

**A COMPERATIVE STUDY OF TWO REGIONAL MESOSCALE MODELS
IN EASTERN MEDITERRANEAN DOMAIN FOR A HISTORICAL
REFERENCE PERIOD**

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Programme : Computational Science and Engineering

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JUNE 2011

**İKİ ORTA ÖLÇEKLİ BÖLGESEL MODELİN DOĞU AKDENİZ BÖLGESİ
ÜZERİNDE VE TARİHSEL REFERANS DÖNEMDE KARŞILAŞTIRMALI
OLARAK İNCELENMESİ**

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FOREWORD

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ABBREVIATIONS

ARW	: Advanced Research WRF
BATS	: Biosphere-Atmosphere Transfer Scheme
CF	: NetCDF Climate and Forecast Metadata Convention
CFL	: Courant-Friedrichs-Lewy condition
CPU	: Central processing unit
CRU	: Climatic Research Unit
CUDA	: Compute Unified Device Architecture
CCSM	: Community Climate System Model
EM	: Eastern Mediterranean
GCM	: General Circulation Model, Global Climate Model
GISST	: Global sea-Ice and Sea Surface Temperature
GLCC	: Global Land Cover Characterization
gpm	: Geopotential meter
GPU	: Graphics Processing Unit
GRIB	: Gridded Binary
ICBC	: Initial and boundary conditions
ICTP	: International Centre for Theoretical Physics
I/O	: Input and Output
IPCC	: Intergovernmental Panel on Climate Change
LAM	: Limited Area Model
LBC	: Lateral boundary conditions
LFS	: Lustre file system
MM4	: Penn State/NCAR Mesoscale Model, Version 4
MM5	: Penn State/NCAR Mesoscale Model, Version 5
MODIS	: Moderate Resolution Imaging Spectroradiometer
MPI	: Message Passing Interface
NCAR	: National Center for Atmospheric Research
NCEP	: National Centers for Environmental Prediction
NCHPC	: National Center for High Performance Computing
NCL	: NCAR Command Language
NetCDF	: Network Common Data Form
NMM	: Non-hydrostatic Mesoscale Model
NNRP	: NCEP/NCAR Reanalysis Project
NWP	: Numerical Weather Prediction
OISST	: Optimum Interpolation Sea Surface Temperature
OpenMP	: Open MultiProcessing
PBL	: Planetary Boundary Layer
RegCM3	: Regional Climate Model version 3
S-N	: South-North
SST	: Sea Surface Temperature
UYBHM	: Ulusal Yüksek Başarımli Hesaplama Merkezi
W-E	: West-East
WRF	: Weather Research and Forecasting Model

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SUMMARY

Global Climate Models are useful tools for predicting future climates. However their spatial and temporal resolutions are too coarse for regional climate studies. Therefore higher resolution regional climate models should be used to examine the regional climate changes.

Eastern Mediterranean Region is a very interesting area for testing the performance of climate models due to its complex topography and variable climate conditions. In this study, NCAR's next generation non-hydrostatic mesoscale model, Advanced Research WRF (WRF-ARW) was used to analyze the regional climate of Turkey and its neighbourhood for the period of 1961-1990 and the results are compared with RegCM outputs and observations. A similar study had been performed successfully with hydrostatic ICTP-RegCM3 model that is based on MM5, the predecessor of WRF. WRF on the other hand, is superior to RegCM and MM5 in both physics, dynamics and numerics, but computationally more expensive accordingly. However, WRF is still under development and requires more performance analyses for its validation in regional climate modelling. Therefore the result of this study is important for the validation of WRF in long term regional climate studies.

The WRF Model was used to downscale NCEP-NCAR Reanalysis data over a domain that spans from 13E - 55E and 28N - 51N. The grid resolution is 27 km in both directions and there are 144 by 100 grid points in east-west and south-north directions respectively. In the vertical direction 35 levels are used and that happens to be the twice the vertical resolution of RegCM3 run. The time step is 60 seconds and the model outputs are saved every 3 hours. Physics and dynamics options are especially chosen for long term regional climate runs and GISST data is used as the additional SST input. In order to handle the steep topography of the domain, MODIS dataset with 30 arcsecond resolution and gravity wave drag (GWD) was used.

