DECADAL CLIMATE FORECASTING PROJECT
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Capability of CSIRO as a global producing centre for annual to decadal climate prediction

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Technical Report

CLIMATE ANALYSIS FORECAST ENSEMBLE system

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Contents

Summary

This report serves as a partial requirement to qualify CSIRO as a designated WMO Global Producing Centre (GPC) for annual to decadal Climate Prediction.

The report provides a brief background of the CSIRO Decadal Climate Forecasting Project (DCFP), a summary of our forecasting system (Climate Analysis Forecasting Ensemble, CAFE), the research we are pursuing and evidence that the CSIRO meets all of the minimum requirements to obtain the designation, namely:

1. CSIRO can produce, with at least annual frequency, the required fields from CSIRO annual to decadal forecast system.
2. CSIRO can provide on the WMO Information System (WIS) the range of products requested by the WMO.
3. CSIRO can prepare the necessary verification statistics.
4. CSIRO can provide an agreed set of forecast and hindcast variables to the lead centre for annual to decadal climate prediction.
5. CSIRO can maintain on a website up-to-date information on the characteristics of its global decadal prediction system.

1 Introduction

Recognizing the huge potential benefit of a decadal forecasting system to the Australian economy, the Australian Federal Government directed CSIRO to prioritise this research effort as part of the Climate Science Centre (as given in the Governments Statement of Expectation for CSIRO). CSIRO, starting in January 2017 committed $37 Million over 10 years to the decadal climate forecasting effort within the Climate Science Centre. Under this initiative, CSIRO funded Decadal Climate Forecasting Project (DCFP), a 10-year, 15-EFT, $37M project (`https://research.csiro.au/dfp/`). The challenge of the CSIRO Decadal Climate Forecasting Project is to improve and advance the use of multi-year to decadal forecasts to enable Australian industries and regulators to better deal with climate variability and climate extremes.

The broad mission of the DCFP is to:

- Improve multi-year to decadal climate forecasts by:
  1. Advancing fundamental climate research into: where does the predictability of the climate system reside, the processes that give rise to that predictability, and the critical observations that will help us to realise the potential climate predictability
  2. Applying state-of-art ensemble data assimilation to determine the initial climate state for the forecasts
  3. Integrating climate processes with the forecasting effort in the development of initialised ensemble climate forecasts
- Advance the utility of climate forecasts by:
  1. Closely integrating verification and applications with forecasting effort (targeted evaluation linked with the application)
  2. Advancing process understanding and process verification to build confidence in the value of forecasts

2 Research Activities of the CSIRO Decadal Climate Forecasting Project

To achieve our DCFP mission, the project is divided into three key activities.

2.1 Data Assimilation, Climate Modelling and Ensemble Generation

The activity combines coupled modelling with ensemble data assimilation and prediction to provide the core of the Climate Analysis and Forecast Ensemble (CAFE) System. The CAFE system is a critical tool to characterise the climate state over the recent past, to investigate the predictability of the climate system, and provide multi-year climate forecasts.

Providing multi-year climate forecasts relies on the development of coupled ocean atmosphere climate models in combination with advanced initialisation schemes underpinned by modern data assimilation methods and a rigorous mathematical framework (Sandery et al., 2020; O'Kane et al., 2019). Several factors enable advances at this point in time including: the availability of modern satellite and in situ ocean observations; increasing knowledge of the relevant climate modes of variability and their predictability over a range of spatio-temporal scales; advances in ensemble prediction methodologies and increased computational resources to enable identification and tracking of the growth of predictable modes; improved climate model configurations with improved biases leading to reduced forecast errors, and; an emerging mathematical framework for prediction in nonlinear multiscale systems to underpin and guide forecast system development (O'Kane et al., 2020, 2019).

