Decadal climate variability and predictability: challenges and opportunities

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Decadal Climate Variability and Predictability:
Challenges and opportunities

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Decadal phenomena and their characteristics

The slowdown in the rate of global surface warming in the early 2000s, and especially its regional characteristics, highlights the importance of “decadal climate variability” (DCV) as modulator of long-term warming trends due to ever-increasing anthropogenic forcings (Medhaug et al. 2017). This event, which was termed in the scientific and public domain as a “pause” or “hiatus” in global warming (Lewandowsky et al. 2016), was argued by scientists to be associated with long-recognized (see for instance the 2nd IPCC report published in 1996 for an early assessment), multi-year phenomena and in particular the undulation of the tropical Pacific ocean-atmosphere system (Kosaka and Xie 2013; Meehl et al. 2016). According to several studies, changes in Earth energy balance at the top of the atmosphere partly related to volcanic aerosols from a series of moderate eruptions in the early 2000s also contributed to the recent ‘hiatus’ (Huber and Knutti 2014; Santer et al. 2017). Yet, because of uncertainties in observational estimates in both radiative forcing and global temperature measures, it is impossible to stringently attribute the early 2000s ‘hiatus’ to a specific origin (Hedemann et al. 2017); it should rather be interpreted as a combination of several factors (Medhaug et al. 2017).

Whether in cases of external forcing due to natural (solar & volcanic) or anthropogenic factors, or during internal climate-system interactions, the oceans play a central role in DCV due to their thermal and dynamical inertia. Decadal variations of both regional and global mean surface temperature can be associated with, and often attributed to, changes in ocean heat uptake and heat redistribution (Yan et al. 2016). The study of the ocean's role in climate has traditionally involved the diagnosis of sea surface temperature (SST) variability as the variable reflecting the interaction with the atmosphere. While the major oceanic basins are usually examined separately when identifying the main climate variability phenomena, what stands out is the related nature of the global patterns and some similarities in their temporal evolution. Specifically, large-scale, long-term SST variability in one ocean basin is associated with variability in other basins. The global view of these patterns reveals a "network of teleconnections", linking neighboring ocean basins, the tropics and extratropics, and the oceans and land regions (Fig 1). The two most prominent patterns in this respect are associated with the Atlantic Multidecadal Oscillation (AMO, Fig.1a, b) and the Pacific Decadal Oscillation (PDO, Fig.1c, d) or its nearly interchangeable companion referred to as Interdecadal Pacific Oscillation (IPO, Han et al. 2014, Dong & Dai 2015)[1], although none of these are true ‘oscillations’.

The apparent inter-basin connectivity seen in DCV SST footprints is likely indicative of the global nature of the associated atmospheric mechanisms that either force, or respond to, the oceanic variability. However, it is challenging to clearly elucidate the origins of DCV phenomena and especially the underlying oceanic mechanisms because of the short observational records and sparse spatial sampling, and because of consistency in terms of instrumental biases. This is even more a limiting factor in the Southern Ocean where low-frequency variability seems to be present (Fan et al. 2014) but cannot be robustly identified because of data issues. Nonetheless it is now well recognized that a superposition of multiple processes underlies both the Atlantic and Pacific DCV (Yeager & Robson 2017; Newman et al. 2016, respectively).

In the Atlantic, coupled model integrations (e.g. Medhaug & Fluverik 2011, Ruprich-Robert & Cassou 2015 and references therein), including decadal hindcasts (Robson et al. 2012, Msadek et al. 2014) and forced-ocean model simulations

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[1] In the rest of the paper, considering the difficulty to distinguish between PDO and IPO, we preferably use the latter term.

(Danabasoglu et al. 2016), demonstrate that the AMO is linked to the variability of the Atlantic Meridional Overturning Circulation (AMOC). Through its associated fluctuations of salt and heat transport and through deep convection-related mechanisms in the North Atlantic subarctic seas, the AMOC is considered as a driver of the upper ocean heat content variability and related SST anomalies that project upon the AMO (Buckley and Marshall, 2016). Fingerprints of AMOC variation were found in the subpolar gyre in the form of SST, salinity and, hence, density anomalies (Hakkinen et al. 2011), particularly in deep-water formation regions. Related changes in the state of the ocean are found in the tropical Atlantic, expressed as anti-correlated variations of surface and subsurface ocean temperatures (Zhang et al. 2013), a relationship which is supported by paleoclimate proxy evidence (Parker et al. 2015), although the connection between AMOC variations and tropical Atlantic SSTs remains ambiguous and the mechanism producing tropical Atlantic SST decadal variability remains elusive.

