Multi-RCM Ensemble Downscaling of NCEP CFS Seasonal Forecasts (MRED)

A Collaborative Proposal: Scripps, NCEP, NOAA/ESRL, ISU, PNNL.

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Summary
For many years, regional climate models (RCMs) have been used to downscale global climate simulations. In contrast the ability of RCMs to downscale seasonal climate forecasts has received little attention. Do RCMs provide additional useful information for seasonal forecasts? The answer to this question may have implications for the kind of information RCMs may add to longer term climate projections. Therefore, in response to the particular CPPA focus on seasonal forecasts, we propose a systematic test of the RCM downscaling methodology. Specifically, RCMs will be used to downscale new National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) seasonal forecasts that will be re-made as part of this project. The initial focus here will be on the CFS wintertime forecasts and the initial forecast ensemble will be comprised of 15 members over a period of 22+ years (from 1982 to 2003+) for the forecast period Dec. 1-Apr. 30, with initial dates at 00UTC Nov. 11-15, 21-25, 29-Dec.3. CFS lateral boundary conditions (3-D atmospheric states every 6 hours) and other land surface initial states (e.g. those from the North American Regional Reanalysis (NARR) land surface conditions) will be made available on a public server to be housed at NCEP for participating RCM groups.

Each of the participating RCMs will cover the conterminous US (CONUS) at approximately 32 km resolution, comparable to the scales of the NARR, which will be used for the evaluations. Each RCM will make a similar set of forecasts and then provide standard hydrometeorological output, on a standard regular analysis grid covering the CONUS, back to the NCEP public server. We intend to compare individual RCM and CFS as well as ensemble mean precipitation and temperature forecasts, which are currently being used to drive macroscale land surface models (LSMs), as well as wind, humidity, radiation, turbulent heat fluxes, which are important for more advanced coupled macro-scale hydrologic models. Metrics of ensemble spread will also be evaluated. Some of these evaluations have already been done for the driving CFS, but more extensive analysis will be performed to link improvements in downscaled forecast skill to regional forcings and physical mechanisms.

Our overarching goal is to determine what kind of additional skill can be provided by a community ensemble of high resolution regional models, which we believe will eventually define a strategy for more skillful and useful regional seasonal climate forecasts. Furthermore, we believe an initial focus on the winter season allows a comparison of topographic forcing, snowmelt, and the potential to demonstrate the usefulness of higher resolution, especially for near-surface fields influenced by high resolution orography. This focus also provides an important link to the cold season hydrometeorological research area of CPPA and may contribute to other potential mountain field projects in the near future. We expect to show that: 1) It is now possible to make ensemble community RCM forecasts routinely; 2) RCMs provide additional skillful regional detail for the CONUS; 3) RCM ensembles provide more skillful forecasts of extreme events; 4) multi-RCM ensembles provide additional large scale seasonal forecast skill; and 5) RCM ensembles provide additional useful information for hydrologic applications of seasonal climate forecasts.

1. Results from some prior research of the participants

1.1 PIRCS

The Project to Intercompare Regional Climate Simulations (PIRCS) was a community-based project hosted by the Regional Climate Modeling Laboratory (RCMLab, 2007) at Iowa State University to evaluate the strengths and weaknesses of regional climate models and their component procedures through systematic comparative simulations. Fifteen modeling groups from the US, Canada, Europe, and Australia participated in PIRCS experiments. Intercomparisons focused on the upper Mississippi River Basin where summertime precipitation is created by both large-scale processes and mesoscale (non-orographic) convection, augmented by moisture transport by a low-level jet. The PIRCS experiments examined extreme events of 2-3 month duration (1988 drought and 1993 flood) over this region. The drought simulations focused on a period with minimal contribution to the surface energy budget from latent heat, whereas the flood simulations investigated the same region during a period of intense rainfall and saturated surface conditions. All models captured the sequence of wet and dry days when the flow was driven by large-scale dynamics, but varied much more randomly for strong summertime convectively driven cases with weak synoptic forcing. Most RCMs were able to simulate the unique nocturnal precipitation maximum in the US Midwest, even though this feature was absent in the climatology of the driving reanalysis. Most RCMs simulated the precipitation maximum during the flood event to be northeast of its actual location and of lower total rainfall than observed.

1.2 The IRI/ARCs Regional Model Intercomparison Over S. America

Roads et al. (2003) described a regional modeling intercomparison project for S. America among the: (1) Scripps Experimental Climate Prediction Center regional spectral model (RSM), (2) Florida State Univ. nested regional spectral model (FSUNRSM), (3) Goddard Institute for Space Studies regional climate model (RCM), and (4) IRI regional climate model (RegCM2) is described herein. All regional models were driven by the NCEP/NCAR I global reanalysis over a S. American domain centered on Brazil. In comparison to new Xie and Arkin .5º land observations, the regional models had a seasonal systematic precipitation error that was somewhat similar to the driving NCEP/NCAR reanalysis systematic error, although the regional model ensemble mean error was somewhat smaller, indicating a potential value for using multiple model ensembles. However, correlations, threat scores and biases were not noticeably improved over individual models. In short, at their current levels of skill, regional models did not yet provide a noticeable improvement over large-scale analyses in this tropical region.

1.3 Accelerated Climate Prediction Initiative (ACPI)

ACPI was funded by the Department of Energy to develop the scientific knowledge and computational infrastructures needed to carry through an end-to-end assessment of the possible effects of human-induced climate change. A nested modeling approach was used in which the effects of greenhouse warming were propagated through a suite of global climate models, regional climate models, and impact assessment models including hydrologic and water management models. Water resources were chosen to be the primary focus of the assessment, and modeling and analysis were performed for the western U.S., where cold season changes in snowpack and runoff were found to be significant as a result of greenhouse warming (see e.g. Leung et al. 2004, Han and Roads 2004).

1.4 Coordinated Enhanced Observing Period (CEOP)

CEOP was originally designed to gather data from in situ stations, satellite remote sensing, and numerical weather prediction (NWP) centers' global model analyses for the 2002-2004 time period. The ECPC contributed enhanced reanalyses from the Reanalysis-2 (RII) s well as a new reanalysis using the Seasonal Forecast Model along with 36-hour forecast experiments from each model initialized daily (Ruane and Roads 2007, 2008). The NCEP Reanalysis II was used to drive the ECPC Regional Spectral Model contributions to the Intercontinental Transferability Study (ICTS) (Meinke et al. 2007). We are now working with the other CEOP NWP centers and ICTS to develop standardized model output variable names and formats according to the climate and forecasting standards (http://www.cgd.ucar.edu/cms/eaton/cf-metadata).

1.5 The North American Monsoon Model Assessment Project (NAMAP)

Gutzler et al. (2005) discussed how the international North American Monsoon Experiment (NAME) was organized to improve understanding and prediction skill of warm-season precipitation fluctuations in the monsoonal region of southwest North America. NAMAP accomplished its primary goal of engaging the modeling community and integrating it into a major field campaign. A new round of comparative model runs, NAMAP2, is currently underway and some of the participants of this proposal have contributed to NAMAP.

1.6 NARCCAP

The North American Regional Climate Change Assessment Program (NARCCAP, 2007) is an international program that will provide high-resolution climate scenarios for impacts studies for both the United States and Canada, using six regional climate models, four global climate models, and high resolution global time-slice experiments. The fundamental scientific motivation for NARCCAP is to understand and quantify the combined uncertainty in future climate projections of 2040-2070 based on an ensemble of global and regional model projections. Many of the participants of this proposal are part of NARCCAP.

1.7 NCEP/ECPC Fire Danger Forecasts

Roads et al. (2007) used the National Fire Danger Rating System (NFDRS) indices, including the: Ignition Component, Energy Release Component, Burning Index, Spread Component, Keetch Byram (1988) drought index, and Fosberg Fire Weather Index, to characterize US fire danger. These fire danger indices, and input meteorological variables, including: temperature, relative humidity, precipitation, cloud cover, windspeed, were also skillfully predicted at weekly to seasonal times scales by a global to regional dynamical prediction system augmentation of the National Centers for Environmental Prediction's Coupled Forecast System, which drives global and regional spectral model ensemble forecasts, which in turn provide required input metrological variables for the fire danger code used by the Experimental Climate Prediction Center. An ensemble (3 forecasts every month prior to Oct. 2004, 10 thereafter) of 7-month US regional forecasts are now being made every month beginning 1982 to present and are displayed at (http://ecpc.ucsd.edu/projects/fire.html). Coarse-scale global predictions are more skillful than persistence and fine scale regional model predictions are more skillful than global predictions, suggesting that some forecast skill improvement occurs from regional downscaling.