The DCFP has successfully developed the CAFE system, the first operational forecast system to employ strongly coupled Ensemble Kalman Filter data assimilation of atmosphere, ocean, ocean biogeochemistry and sea ice. CAFE is also the first system to deliver a large (96-member) ensemble climate reanalysis (1960 to present) with sufficient realisations to enable probabilistic studies of the recent climate and to provide self-consistent and balanced initial conditions for up to 96 climate forecasts each month. The project has produced several targeted studies to elucidate how to tackle the coupled data assimilation problem where covariances between the respective domains of the climate system are considered (Sandery et al., 2020). To date 10-members of our climate reanalysis were used as initial conditions for decadal climate forecasts initialised every November 1 from 1960 to 2019 - a necessary requirement for meeting the GDPC criteria. The DCFP is committed to extending the reanalysis and providing the ongoing forecasts required by the WMO annual to decadal climate prediction effort.

2.2 Processes and Observations

The observation and process activity provides observational data for model initialization, and uses observations and models to identify key ocean-atmosphere processes that have the ability to drive multi-year coherent variability in the climate system (e.g. Sloyan and O'Kane (2015); O'Kane et al. (2014b,a)). Key components of this activity are briefly described below.

2.2.1 Observations

The technologies comprising ocean observing systems include a wide array of instruments and platforms (e.g. Argo, moorings, surface drifters and satellites). The heterogeneous nature of the ocean observing system requires a sophisticated data integration and interpretation activity for all available in situ and satellite observations. This activity will provide integrated satellite and in situ observational datasets for initialising the CAFE forecasting system, providing withheld datasets and data products for model validation and, providing process resolving observations to inform model physics assessments and improve the realism of CAFE.

2.2.2 Ocean Processes

As the forecast timescale increases (seasonal to decadal), processes in the ocean become increasingly more important. Knowledge of the dynamical processes that generate coherent long-lived ocean anomalies is key to understanding the potential predictability for the climate system. We intend to identify key ocean processes that drive multi-year coherent variability in the ocean and assess what is their impact on climate variability and climate forecasting (Chapman et al., 2020; O'Kane et al., 2013).

2.3 Atmospheric Dynamics and Applications

This activity works on atmospheric dynamics, mechanisms of climate variability, verification of climate forecasts, and climate forecast applications. This work comes together for example in understanding processes giving rise to droughts, where and when forecast skill is present on timescales of relevance to drought, and how to apply it. Key elements of this activity are briefly listed below.

2.3.1 Verification

The post-processing of forecast outputs is built in the Pangeo framework. The verification system within this is Doppyo (python based software package), which provides diagnostic and skill assessment. The skill scores are used to track the performance of the ensemble forecast system in oceans, atmosphere, land, and cryosphere (Risbey et al., 2020) . The verification work is strongly process-based and aims to assess the processes giving rise to variability and predictability in the climate system (e.g. Tozer et al. (2020)).

2.3.2 Skill pathways and teleconnections

The predictable climate signal usually emerges from the oceans and relies on teleconnection processes to carry the signal to land regions. Our work assesses the processes via which these information transfers take place in order to better understand limitations on forecast skill and its spatial variability.

2.3.3 Modes of climate variability and extremes

Variability and extremes of climate are intimately related to the storm track regions in the atmosphere. Our work assesses the behaviour of the storm track and its relationship to extreme events, including drought around the hemisphere (Tozer et al., 2018). This work aims to provide a basis for understanding and applying seasonal to multiyear forecasts of drought and other climate extremes.

2.3.4 Applications of climate forecasts

Our applications work seeks to identify those parts of the climate system where there is usable skill in seasonal to multiyear to decadal climate forecasts. Where skill does exist on these timescales it is usually moderate. A key challenge of our applications work is to apply moderate skill in sectors capable of benefiting from probabilistic forecast information to improve outcomes. We are working with the water resources and agricultural sectors to understand and apply forecast skill in strategic planning.

2.4 Big Data

The Decadal Climate Forecasting Project (DCFP) has embarked on building a big data climate science platform to address the opportunities and challenges in the large ensemble datasets generated by our models. Given the explosive growth of these datasets it is becoming increasingly impossible to interactively explore our climate model results and this is hindering scientific inquiry and discovery. The resulting fragmentation of workflow solutions renders most geoscience research effectively unreproducible and prone to error. Ultimately this big data crisis is not limited to the field of climate science. The solutions we are developing will almost certainly be directly applicable to CSIRO-wide data science challenges. To this end, we have joined the Pangeo project (https://pangeo.io/) as a partner.

