DCVP-RF Final Report outline

1-Foreward:

The CLIVAR SSG, during its meeting in September of 2012, decided to declare the theme of Decadal Climate Variability and Predictability (DCVP) as one of its Research Challenges. In order to advance action on its 2012 Research Challenges decision, the SSG later promoted the establishment of several Research Foci (RF), including the DCVP-RF. The intent was to identify a small number of exciting, ready to go and attainable objectives under each RF. An open, broad community discussion addressing the DCVP-RF was held during the Pan-CLIVAR meeting in The Hauge, Netherlands during July of 2014.

The DCVP RF and other RF efforts established after the 2014 Pan-CLIVAR meeting were created as a small number of topics that would define and generate research in their designated field over a limited number of years to advance the objectives of CLIVAR. DCVP RF Terms of Reference formulated in 2015 can be found at http://www.clivar.org/research-foci/dcvp

In its 24th annual meeting in November 2018, the CLIVAR SSG decided to "sunset the DCVP RF and handover of future responsibility for further advancing the DCVP theme to the Climate Dynamics Pane by the end of March 2019." After initial coordination with the co-chairs of the Climate Dynamics Panel (CDP) it was agreed that DCVP-RF Working Group will prepare this final report as part of the handover of the activity to be presented and discussed by the CDP during its anticipated annual meeting in October of 2019.

2-DCVP-RF Milestones

2014: DCVP "tiger Team" presented a tentative framework for a RF during Pan-CLIVAR 2014 meeting and agreed on the initial RF objectives.

2015: DCVP WG was created with representation from different countries and CLIVAR Panels. DCVP Foci were defined in coordination with the WCRP/WGSIP Decadal Climate Prediction Project (DCPP) – the two working groups included shared membership to facilitate better communication and coordination. The two themes that emerged from the discussion were: (i) a focus on understanding and predicting the decadal modulations of the long-term anthropogenic warming trend and (ii) Studying the role of volcanic eruptions in decadal climate variability and their impact on decadal climate prediction. These two themes contributed to the design of protocols for the DCPP Component C experiments (Boer et al. GMD 2016).

2015: The WCRP established the Grand Challenge on Near-Term (Decadal) Climate Prediction. The Grand Challenge is co-chaired and includes membership from the CLIVAR DCVP-RF Working Group (see: https://www.wcrp-climate.org/component/content/article/695-gc-near-term-climate-overview?catid=138&Itemid=538).

2015: DCVP-RF planned and held the ICTP/CLIVAR/PAGES International Workshop on "Decadal Climate Variability and Predictability: Challenge and Opportunity" in November of 2015. Immediately after the meeting DCVP held an in-person WG meeting to discuss the workshop results, review/revise its objectives (in response to the Workshop presentations and discussions) and draw plans for near-term action.

2016: Revised the DCVP foci reflecting results of the ICTP workshop deliberations. Introduced the “Networks of Teleconnectivity” theme, which emphasizes the global/inter-basin expression of observed decadal and multidecadal variability.

2016: DCVP-RF contributed to planning the session on Decadal Climate Variability in the CLIVAR OSC, Qingdao, China. DCVP held in-person DCVP-RF WG meeting and presented its recent activities and the new DCVP theme of Networks of Teleconnectivity to the SSG during its post OSC meeting.

2016: DCVP co-chair was invited by WCRP JSC to co-chair a working group tasked to develop the concept of a Grand Challenge on decadal prediction. The group developed a Concept Note for a Grand Challenge on Near Term Climate Prediction (GC-NTCP) that was endorsed by the JSC. In the following years GC-NTCP reached out to the different WCRP Projects and working groups, including CLIVAR, to gather information on WCRP activities relevant to achieving its objectives.

2017: DCVP-RF planned, edited and published CLIVAR Exchanges issue No. 72 – “Decadal Climate Variability”. A joint effort of PAGES and CLIVAR. DCVP-RF reported progress to the SSG annual meeting in Pune, India. The report included the DCVP involvement in the design of the DCPP Pacemaker experiments and the analysis of the experiments early results.

2017-2018: DCVP-RF co-chairs and representative members wrote and published the BAMS “In-Box” article on Decadal Climate Variability and Predictability” (Cassou et al., 2018). The article describing the nature of the DCVP problem, the existing mechanisms, remaining challenges and a proposed framework for addressing them.

2018: DCVP-RF contributed to the CLIVAR Science Plan on the subject of DCVP. WG members promoted and contributed to DCVP research in their countries and, as part of their participation in CLIVAR panels, worked to introduce and plan activities on the subject of DCVP.

2018-2019: DCVP-RF members produced the first DCPP-C pacemaker experiments with the newly developed models for CMIP6. Several working groups including DCVP-RF members were created to coordinate the analysis of the experiments.