In addition to such ocean dynamical processes, decadal North Atlantic SST evolution since the early 20th century has also been attributed to external radiative forcing by either anthropogenic (Booth et al. 2012, but see Zhang et al. 2013 for further discussion) or natural aerosols. Results combining paleoclimate reconstructions, simulations and observations, have pointed to decadal climatic impacts of volcanic eruptions and to their possible role in the modulation or phase-locking of the AMOC/AMO pattern (Ottera et al. 2010, Swingedouw et al. 2015).

In the Pacific domain, evidence suggests that the PDO should be viewed as the superposition of several phenomena, each governed by different physical processes, each of which is manifested in SST variability in a different part of the basin, rather than being a coherent, single, physical mode. Possible physical drivers include the integration of extratropical atmospheric weather noise by the extratropical ocean basins, teleconnections through Rossby wave propagation from the decadal tropical footprint of ENSO, re-emergence of persistent subsurface heat content anomalies, and variations in wind stress driven gyre circulation (Newman et al. 2016). The subtle distinctions between the PDO and IPO may be linked with the multiplicity of governing processes.

According to several studies, the IPO underlies part of the slowdown in the rate of global warming during the early 2000s (see Xie & Kosaka 2017 for a review) and could also be considered as the primary driver of past-observed warming slowdowns and accelerations over the historical period (Fyfe et al. 2016, Kosaka & Xie 2016). Model control simulations (with constant external forcing) exhibit IPO-like variability, thus pointing at an internal, i.e. unforced origin of this phenomenon. However, similarly to AMO, it was suggested that aerosol forcing played a role in determining the temporal phase of the IPO in the late 1990's (Smith et al., 2016, but see Kuntz and Schlag 2017 for further discussion). In any case, determining the cause for the particular IPO event that led to the slowdown in warming in the early 2000s, still faces lingering uncertainties (Hedemann et al. 2017).

The climate literature is rich with studies that have linked the AMO and IPO to past observed worldwide climate variations over land. For example the AMO has been related to the multi-decadal fluctuation in Atlantic tropical cyclone activity (Wang et al. 2012), and the variations of rainfall in the Sahel, which led to the devastating droughts and famines of the 1970s & 1980s. Similarly, the multi-year pulses of droughts in the US and Mexico (e.g., the “dust bowl” in the 1930s and the most recent protracted dry period in California over 2007-2016) have been associated with the combined effect of the AMO and IPO (Schubert et al. 2004, Chylek et al. 2014), while the so-called Millennium drought and warming in Australia has been attributed to a combination of DCV phenomena in the Indo-Pacific and Southern Ocean regions (van Dijk et al. 2013). Controlled experiments in which global climate models are forced to follow AMO and IPO temporal evolution, confirm that many of the past observed changes in the climate could be partly attributable to these oceanic anomalies (Zhang & Delworth 2006; Kosaka & Xie 2013, Ruprich-Robert et al. 2017). This motivates the ongoing development of "initialized decadal prediction", in which coupled models are initialized with the observed state of the ocean while anthropogenic and natural forcings are prescribed. Models are integrated for multiple years to try to predict the combined impact of radiative forcing and natural climate variability since the 1960s (Kirtman et al. 2013, among others).

Challenges and outstanding questions

In the context of adaptation to (and mitigation of) the impact of climate change, it is important for a broad range of stakeholders and decision makers to know how the response to anthropogenic forcing and the impact of natural DCV phenomena will mix together to shape the near term evolution of climate, especially at regional scales. A major objective of CLIVAR's study of DCV and its predictability, the research focus on Decadal Climate Variability and Predictability (DCVP[2]), is to advance the dynamical understanding of the associated phenomena and improving their representation in models. This is an essential component of the World Climate Research Programme (WCRP) plan to facilitate a robust and reliable provision of decadal information to society under its Grand Challenge on Near Term Climate

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[2] http://www.clivar.org/research-foci/dcvp

Prediction[3]. Decadal forecasts were part of the 5th phase of the Coupled Model Intercomparison Project (CMIP5, Taylor et al. 2012) and the Decadal Climate Prediction Project (DCPP[4]) ensures the coordination and design of the modeling experiments in the ongoing 6th edition (Boer et al. 2016).