2. Motivation and Objectives

Global climate models (GCMs) are the foundation for climate forecasting, but they have difficulty simulating well the climatology of regional features, notably precipitation (e.g., Wood et al. 2002; Zhu et al. 2004). These difficulties persist even when GCMs constrained by observations in the data assimilation cycle of reanalyses (Mo and Higgins 1996; Gutowski et al. 1997; Mo et al. 2005). These problems continue for more recent GCMs underlying reanalyses (Nigam and Ruiz-Barradas 2006) and simulating climate (Dai 2006; Ruiz-Barradas and Nigam 2006b), suggesting that the problems will persist for some time. Part of the difficulty stems from the challenge of parameterizing subgrid cloud microphysics and convection, but other problems also abound, such as excessive land-atmosphere moisture recycling (Ruiz-Barradas and Nigam 2006a) and inability to resolve regional-scale circulations such as mountain-valley, sea –land breezes, orographic precipitation controls, etc. A coarse-scale global model's ability to simulate precipitation extremes is also compromised and in this regard, regional climate models (RCMs) have been more successful at producing episodes of extreme regional precipitation (de Sales and Xue 2006). Regional models still produce lower precipitation intensity than observed, suggesting that even higher resolution may still be needed (Gutowski et al. 2003, 2004, 2007).

Members of our team have already participated and led a large number of community Regional Climate Model (RCM) projects focused on dynamical downscaling of large scale climate projections, including PIRCS (Takle et al. 1999), the IRI/ARCs Intercomparison (Roads et al. 2003); ACPI (Leung et al. 2004), and the current NARCCAP projects, all of which are briefly summarized in Sec. 1 above. However, it is probably two European Union-sponsored projects, the recent PRUDENCE and the current ENSEMBLES projects, that provide better examples of what we are trying to propose here. PRUDENCE (Christensen et al. 2002, 2007) and ENSEMBLES (Hewitt 2005), demonstrated the value of ensemble, regional-climate simulations and the feasibility of multi-institutional partnerships to produce and analyze the ensemble. In particular, PRUDENCE produced a series of high-resolution climate-change scenarios for 2071-2000 for Europe. PRUDENCE could account for geographic details, such as topography and land-ocean distributions that global models smeared. ENSEMBLES built on the PRUDENCE experience and involves a suite of global and regional simulations with a more explicit goal of providing probabilistic, high resolution climate-change scenarios. Although starting at the same baseline resolution as PRUDENCE (50 km), ENSEMBLES regional simulations are targeting 20 km for at least some sub-regions of Europe. ENSEMBLES includes more direct linking of model output to such applications as agriculture, health, water resources and weather-risk management. The North American Regional Climate Change and Application Project (NARCCAP) is developing a similar community of RCMs with similar targets and given that many of us are working on NARCCAP, we hope to also build a link to this community.

However, despite a number of notable RCM achievements including the adding of more regional detail and including the development of the many coordinated projects, in our estimation we have not yet definitively answered a major question: Do RCMs add significant regional skill to current global model forecasts? Comparison of analysis driven RCM runs (e.g. Roads et al. 2003) found that long term RCM simulations were slightly degraded for some variables in some regions in comparison to the large-scale analysis, although it could be argued that this has been a somewhat unfair comparison in that an analysis, which is updated with local observations every day, was being compared to a long term simulation, which was forced only by large scale analyses and did not have the local updates like the large-scale analyses. In short, although it has been asserted that RCMs will certainly add value to coarse-scale climate projections, we have not been able to come up with a definitive comparison experiment, until now.

We now have the potential to address this issue from a seasonal forecast standpoint because of the current CPPA desire to evaluate RCM downscaling for fully prognostic and verifiable seasonal forecasts. In particular, we are proposing here to provide NCEP CFS ensemble seasonal forecast products capable of driving RCMs and then encouraging multiple RCM groups, to execute multiple RCMs in fully-prognostic mode for seasonal predictions comprised of 15 members from each participating RCM for a winter to spring season (DJFMA) over a period of 25+ years (likely 1982-2003+). In short, each RCM will make the same forecast as the driving CFS and compare its results to the CFS. Given our previous experience with the CFS/GSM/RSM fire danger forecasts described in Sec. 1, and given our experience in developing coordinated efforts for many previous comparison projects including the current NARCCAP project, we believe we have the experience to propose to this CPPA request and moreover, we have chosen to respond to this CPPA request in a truly coordinated fashion with a number of unique RCMS (RSM, WRF-NMM, ARW, MM5). Not only will we be running and providing the CFS forecast boundary conditions as part of this coordinated project, we will be evaluating multiple RCM ensembles, and we will lead a number of coordinated analysis efforts by participating RCM groups. We describe below how we intend to coordinate and analyze these and other RCM results. It should be noted that we are also fully prepared to include other groups' contributions that are willing to contribute standard output to this RCM evaluation effort. We describe the initially proposed output below although the final details will be worked out in an initial series of teleconferences with participating RCMs. Finally, although our initial focus will be on the CPPA US domain, we believe the archival and provision of global forecasts could stimulate similar work in other global regions and there has been some informal interest already expressed within the GEWEX/CEOP Inter-Continental Transferability Study Working Group.

In any event, our overall goal for our project is to **demonstrate the usefulness of Multi-RCM Ensemble Downscaling (MRED)** of the NCEP CFS seasonal forecasts. We will evaluate 5 hypotheses:

1. It is possible to provide, routinely, sufficient CFS output to drive multi-RCM ensembles.
2. Multi-RCM ensembles provide additional skillful regional detail not available in coarse scale CFS predictions, especially over mountainous regions and especially for surface properties such as snow and soil moisture and other variables and processes important for hydrologic forecasts.
3. Multi-RCM ensembles provide more skillful forecasts of extreme events than the driving coarse scale CFS seasonal ensembles.
4. Multi-RCM ensembles provide additional large scale seasonal forecast skill
5. Multi-RCM ensembles provide additional useful information for hydrologic applications of seasonal climate forecasts.

3. Models

Brief descriptions of the CFS and RCMS we are proposing here are described in this section. Again, it should be noted that we are aware of additional outside interest as well as interest by the CPPA core project in participating in this experiment and, again, we are more than willing to eventually include and coordinate all successful proposals as part of our overall coordinated effort. A summary model **Table 1** for this proposal's community effort is provided below and again this table will be expanded to include all additional participating models. It should be noted that 3 of the 6 RCMs currently participating in the NARCCAP experiment (RSM, ARW, MM5) will participate in this project. We have also included the WRF-NMM, the primary mesoscale model in use at NCEP, for comparison and again realize that additional participants with unique modeling capabilities or significant parameterization differences may eventually become entrained. For example, the CPPA core project has expressed an interest in contributing predictions from the Eta model, which was previously used for the North American Regional Reanalysis (NARR). In that regard, NARR will be the primary data set used for the evaluation of these US seasonal forecasts. Fixed fields used by each model (e.g., topography, land use) will be archived following NARCCAP standards (http://rcmlab.agron.iastate.edu/narccap/output_archive.html. In addition, the fixed fields associated with the interpolation to the analysis grid described below will also be archived.

3.1 CFS NCEP

The CFS currently starts from the operational T382L64 atmospheric and 40 level, 1-1/3 degree ocean analysis, using a coupled ocean-atmosphere model comprised of a similar but lower resolution (T62L64) and older version of the T382L64 Global Forecast System (GFS) that underlies the atmospheric analysis (and medium range forecasts), a similar resolution (40 level, 1-1/3 degree) Modular Ocean Model (MOM3), and a coupler that exchanges heat, water, and energy between the two models (Saha et al. 2006). Corresponding CFS climatology runs, which are runs starting on the same calendar month but for previous calendar years (1982-present) start from the T62L28 RII (Kanamitsu et al. 2002) and historical 40-level, 1-1/3 degree MOM3 ocean analyses. These historical runs are used to correct model biases in the real time forecast and to provide the necessary forecast anomalies.