Monthly means of the model outputs show that WRF is superior to RegCM over complex topography. WRF can simulate regional features better than RegCM. Generally, WRF has a negative bias in surface temperatures but it can solve the temperature distribution better than RegCM that has a positive temperature bias. Especially in Mediterranean shores the difference is very clear. Moreover GWD enabled WRF runs can solve the temperature field better over steep topography. Boundary conditions are also handled better in WRF than in RegCM. RegCM generates superfluous distributions in southern and eastern boundaries whereas such problems are not seen in WRF results. Statistical analyses have shown that WRF has a greater spatial correlation and smaller spatial variability than RegCM when compared against observations.

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ÖZET

Küresel iklim modelleri gelecek iklimlerin öngörüsü için yararlı bilimsel araçlardır, fakat yersel ve zamasal çözünürlükleri bölgesel iklim çalışmaları için yetersiz kalmaktadır. Dolayısıyla bölgesel iklim değişikliğini incelemek için daha yüksek çözünürlüğe sahip bölgesel iklim modelleri kullanılmalıdır.

Doğu Akdeniz bölgesi sahip olduğu karmaşık yer şekilleri ve değişken iklim koşulları ile iklim modellerinin başarımının incelenmesi açısından çok ilginç bir bölge olma özelliğine sahiptir. Bu çalışmada NCAR'ın yeni nesil hidrostatik-olmayan orta ölçekli WRF-ARW modeli Türkiye ve civarının bölgesel ikliminin analizini yapıp ve modelin başarımı incelenmiştir. 1960-1990 yılları için NCEP-NCAR Reanaliz verileri ile çalıştırılan WRF modelinin çıktıları aynı zaman aralığında ve aynı yapılandırma seçenekleri ile çalıştırılmış olan RegCM3 modelinin çıktıları ile karşılaştırılmıştır. RegCM3 modeli MM5 modelini temel alan hidrostatik bir bölgesel iklim modelidir ve Dünya'nın pek çok bölgesinde başarı ile uygulanmıştır. WRF ise MM5'in üzerine geliştirilmiştir ve fizik, dinamik ve sayısal formülasyonu hem MM5'dan hem de RegCM3'ten çok daha gelişmiştir. Fakat bu modellere göre oldukça yeni sayılan WRF ile yeteri kadar bölgesel iklim çalışması yapılmamıştır ve Doğu Akdeniz bölgesindeki başarımı bilinmemektedir. Dolayısıyla bu çalışmanın sonuçları WRF modelinin uzun süreli bölgesel iklim çalışmalarındaki başarımı açısından önemlidir.

Çalışmanın yapıldığı alan Türkiye'yi merkez olarak alan ve 13-55° Doğu ve 28-51° Batı koordinatları arasındadır. Model çözünürlüğü yatayda 27 km'dir ve doğu-batı yönünde 144, kuzey-güney yönünde ise 100 ızgara noktası kullanılmıştır. WRF modelinde düşeyde 35 seviye kullanılırken RegCM modelinde ise 18 düşey seviye kullanılmıştır. Zaman adımı 60 saniye olarak seçilmiş olup model hesaplamaları her üç saatte dosyaya yazdırılmıştır. Modellerde kullanılan fizik ve dinamik paketler uzun süreli iklim çalışmaları için özel olarak seçilmiştir. Denizlerin uzun vadede yaratacağı etkiler göz önünde bulundurularak GISST veri kümesindeki deniz suyu sıcaklığı verileri ek sınır koşulu olarak eklenmiştir. WRF modelinde karmaşık topoğrafyayı daha iyi temsil etmesi amacıyla 30 saniye çözünürlüğe ve dalga sürüklenme (İng. gravity wave drag) alanına sahip MODIS yer veri kümesi kullanılmıştır.