In the Atlantic, initialized near-term prediction systems demonstrate substantial skill in hindcasting decadal AMO-like SST anomalies (Oldenborgh et al., 2012; Kim et al., 2012, Marotzke et al. 2016, among others) but noticeably, the added-value of the initialization in temperature and precipitation over adjacent land is lost very rapidly (beyond a couple of years), especially over Europe and the American continents (Doblas-Reyes et al., 2013; Meehl et al., 2014). More robust skill seems to be found when statistical methods to overcome sampling issues are applied (e.g. Robson et al. 2013) or when investigations are focused on case studies (such as the 1960s or 1990s AMO phase transitions). This is perplexing in light of the findings that coupled models with restored SST to observed anomalies over the Atlantic are able to display part of the ocean's influence on land climate. Part of the loss of predictability over land may be related to systematic errors in the simulation of the spatial structure and temporal properties of the AMO in free-coupled models and/or the weak associated teleconnections that communicate ocean signals to the continents (Eade et al.2014, Qasmi et al. 2017). Skill in a given prediction system might be also dependent on the model representation of processes or chain of events leading to AMO phenomena. In particular, the AMOC-AMO relationship varies considerably from model to model and leads to a wide range of amplitudes, spatial properties and preferred timescales of the simulated AMO and associated teleconnections (Ruiz-Barradas et al. 2013, Zhang and Wang 2013, Ba et al., 2014; Peings et al., 2016). Moreover, recent

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[3] https://www.wcrp-climate.org/grand-challenges/gc-near-term-climate-prediction

[4] https://www.wcrp-climate.org/dcpp-overview

studies also showed that a pattern akin to the AMO SST expression could be identified in a model in which the atmosphere is coupled to a motionless, slab-ocean model, calling into question the active role of the ocean dynamics in the phenomenon that could be consequently attributed to random atmospheric forcing (Clement et al. 2015, Cane et al. 2017 but also Zhang et al. 2016 and O'Reilly et al. 2016 for further discussion of this controversy). In that context, it is notable that the frequency-dependence of the relationship between the AMV and the North Atlantic Oscillation (NAO), which displayed substantial variability on multidecadal time scale during the 20th century, seems to be a key aspect for DCV mechanisms (Delworth et al. 2017). Altogether, the role of atmosphere and ocean thermodynamics and dynamics in the surface expression of the AMO and its remote impacts over land remains an active area of research. Resolving the reasons for the very large diversity in model simulations of the AMO is an outstanding challenge, especially the nature and respective weight of the physical mechanisms that contribute to the development of DCV in the Atlantic.

In the Pacific, even if such conclusions are still topics of contention and discussion, initialized coupled models have shown some success in simulating the recent IPO cool phase in the late 1990s (Ding et al. 2013, Meehl et al. 2014); yet, overall performance and results remain inferior to the Atlantic case (Doblas-Reyes et al., 2013). Here too, more research is needed to elucidate the role of the relevant processes and mechanisms that govern the IPO. Fluctuations in tropical Pacific trade winds have been suggested to be a key factor (England et al. 2014) but models fail in reproducing the observed strengthening over the last 30 years (Kociuba and Power 2015). In non-initialized simulations, the basin-wide spatial characteristics of the IPO are reasonably well represented (Henley et al. 2017), but the overall ratio of decadal-to-total variance for SST and oceanic fields is underestimated in most of the models and errors are pronounced in the extratropics (Farneti, 2016; Nidheesh et al. 2017). Discrepancies could be explained by the (in)ability of the coupled models to effectively simulate all processes generating the IPO (Newman et al. 2016) and/or by their respective ability to represent the different processes that govern the phenomenon (e.g., the models ability to simulate oceanic re-emergence, Kuroshiro dynamics, stochastic midlatitude atmospheric forcing associated with the variability of the Aleutian Low, etc.).