The CFS (Saha et al. 2007) became operational at NCEP in August 2004 and replaced the earlier Seasonal Forecast Model (Kanamitsu et al. 2002), which was forced by predicted SSTs from other models. As part of the NCEP operational suite, the CFS now runs twice a day (00 12 UTC). The atmospheric model initial condition is from NCEP R2 and the ocean model initial condition is from the NCEP Global Ocean Data Assimilation. The forecast length includes the first partial month, which provides 15 unique initial states, plus the following 9 months. The monthly mean data (not bias corrected) is available in the NCEP ftp server or NOMAD archive. The NCEP CFS is also run in retrospective mode for 25 years (1981-2005).

A new release of the CFS is scheduled for January 2010 (S. Saha 2006). The new CFS will be accompanied by a reanalysis data set (1979-2007), a dataset of retrospective forecasts (1981—2007), and many upgrades to the model formulation. The list of model upgrades includes a finer resolution atmospheric model, the Noah LSM with better representation of snow, frozen soil, and glaciers, a sea-ice model, sub-grid mountain blocking, reduced vertical diffusion, RRTM long-wave radiation,revised Arakawa-Schubert convective parameterization, and more sophisticated microphysics parameterization based on the Ferrier scheme. Of particular interest to the proposed project is that the new CFS will be based on the T126L64 GFS, which corresponds to approximately 105 km average grid point spacing. This suggests that results from dynamical downscaling as described in this proposal will still remain relevant when the new CFS becomes operational, and if we are successful may stimulate further downscaling research in the future.

3.2 RSM-NCEP/ECPC

The NCEP/ECPC RSM (Juang et al 1997) is a primitive equation regional spectral model with a model physics package similar to the NCEP GFS including mesoscale cloud schemes, and it can easily nest inside the NCEP GFS and CFS for daily weather and seasonal climate forecasts. Due to its good performance and simplicity, there are now many international users with several different versions. For more than ten years, the RSM has been used at NCEP operational center for Hawaii 10km weather forecast and five 40km ensemble members for the Short Range Ensemble Forecast SREF system for North America. The RSM has also been used for experimental seasonal forecasts of fire danger (Roads et al. 2007). NCEP has recently been developing the RSM under the SVN system, which has rearranged and reduced computational processes needed for the spectral transforms. A similar RSM is run experimentally at the Experimental Climate Prediction Center (ECPC).

3.3 WRF-NMM

WRF-NMM is a primitive equation finite-difference model. The dynamical core is fully compressible and non-hydrostatic (Janjic 2003). It is the primary mesoscale forecast model in operational use at NCEP/EMC where it is called the North American Model (NAM). The operational NAM configuration will be mimicked to the extent that it is possible to do so (Table 1). It should be noted, however, that the NAM domain is much larger than what is proposed for this experiment.

3.4 WRF-ARW

The Advanced Research WRF (ARW) is developed and maintained by the National Center for Atmospheric Research (NCAR). This model differs from WRF-NMM in the use of a terrain-following hydrostatic pressure vertical coordinate, the Arakawa-C grid, a third-order Runge-Kutta time integration scheme, and a 2nd to 6th order spatial discretization scheme (Skamarock et al. 2005). Since 2003, Leung has been leading an effort to develop regional climate modeling capability in WRF (Leung et al. 2005; 2006a). It has recently been applied as a Tropical Channel Model (Leung et al. 2006b) and to the western U.S. to simulate the effects of orography on the regional hydrological cycle. For this proposed project, we will use the Variable Infiltration Capacity (VIC) land surface model (Liang et al. 1994), which is being coupled to WRF by Leung and collaborators, following their successful coupling of VIC with MM5. Since VIC is being used in the West-wide and East-wide Seasonal Hydrologic Forecast Systems [http://www.hydro.washington.edu/forecast/westwide/], this proposal provides an opportunity to test the value of using a consistent hydrologic representation in generating the atmospheric and hydrologic forecasts.

3.5 MM5-ISU

MM5 is a finite-difference primitive-equation model with a long history of research and semi-operational use by numerous researchers worldwide. Its extensive use before the recent development of WRF in regional climate modeling is advantageous in that the characteristics of the model are now well known. The version to be used here is briefly described in Table 1 and makes use of our recent refinements to the model's parameterization of deep convection

(Anderson et al. 2007). Our experience using MM5 in PIRCS and NARCCAP will allow the simulations to be configured and efficiently executed.

4. Methodology

4.1 CFS forecasts and boundary conditions

In principle, RCMs require significant CFS forecast output every 6 hours and the magnitude of the required storage has up to now been, well, prohibitive. However, storage capability has been slowly growing and we believe we can now begin to test the feasibility of having a routine CFS forecast archive for driving RCMs. In particular, an initial NCEP CFS cold season run will be conducted and all the ensemble forcings and initial conditions will be provided through our coordinated and collaborative project. Initial conditions will be those from Nov. 29-Dec. 3, Nov. 21-25, Nov. 11-15 for the years 1982-2003+ for forecasts up to end of April of following year. In short, we will provide 6 month forecasts with 15 ensemble members for each cold season corresponding to each of the 15 initial conditions. We estimate the size of this externally acessible archive will be on the order of 2 TB, which we believe is no longer overly prohibitive and will allow timely access by RCM groups associated with this project as well as other groups interested in testing the feasibility of having readily available large scale predictions to downscale. Depending upon community interest the archive could be expanded later on to include additional months.

The CFS will provide in the same format the same lateral boundary conditions that are currently provided by the NCEP reanalysis I and II, and which every model participating in this project has already used many times before. In particular, spectral sigma files with all atmospheric variables as well as a surface file are used by some RCMs. Other RCMs use the pressure files, which have both atmospheric variables interpolated to regular pressure files as well as surface variables. One difference here is that the pressure files will have at least 40 levels, following NARCCAP standards. We may also add a few additional upper level pressure fields in order to better resolve the stratosphere.

In addition to the CFS forecast data, NARR data will be provided for either forcing offline LSMs or for initializing the land states for the RCMs and for RCM forecast verification. In particular, we will provide NARR near surface T, Q, DSW, U, V, PS, snow equivalent water, precipitation, runoff, 500 and 1000 mb heights and other community requested variables to be firmed up at the beginning of the project. Output from the Global Land Data Assimilation System (GLDAS) and North American Land Data Assimilation System (NLDAS) may also be useful for different modeling groups.

4.2 RCM forecasts

Each regional modeling group will generate a 15-member ensemble of RCM forecasts covering the entire continental U.S. for the winter months of November through April of 1982 – 2003+. The ensembles will be generated using the CFS initial and boundary conditions described above. The RCM analysis domain will be similar to the North American Regional Reanalysis (NARR) domain at 32 km spatial resolution. Owing to the use of different map projections, the horizontal grids of the RCMs differ slightly from each other and from the NARR and from the analysis domain, which again is a regular latitude longitude domain covering the continental U.S. The latter grid will be the primary focus for evaluation and analysis of the RCM simulations.

Atmospheric initial fields and boundary conditions will be provided by the CFS simulations. For the forecast lead times of months to seasons, initialization of the land surface states can be important, as the land surface memory associated with soil moisture, soil temperature, and snowpack can influence both land and atmospheric processes. Initial conditions of land surface fields will therefore be provided from the NARR. CFS boundary conditions will also be available. Each group can use alternative methodologies for LSM initialization, including spinning up their own LSM with NARR and other fields. In order to mimic the constraints of operational use, only information up to the day and hour of the driving forecast will be utilized.

The ensemble of seasonal forecasts generated by a global model (CFS), four regional models with 15 different initial conditions will provide a unique opportunity to assess the relative roles of model resolution, physics and dynamical representation, and model internal variability on seasonal forecast skill across different regions of the U.S., where we expect the relative influence of the large scale circulation and regional forcing such as orography to be markedly different.