Aylık ortalama değerler özellikle karmaşık topoğrafya üzerinde WRF modelinin RegCM'den daha iyi olduğunu göstermektedir. WRF yüzey sıcaklıklarında negatif tarafa sahipken yersel dağılımı daha iyi çözmüştür. Yersel istatistik analizler de bunu desteklemektedir. Bununla beraber dalga sürüklenme şemasının özellikle yüksek kesimlerde sonuçları gözlemlerle daha uyumlu verdiği de görülmüştür. Sınırdaki değerler ise RegCM'de dalgalanmalı değerlere sahipken WRF'ta bu durum gözlenmemektedir. Gözlemler temel alınarak yapılan istatistiksel analizin sonuçları WRF'un yersel korelasyonunun RegCM'den daha yüksek; hata ve varyansının ise daha düşük olduğunu göstermektedir.

1. INTRODUCTION

1.1 Introduction and Definition of the Problem

The definition of the climate is as complex as itself. It is commonly defined as the *average weather*, however without considering the deviations from the mean state, climate can not be exactly defined. Therefore climate can be expressed as collection of the statistical properties of the weather phenomenon over a specified region through multiple decades [1]. The statistical properties include the mean state, variances and extreme events [2]. Surface temperature and precipitation is the two most important meteorological variables for defining and classifying the climate of a region.

The climate has very important socio-economic effects such as the agriculture and food supply, as well as effects on fishery, forestry, water resources and global ecosystem. Moreover, climate extremes such as heat waves cause a large number of fatalities. As stated in the World Economic Forum 2000 meeting report, 21st century's greatest problem is the climate change [3]. Consequently, prediction of the future state of the climate is very important for the mankind.

Climate exhibits a high degree of variability. Variability refers to the short term fluctuations whereas climate change is used to define the long-term shifts [4]. This variability is the result of the complexity of the climate system as illustrated in Fig. 1.1, and the non-linear feedbacks of its componets. According to Müller and Storch, complexity of the system, which is defined by the infinite number of degrees of freedom, prevents the scientists to predict the possible response of the climate with physical experimentation. Consequently, numerical modeling experiments are the only available quantitative tool for analyzing the evolution of the climate system [2].

Starting from 1950s GCMs have been used for modeling the global climate and general circulation [6]. The current GCMs used for climate projections are operating with horizontal grid resolutions larger than 100 km, which makes them inadequate for answering questions regarding regional climate [5]. Regional climate in this study is

