.5), Neutral conditions (-0.5 < N3.4 < 0.5), Warm (N3.4 > 0.5) and Extreme warm (N3.4 > 1.8) events for December of year 1 and December of year 2. The two reference experiments are able to discern the contrasting ENSO evolution during 1997–99 and 2014–16. The perturbed forecasts exhibit a marked shift in ENSO probabilities compared to their respective reference. The perturbed 2014–16 forecast more than doubles the probability of a strong El Niño event in year 1 compared to the reference forecast (48% versus 18%). The main reason for this change is the increased probability of a positive Indian Ocean Dipole event, which promotes development of a strong El Niño event through atmospheric teleconnections (atmospheric bridge, not shown). In year 2, the perturbed forecasts exhibit an enhanced probability of a La Niña event (18% versus 4%), mainly due to the much stronger ITF transport, which leads to more heat loss in the Tropical Pacific, preparing the ground for the switch to cooler La Niña conditions. The perturbed 1997–99 experiment (not shown) confirms that the Indian Ocean initial conditions matter for the 24-month ENSO predictions.

In summary, the Indian Ocean state in 2014 decreased the probability of an extreme warm event in the Pacific in 2014/15 but increased the probability of the warm conditions in 2015/16 that actually occurred. The influence of the Indian Ocean on ENSO is via the atmospheric bridge in the first year, and via the ocean tunnel in the second year. These results demonstrate the importance of the Indian Ocean low frequency variability and trends for seasonal forecasts. They also highlight the potential merit of two-year-long ENSO predictions, as forecasters may have interpreted the predictions in 2014 differently if lead times beyond a year had been available.
Figure 1: Probability of occurrence of ENSO events in the reference and perturbed experiments. The first two charts show the probability of ENSO events in December 2014 and December 2015 according to a reference forecast starting in February 2014 and a perturbed forecast where Indian Ocean initial conditions were swapped with those from February 1997. The third chart shows a reference forecast starting in February 1997. The probabilities were derived from counting ensemble members. Bars represent probabilities of La Niña, neutral, moderate and strong El Niño events. Observed values for N3.4 are shown as well. The bars are medians and the whiskers 5% and 95% quantiles of the probabilities. The figure has been adapted from Figure 5 in Mayer and Balmaseda (2021).

Case Study of SST as boundary forcing: Attribution of seasonal predictability of the positive NAO in DJF 2019-2020

The positive NAO signal during DJF 2019-2020 was well predicted by several seasonal forecasting systems from November 2019, including SEAS5. This provided a unique opportunity to investigate the source of the NAO predictability by deconstructing a successful forecast. First of all, we verify that the SEAS5-atmospheric component, when forced by observed SST, is able to capture the NAO signal. Then, using the uncoupled SEAS5 as testbed, we conduct a series of perturbed experiments in which the SST in different basins (Tropical Indian Ocean, Tropical Pacific and Tropical Atlantic) are replaced by their climatological values. All experiments are initialized in November 2019, and consist of 50 ensemble members. The results indicate that the high predictability of NAO in DJF 2019-2020 was due to the forcing exerted by the SST anomalies in Indian Ocean (Senan et al. in preparation). This is illustrated in figure 2 by the difference in Z200 between the experiment forced by observed SST and the one using climatological SST over the Indian Ocean. Hardiman et al 2020, using a different methodology, also conclude that the Indian Ocean anomalies were responsible for the NAO signal. Our experiments also indicate that the Pacific SST did not contribute to the NAO signal, but they contributed to the SEAS5 errors over Alaska (not shown). Although on this occasion the errors from the Tropical Pacific teleconnections did not interfere with the NAO, we conclude that representing the balance between the forcing exerted by the different tropical basins and their teleconnections is key for reliable forecasts in the extratropics at seasonal time scales.