The Pangeo vision is a community platform for big data geoscience, and provides interactive data exploration workflow that scales to meet our current and future challenges. The workflow is more open and reproducible, containerised and portable, and ultimately, collaborative. Our Pangeo and related python-based software stack is deployed on CSIRO HPC resources. The performance we have seen in latest deployment successful demonstrates we have scalable workflow to meeting the big data challenge of ensemble climate prediction.

3 Minimum Requirements

3.1 Preparation, with annual frequency, of global forecast fields of parameters relevant to multi-annual to decadal prediction

The project has built the CAFE system, which uses an ensemble Kalman filter approach to assimilate a comprehensive set of ocean (in situ and satellite data), sea ice and atmospheric observations to constrain the evolution of the modelled climate system to observations over the period 1960 to present. The system was run to completion through 2019 producing 96 realizations of the climate state (CAFE60 reanalysis) over recent decades (O'Kane et al. submitted to J. of Climate). The reanalysis product used the EnKF-C ensemble data assimilation system and a configuration of the GFDL CM2.1 climate model with all code contained within the MOM5 software stack and or publicly available. The attributes of CAFE are summarised in Table 3.1. The individual state estimates from CAFE60 potentially provide the initial conditions for 96 individual forecasts every month over the last six decades. The CAFE system has already generated 10-member, 10-year climate forecasts from November 1 of each year from 1960 to 2019 and is currently the only system in the Southern Hemisphere to contribute to operational near-term climate forecasts for the World Meteorological Organization.

3.2 Make available on the WMO Information System (WIS) a range products

CSIRO has produced the products required to be recognised as a contribution centre to the WMO annual to decadal climate prediction. The forecast dataset comprising 10-member decadal forecasts initialised every November 1 from 1960 to 2019 was provided to the lead centre coordinating for the WMO annual to decadal climate prediction. For example, the surface air temperature (T2m), using our latest forecast initialized on November 1, 2019 as shown in Figure 3.1a for the year 1 and year 2-5 lead times. The forecasts are shown as anomalies with respect to the 1981- 2010 climatology. The forecasts of all the variables required (i.e. T2m, precipitation, sea level pressure, Atlantic Meridional Overturning) are available and are displayed on the WMO site for forecasts initialised in Nov 1, 2019.

3.2.1 Global maps of the ensemble mean anomalies

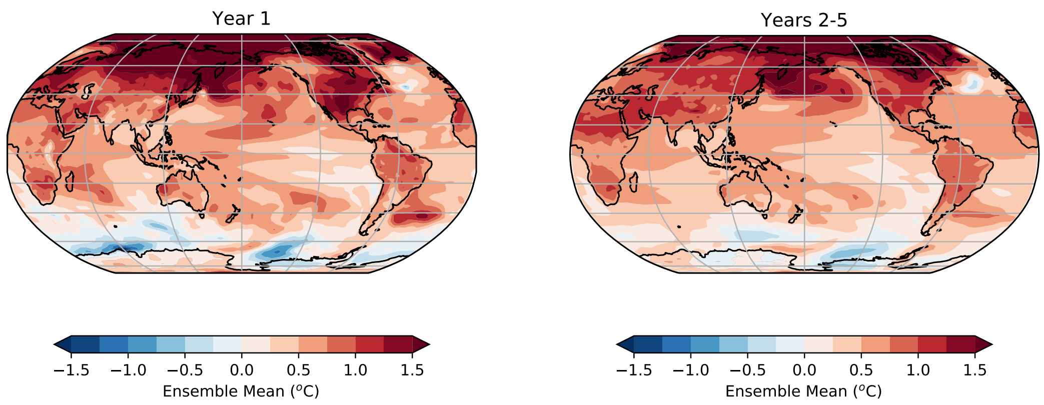

Figure 3.1: Surface temperature anomaly (T2m) forecasted for Year 1 (November 2019 to October 2020) and Years 2-5 (November 2020 to October 2024).