Forecast output to be provided by the CFS and RCMs is described below in **Table 2**, which combines variables from separate NARCCAP tables. These output variables were chosen because they are critical to hydrological applications and to the evaluation of the RCM ensemble forecasts and comparison with the CFS forecasts. This output list may be further modified after consultations with additional modelers and users, especially the CPPA core project, which includes an atmospheric component (K. Mitchell) and a hydrologic component (J. Schaake). The archive data format will follow the NARCCAP specifications, which itself follows the CF standards. Through the NARCCAP effort, we have already developed software for generating model outputs in NetCDF format that follows the CF standard.

The central RCM archive, which will also be situated at NCEP, may be another 2 TB or so, depending upon the number of participating RCMs (<10?). All RCMs will interpolate their data to a regular latitude, longitude domain before transmitting results to the central archive for analysis. The standard latitude, longitude grid shown in **Fig. 4**. The choice of interpolation method will be left to each RCM group. Fixed fields associated with each model's native and interpolated grid (e.g., topography, land use) will also be archived for later comparison. For some variables (e.g. soil moisture) we want to make sure we are only over land.

4.3 Diagnostic strategy

4.3.1 Comparisons of RCM and CFS skill

We will focus initially on analyzing the bias, RMS, and anomaly correlations of the CFS and each RCM, and then the ensemble mean CFS and RCM with respect to the NARR variables for each month of the 5 month prediction, then for each season (DJF, JFM, FMA), then for the entire winter season (DJFMA). Anomaly correlations will permit a direct comparison with a measure that is used as a skill measure of the operational CFS and reported to the operational community on http://www.cpc.ncep.noaa.gov/products/people/wwang/cfs_skills/. The combination of bias, RMS, and anomaly correlation can also be analyzed within the parameter space of a Taylor diagram (Taylor 2001). The distance in the Taylor diagram space of a model or ensemble value from the observed value is a summary measure that is useful for comparing the overall performance of each model or ensemble to each other. Besides NARR, we may include other gridded datasets of precipitation and surface temperature for model evaluation, noting that there is a range of uncertainty in the observations, particularly in regions of complex terrain. We will use each model's climatology to extract its anomalies before making ensemble mean anomalies and distributions. If noticeable outliers exist, we intend to first point this out to the RCM group but will continue to keep the outliers as part of the RCM ensemble unless there are reasons to believe that any RCM (or CFS) is clearly outside normal bounds. Our previous comparison experiences have indicated that all models will have outliers for some variables in some places at some times and it is not easy to predict in advance which variables will be the best predicted. For example, some models may have useful humidity predictions even though the precipitation predictions may be less well predicted.

Besides bias, RMS, and anomaly correlations, we will also use other measures of forecast skill for comparing the RCM and CFS forecasts. **Figure 5** shows an example of forecast skill measured by the Equitable Threat Score (ETS). Our previous experience in downscaling the NCEP extended weather forecasts suggests that downscaling significantly increases the ETS of cold season precipitation forecasts in the western U.S., particularly for heavier precipitation events. Care must be taken when applying conventional skill measures such as ETS to ensembles. For example, the smoothing inherent in taking an ensemble mean tends to increase the ETS for low precipitation categories while decreasing ETS for higher precipitation categories. Ebert (2001) provides a useful overview of such measures for a multi-model ensemble. We will also evaluate the grand ensemble mean of the CFS and RCM ensemble to determine how much additional large-scale skill might be obtained by having this community ensemble. We hypothesize that our additional ensemble members will add skill to the CFS ensemble.

4.3.2 Distributions

We will examine the forecast distributions of variables over specific regions, such as the US West and US East, including select hydrological basins, to determine if the RCM ensemble is significantly different from the CFS ensemble and if so, how, and at what spatial or temporal scales. We want to know if a measure of the ensemble spread, say RMS, is related to the forecast skill of the ensemble mean. Previous studies have given mixed results for spread-skill relationships in ensemble forecasts (e.g., Whitaker and Loughe, 1998; Atger 1999; Scherrer et al. 2004; Grimit and Mass, 2007). Most such studies have focused on ensembles using a single model and on short- or medium-range weather forecasts rather than seasonal forecasts, so that spread-skill relations for a multi-model seasonal forecast ensemble such as that proposed here are largely unknown. We also want to know how accurately the forecast spread can be forecast. There are a number of application models that could presumably use this probability information although these application models may also simply use the actual ensemble variables as inputs to generate their own probability spreads. Both the individual ensemble mean and probabilistic information will be made available from the RCM forecasts. Verification of ensemble distributions will focus on the ensemble resolution and reliability of variables that are critical to current operational hydrological forecast services. The reliability of an ensemble forecast is a measure of the frequency with which an event is forecasted and subsequently observed, while the resolution of an ensemble is the capacity to forecast events that differ from the climatological mean (Murphy, 1973; Atger, 1999). Measures that summarize these ensemble attributes include the reliability diagram, rank histogram (also called Talagrand diagram; Candille and Talagrand, 2005), ranked probability skill score (Mason, 2004), Brier score decomposition, and relative operating characteristic (Mason, 1982; Mason and Graham, 1999). We have used a number of these measures in past research (e.g., Yang and Arritt, 2002) so that we are prepared to implement them for the present project.

4.3.3 Linking RCM skill to regional forcings and physical mechanisms

An important part of our comparison is to explore the physical mechanisms that distinguish the skill between the RCM and CFS forecasts. In other words, we want to know if we obtain better predictions of temperature and precipitation anomalies for the correct physical reasons. As suggested by Leung et al. (2003), RCMs better capture the spatial patterns of precipitation anomalies because they can more realistically capture the directional dependencies of the wintertime flow during an El Nino or La Nina event and their interactions with the rugged orography of the western U.S. Recent NARCCAP results focusing on the 1982-83 and 1997-98 El Nino events show that RCMs (including several of those used here) accurately predict the influence of coastal terrain on heavy precipitation during these events (Arritt et al. 2007). We expect that improvements in simulating surface temperature and atmospheric temperature inversions over complex terrain will lead to improvements in simulating precipitation amount and phase in the RCM compared to the driving CFS.

We are also interested in learning how well other variables, in addition to temperature and precipitation anomalies can be predicted. These variables are of interest both intrinsically and for the insight they provide into prediction of temperature and precipitation. For example, is the incoming and reflected radiation better described by the RCM ensemble than the CFS ensemble? If so, is such improvement a result of improved simulation of cloudiness associated with mountains/valleys, land-sea contrasts, or lake effects, or improved simulation of snowpack, and hence, surface albedo, in narrow mountains? Are the surface energy and water budgets better simulated in the RCMs than the CFS, and what are the impacts on precipitation and temperature forecast skill? What improvements, if any, will be evident in the downscaled mesoscale circulation such as mountain blocking, on-shore flow, and cold air damming, and how they influence the temperature and precipitation forecasts? Our analysis of different variables will provide additional evidence and arguments for why the downscaled forecasts should provide more useful information than the large-scale CFS forecasts at various temporal and spatial scales.

As part of our hypothesis that downscaling provides more skillful forecasts of extreme events, we will have a special focus on heavy rain events. **Figure 6** shows an example where an RCM was used to downscale a global climate simulation over North America. At 36 km resolution, the extreme precipitation simulated by the RCM compared much better against observations than the global simulation not only in the western U.S. where topographic forcing dominates, but also in the southeastern U.S. The resolution used in previous RCM intercomparisons for North American such as PIRCS and NARCCAP was 50 km, which is just at the borderline where mesoscale precipitation systems can begin to be resolved; Anderson et al. 2007 showed that RCM simulations at such resolution captured some MCS occurrences but substantially underpredicted their number. The resolution proposed for the present study (32 km) should provide a much better depiction of mesoscale precipitation systems although some of their finer-scale details will not be resolved. We will evaluate the extreme precipitation simulated by the RCMs for different regions and compare similar statistics based on the CFS forecasts.

4.4 Potential Hydrologic Applications

Important applications of seasonal climate forecasts are hydrologic prediction and water management, which is also a primary focus of CPPA's application research. To advance this goal, we will work closely with the CPPA core projects and others to investigate how the grand ensemble of CFS and RCM forecasts may improve hydrologic forecasts. One aspect is to evaluate the RCM forecasts of snowpack and runoff, although we realize that the evaluation databases for both (e.g., NARR, GLDAS, NLDAS, GRDC) are influenced heavily by the underlying models. For example, we want to find out how accurately we can forecast, say spring snowpack and runoff from the RCMs, and to the extent possible, relate forecast errors to errors in the large scale circulation provided by CFS and differences among the RCM land surface schemes.