Impact of Ocean In-situ Observations on S2S forecasts

A series of seasonal forecasts observing system experiments (SF-OSE) has been conducted to evaluate the impact of ocean observations on the patterns of atmospheric variability. The reference experiment is a low-resolution seasonal reforecast experiment spanning the period 1993-2015, from May and November starts, and each individual forecast set consists of 15 ensemble members. The ocean initial conditions are given by an ocean reanalysis (ORA) equivalent to the operational ORAS5 (Zuo et al. 2019), but at low resolution and without assimilating altimeter data. The perturbed reforecasts have been initialized from an ocean reanalysis where the ocean in-situ observations have been selectively withdrawn. In one experiment, the ocean reanalysis did not assimilate in-situ observations, and only SSTs were constrained in the production of initial conditions. In a second experiment, the in-situ observations were assimilated everywhere except in the Atlantic basin. We find that the atmosphere responds to large-scale SST gradients. In seasonal forecasts, the impact of in-situ ocean observations in the Atlantic are felt at a global scale, as shown in figure 3, which depicts the differences in SST and MSLP from seasonal experiments with and without in-situ observations in the Atlantic. The differences are for JJA from experiments starting in May. The pattern of impact is different from that obtained when all the in-situ observations are removed globally (not shown), suggesting the interaction and interference of signals from different areas. These results indicate the importance of uniform large-scale observation coverage, so signals from different ocean basis are balanced.
Figure 3: Impact of Atlantic in-situ ocean observations on seasonal forecasts bias of SST and MSLP. The results are from reforecasts for the period 2005-2015, initialized in May, and verified for JJA. Shown is the bias difference between an experiment initialized with all observations, and another where the Atlantic in-situ were withdrawn. Stippling denotes differences significant at the 95% confidence level based on a two-sided t-test.

References


Complex Network Approach for detecting periods of collective tropical interactions

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1. Introduction

El Niño-Southern Oscillation (ENSO) is the dominant interannual variability mode of the ocean-atmosphere coupled system, with strong impacts worldwide. It is accepted that El Niño - Southern Oscillation exerts an important impact on the sea surface temperature (SST) anomalies in other tropical basins such as tropical north Atlantic (Wu et al. 2020; García –Serrano et al. 2017) and Indian Ocean (Wang and Wang 2014). Nevertheless, ENSO’s impact on the equatorial Atlantic has been found to be inconsistent (Latif and Grötzner 2000; Chang et al. 2006) due to the existence of counteracting effects. Interaction of ENSO with tropical basins occurs mainly through alteration of the Walker circulation but also through extratropical Rossby waves.

Only in the last decade have studies have shown that the SST anomalies in the tropical Atlantic (Ham et al. 2013a and 2013b), equatorial Atlantic (Rodriguez-Fonseca 2009; Polo et al. 2015) and Indian Ocean (Luo et al. 2009) could in turn influence equatorial Pacific SST (Cai et al. 2019). Nevertheless, it has been found that these interbasin connections between the interannual SST variability of tropical basins are not stable and occur only in particular decades (Rodriguez-Fonseca et al. 2020; Martin-Rey et al. 2014, 2015; Polo et al. 2015; Wang et al. 2017). Tropical Basins Interactions (TBI) is a new paradigm of research that deserves further investigation.

Many studies have focused on how the SST anomalies of one particular basin can influence the SST anomalies in another particular basin but there are no studies which analyze the degree of connectivity among the three tropical basins collectively. Also, the 2-way “ENSO” impact on tropical basins” and “tropical basins’ impact on ENSO” has not been studied as a whole. In this article, we introduce a tool from the complex network theory, called mean network distance, that is very useful when studying the degree of collective connectivity among different interactive agents and detects periods of maximum degree of interaction (Tsonis et al. 2007; Martín-Gómez and Barreiro 2015). The main objective is to analyze the degree of collective connectivity among the tropical oceans during the last century focusing on the detection of periods of maximum connectivity.

2. Complex Network perspective

To analyze the collective connectivity among the tropical oceans we consider a complex network perspective. To do so, we first construct a climate network defining its nodes (interactive agents) and the criterion through which we consider that two nodes are connected (interacting). In our work, the climate network is constructed considering as nodes the tropical North Atlantic (TNA), the equatorial Atlantic (Atl3), the eastern equatorial Pacific (Niño3) and the Indian Ocean Dipole (IOD) (figure 1). Each one of these nodes is characterized by an index that represents the variability of the SST anomalies during the period 1871-2017. The SST values considered come from HadISSTv1.1 (Hadley Center Sea Surface Temperature; Rayner et al. 2003), with a spatial resolution of 1° x 1°. The SST anomalies are computed by removing the seasonal cycle and the trend from the data. The specific domains where indices are averaged are shown on figure 1. Additionally, each node is centered on the season of its peak of variability. Therefore, Niño3 is centered on November - January (NDJ), Atl3 is centered on June - August (JJA), TNA is centered on March - May (MAM) and the Indian Ocean Dipole on September - November (SON). A butterworth filter is applied to the indices, using a cutoff frequency of 1/11 years-1 in order to remove low frequencies. The obtained anomalies are standardized. Finally, we consider that two nodes are connected when the Spearman correlation coefficient is statistically significant based on a one-tailed t-test with a 90% confidence level.