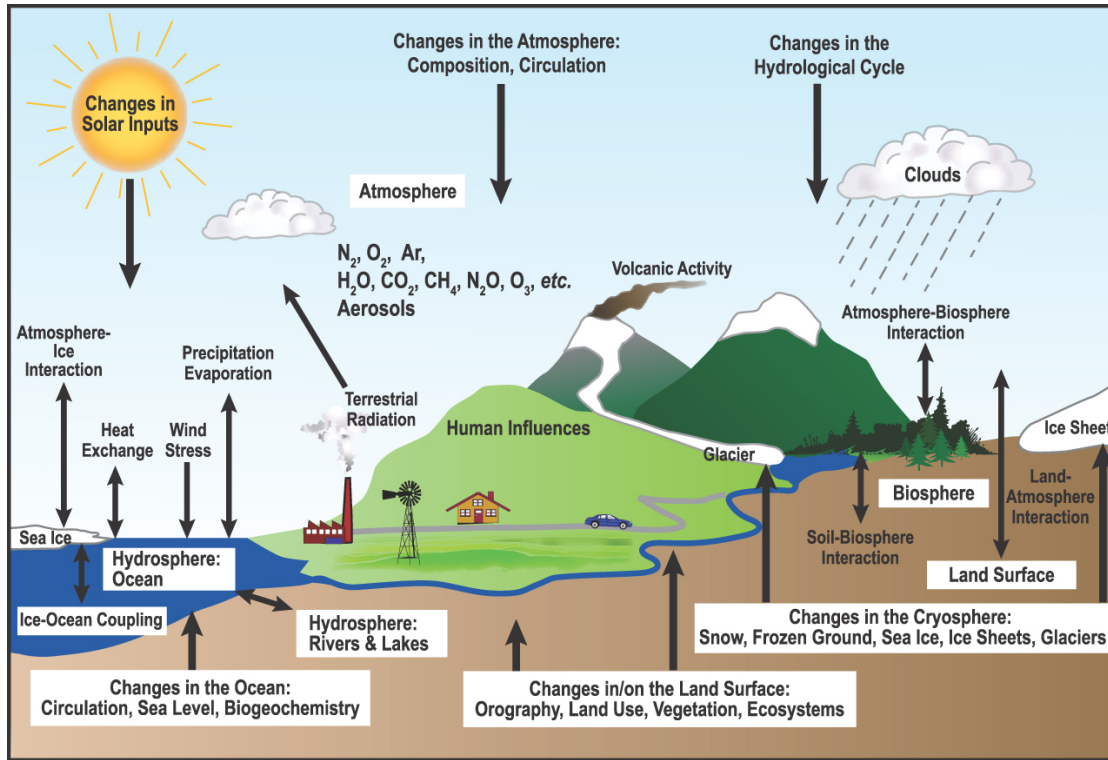


Figure 1.1: Climate system, the compoenets, processes, and interactions; adapted from [5].

used for mesoclimatology where the mesoscale meteorological phenomenon are the interested weather systems. These are defined with spatial scales upto hundreds of kilometers and occur mainly in troposphere [1]. The spatial and temporal scales of various atmospheric phenomena are shown in Fig. 1.2. Regional scale atmospheric phenomenon are important since these are the main contributors for determining the local climate of a region [8]. Therefore, as stated by Randall, to predict the local climate of a region, regional climate models must be used instead of GCMs [9].

1.2 Goals and Motivation

This study aims to evaluate the performance of WRF-ARW model in regional climate modeling. WRF is NCAR's next generation mesoscale atmospheric modeling system and ARW is the advanced dynamical core of WRF. Our hypothesis is WRF is an adequate model to be used in climate modeling, whereas the alternative hypothesis states that it is not suitable for these studies. Our scientific method is running the WRF model on a test domain for a reference period for which we have observational data to compare the results with. The results of the WRF model is then tested against these observations (reference field) and another test field. The second test field is the outputs