Besides evaluating the snowpack and runoff simulated directly by the RCMs, it will also be of interest to evaluate how well macro-scale hydrologic models driven by the RCM forecasts reproduce the observed snowpack and streamflow. Currently, the West-wide and East-wide hydrologic forecasting systems use only CFS forecasts of temperature and precipitation to force an uncoupled hydrologic model (the Variable Infiltration Capacity Model, VIC) to produce streamflow forecasts. It has already been demonstrated that RCM output, including daily max and min temperature, solar radiation, precipitation, mean wind speed, and mean relative humidity, can also be used to drive hydrologic models over small watersheds (e.g., Leung et al. 1996; Miller and Kim 1996, Kim et al. 2000). In large river basins, hydrologic models aggregate sub-basin flows and compensate for modest model errors in spatial distributions (e.g., Wood et al. 2004; Jha et al. 2004). As an example, Arnold et al. (1998) demonstrated skill in using a hydrologic model to simulate the interannual mean, variability, and extremes of annual streamflow in the upper Mississippi River Basin for the decade of the 1980s when driven by an RCM with updated reanalysis lateral boundary conditions. The seasonal cycle also was well simulated albeit with less skill than annual totals. These results provide encouragement that output from individual RCMs driven by the NCEP CFS can be used to drive hydrologic models that will demonstrate additional skill in seasonal-to-annual streamflow forecasts. Such skill would have major advantages for the economics, safety, and water resource management of large-scale regions.

Related to the analysis of extreme precipitation discussed in 4.3.3, more analysis will be performed to investigate flood producing mechanisms and how well they are captured by the downscaled forecasts. As an example, rain-on-snow events are important contributors of winter time flooding in the western US. Recent analyses by Leung et al. (2004) and McCabe et al. (2007) based on regional climate simulations and observations, respectively, suggest that the frequency of rain-on-snow events is sensitive to temperature, which influences the ratio of precipitation falling as rain versus snow, and the amount of snowpack on the ground. There is a marked difference between the seasonality of rain-on-snow events along the coastal region of Washington, Oregon, and California, versus the interior western states (e.g., Colorado). McCabe et al. (2007), in particular, found that the changes in temperatures and precipitation associated with the increased frequency of El Niño events since the mid-1970s are consistent with a decrease in rain-on-snow events in the Pacific Northwest region. This highlights the importance of forecasting temperature, precipitation (amount and phase), and snowpack anomalies collectively in association with ENSO in order to improve the skill of forecasting rain-on-snow events and the resulting anomalous runoff. Besides rain-on-snow events, additional analyses will be performed to investigate models' skill in simulating other physical mechanisms linked to extreme events, such as the role of mountains in extracting moisture from the atmospheric rivers (Ralph et al. 2006), and whether RCM downscaled CFS forecasts capture some of these events.

Finally, the National Integrated Drought Information Service will conduct a pilot program focused on the upper Colorado River Basin beginning in FY2009 (NIDIS Program Implementation Team 2007). The pilot program will establish methodologies for providing early drought warning information to local, state, and federal agencies that will then incorporate the drought monitoring and forecast information into existing and developmental management decision aids. MRED data could be evaluated within the infrastructure built during the pilot program in an offline analysis in order to examine how detailed seasonal forecast products could be incorporated effectively into the early warning and management process.

5. Expected Outcomes

5.1 Routine multi-RCM ensemble forecasts

We expect to demonstrate that it is possible to make these multi-RCM forecasts routinely. We believe it is possible for NCEP to more fully engage the RCM community when it forecasts US monthly to seasonal variations. In particular, the RCM community will become interested in having ready access to large-scale climate forecasts that would allow them to not only test their models for varous climate change downscaling but to also better reach out to application communities not yet engaged with digital use of forecast products. We also believe the RCM community is international in scope and NCEP CFS forecasts capable of driving RCMs could become as internationally well known as the current NCEP global reanalyses products.

5.2 RCMs provide additional regional detail

We expect to show that RCMs coulde provide additional skillful forecast information, especially over mountainous regions and especially for interactive surface conditions such as snow and soil moisture. Extensive analysis will be performed to link improvements in downscaled forecast skill to regional forcings and physical mechanisms. We will work toward making higher resolution RCMs provide more useful surface boundary conditions for hydrologic models as an augmentation to current large-scale CFS surface boundary conditions.

5.3 RCM ensembles provide more information about extreme events.

We expect to show that RCMs provide more skillful forecasts of extreme events than the driving coarse scale CFS. In particular, we will be comparing the forecast distributions and spectral characteristics of the individual and ensemble mean RCM distributions to the CFS distributions. We will also evaluate circulation, temperature and humidity anomalies associated with extremes: do the models' extremes have the same physical basis as reality? We expect to understand better the kind of additional information that RCMs may be capable of providing to climate change projects such as NARCAAP, etc.

5.4 RCM ensembles provide additional large scale skill

We expect to show that RCM ensembles can increase the overall skill of large-scale ensembles. In particular, we will first evaluate the skill of the CFS forecasts and compare the skill of these forecasts to the forecast skill at http://www.cpc.ncep.noaa.gov/products/people/wwang/cfs_skills Assuming that our estimate of the skill will be similar if not the same as the documented skill at this site, we will then rigorously compare the CFS skill to the individual RCM ensembles and the overall RCM ensemble mean on our analysis grid. We believe the additional regional detail will significantly influence the large scale features; however, we still need to be careful how we make the comparison, do we evaluate the skill on the NARR grid or on the CFS grid and does it make a difference?

5.5 RCM ensembles provide additional information useful for hydrologic applications

We expect to show that RCM ensembles can provide more accurate and spatially resolved seasonal climate forecasts for driving hydrologic models that are used to produce hydrologic forecasts. Our proposed analysis of flood-producing mechanisms such as rain-on-snow events will demonstrate the advantage of downscaled climate information for hydrologic applications such as flood forecasting.

6. Project management and Time line

We will set up regular teleconferences to discuss our progress and plans. These teleconferences will be especially important at the start of the project. We expect that these teleconferences will eventually include not only the participants in this proposal but also other investigators willing to contribute to and help analyze this potentially unique global and regional climate seasonal forecast archive. These teleconferences will also be important for helping us to understand the level of detail needed to fully explain to all RCM modeling groups how to get the CFS forecasts (Appendix I) and how to send resultant RCM forecast products (Appendix II) to the NCEP archives on the MRED grid in NetCdf format.

We will also set up a WWW site to describe our work to the outside world as well as to facilitate comparisons of the RCMs to each other and to the CFS. This WWW site will include:

- documentation describing the experiment design, which includes: (1) a description of the initial month and day of forecast (Dec. 1), initialization days (Nov. 29-Dec. 3, Nov. 21-25, Nov. 11-15) and required forecast end date (April 30 18UTC); (2) forecast duration (1982-2003+); (3) RCM geographic extent (RCM lateral boundaries should lie outside the CONUS (**Fig. 2**), RCM resolution should be (35 kms or less) over the analysis domain (**Fig. 4**) and we intend to upscale some of these fields to the CFS resolution (**Fig. 3**), in order to better compare CFS input and RCM output.
- requested documentation describing CFS and NARR input files and RCM output files.
- frequently asked questions (FAQ)
- links to NCEP input and output archives
- links to associated RCM WWW sites
- links to associated papers and talks describing our effort.