Two networks are defined. In the first one, all nodes lead Niño3, so we could interpret the network as the group of nodes that interact together and influence Niño3 (El Niño lagging network). The design of the network is done for predicting El Niño (figure 1a). In the second one, all nodes lag Niño 3 (El Niño leading network), so we could interpret the network as the group of nodes that interact together after an El Niño event (figure 1b).

Once the network is constructed, we focus on analyzing the degree of collective interaction among the network nodes. For this purpose, we consider the mean network distance, a useful tool from the complex network theory that allows to quantify the degree of collective interaction among the network nodes and
detects period of maximum and minimum degree of collective connectivity (Tsonis et al. 2007; and Martín–Gómez and Barreiro 2015). Mathematically, it is defined as:

\[ d(t) = \frac{2}{N(N-1)} \sum_{i<j}^{N} \sqrt[2]{1-(r_{ij})^2} \]

where \( N \) represents the number of network nodes (4 in our case), and \( r_{ij} \) represents the correlation coefficient between the node \( i \) and \( j \). Here, we use the Spearman rank correlation coefficient, which is computed considering a centered moving window with 22 years length. The time step considered for consecutive correlation is 1 year.

Eq. (1) considers the absolute value of the correlation coefficient. This is related to the fact that this measure quantifies the degree of interaction, which is independent of the sign of the correlation. The maximum (minimum) value of the mean network distance is (0), which corresponds to a completely disconnected (connected) network. Therefore, the smaller than mean network distance, the larger degree of collective interaction among nodes. This measure has been also used in previous studies which demonstrate its potential to detect periods of maximum/minimum connectivity among several interactive agents (Tsonis et al. 2007; Martín-Gómez and Barreiro 2015).

Finally, synchronization periods are defined as those periods when the mean network distance is smaller than a certain threshold value, and therefore, in such periods we will say that there is a statistically significant collective interconnectivity among the tropical oceans. This threshold is computed applying the Monte Carlo method to the nodes’ indices. Surrogate time series of each node are computed considering the nodes as red (white) noise if their autocorrelation at lag 1 year is (not) statistically significant in a one-tailed t-test at the 95% confidence level. Using these series, we compute 500 surrogate time series of the mean network distance, which allows determining the 5% level.

Figure 1: Domains of the network’s nodes where the SST anomalies are averaged when computing the indices: Niño3 (150°W–90°W, 5°N–5°S), red box; Atl3 (20°W–0, 4°N–4°S), blue box; TNA (90°W–20°E, 0–10°N), green box and IOD (western box: 50°E–70°E, 10°S–10°N), eastern box: 90°E–110°W, 10°S–0°), magenta boxes). For the case of the IOD, the index is constructed as the difference between western box and the eastern box. (a) El Niño lags the other nodes and (b) El Niño leads the other nodes.

3. Results
Figure 2 shows the mean network distance time series computed considering the nodes indicated on figures 1a and b. Focusing on the El Niño lagging network (figure 1a), it is possible to see that the mean network distance presents a large multidecadal variability, with two periods when the degree of collective connectivity among the nodes is significantly stronger (red line in figure 2). These periods can be considered as periods of maximum synchronization among nodes and develop: 1900-1930 and 1980-2007. This result agrees with other authors that have put forward a multidecadal modulation of tropical basin interactions (Martin-Rey et al. 2014, 2015; Polo et al. 2015; Wang et al. 2017; Cai et al. 2019, Rodriguez-Fonseca et al. 2020). Nevertheless, this is the first time that all the connections are analyzed together indicating a clear multidecadal oscillation.

An interesting feature emerges when analyzing the network distance when ENSO leads the rest of the tropical nodes (blue line). The distance is higher when ENSO leads, indicating less synchronization among the different modes. In this network the variability of the distance is also weaker and the multidecadal feature of the red line is less evident. The difference between both networks resides in the connections with El Niño, which is the only node that we change, as we use the previous NDJ season, with the aim of analyzing ENSO impact on the rest of nodes. To further investigate the connections involved in the network distance, figures 3a and b show the running correlation between each pair of network nodes. In particular, the correlation between Niño3 and the IOD is stronger when IOD leads (compare figure 3a and b, first row). The same happens with the relation between Niño3 and Atl3 (compare figure 3a and b, second row). In the case of TNA-Niño3, the robust impact of El Niño over this region is evident and very stable (figure 3b).