For both Atlantic and Pacific DCV, part of the inter-model divergence can be explained by model biases of both mean state and intrinsic variability. For instance, the formation of Labrador Sea Water, that is critical for AMOC variations leading to DCV, is either controlled by salinity or temperature variations as a function of systematic errors in the model’s mean state (Menary et al. 2015); this is expected to influence the spatio-temporal characteristics of the simulated AMO. For the IPO, the failure in reproducing the pan-Pacific imprint of the decadal mode in some models is related to their intrinsic deficiencies in simulating interannual teleconnections linked to ENSO (Nidheesh et al. 2017).

Yet, evaluating the authenticity of model simulated DCV is challenging due to sparse and short observational records. Based on long control experiments, Qasmi et al. (2017) provides evidence for non-stationarity, in a statistical sense, of the intrinsic spatio-temporal properties of the AMO (variance, persistence, etc.) and associated teleconnections in all CMIP5 models. The identification of the processes that have led to observed DCV since the end of the 19th century is further complicated by the presence of external forcing, both natural and anthropogenic. Uncertainties and controversies remain concerning the role of anthropogenic aerosols for both the AMO and IPO transitions. This remains an outstanding issue because of the interplay between the response of SST patterns to aerosols and GHGs (Xie et al. 2013) and because external forcing can interfere with internal DCV phenomena (Ottera et al. 2010, Tandon and Kushner 2015). In addition, there is no unique and perfect way to remove the impact of external forcing in the observations and the chosen method may have significant implications for the outcome and hence the interpretations of DCV expression during the historical period (Tandon and Kushner 2015, Lyu and Yu, 2017).

Finally, the presence of drifts and initial shocks in decadal hindcasts is a hindrance for prediction and understanding of recent DCV events. Several drift-adjustment procedures, which are mandatory prior to evaluation, exist but are not yet satisfactory in an operational context (Hawkins et al. 2014). Difficulties are mostly related to the temporal non-stationarity of the model drifts due to errors in initial conditions (Fučkar et al. 2014, Sanchez-Gomez et al. 2015, Pohlmann et al. 2016, among others) and interactions with the model representation and responses to external forcings (Kharin et al. 2012).

Addressing all these challenges and distinguishing the processes contributing to DCV is all the more important since both the latest observations and initialized decadal forecasts are suggesting that the AMO is undergoing a transition from a warm to a cold phase (Hermanson et al. 2014, Robson et al. 2016) and that the IPO is trending toward its warm phase (Thoma et al. 2015, Meehl et al. 2016). Over the Arctic, Yeager et al. (2015) also reported a prediction for a near-term decadal transition, signaling that the decline rate of sea-ice due to GHG forcing is expected to slow down due to a weakened AMOC in the 2010s associated with the transition of the AMO to its cool phase. These predictions will be put to test in the next few years (e.g. Smith et al. 2013) and there is urgency to assess their reliability based on a process-based evaluation.

Framework for progress and recommendations

All the above-listed obstacles and challenges test our ability to *attribute* past variations to the combined role of internal variability and external forcing, as well as *predict* the near-term future climate evolution on a global and regional scale. Research is needed to deepen our understanding of the physical mechanisms contributing to DCV phenomena and to make progress, we propose to address DCV issues in terms of teleconnections based on the intrinsic nature of the observed SST variability (Fig.1). More specifically:

1. *tropical-extratropical teleconnections.* Studies are needed to better understand the oceanic basin scale properties of the DCV patterns and, in particular, the respective origins and roles of their tropical versus extratropical components. Over the Atlantic, a focus is recommended on the processes that facilitate the link between decadal subpolar gyre and tropical Atlantic SST variations -- the latter being the primary bridge to global climate variability (Chikamoto et al. 2016, Ruprich-Robert et al. 2017). The interaction and possible feedbacks between the AMOC and AMO variations and the NAO and other atmospheric circulation anomalies (such as blocking events), is a key question in this respect as these are also very important for driving basin-wide Atlantic Ocean variability (Barrier et al. 2014). In addition, uncertainties remain regarding the influence of the external forcing on the North Atlantic modes of variability. The attribution of the late 20th century observed trend of the NAO to external forcing (Gillett et al. 2003) has been disputed in some recent studies (e.g.