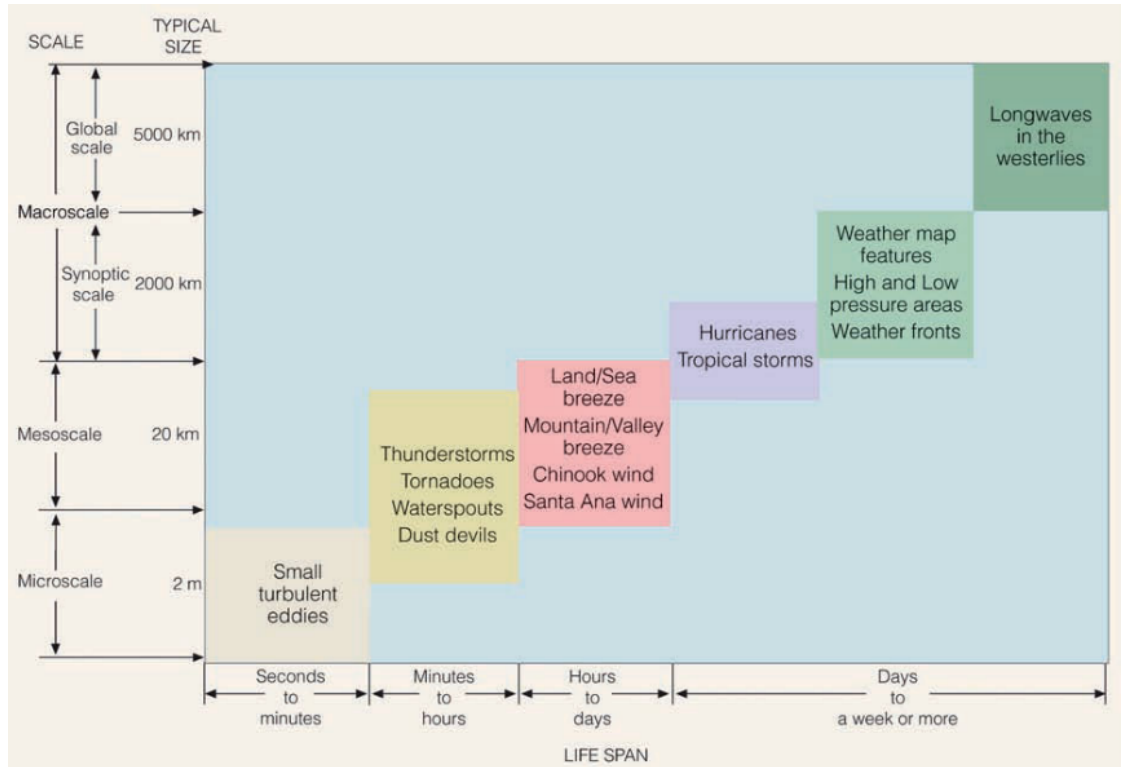


Figure 1.2: The spatial and temporal scales of various atmospheric phenomena, adapted from [7]

RegCM3 model which was run with the same initial and boundary conditions. RegCM3 is a validated regional climate model for our simulation domain and it is also used in other parts of the world for both case studies and climate projections. The comparison between two models and the reference field will not only show the performance of the WRF model but it will also show the relative performance with respect to a reliable climate model.

The simulation domain used in this study is Eastern Mediterranean (EM) region. This region was chosen for its interesting climatological features and Turkey is also located inside this domain. EM has a very complex morphology and landuse characteristics as seen from Fig. 1.3. This region exhibits a great amount of variability (Fig. 1.4) and regarded as a *climate test basin* by Garrett [10]. Various cooperative projects such as MedCLIVAR and MEDEX are researching the climate variability of the Mediterranean region [12].

It should also be noted that validation is the first step which is mandatory for other following studies. These include construction of a high resolution (10 km or higher) climatology of Turkey, and regional climate change projections. Since not many



Figure 1.3: Topography of the Eastern Mediterranean domain, adapted from [11]