Regarding the relation between IOD and Niño3, during those decades in which IOD does not impact Niño3, Niño3 has a significant impact on IOD (compare figure 3a and b, first row). IOD and Niño3 are known to be coupled, but this period marks an exception as El Niño becomes a predictor of IOD. This fact can be seen in the El Niño leading network distance in the periods (1900-1930) and (1970-2007), when the values of the distance are larger than in the El Niño lagging network (compare red and blue lines in figure 2).

In relation to Atl3-Niño, it seems that the impact of Atl3 on the Pacific is stronger than the opposite and El Niño’s impact on the equatorial Atlantic occurs in the decades in which Atl3 is not correlated with the next Niño3 event (compare figure 3a and b, second row). This fact makes the network distance take higher values in the periods (1900-1930) and (1970-2007), as with the IOD.
The analysis of TNA impact on Niño 3 allows us to distinguish 3 periods. One in which TNA leads Niño (1995-2007) but El Niño does not lead TNA. A second period in which both relations take place (1910-1940) and, finally, a third block of periods in which TNA does not lead El Niño but El Niño leads TNA ((1880-1900) and (1945-1995)) (compare figures 3a and b, third row). The period with the lower synchronization occurs in (1930-1970), when the only connection occurs in relation to Niño leading TNA.

Figure 2: Mean network distance (MND). The horizontal black dotted line represents the threshold level under which there is a statistically significant synchronization among the network nodes. Red (blue) line indicates the MND when ENSO lags (leads) the rest of the nodes.

Finally, focusing on the El Niño lagging network and on the Niño3 node, the synchronization periods are also the periods when the SST anomalies in the equatorial Pacific are more influenced by the SST anomalies of other remote tropical basins. This result would suggest that during these periods the development of El Niño could have an important forced part, while during periods of no synchronization (such as the one from 1930 to 1975) the development of ENSO could be more internal. These results could also suggest a larger ENSO predictability during the periods of minimum degree of connectivity (1900-1930 and 1975-2007). Nonetheless, it must be noted that the influence of several basins at the same time on the equatorial Pacific could also have associated counteracting SST effects, reducing in such case the ENSO predictability.

4. Summary and Conclusions
In this study, we consider a complex network perspective to analyze the collective connectivity among tropical basins. To do so, we define two different networks using as nodes: Niño3 (NDJ), IOD (SON), Atl3 (JJA) and TNA (MAM). The main difference between them is in the El Niño3 node. While one of the networks presents El Niño3 lagging the rest of the nodes, in the other the El Niño3 leads. Although both networks present two periods of stronger connectivity among nodes during the last century, the multidecadal variability of the mean network distance in the “El Niño leading” network is lower than in the “El Niño lagging” Network (figure 2). This difference is directly related to the El Niño connectivity. It is found that its connectivity is larger when the IOD and Atl3 lead (compare figure 3a and b). For the case of TNA, three different types of periods are identified: one in which TNA leads El Niño (1995-2007) but El Niño does not lead TNA, a second one in which both relations take place (1910-1940) and, finally, a third block of periods in which TNA does not lead El Niño but El Niño leads TNA ((1880-1900) and (1945-1995)) (compare figures 3a and b).

Tropical basin interactions are crucial in particular periods when assessing ENSO predictability. Several studies have indicated how the tropical Indian and Atlantic oceans can be considered as optimal predictors of ENSO (Jansen et al. 2009; Frauen and Dommenget 2012; Keenlyside et al. 2013; Cai et al. 2019; Exarchou et al. 2021). Nevertheless, this is the first time that all basins have been considered together to establish periods in which all tropics act collectively to enhance ENSO predictability.

Focusing on the El Niño lagging network, it has been
found how the connection occurs, for a warming in the Niño 3 region, when the equatorial and North Tropical Atlantic present colder conditions in the previous months, while the Indian Ocean is warmer. The opposite takes place during La Niña years. As all basins interact, there is a positive correlation between the Atlantic nodes on the one hand, and the Indian and Pacific oceans on the other; being negative correlations between the Indian ocean variability with the Atlantic. On the other hand, note that during the periods of strong connectivity, the Niño3 is more influenced by the other tropical basins (IOD, TNA and Atl3), suggesting that during these periods the development of ENSO could present a stronger forced component than in periods of lower connectivity (such as 1930-1975), when its development could be more internal.

Finally, results from this study have shown that the mean network distance is a useful tool to quantify the degree of collective interaction and detect periods of maximum and minimum degree of connectivity among different tropical basins.

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