Kelly et al. 2012, Cattiaux and Cassou 2013, Deser et al. 2016) and a better evaluation and understanding of the weight of external forcing in the recent decadal changes of the North Atlantic climate is still a research priority. Over the Pacific, it is essential to resolve and understand the exchange of heat between the extra-tropical and tropical Pacific in governing the IPO as well as the role of midlatitude atmospheric stochastic forcings (Drijfhout et al. 2014; Newman et al. 2016).

2. *inter-basin teleconnections.* Motivated by the temporal quasi-synchronization of the main modes of DCV (Fig.1), research is needed to better characterize and understand the interconnectivity of the different oceanic basins as well as with the polar regions, and to evaluate the robustness and stationarity of these relationships. The role of the AMV in the phase shift of the IPV in the late 1990s (Kucharski et al. 2016) and more broadly in the modulation of ENSO variance (Dong et al. 2006), the role of the IPO/AMO in the cooling of the Southern Ocean and increased sea-ice cover over the last 30 years, the atmospheric bridge between tropical oceanic basins through Walker cell recent reinforcement, among others, are key questions to elevate our understanding of decadal variability and predictability, especially if robust lagged relationships between modes are identified.
3. *ocean-land teleconnections*. Motivated by the strong relationship at regional scales between observed oceanic DCV modes and land anomalies, emphasis should be placed on improved understanding of the ocean-land connection at low-frequency, especially as CMIP5 models tend to underestimate the overall relationship (Qasmi et al. 2017 for the AMO) and decadal hindcast skill is critically reduced over the continents. The spatial imprint of the observed early

2000s ‘hiatus’ (strong cooling over North America and Eurasia during wintertime as an important contributor to the slower rise in annual global temperature) as well as recent modeling studies highlight the importance of investigating these issues on a seasonal basis and in terms of changes in the entire probability density function of key parameters such as surface air temperature and precipitation (surmising that the ocean-land connection could take place through changes in the probability of extremes).

4. *vertical teleconnections*. Motivated by (i) the importance of surface-subsurface relationship in the ocean as key factor for DCV genesis, (ii) the huge discrepancies between oceanic reanalysis products on the three dimensional thermohaline properties of the water masses (Karspeck et al. 2015), (iii) the recent evidence for the important role of the troposphere-stratosphere coupling in the atmosphere in response to natural decadal forcing (Dunstone et al. 2016), process-oriented approaches and emerging high resolution model configurations (stratosphere-resolving atmosphere and refined vertical levels in the ocean component to better simulate vertical processes), should be promoted to tackle this issue. Resolving and understanding the exchange of heat between the upper and deep ocean in governing the AMO and the IPO is essential for progress.

Across all the four teleconnections, it is essential to assess the respective roles of internal variability and external forcing in DCV at *regional* scale, i.e., characterize and understand the observed and simulated spatial responses to external forcing agents and to how these forcing agents affect circulation change in the ocean and the atmosphere and related teleconnections, in presence of internal variability.

Within this *“drivers of teleconnectivity”* framework, recommendations are to:

(1) *use a hierarchy of models and dedicated modeling protocols to study DCV mechanisms and improve their simulations*. Both coupled historical simulations and initialized hindcast experiments, together with targeted model sensitivity experiments (e.g. pacemaker or partial coupling configurations, etc.), are crucial for mechanistic and process understanding of DCV that is necessary to ultimately advance decadal climate prediction skill and capacities, especially at regional scale. Empirical approaches to make decadal predictions and utilize observed teleconnections between ocean and land should be also encouraged (Lean & Rind 2009; Suckling et al. 2017).

(2) *reduce model biases and drifts*. Presence of systematic errors in models has been shown to hamper the representation of DCV patterns and variability. In forecast mode, drift and shock when models are initialized from observed conditions, correspond to a sequence of physical processes by which models adjust towards their own biased equilibria. The determination of the physical origin of model drift and systematic errors should be promoted since such a framework provides clues for the mechanisms underlying DCV in models (Toniazzo & Woolnough 2014; Sanchez-Gomez et al. 2015) and is therefore a promising pathway toward improved simulation and related prediction capability/skill of DCV.

(3) *improve the knowledge and observational capacity necessary to track the energy flows through the climate system*. This is critical for a better understanding of the relationships/interactions between external climate forcing and internal DCV in affecting past and near-term future changes. Accurate measurement and physical interpretation of three-dimensional ocean heat content (heat uptake and heat redistribution) are crucial to make progress in DCV (Trenberth et al, 2016). This should be combined with the precise estimation and analysis of the planetary energy

budget at the top of the atmosphere and at the surface (Allan et al. 2014, Smith et al. 2015), from global to regional scale.

