TAMU HPC Allocation Renewal Proposal:
Simulating and Predicting Climate Variability Using High-Resolution Climate Models

Principal Investigator: Ping Chang

Department of Oceanography
Department of Atmospheric Sciences
Texas A&M University, College Station TX

1. Problem Statement

The scientific objectives of the project are two-fold: 1) to reduce climate model biases by identifying and quantifying the atmospheric and oceanic sources of the bias, as well as feedbacks due to air-sea interactions, which will ultimately lead to improvements in projections of future changes in extreme climate events; and 2) deepen our understanding of the role of ocean eddies in North Pacific and Atlantic climate variability. For the first objective, the main thrust of this research lies in the use of high-resolution climate models that allow for explicitly resolving oceanic mesoscale eddies, fronts and upwelling dynamics, as well as atmospheric convection and steep orography effects, and thus minimizing model systematic errors due to uncertainties associated with parameterizations of subgrid-scale processes. This high-resolution modeling approach also isolates sources of biases from other ocean basins and helps to pinpoint the causes of the biases within the region of interest. It further facilitates a better model-data comparison as recent intense observational programs in different ocean basins have together produced an array of fine temporal and spatial resolution data sets that require high-resolution model simulations to fully utilize their advantages.

For the second objective, the focus of the proposed project is on exploring the role of ocean mesoscale eddy-atmosphere (OMEA) feedback in maintaining the sharp SST gradient along oceanic fronts and the associated current systems in order to improve our understanding of the importance of midlatitude air-sea interaction in the climate system. To achieve this objective, we will conduct a set of high-resolution climate simulations to test the following scientific hypotheses: *1) Energetic ocean eddies along the Kuroshio and Gulf Stream can exert significant remote influence on North Pacific and Atlantic storm tracks and weather patterns through their effects on moist baroclinic instability; 2) OMEA feedback is fundamental to the maintenance of the Kuroshio and Gulf Stream fronts.* The modeling analysis will be complemented and validated by an in-depth analysis of *in situ* field measurements generated by recent CLIVAR-endorsed field programs in the North Pacific and Atlantic, such as Kuroshio Extension System Study (KESS) and CLIvar MOde water Dynamic Experiment (CLIMODE), as well as high-resolution reanalysis and remote sensed satellite data sets.

2. Background

The proposed research activities build on eight years of experience running regional and global atmosphere and ocean models on TAMU and TACC HPC systems. We have trained many students and postdocs in climate modeling and prediction. Many of the students graduated from our group are leaders in the field. Over the past four years (since 2013), we have published more than 30 journal papers, including high-impact journal articles in *Nature*, *Nature Geoscience*, *Scientific Reports*, and generated six funded projects.

The modeling efforts described here are supported by two NSF-funded projects:

Title: Understanding Causes of Climate Model Biases in the Southeastern Tropical Atlantic (PI: P. Chang, Co-PI: Christina Patricola); Sponsor: NSF; Period: 9/1/2013-8/31/2018 Amount: $796,305 for 3 years

Title: Role of Ocean Mesoscale Eddy Atmosphere Feedback in North Pacific and Atlantic Climate Variability: A High-Resolution Regional Climate Model Study (PI: P. Chang, Co-PIs: R. Saravanan and

R. Montuoro); Sponsor: NSF; Period: 3/15/2015-3/14/2018; Amount: $798,215.00 for 3 years

3. Computational Methodology

Our computational methodology employs three main computer models to produce simulations of the climate at regional scales: WRF (atmosphere model), ROMS (ocean model), and CRCM (Coupled Regional Climate Model), and at global scales: NCAR CESM. These models use large high-resolution horizontal latitude/longitude grids and finely tuned sets of vertical levels to integrate discretized fluid dynamics equations for the ocean and the atmosphere. Given the large number of grid points in a simulation, the models are implemented as computer codes that allow for distributed-memory configurations, in which a full-domain integration is achieved by partitioning the computational grid horizontally among distinct processors, constantly exchanging boundary conditions between the resulting grid cells.

The models used in this research are available as computer codes written in Fortran 77/90 and C, and will be built exclusively in distributed-memory configurations that use the Message Passing Interface (MPI). Parallel disk I/O will be performed using the Parallel NetCDF library (https://trac.mcs.anl.gov/projects/parallel-netcdf) when writing output and restart files for the atmospheric model, both in standalone (WRF) or coupled configuration (CRCM) or high-resolution global CESM configuration. In all the other cases, single-task, serial NetCDF will be used for disk I/O. Details for each model are provided below.

3.1. Regional Ocean Model

The Regional Ocean Modeling System (ROMS) is a free-surface, terrain-following, primitive equation ocean model in wide use (http://myroms.org). It is based on a finite difference discretization on a staggered Arakawa C-grid. The algorithms that comprise ROMS computational nonlinear kernel are described in detail in Shchepetkin and McWilliams [2003, 2005]. Open boundary conditions are incorporated to allow for realistic tracer and momentum forcing. Mixed layer dynamics is parameterized using KPP scheme. In the vertical, ROMS has a terrain-following vertical coordinate system, derived using vertical transformation equations. The classic transformation and stretching methods (Vtransform=1, Vstretching=1) had few serious limitations. We will adopt a new transformation and stretching method (Vtransform=2,Vstretching=4) with a minimum depth of 20 m and maximum depth of 5500 m in the Atlantic domain. Preliminary tests show that with 50 levels in the new vertical grid (~8 m in upper 100m, ~16 m at 200m, ~28 m at 300 and ~60 m at 500m depth) ROMS has dramatically reduced upper thermocline biases. In this research proposal, the horizontal resolution of ROMS will be kept at 9 km.