2019: In collaboration with the CLIVAR Pacific Regional Panel the DCVP-RF proposed and developed a session on “Decadal Climate Variability, Predictability and Prediction” to be held at the AGU 2019 Fall meeting in San Francisco.

2019: Rym Msadek, DCVP co-chair, was invited to co-organize a WCRP Town Hall discussion on “Prediction of the near-term evolution of the climate system”. The Town Hall is aligned with one of the four recent Scientific Objectives announced recently by the WCRP and its goal is to survey and stimulate community discussions on the research directions and frameworks that will be needed for meeting this objective.

2019: DCVP-RF members have prepared this report as part of the RF sunset process. DCVP co-chair, now also a member of the CDP Panel, will present a summary of this report to the CDP Panel in their upcoming meeting in early October 2019.This work should be coordinate with the CLIVAR Pacific Regional Panel.

3-Current state of DCVP research

This section offers a brief survey of the recent advances in DCVP research that are of relevance to future work on this theme. We also call attention to a few recent articles published on the subject of the DCVP that provide a background for the specific discussion below: Zanchettin (2017); Cassou et al. (2018), Yeager et al. (2018), Boer et al. (2018); Kushnir et al. (2019).

3.1 Understanding and predicting Pacific decadal variability.

Decadal phenomenon in the Pacific have been determined by the changes in the Basin SST variability (Newman et al., 2016). While the brevity of reliable historical data and climate model imperfections limits our ability to characterise and understand Pacific Decadal Variability (PDV), recent progress in understanding PDV (Liu and Di Lorenzo, 2018) and its interactions with other basins (Cai et al., 2019) has recently been reviewed. In addition, the CLIVAR Pacific Region Panel is currently synthesizing the literature on the character, cause and impacts of multi-year to decadal variability in the tropical Pacific, its predictability, and our current ability to predict it.

In terms of mechanisms, the *null hypothesis* is that internally generated tropical PDV arises as a residual of random irregularity in ENSO activity (Vimont, 2005; Power and Colman, 2006). PDV in extratropical regions can be understood as a low-frequency ocean response to variability in ENSO-driven surface fluxes (Newman et al., 2003; Power and Colman, 2006). If the null hypothesis were the only mechanism at play, there would be little hope for multi-year to decadal predictions of the tropical Pacific state and of its influences on other regions. Much of the recent research is thus aimed at investigating other possible internal mechanisms responsible for some aspects of PDV that could lead to some degree of predictability (Liu and Di Lorenzo, 2018). Some of the proposed mechanisms for the tropical Pacific include changes in the strength of the wind-driven upper-ocean overturning circulation in the Subtropical-Tropical Cells (STCs) and wind-forced subsurface temperature anomalies that are advected by the mean circulation from different subtropical regions to the equator, where they can reach the surface and alter equatorial SSTs (Luo and Yamagata, 2001; Luo et al., 2003; Tatebe et al., 2013).

External radiative forcing arising from natural, *i.e.*, volcanoes (Khodri et al., 2017) and anthropogenic sources, *i.e.*, greenhouse gases (Liu et al., 2005; Collins et al., 2010; Xie et al., 2010; Kociuba and Power, 2015) as well as sulphate aerosols (Takahashi and Watanabe, 2016; Smith et al., 2016) may also generate PDV. Research is also being conducted to estimate the relative importance of anthropogenic and natural processes in the PDV evolution (Kociuba and Power, 2015). The potential importance of interactions between basins in driving PDV has also been recently emphasised (Cai et al., 2019, McGregor et al., 2014, Ruprich-Robert et al., 2017).

Recent research is also directed towards quantifying the skill of Pacific multi-year to decadal predictions (DiNezio et al. 2017; Boer et al., 2018), including some biogeochemical quantities (Séférian et al., 2014, Lovenduski et al., 2019), and the influence of PDV on future global temperature evolution (Henley and King, 2017). A large multi-model ensemble of initialised decadal predictions shows positive skill over much of the tropical Pacific mainly from the warming trend, but does not capture the negative PDV pattern in the early 2000s, especially in the southern Pacific (Smith et al., 2019). Further work is needed to reconcile generally low skill for predicting PDV (Kim et al., 2012, Lienert and Doblas-Reyes, 2013) with an apparent ability to predict phase transitions (Meehl et al., 2016).