3.2.2 Global maps of the ensemble spread (standard deviation)

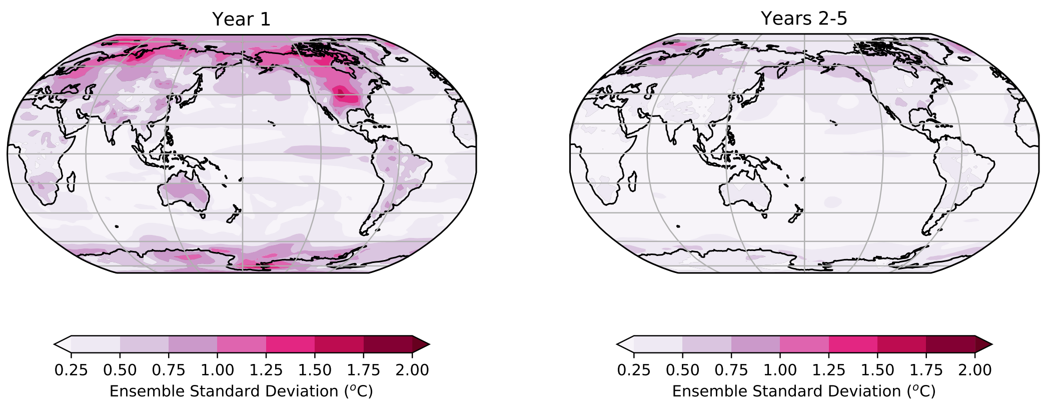

Figure 3.2: Surface temperature (T2m) ensemble spread forecasted for Year 1 (November 2019 to October 2020) and Years 2-5 (November 2020 to October 2024) computed as the standard deviation of the 10-member forecast.

3.2.3 Forecasted global surface temperature (T2m) anomaly and spread

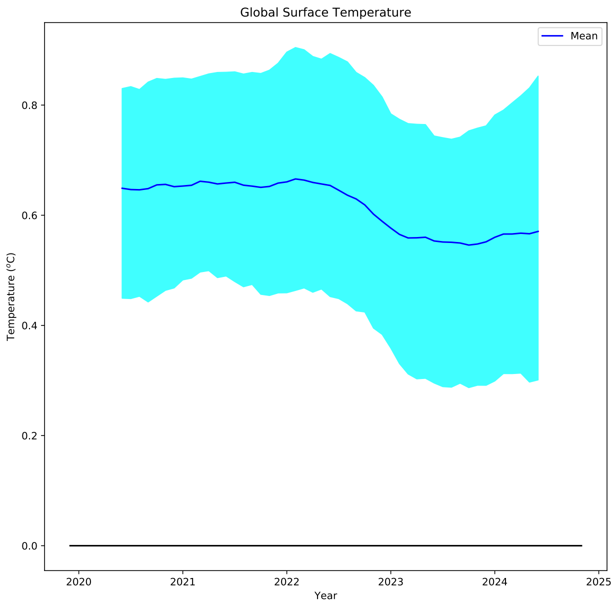

Figure 3.3: Mean annual global surface temperature anomaly (T2m) for a forecast initialised on November 1, 2019. The thick blue line represents the ensemble mean and the shading the minimum and maximum of the ensemble of forecasts. Anomalies are computed with respect to the 1981-2010 climatology. The forecasted drop in global mean temperature at the beginning of 2023 reflects the development of a La Niña.

3.3 Preparation of verification statistics

The CSIRO DCFP has developed the python based Doppyo package for verification statistics of the climate predictions. The package has evolved from diagnostics developed by the DCFP to analyse model performance and characteristics with direct comparison to observations and various comparable model and data products (O'Kane et al., 2020; Risbey et al., 2020), and to advance climate understanding. The Doppyo package now incorporates important skill metrics for assessing ensemble and probabilistic forecasts. As an example, the plots and score shown in sections 3.2 and 3.4 have all been produced using this package. Finally, the package also includes the necessary functions to provide the products and verification outlined in stage 2.