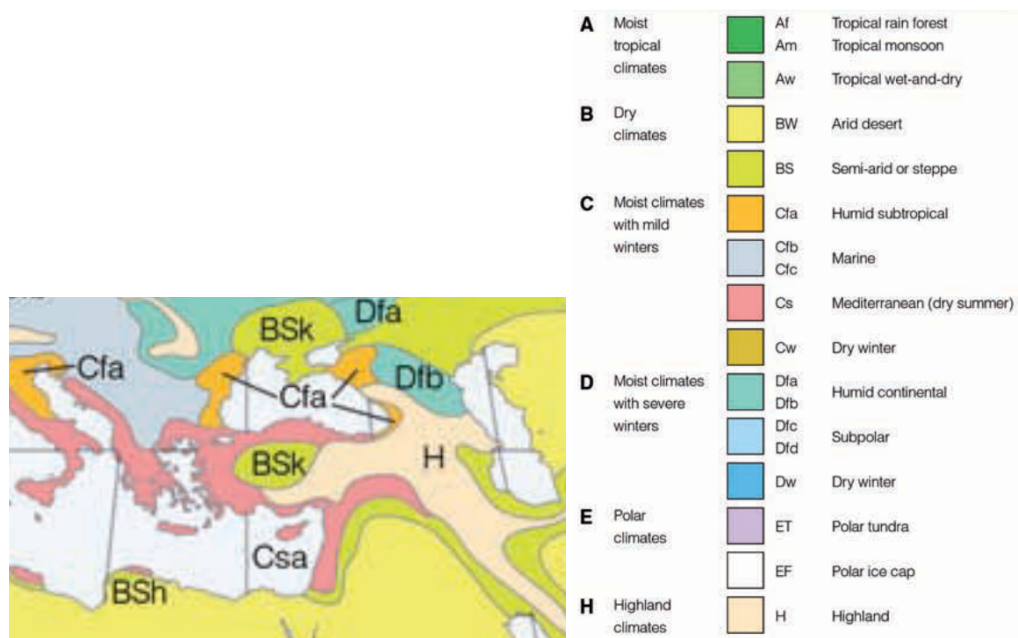


Figure 1.4: Climate of the Eastern Mediterranean region according to Köppen classification, adapted from [7]

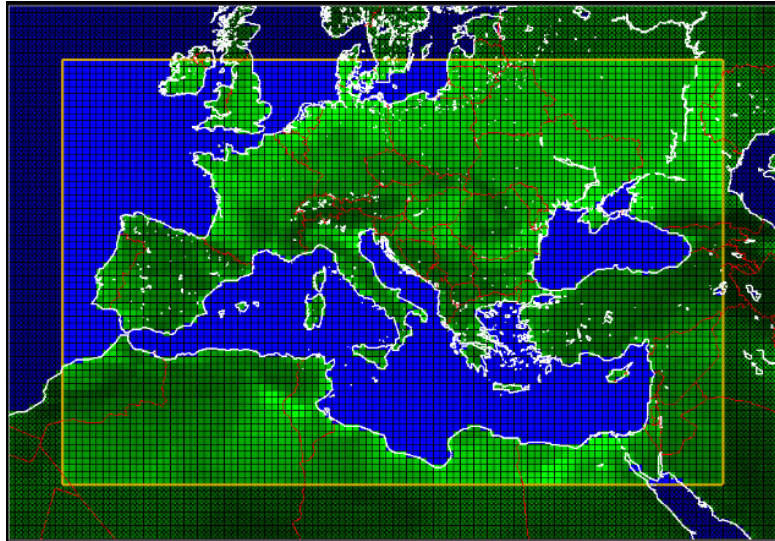


Figure 1.5: Mediterranean domain used in CORDEX projec

multi-decadal regional climate studies have been conducted with WRF model, the results of this study is expected to serve a road map to the future researchers and the model developers.

1.3 A Short Review of the Previous Studies

Applications of the first nested regional climate simulations started in late 90s with Dickinson [13] and Giorgi [14]. Following that Giorgi and Mearns performed multi-year regional climate simulations [15]. As shown by Warner [16], the dynamical climate downscaling practices consists of

1. performing multi-year simulations with LAMs with boundary conditions coming from a GCM or reanalysis dataset,
2. globally stretched GCM with fine mesh over the region of interest,
3. uniformly high resolution GCM,
4. and very high resolution orographic forcings used in coarse resolution GCMs.

More research is done with the first method. Several coordinated regional climate downscaling and model intercomparison projects such as PIRCS ([17]), RMIP ([18]), ENSEMBLES ([19]), and CORDEX have been applied to the various regions of the world. Fig. 1.5 shows the Mediterranean domain used in CORDEX project.

As mentioned before, two regional models RegCM and WRF were used in this study. These models have been applied to various different regional climate studies. RegCM has been practically used since early 90s. It has been applied to different regions of the world such as Australia [20], United States [21], Mediterranean region [22, 23], Africa [24], and Anatolia [25]. Furthermore it has been also used for downscaling GCMs for a reference period and future scenarios [26]. RegCM is currently being used for future climate projections by many research groups worldwide.