3.2 Understanding and predicting Atlantic decadal variability.

The primary decadal phenomenon in the Atlantic Basin is the multidecadal variability of the Basin SST, referred to as the Atlantic Multidecadal Variability (AMV, or in the past, the Atlantic Multidecadal Oscillation – AMO). The AMV has traditionally been measured, in a rather ad hoc manner, by the North Atlantic Basin averaged SST due to its observed pattern. A role for the oceanic circulation and in particular the Atlantic Meridional Overturning Circulation in driving the AMV has been stipulated since the 1960s and has been recently reviewed by Zhang et al. (2019). There is strong evidence from paleoclimate reconstructions, modern observations and climate model studies that multidecadal AMOC variability driven by the NAO is a dominant driver of the observed AMV and of its associated climate impacts (Delworth et al., 2017). While climate models do simulate a wide array of climate impacts associated with AMV (Martin et al. 2013, Ruprich-Robert et al., 2017; Monerie et al., 2019), it appears that most models underestimate the role of the AMOC in AMV and the associated climate impacts because of missing processes and persistent biases in the ocean and/or the atmosphere. For instance, most CMIP5 models underestimate the tropical part of the AMV SST and its teleconnection with the subpolar SST. This leads for instance, to a weaker European summer surface air temperature response to AMV (Qasmi et al., 2017), a weaker than observed Sahel rainfall response to AMV, and no precipitation response to AMV over North America (e.g. Martin et al., 2014, Kim et al. 2018). The impact of AMV on the multidecadal variability in winter NAO seems also to be underestimated (e.g. Ting et al., 2014; Peings et al., 2016; Kim et al., 2018; Yan et al. 2018), which has implications for the AMV-driven teleconnections (Ault et al., 2012; Menary et al., 2015). Increasing the horizontal and vertical resolutions in the oceanic and atmospheric components of coupled models seem to partly reduce the tropical Atlantic biases and leading to better air-sea feedbacks and improved teleconnections between the subpolar and tropical part of the AMV and the associated climate impacts (e.g., Harlaß et al., 2018; Xu et al., 2014).

While the role of oceanic internal variability has been shown to be important in the AMV, the role of external forcing appears to be important too, and the relative role of internal and external forcing remains hotly debated (Clement et al. 2015, Cane et al., 2017; Zhang et al., 2019). The role of external anthropogenic forcing appears to have been particularly important during the latter half of the 20th century, with a competition between GHG warming and anthropogenic sulfate aerosol cooling (Booth et al. 2012, Murphy et al. 2017, Steinman et al. 2015, Undorf et al. 2018). Natural forcing from volcanic eruptions may also have played a role, though to a lesser extent (Bellucci et al. 2017, Swingedouw et al. 2017. See also section 3.3 for a summary of the role of volcanoes in decadal climate variability). Further investigations are needed to better estimate the relative importance of anthropogenic external forcing in the AMV in relation to internal atmosphere ocean variability, keeping in mind that the AMV is non-stationary in time and that its spatial pattern has been simplified due to the constraints of the observed record. These complicates the evaluation of historical simulations and of the instrumental records (Tandon and Kushner, 2015; Qasmi et al., 2017).

Recent decadal prediction experiments have shown that decadal prediction skill is larger in the Atlantic basin than in the Pacific (e.g. Hermanson et al., 2014; Yeager and Robson, 2017; Yan et al., 2018). Decadal prediction experiments that use observed ocean initial conditions, successfully predict the observed decadal warming shift of the mid-1990s in the North Atlantic, which is not predicted by uninitialized hindcasts (e.g. Robson et al., 2012; Yeager et al., 2012; 2018; Msadek et al., 2014). The enhanced Atlantic decadal prediction skill is achieved primarily by initializing AMOC anomalies. Idealized experiments show that the AMOC is predictable 5 to 10 years in advance with enhanced predictability in the models that simulate a stronger low-frequency AMOC variability in their control runs. Improved understanding and modeling and additional observations of the linkages between AMOC and surface heat and freshwater buoyancy flux forcing are needed to advance the prediction of the AMOC in initialized decadal prediction systems. This is also important for improving predictions of the AMV and its associated climate impacts. Recent results based on a large number of hindcast runs start dates and ensemble members, paired with a large ensemble of uninitialized historical simulations (e.g., the coupled model Large Ensemble, Kay et al., 2015) show promising level of decadal skill for many different fields including Sahel rainfall and European hydroclimate (Yeager et al., 2018). This set of decadal predictions, together with the other upcoming CMIP6 DCPP sets of experiments that will soon be available to the whole community, offer a unique tool to advance our understanding on long-standing issues in DCVP like the low signal-to-noise ratio over land or the respective contribution of internal processes and external forcing to decadal prediction skill.