3.4 Providing an agreed set of forecast and hindcast variables to the Lead Center of the NTCP

CSIRO has demonstrated the ability to compute all the verification statistics required at stage 1 through dopyyo software on a scalable HPC system required for the big data analysis of ensemble climate prediction datasets. Dopyyo and its Pangeo deployment provides a flexible and efficient way to interrogate our climate forecasts datasets.

3.4.1 Hindcast - Global maps of grid-point temporal correlation of the ensemble mean with observations

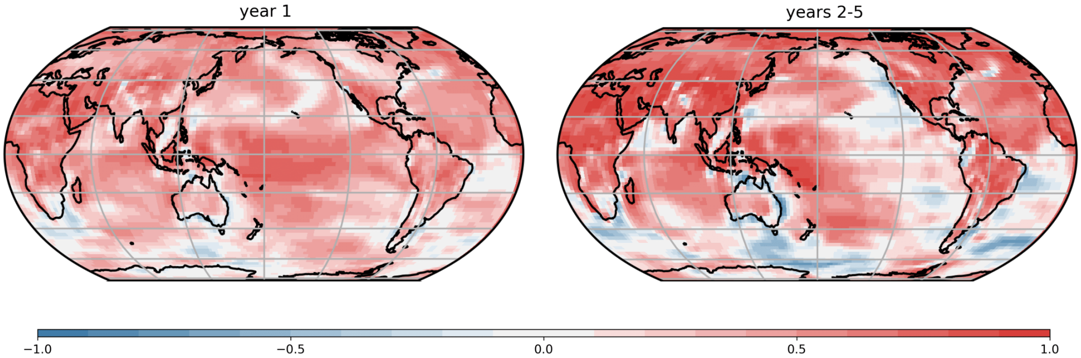

Figure 3.4: Surface temperature anomaly correlation between the CAFE ensemble mean forecast and the observations over the 1960-2018 period, for first year of the forecast and years 2-5.

3.4.2 Forecast Verification - Maps of ensemble mean predicted and observed anomalies

The JRA-55 atmospheric reanalysis (Kobayashi et al., 2015) is used for the observations in the following figures .

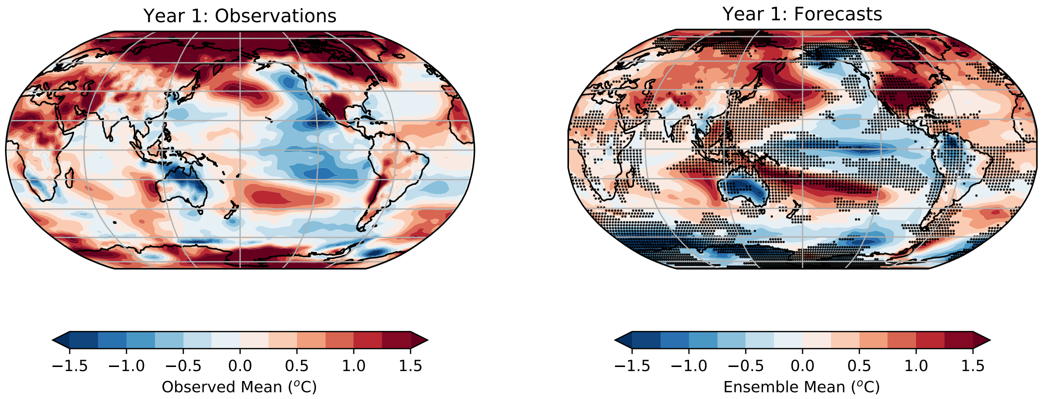

Figure 3.5: Surface temperature anomaly for November 2010 to October 2011 (Year 1) for the observations based on JRA55 reanalysis and the CAFE ensemble mean forecast initialised on November 1, 2010. Stippled areas show the regions where the observations lie outside the 5 – 95% model predicted range. The spatial correlation coefficient between the observations and the ensemble mean forecast is 0.45 .