The 5-10 TB input and output archive to be based at NCEP will include:

CFS input (775x15x6x27=1.88TB)

- 4xdaily sigma tgz files =525MB/month
- 4xdaily surface tgz files=50MB/month
- 4xdaily pgb grib files=200MB/month
- 15ensemble members

- 5-6months forecasts
- 1981-2007?=27? years

NARR input (50x27x12=60GB)

- 8xdaily surface grib files=50MB/month

CFS and RCM output (100x10x15x6x27=2.4TB)

- 8xdaily surface files=100MB/month?
- 5-10 models

It will be possible to store all of the input and output data with the purchase of a proposed 10 TB raid system to be housed at NCEP. By staging the CFS forecasts and RCM input, say 5 initial condition forecasts (Nov. 29-Dec. 3) beginning from present (there is some interest in an expansion from 2003 to present) and then going back to 1982, and then repeating for the next set (Nov. 21-25) and then finally the last set (Nov. 11-15), it will be possible for the individual PIs to make and transfer to the archives the requested variables by the beginning of the third year and for the analysis of the ensembles to begin in the first year.

Estimated computing costs (2.5x15x6x27=253 days)

- A 193x129 32 km RSM requires 2.5 hours per month on 2 nodes (32 cpus) on the NCEP HAZE (IBM SP).
- Other models will have similar computational requirements and these other RCM forecasts will be done at each individual RCM site. However, computing resources at NOAA/ESRL/GSD will be available upon request through facility fees charged to the NOAA/ESRL/GSD participant's budget. These resources include access to high performance cluster computing platforms that contain over 1500 CPUs.

We expect this will be an intensive computing effort that will take each individual RCM group 1-2 years to finish.

Year 1: Begin monthly teleconferences to discuss MRED. Set up WWW site to describe CFS data. Discuss land initialization strategies. Begin and finish 1st set (Nov. 29-Dec. 3) of initial value runs and begin second set (Nov. 21-25). Begin comparison of ensemble RCMs with CFS. Initially focus on temperature and precipitation but also analyze other variables of potential interest, like downwelling solar radiation, surface humidity, etc.

Year 2: Finish 2nd set (Nov. 21-25) of initial value runs and begin third set (Nov. 11-15). Begin comparison of surface hydrologic features, such as snow, soil moisture, runoff with GLDAS, NLDAS, NARR, GRDC

Year 3: Finish 3rd set third set (Nov. 11-15) of initial value runs as well as final ensemble analysis. Based on successful outcome, propose a continuing project for a summer season. Perhaps it will be useful at this point to even consider community RCM ensemble downscaling forecasts every month. In that regard, relevant winter forecasts will continue to be provided as part of this project for each year (2008-2010) although we recognize that some groups may want to just provide the minimum forecasts needed for the ensemble evaluation (1982-2003).

Finally, it should be stressed that we intend to fully involve the CPPA core project (K. Mitchell, John Schaake) in the final design of this project as well as the analysis protocol. In addition to providing the initial white paper and subsequent call, the core project at NCEP's Environmental Modeling Center (EMC) has indicated a willingness, depending on resources, to eventually contribute a unique model (Eta model) to the RCM ensemble. The Eta model will be especially valuable since many of the evaluations will be made with NARR, and the model used for NARR was the Eta model. The core project at the Office of Hydrology and other hydrologic prediction efforts are also interested in comparing these ensemble RCM forecasts to currently available CFS forecasts to determine whether these RCM forecasts could potentially add significant skill to their current efforts to make hydrologic forecasts for individual river basins from the coarser-scale CFS.

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8. Figures and Table

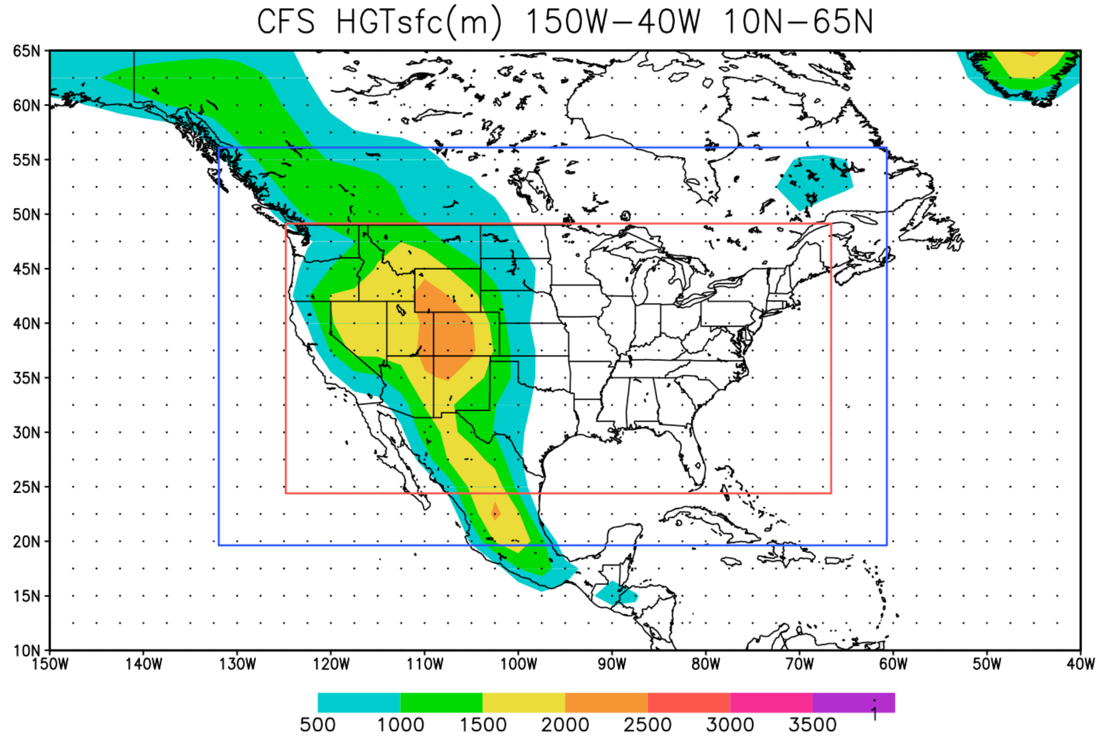

Fig. 1 Gridpoints and orography for the driving CFS

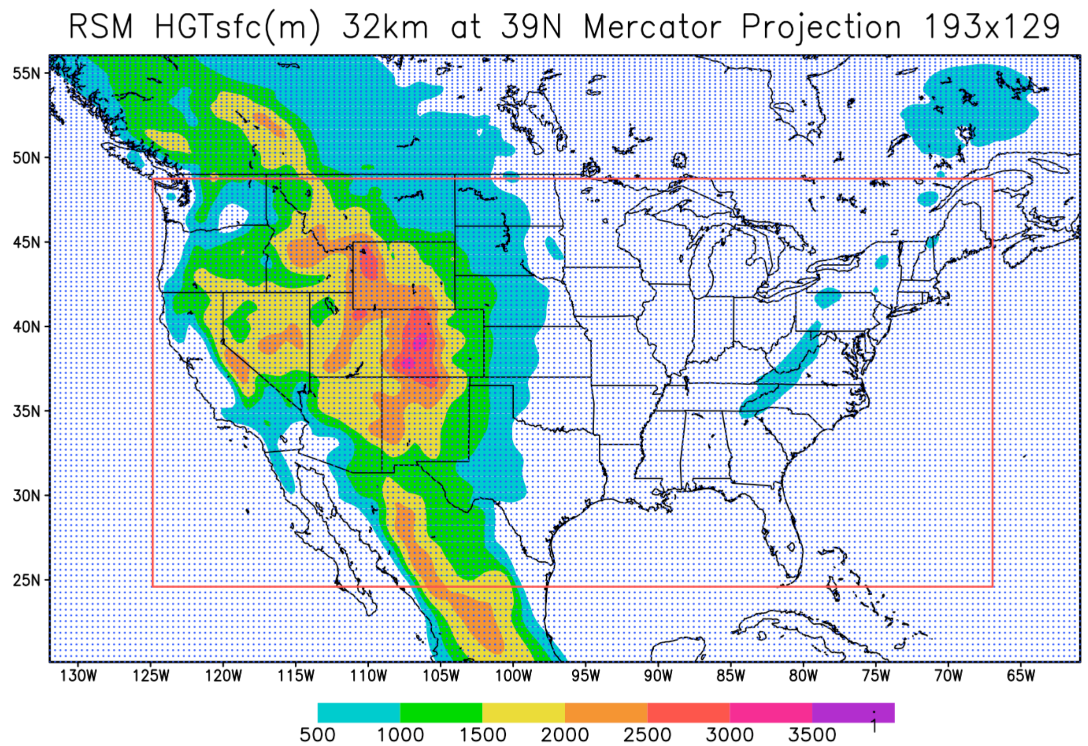

Fig. 2 CFS gridpoints and orography for the proposed RSM computational domain. Note that the analysis domain will only cover the coterminous US.