3.3 Understanding and predicting the decadal impact of external forcing agents.

The effect of external forcing on decadal climate variability and predictability is significant and well recognised. Two components of anthropogenic forcing are primarily involved, these are the current and projected, near-term GHG concentrations and the current and projected spatial distribution of industrial and natural aerosols. Both the direct, rapid response of the land surface to anthropogenic forcing and the indirect, slow response of the upper ocean shape the reaction of the climate system that society is concerned with. In addition, there are two major, natural external sources of DCVP: one is the quasi-regular variations in solar irradiance (Gray et al., 2010) and the other is the aerosols from volcanic eruptions (Zanchettin et al., 2016). Through direct interaction with the surface heat balance and through chemical-radiative interactions with stratospheric Ozone, the quasi-regular 11-year solar cycle is arguably an important source of near-term predictive skill for the winter North Atlantic Oscillation and its hemispheric impacts (Gray et al., 2013; Scaife et al., 2013; Thiéblemont et al., 2015) and possibly the forced warming of the east equatorial Pacific (Meehl et al., 2008) although these claims have been questioned (Chiodo et al., 2019). Volcanic eruptions affect the global climate by interfering with solar radiation and triggering large-scale modes of climate to affect global and regional surface temperature and precipitation anomalies (Timmreck et al., 2016). These eruptions are thought to be episodic and unpredictable at the lead time considered in NTCPs and therefore require special treatment (Boer et al., 2016). It has become clear recently that the long-term variability of the Atlantic Ocean-atmosphere system as well as its Pacific counterpart are affected by anthropogenic and natural external forcing (Booth etal., 2012). In his review of the significant influence of external forcing on climate, Zanchettin (2017) details the “outstanding issues for progress” in understanding the underlying physical mechanisms by which these forcing agents interact with the climate system, incorporating them in coupled models and predicting their impacts. These issues are reflected in the summary in section 4 below.

4-Remaining challenges

Despite the progress made to understand DCVP since the RF inception, challenges to progress under this theme still remain. The biggest remaining challenges are listed below.

- Overcoming modeling impediments to simulating and predicting decadal variability, such as:
    - Biases in representing the climatology.
    - Deficient model simulations of decadal variability, including the space and time scales and low signal-to-noise ratio.
    - Initialization shock and drift of model states when assimilating observations.
    - Incorporation of external forcing agents in models and soundly simulating the key related physical mechanisms (e.g., aerosol, natural and anthropogenic, direct and indirect interactions with the circulation and clouds; Ozon and other stratospheric chemical-radiative interactions).
- Understanding predictability and mechanisms of decadal variability
    - The role of external natural forcing – solar variability and volcanic eruptions – in decadal climate variability and their impact on predictability and prediction.
    - Low signal-to-noise in decadal prediction over land and in the atmosphere.
    - Pacific *vs.* Atlantic decadal predictability: While models show decadal skill in the Atlantic, it remains limited in the Pacific. Address the impediments to predicting Pacific decadal variability.
    - Understanding the origin, role and mechanisms of decadal inter-basin interactions.
    - Role of background mean state: how will decadal climate anomalies change in a warmer climate? How does the impact of volcanic eruptions depend on the background state? How do we address this issue of mean-state dependence?
- Data issues
    - Advancing the use of paleoclimate information (particularly high-resolution proxies from the Common Era) in DCVP.
    - Using prediction ensembles to understand decadal mechanisms.
    - Improving data on external forcing agents: natural and anthropogenic aerosols; solar forcing.

6-Recommendation for continued pursuit of the DCVP theme:

A very large number of experiments, including coupled model runs with partial relaxation to observed decadal patterns (pacemaker experiments) and with prescribed external forcing (natural and anthropogenic) are currently being run as part of CMIP6 by different modeling groups across the world. We believe that a planned and coordinated analysis of some of these experiments can help address some of these challenges. New dedicated experiments are needed to be designed to tackle remaining issues. These can help address many of the recommendations listed below:

- Continue the execution and analysis of multi-model pacemaker experiments to address, in particular, the issues of predictability of climate over land and inter-basin interactions.
- Investigate CMIP6 externally-forced multi-model experiments (e.g., VolMIP AerChemMIP, SolMIP etc.**)** to determine and understand the effect of such forcing on decadal climatic variability and predictability.
- Advance understanding of decadal ocean mechanisms and the role of ocean dynamics in decadal prediction by promoting coordinated multi-model experiments based on the experience of the DCPP Pacemaker experiments. These should aim at continuing and

addressing the role of the ocean in decadal prediction (possibly in collaboration with OMIP).

- Maintain Internal communication between CLIVAR panels and external communication between CLIVAR and other WCRP activities (GC-NTCP and DCPP in particular). These have been rather loose so far and need to be tightened and formalized. This is particularly important as WCRP is moving towards operational near-term prediction in collaboration with the WMO. CLIVAR needs to stand behind this operational effort (together with the other core WCRP projects) to assure scientific progress on DCVP.
- Make better use of paleoclimate information (particularly high-resolution proxies from the Common Era) and build closer relations to PAGES, particularly PAGES-2K
- Design new coordinated experiments that can address remaining issues, for example: to investigate the impact of regional, short-term forces (black carbon, dust); to understand model signal-to-noise issues; to understand the interaction between internal and forced variability; to address the role of background mean state; and to overcome modeling issues such as model biases, initialization shock and initialization drift.

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