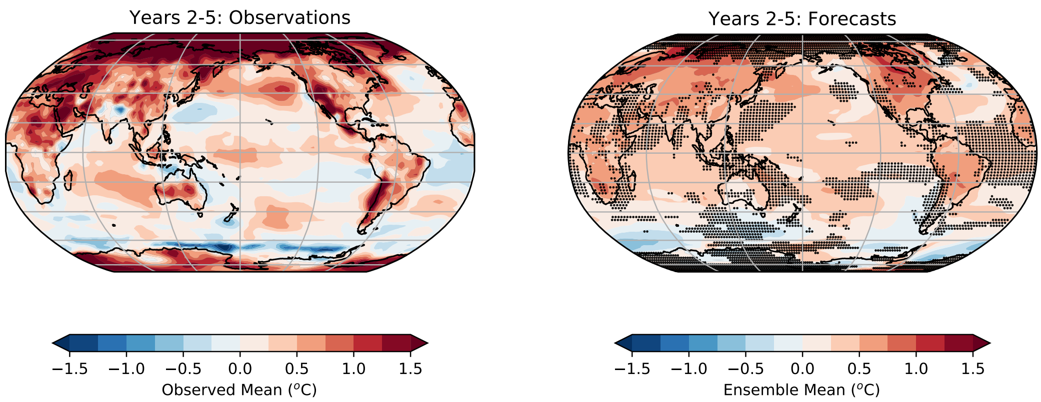

Figure 3.6: Surface temperature anomaly for November 2011 to October 2014 (Years 2-5) for the observations based on the JRA55 reanalysis and the CAFE ensemble mean forecast initialised on November 1, 2010. Stippled areas show the regions where the observations lie outside the 5 – 95% model predicted range. The spatial correlation coefficient between the observations and the ensemble mean forecast is 0.51 .

3.4.3 Comparison of observed and forecasted annual mean global temperature time series

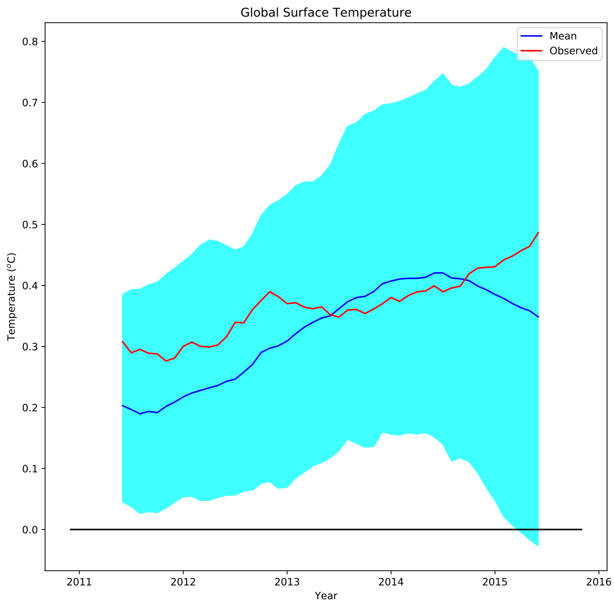

Figure 3.7: Annual mean global surface temperature anomaly for the forecast initialised on November 1, 2010 where the thick blue line is ensemble mean and the shading the spread of the forecasts. The red line shows the observations based on the JRA 55 reanalysis. Anomalies are computed with respect to the 1981-2010 climatology.

3.5 Public global decadal prediction system information

The following table 3.1 will be made available with up-to-date information on the characteristics of the CAFE global prediction system on both the CSIRO DCFP website and the LC-NTCP site.