WRF, on the other hand, has been in use since 2001 and studies on regional climate started recently. WRF has been applied to United States for extreme precipitation events by Duliere [27]; for seasonal precipitation analysis by Bukovsky and Karoly [28]; and for high resolution climate change by Zhao et al [29]. Moreover, Awan and Gobiet applied WRF to Alpine region and performed sensitivity analyses with different model configurations for long term climate modeling [30]. Hill and Lackmann investigated the tropical cyclone intensity change in a warming climate with very high resolution simulations [31]. Mukhopadhyay et al studied climatology of Indian monsoon precipitation with a high resolution two way nested simulation [32]. It is important to notice that these studies are performed at higher resolutions than any RegCM simulation on account of the hydrostatic formulation of RegCM. It is therefore possible to construct a nearly kilometer scale climatology with WRF model.

Other very recent studies with WRF include application of WRF to CORDEX domains for model validation and future projections [33, 34]. Multi-decadal studies are performed Argueso et al [35] on Mediterranean region with nested domains. Evans applied WRF to Australia with the resolution of 10 km for 24 years and captured a drought event [36]. Gula and Peltier [37] investigated the regional climate of the Great Lake Basin of North America for a 20 year reference and two future periods with a nested configuration. Mayer et al [38] studied the validity of WRF by using a simple physical configuration over a large domain that focuses on North Sea. Their study consists of a 30 year validation run and a 30 year future prediction run.

1.4 A Brief Outline of the Thesis

The rest of this thesis is as follows. Chapter 2 gives detailed descriptions of the models used in this study. In Chapter 3 simulation setup and model configurations are explained in detail as well as the computational performance of the models in NCHPC. Model results and comparisons are given in Chapter 4. Chapter 5 concludes the thesis and discusses the further studies and improvements. In the appendix model configuration files, code modifications and developments and further model results can be found.

2. DESCRIPTIONS OF THE REGIONAL CLIMATE MODELS

2.1 Description of WRF-ARW Modeling System

The WRF model is the NCAR's next generation mesoscale atmospheric modeling system. WRF is a very complicated atmospheric model. Since late 1990s it has been developed by various institutions such as NCAR, NCEP, NOAA and currently 16 working groups are focused on its development. Since WRF is the successor of the MM5 model, it is built upon the results and experiences of the past 40 years.

WRF is a very flexible modeling system. It can be used for spatial resolutions varying from meters to thousands of kilometers and applications ranging from NWP to air pollution modeling. Unlike other atmospheric models, WRF has various dynamical cores. These cores contain the dynamical and physical model formulations and are used in different applications. For example NMM core is mainly used in operational NWP. ARW core, on the other hand, is a more flexible and developed research and development core. It has more dynamics and physics options and offers a more advanced treatment for LBC and nesting. ARW also supports regional climate modeling. In this study ARW core was used.

The formulation of ARW core is scalar conservative and fully compressible. It is Eulerian, non-hydrostatic and uses a mass based terrain following vertical coordinate system. It contains various prognostic (forecast) variables such as velocity, pressure, temperature and various thermodynamics quantities namely mixing ratios and kinetic energy. For both time and space dimensions it uses higher order finite difference schemes (up to 6th order) than MM5. Time integration is adaptive which makes it very stable. Additionally, the physics package is richer in ARW. This enhances the model's ability to be adjusted in complex domains such as EM but also increases the complexity in interactions and the effort for sensitivity analysis. An inline chemistry model (WRF-Chem) is also available.

The software infrastructure of WRF is highly modular and has a hierarchical structure

which makes it possible for more advanced studies such as coupling with other models. It has been developed for variety of different computer architectures ranging from laptop computers to GPUs and has a good scalability in parallel computers.

2.1.1 Model Formulation and Dynamics

ARW uses fully compressible, non-hydrostatic Euler equations. The equations are in flux form and conservative for scalar quantities. These equations are vertically formulated on a terrain-following hydrostatic pressure denoted by η . This vertical coordinate is also known as the mass vertical coordinate and is depicted in Fig. 2.1. Here $\eta = (p_h - p_{ht})/\mu$ and $\mu = p_{hs} - p_{ht}$, where p_h is the hydrostatic component of the