(4) *combine the analysis of instrumental observations and models together with the information emerging from high-resolution paleoclimate proxy data*. Evidence of coherent spatial and temporal patterns of DCV emerge from tree ring atlases, coral and mollusc records and other paleoclimatic archives (e.g Linsley et al., 2015, Tierney et al., 2015, Emile-Geay et al., 2017, Reynolds et al., 2017). These can shed light on underlying physical processes and provide validation to patterns emerging from the short observational record. Instrumental data rescue efforts should also be expanded to recover the wealth of un-digitized records, filling gaps and increasing overlap with the paleoclimatic archives (e.g. the ACRE and OldWeather.org initiatives, Allan et al., 2011).

(5) *revisit the traditional definition of DCV phenomena.* Care is required when representing and interpreting the climate system with single univariate and basin-wide indices, as is too often done in the case of the AMO and IPO indices (see examples in Yeager and Robson 2017's review). It is recommended that the community adopts (i) the use of multivariate metrics ('fingerprints') to identify and discriminate between processes involved, especially when comparing model simulations to observations and (ii) the notation of decadal variability acronyms (e.g. AMV and IPV) to think in terms of broad spectrum variability instead of temporal oscillations with preferred time-scales.

The "drivers of teleconnectivity" theme provides a way to approach the goal of advancing the study of DCV and predictability from different research directions. It goes beyond a preoccupation with changes in the global mean temperature "popularized" by the early 2000s 'hiatus', a shorthand term for a very complex phenomenon, and directly promotes regional analyses in line with societal needs for local climate information. It fosters an approach to address the intrinsic trans-disciplinary issues that challenge progress in DCV and predictability and encourage strengthened links across international community programs such as the CLIVAR DCVP and CONCEPT-Heat[5] research foci, PAGES2K[6], WCRP GEWEX[7], DCPP, VolMIP[8] and the WCRP Near-Term Prediction Grand Challenge. Because of the difficulties to observe and model the Earth's climate at timescales of a decade or longer, this area of research is wholly dependent on emerging connections between those who perform, collect and analyze instrumental observations of the present, those who develop and analyze proxies of past climate, and with scientists who develop models and perform dedicated modeling experiments. This "drivers of teleconnectivity" framework has been discussed and adopted at the end of the DCVP Research-Focus workshop organized by CLIVAR and the International Centre for Theoretical Physics in Trieste (Italy) in November 2015[9].

More specifically, the continued PAGES2K effort towards collecting, analyzing and interpreting high-resolution climate records, including the development of spatio-temporal reconstructions of climate (temperature and precipitation) variability both in the tropics and at midlatitudes, especially for the last two millennia, should help better understand tropical-extratropical and inter-basin teleconnections at decadal timescales. Progress on the interpretation of ocean-land connectivity would gain from

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[5] http://www.clivar.org/research-foci/heat-budget

[6] http://pastglobalchanges.org/ini/wg/2k-network/

[7] http://www.gewex.org/

[8] http://volmip.org/index.html

[9] The Workshop was organized towards meeting the objectives of the CLIVAR Research Focus on DCVP to advance the understanding of the mechanisms and predictability of decadal climate variability. The organizers integrated the plans to establish a new WCRP Grand Challenge on "Near Term Climate Prediction" and the development of coordinated modeling strategies to address decadal variability and prediction under CMIP6 led by DCPP. The Workshop was attended by around 150 participants and was streamed live to a global audience.

studying the relationship between land (e.g. tree rings) and ocean proxies (corals, shells etc.).

On the modeling side, coordinated experiments based on “pacemaker” or partial coupling modeling strategies have been designed to directly address teleconnectivity (DCPP Component C; Boer et al., 2016) and thus perfectly fit within the proposed framework. The emergence of high-resolution models now compatible with DCV studies, together with increasing computing resources, is a promising opportunity for improved model fidelity and better simulation of the four above-listed teleconnections. Recent work has highlighted (i) the role of meso-scale oceanic fronts in driving the atmosphere and (ii) the role of the stratosphere and storm-tracks as transmitters of SST variability towards the continents (Kidston et al. 2015, Ma et al. 2016). To make progress, increasing computing resources should be also prioritized to promote the production of large ensembles to correctly characterize internal variability; this is essential to accurately attribute observed DCV events, their nature and physical origins and interaction with external forcing.