Date of implementation of current long-range forecast system	January 2020
Coupled forecast system	Yes
Tier-2 forecast system	No
Atmospheric model and resolution	AM2 (2° in latitude and 2.5° longitude, and 24 hybrid sigma-pressure vertical levels).
Ocean model and resolution	MOM 5, ACCESSo grid (1 degree horizontal resolution with enhance resolution in the tropics and Southern Ocean and 50 vertical levels);
Sea Ice model	Sea Ice Simulator (SIS)
Land model	Land Model 2 (LM2)
Source of atmospheric initial conditions	model restarts from CAFE60 ensemble climate reanalysis (strongly coupled ensemble Kalman filter) assimilation of atmosphere, ocean and sea ice observations)
Source of ocean initial conditions	CAFE60 ensemble climate reanalysis
Source of sea ice initial conditions	CAFE60 ensemble climate reanalysis
Hindcast period	1960-2018
Ensemble size for the hindcasts	10 members
Hindcast ensemble configuration	A set of hindcast has been run over the period 1960- 2019, with one forecast initialised on November 1 of each year. The initial conditions come from a subset of the ensemble CAFE60 climate reanalysis (10 of the 96 members available).
Length of forecasts	10 years
Data format	Netcdf
What is the latest date predicted anomalies for the next month/season become available?	Forecast initialised on November 1, 2019 out to a 10 year lead time
How are the forecast anomalies constructed	Departure from 1981-2000 climatology
URL where forecast are displayed	https://hadleyserver.metoffice.gov.uk/wmolc/
Point of contact	Richard.matear@csiro.au

Table 3.1: Summary description of the CAFE forecasts

4 Future Plans

CSIRO is committed to ongoing support of the Decadal Climate Forecasting Project (DCFP) with funding in place till January 2027. The project is in an exciting place having just produced the key dataset required to join the WMO annual to decadal climate prediction effort. CAFE60 is an innovative and exciting product that for the first time uses a large ensemble strongly coupled data assimilation framework to assimilate observations from satellite sea surface temperature and sea level anomalies, in situ ocean, gridded atmospheric reanalysed data and satellite sea ice concentration and extent observations, including their respective cross domain covariances into a climate model to reconstruct the recent climate and quantify climate risk. The CAFE60 reanalysis represents a valuable product to investigate climate variability and change over the last six decades.

Further, the project has secured the largest Australian compute grant ever allocated to deliver ensemble decadal climate forecasts initialised with start dates over the last decade. The proposal will use all 96 members of the CAFE60 climate reanalysis to generate 96-member ensemble climate forecasts and, for the first time, provide predictions of the global climate probability distribution at daily resolution. We will generate decadal climate forecasts starting 2010 and extend them into the coming decade to facilitate the investigation of the predictability of the climate system and to assess near term climate risk. The large ensemble of forecasts will be a unique dataset to investigate the utility of climate forecasts for the benefit of Australian communities and industries who are vulnerable to climate variability and extremes.

Combined with generating new forecasts, the DCFP has ongoing work investigating the utility of the climate forecasts for a suite of applications. For example, the project has existing collaborations with industry partners in Energy (e.g. Hydro-Tasmania), Agricultural (e.g. CSIRO Digiscape) and Australia Fisheries Management Authority (e.g. FRDC funded project exploring the use of multiyear climate forecasts for the management of the Southeast Australia Tuna and Billfish fisheries). All three of these initiatives will utilise our forecast products to investigate the value they could provide for management decisions.

The DCFP is also committed to the further development of the CAFE system. Currently, CAFE includes ocean biogeochemistry and we are actively investigating how to utilise the remotely sensed ocean colour observations to constrain the phytoplankton and other biogeochemical fields to provide reanalysis and forecasts of products like marine primary productivity and air-sea carbon fluxes. A complimentary effort is also investigating how to use observations to constrain the land surface via assimilation of remotely sensed observations.

Model error is a fundamental problem limiting our forecast skill and the DCFP is exploring ways to reduce model bias and improve realism through formal methods of parameter estimation in application to sea ice modelling, surface ocean-atmosphere fluxes and ocean biogeochemistry. We are exploring targeted perturbations of the ocean state with our climate model. The approach is to systematically catalogue the atmospheric response to ocean perturbations on various spatiotemporal scales to elucidate how the ocean influences our climate. We are advancing our understanding of how subsurface Indian Ocean thermocline variability is transferred to the atmosphere. We show the 2 to 10-year variability of the mid-latitude Indian Ocean influences atmospheric temperatures in the tropical Indian Ocean. We are now exploring the implication these temperature changes have for interannual climate predictability.

CSIRO will provide quasi-operational decadal forecasts, with an ever improving system, for the foreseeable future.

5 References

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FOR FURTHER INFORMATION

CSIRO Decadal Climate Forecasting Project

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