3.2. Regional Atmospheric Model

The Weather Research and Forecasting model (WRF http://www.wrf-model.org; Skamarock et al. 2008) is a non-hydrostatic, terrain-following atmospheric model developed at the National Center for Atmospheric Research (NCAR). The spatial discretization in the WRF solver also uses finite difference on a staggered Arakawa C-grid. In this research, we will use a grid with 32 vertical levels and a horizontal spacing up to 9 km to keep the computational cost manageable. We plan to enhance horizontal spacing to 3 km in future projects to decrease, or even eliminate, dependence on convective parameterizations, resolve changes in precipitation-producing mesoscale dynamics, and resolve surface/atmosphere exchanges of heat, water, and momentum, as well as steep orography effects.

3.3. Coupled Regional Climate Model

The Coupled Regional Climate Model (CRCM) consists of the WRF atmospheric model, the ROMS ocean model, and a coupling framework to handle the bidirectional exchanges of surface energy and momentum fluxes between the ocean and the atmosphere models. It is developed and maintained at Texas A&M University building on a decade of experience.

The most recent versions of the CRCM are based on a coupling infrastructure fully developed and maintained by one of the investigators (RM). This code—written in Fortran 90 and based on MPI for handling of distributed-memory communications—allows both the WRF (atmosphere) and ROMS (ocean) models to run simultaneously by assigning fixed groups of MPI tasks to each model. The coupled models synchronize their execution status at each coupling step, when quantities at each model's interface are exchanged according to a given coupling frequency. The need for constant synchronization of all coupled models during a fully coupled simulation run introduces unavoidable inefficiencies in the computation, which may be minimized by optimizing the coupling frequency and load balance among the models for a given coupled configuration.

For our computational experiments we plan to use the latest available version of CRCM (2.2.6), which has been fully tested on Ada and Lonestar. Among the major features included in version 2.2.6 are: a) conservative remapping [Jones, 1999] of surface quantity when coupling models with different resolution grids; b) energy and momentum fluxes at the air-sea interface may be computed optionally according to the COARE flux algorithm version 3.0 [Fairall et al, 2003]; c) ability to rerun a coupled simulation using only one active model and a flux history file. The latest version of CRCM also makes it possible to use parallel disk I/O in the coupled atmospheric (WRF) model with the aid of the Parallel NetCDF library.

The fact that CRCM is developed within our research group will allow us to fine tune its coupling framework before conducting our experiments, for the most efficient use of the allocated computational resources.

3.4. High-Resolution CESM

In addition to the regional modeling tools, we will also be using high-resolution CESM with 10 km horizontal resolution for the ocean and sea ice and 25 km resolution for the atmosphere. This high-resolution configuration has been tested on Ada. Using 6,000 cores, we have obtained a throughput of 5-month model simulation per day on Ada.

4. This Year's Computational Research Plan

4.1. Tropical Channel Model Prediction Experiment

We will carry out a set of WRF prediction simulations with a tropical channel configuration at 27 km covering the entire tropics from 30°S to 50°N. The experiment is designed to understand how model tropical biases and mesoscale air-sea coupling can have an impact on model skills in predicting interannual variability of tropical cyclones. An ensemble of 10 forecast simulations will be conducted for each year forced by predicted sea-surface temperature provided by NCAR decadal prediction system, starting from 1990 to 2016. Each forecast simulation will start in May 1 and end in November 30 (7-month integration). A total of 27 ensembles will be performed, which is equivalent to 157.5 years of continuous model integration.

4.2. Tropical Channel CRCM Prediction Experiment

We will repeat the above WRF prediction experiment using CRCM in the same tropical channel configuration with 27 km WRF coupled to 9 km ROMS. The computational cost of the tropical channel CRCM is estimated to be twice the cost of WRF.

5. Justification of Requested Resources

Estimates of computational resources are based on the parallel scaling analyses and initial production runs performed on Ada and lonestar. Performance metrics from our production runs have been fully taken into account to calculate updated estimates of the compute resources required to complete this study. The higher computational cost reflected in the new estimates is mostly a consequence of having increased the extension of both our regional domains for the ocean and the atmosphere to improve the models' description of the region of interest.

One 7-month forecast simulation using the tropical channel WRF at 27 km running on 768 cores on LONESTAR with parallel NetCDF will require about 12 wall-clock hours, or *9,216 core hours*. An ensemble of 10 runs will require *92,160 core hours*. The prediction experiment consists of 27 ensembles, which requires *~2.5 million core hours*.

As mentioned above, the tropical channel CRCM is twice the cost of the WRF. Therefore, to complete the CRCM prediction experiment will require approximately *5 million core hours*.

We also request *0.5 million core hours* to perform pre-processing of the model simulations and initial optimization tests for our CRCM simulations. Therefore, the total requested SUs for this project is **8 million** for this year.