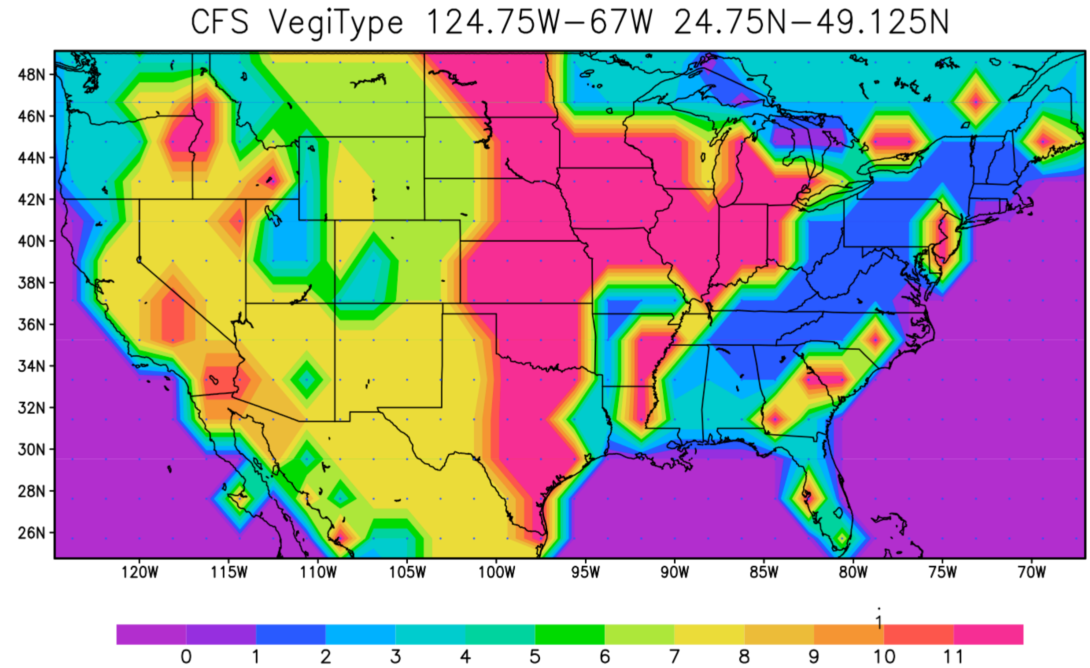

Fig. 3 CFS vegetation for the CONUS: 0) ocean; 1) broadleave-evergreen trees (tropical forest); 2) broadleave-deciduous trees; 3)broadleave and needle leave trees (mixed forest); 4) needleleave-evergreen trees; 5) needleleave-deciduous trees (larch); 6) broadleave trees with groundcover (savanna); 7) groundcover only (perenial); 8) broadleave shrubs with perenial groundcover; 9)broadleave shrubs with bare soil; 10) dwarf trees and shrubs with ground cover (trunda); 11) bare soil; 12) cultivations (use parameters from type 7); 13) glacial.

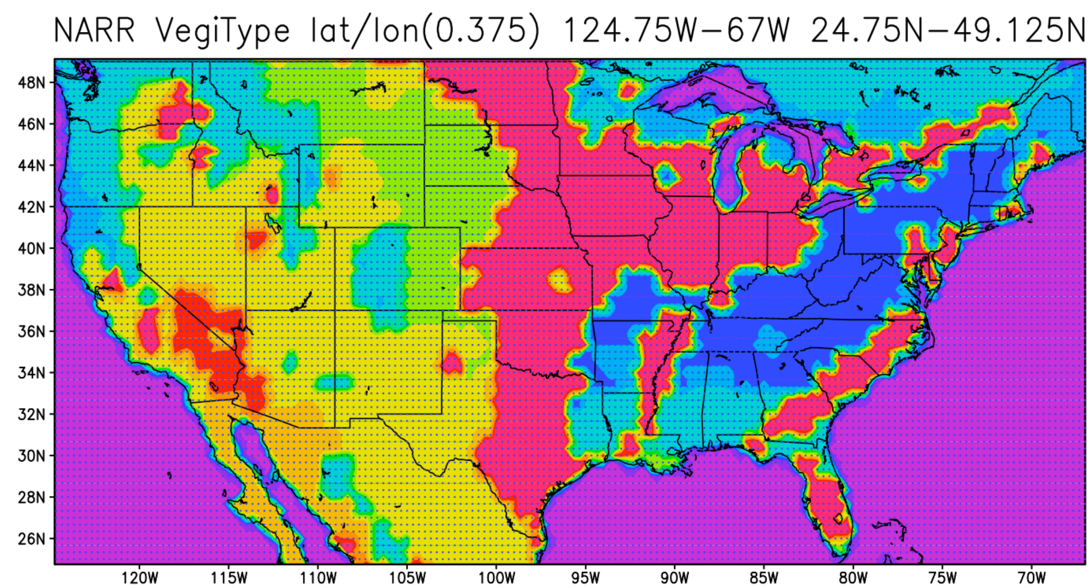

Fig. 4 NARR vegetation on the 155x66 grid (124.75W,24.75N – 67W,49.125N) to be used for the various comparisons. All RCMs will interpolate their data to this grid before sending it to the NCEP archive.

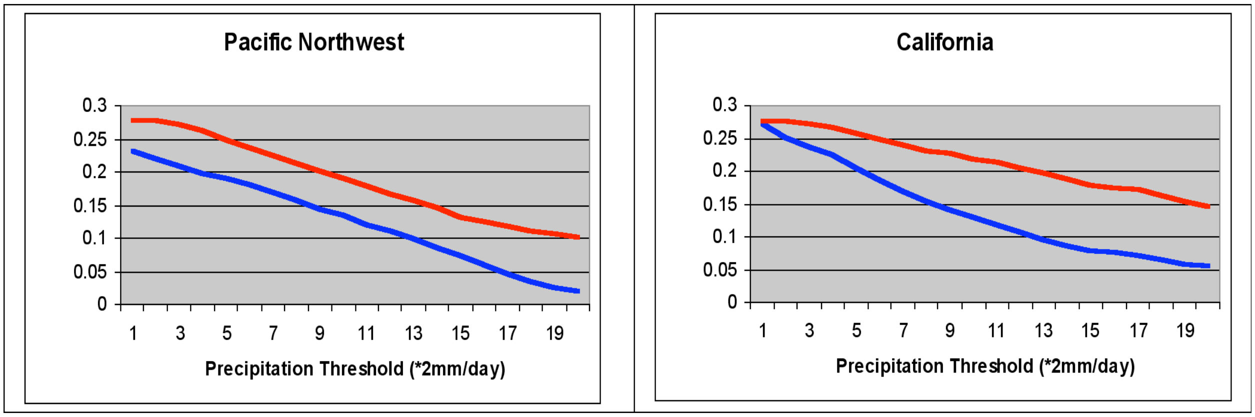

Fig. 5 The Equitable Threat Score (ETS) of precipitation forecasts for different precipitation thresholds in the Pacific Northwest (left) and California (right). The red and blue curves are based on the downscaled and global extended weather (8 days) forecasts respectively.