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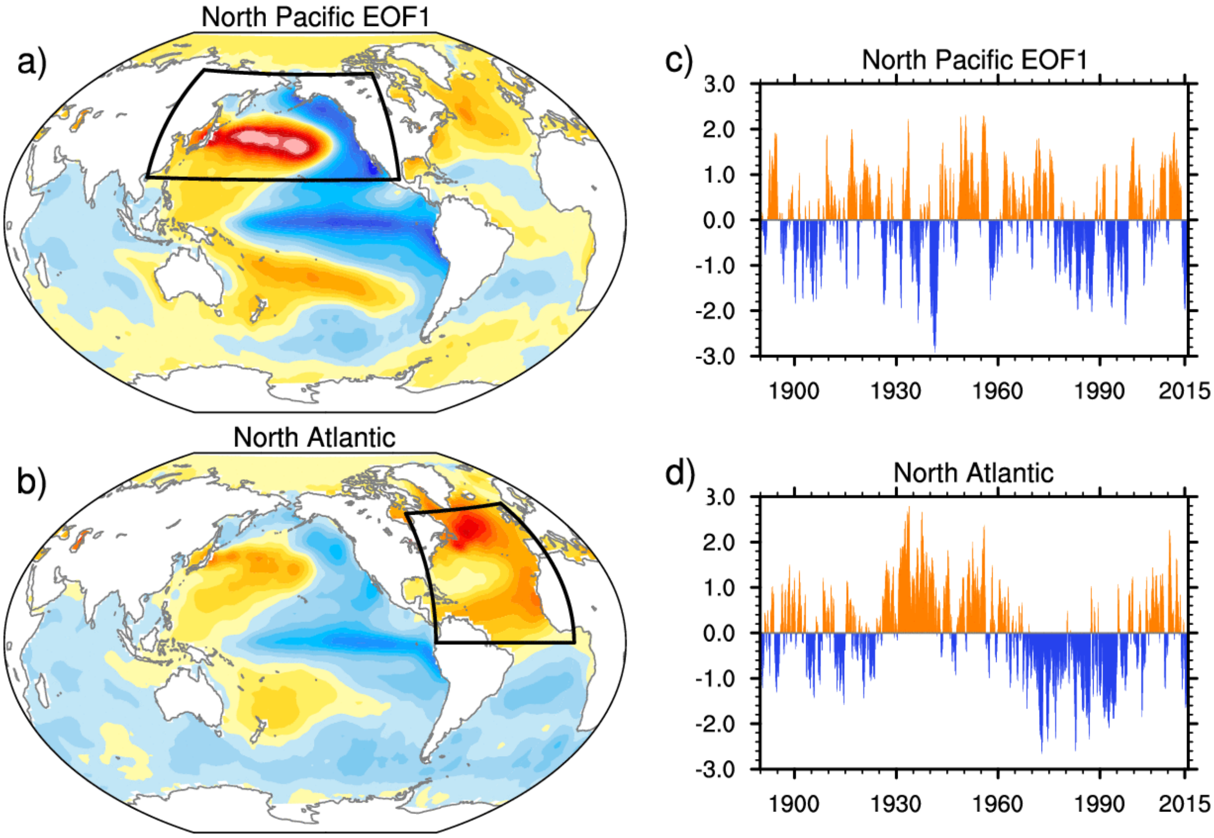
Figure captions

Figure 1: Spatial and temporal characteristics of sea surface temperature anomaly (SSTA) variability in selected ocean basins. (Left column) Global SSTA regression maps (degrees C) based on the (a) leading principal component of North Pacific SSTA, (b) North Atlantic SSTA. All indices were standardized prior to computing the regression maps. Index regions are outlined by black boxes. (Right column) Standardized 3-month running mean time series of the (a) leading principal component of North Pacific SSTA, (b) North Atlantic SSTA. Global mean SSTA was removed prior to computing the time series and regression maps. Figure adapted from Deser and Phillips (2017), CLIVAR exchanges.

Figure 1:



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