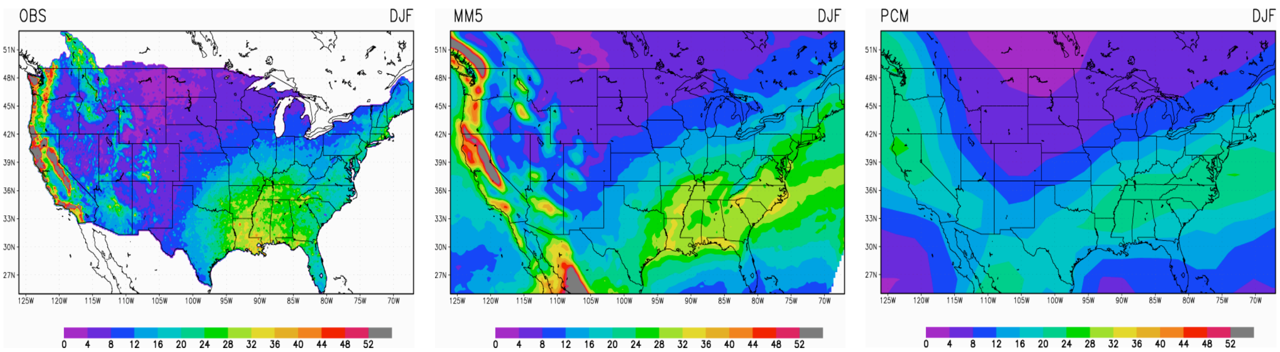

Fig. 6 Extreme (95th percentile) precipitation (mm/day) based on 20 years of statistics from observations at 1/8 degree resolution (left), a regional simulation at 36 km horizontal resolution (center) driven by a global simulation, and the global simulation at T42 horizontal resolution (right) for winter (December-January-February). The regional simulation compares much better with the observations, showing heavy precipitation along the coastal mountains in the western U.S., as well as more realistic amounts in the Southeast.

Table 1. RCM characteristics

Model Name and Investigators	**Dynamics**	**Lateral Boundary Treatment**	**Land Surface; Temp./ Water Layers+snow**	**Vegetation Types**	**Boundary Layer**	**Radiation**	**Explicit Moist Physics**	**Cumulus Param.**
CFS Juang	Hydrostatic Compressible	N/A	OSU; 2 + 1 Snow	13 vegetation classes	Hong-Pan non-local K	GFDL RRTM long-wave NASA Chou scheme SW	Prognostic cloud with Ferrier scheme	Relaxed Arawaka-Schubert
RSM-NCEP/ECPC Juang, Roads	Hydrostatic Compressible	Relaxed at boundaries; perturbation spectral filter	OSU; 2 + 1 Snow	13 vegetation classes	Hong-Pan non-local K	GFDL RRTM long-wave; NASA Chou SW	Prognostic cloud with Ferrier scheme	Relaxed Arawaka-Schubert
WRF-ARW Leung	Non-hydrostatic, Compressible	15 grid points (exponential relaxation)	VIC; 4+1 snow	24 classes from USGS	Yonsei University (explicit entrainment)	CAM shortwave CAM longwave	Prognostic cloud liquid and ice, rain, snow	Kain-Fritsch2 mass flux
WRF-NMM/ESRL Anderson	Non-hydrostatic, Compressible	12 grid points (linear relaxation)	NMM LSM; 4+1 snow	24 classes from USGS	Mellor_Yamada-Janjic , Levell 2.5 TKE closure	GFDL longwave, GFDL shortwave	Prognostic cloud liquid and ice, bulk precipitation	Betts-Miller-Janjic
MM5-ISU Arritt, Gutowski, Takle	Non-hydrostatic, Compressible	15 points (exponental relaxation)	NOAH; 4+1 snow	24 classes from USGS SiB model	Hong-Pan non-local K	GFDL RRTM	Reisner mixed phase	Kain-Fritsch2 mass flux

Appendix I. CFS Input Archive

As part of this project we will provide 64 sigma level global spectral values for divergence, vorticity, specific humidity, virtual temperature, and surface pressure as an IEEE sigma file. A corresponding surface file in IEEE will provide soil moisture and subsurface temperature at 2 levels, as well as a seasonally varying bottom temperature. A 40-pressure level 2 deg. PGB file in GRIB will be developed that will provide zonal and meridional winds, specific humidity, temperature, as well as surface pressure. We will provide global output assuming that other regional forecast comparisons will eventually be launched in other regions.

Appendix II. Output Archive

RCM and CFS output will be provided in NetCDF (http://badc.nerc.ac.uk/help/formats/netcdf/index_cf.html) format. Variable names and units will be consistent with IPCC and NARCCAP. Output will be interpolated to the standard lon. Lat. analysis grid shown in **Fig. 4**. File names should follow this structure: VariableName_ModelName_Time.nc, where: “VariableName” is the IPCC/CF-convention Variable Name in the tables below; “ModelName” is a 4-character identifier chosen by the modeling group; “Time” is the starting time of the file, in the form “YearMonthDayUTC”, e.g., 1979010100 for 00 UTC on 1 Jan 1979. For each day, values reported at 03 UTC, 06 UTC, … 24 UTC. Solar radiation is averaged over the 3-hr period prior to the reporting time. Precipitation is the 3-hour accumulation up to the reporting time. Other quantities are instantaneous values as noted. Winds should be the true west-east and south-north winds (i.e., rotated from the model’s grid as needed to the earth’s longitudinal and latitudinal directions). The surface air temperature and specific humidity should be in the range 1.5 – 2 m above the surface. Surface winds should be recorded from 10m “anemometer level” values. Note units for precipitation and surface pressure (MKS – following CF standards). Essential static surface fields within the model will be included in the archive. These will include the capacity of soil to store water, surface altitude, root depth, land-cover type, longitude of grid points, latitude of grid points, and land area fraction. Information for each of these variables can also be found on the following NARCCAP webpage: http://rcmlab.agron.iastate.edu/narccap/output_archive.html

Table 2. Ouput Archive of prognostic and diagnostic variables

Long Name	**Units**	**Variable Name**	**Standard Name**	**Notes**
Precipitation	kg-m^{-2}-s^{-1}	pr	precipitation_flux	Accumulation
Surface Specific Humidity	kg-kg^{-1}	huss	specific_humidity (In CF convention: specific_humidity with a vertical coordinate in height of 2 m)	Instantaneous
Surface Air Temperature	K	tas	air_temperature (In CF convention: air_temperature with a vertical coordinate in height of 2 m)	Instantaneous
Maximum Surface Air Temperature	K	tasmax	air_temperature (In CF convention: air_temperature with a vertical coordinate in height of 2 m and a cell_methods attribute including time: maximum within 3-hr period)	3-hr maximum

Minimum Surface Air Temperature	K	tasmin	air_temperature (In CF convention: air_temperature with a vertical coordinate in height of 2 m and a cell_methods attribute including time: minimum within 3-hr period)	3-hr minimum
Surface Downwelling Shortwave Radiation	$W\text{-}m^{-2}$	rsds	surface_downwelling_shortwave_flux_in_air	Average, Positive down
Zonal Surface Wind Speed	$m\text{-}s^{-1}$	uas	eastward_wind (In CF convention: eastward_wind with a vertical coordinate in height of 10 m)	Instantaneous, Positive to East
Meridional Surface Wind Speed	$m\text{-}s^{-1}$	vas	northward_wind (In CF convention: northward_wind with a vertical coordinate in height of 10 m)	Instantaneous, Positive to North
Surface Pressure	Pa	ps	surface_air_pressure	Instantaneous
Sea-level Pressure	Pa	psl	air_pressure at_sea_level_air_pressure	Instantaneous
500 hPa Geopotential Height	m	zg500	geopotential_height (ID for singleton level: geopotential_height with a vertical coordinate in pressure of 500hpa)	Instantaneous
200 hPa Geopotential Height	m	zg200	geopotential_height (ID for singleton level: geopotential_height with a vertical coordinate in pressure of 200hpa)	Instantaneous
Snow Depth (equiv. water)	m	snd	surface_snow_thickness(equiv. water)	Instantaneous, Snow-water equivalent
Surface and Subsurface Runoff	$kg\text{-}m^{-2}\text{-}s^{-1}$	mrro	runoff_flux	Average
Surface Runoff	$kg\text{-}m^{-2}\text{-}s^{-1}$	mrros	surface_runoff_flux	Average
Surface Latent Heat Flux	$W\text{-}m^{-2}$	hfls	surface_upward_latent_heat_flux	Average, Pos. up
Surface Sensible Heat Flux	$W\text{-}m^{-2}$	hfss	surface_upward_sensible_heat_flux	Average, Pos. up
Surface Downwelling Longwave Radiation	$W\text{-}m^{-2}$	rlds	surface_downwelling_longwave_flux_in_air	Average, Positive down
Precipitable Water	m	prw	atmosphere_water_vapor_content	Instantaneous