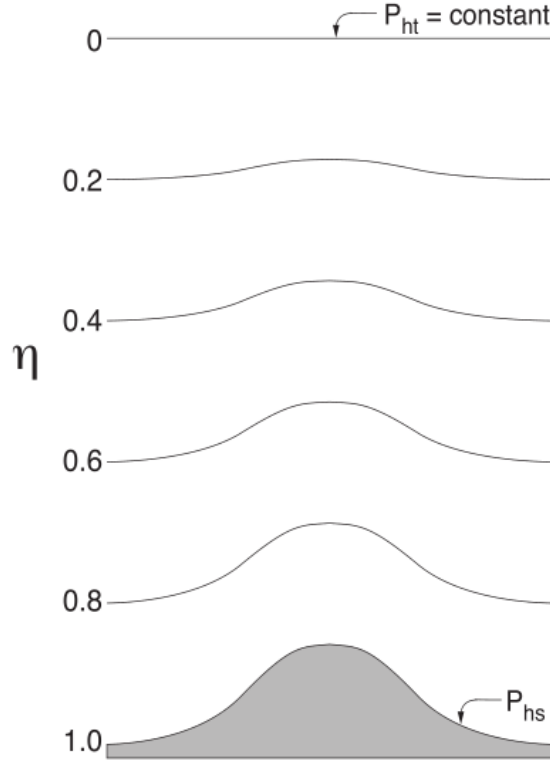


Figure 2.1: ARW mass vertical coordinate, adapted from [39]

pressure and p_{hs} and p_{ht} are its' values at the surface and top of the domain respectively.

Flux form of the governing equations of ARW core can be written as follows.

$$\partial_t U + (\nabla \cdot \mathbf{V}u) - \partial_x(p\partial_\eta \phi) + \partial_\eta(p\partial_x \phi) = F_U \quad (2.1)$$

$$\partial_t V + (\nabla \cdot \mathbf{V}v) - \partial_y(p\partial_\eta \phi) + \partial_\eta(p\partial_y \phi) = F_V \quad (2.2)$$

$$\partial_t W + (\nabla \cdot \mathbf{V} w) - g(\partial_\eta p - \mu) = F_W \quad (2.3)$$

$$\partial_t \Theta + (\nabla \cdot \mathbf{V} \theta) = F_\Theta \quad (2.4)$$

$$\partial_t \mu + (\nabla \cdot \mathbf{V}) = 0 \quad (2.5)$$

$$\partial_t \phi + \mu^{-1} + [(\mathbf{V} \cdot \nabla \phi) - gW] = 0 \quad (2.6)$$

$$\partial_\eta \phi = -\alpha \mu \quad (2.7)$$

$$p = p_0 (R_d \theta / p_0 \alpha)^\gamma \quad (2.8)$$

Here equations from (2.1) - (2.6) are the Euler equations written in the flux form where subscripts denote the differentiation. Equations (2.7) and (2.8) are diagnostic equation for inverse density and equation of state respectively. To include moisture terms to these equations first vertical coordinate is defined with respect to the dry air mass and then the moisture terms are added as source terms.

Next step in model formulation writing these equations for a limited area on the sphere. This requires map projections and ARW supports four projections namely, Lambert conformal, polar stereographic, Mercator, and latitude-longitude projections. Map scale factors are defined as the ratio of the size of the grid box to actual distance on the Earth. These map scale factors and curvature terms are used to redefine the momentum variables. This concludes the analytical model formulation however for the numerical discretization it is convenient to split the equations to hydrostatically-balanced reference state and perturbation variables. This final form of the equations is known as the perturbation form of the governing equations.

Numerical core of ARW solver uses Arakawa C staggering. In this grid, the normal velocities are moved away one-half grid size from the thermodynamic variables. The velocities are solved at the sides of grid boxes and thermodynamic variables are solved at the center. The horizontal grid is uniform that is the Δx and Δy is constant over the whole domain, whereas vertical grid length $\Delta \eta$ is not constant. The horizontal grid is generated with the WRF preprocessing system (WPS) and vertical grid is generated with the real.exe program. The vertical grid can be constructed automatically or manual

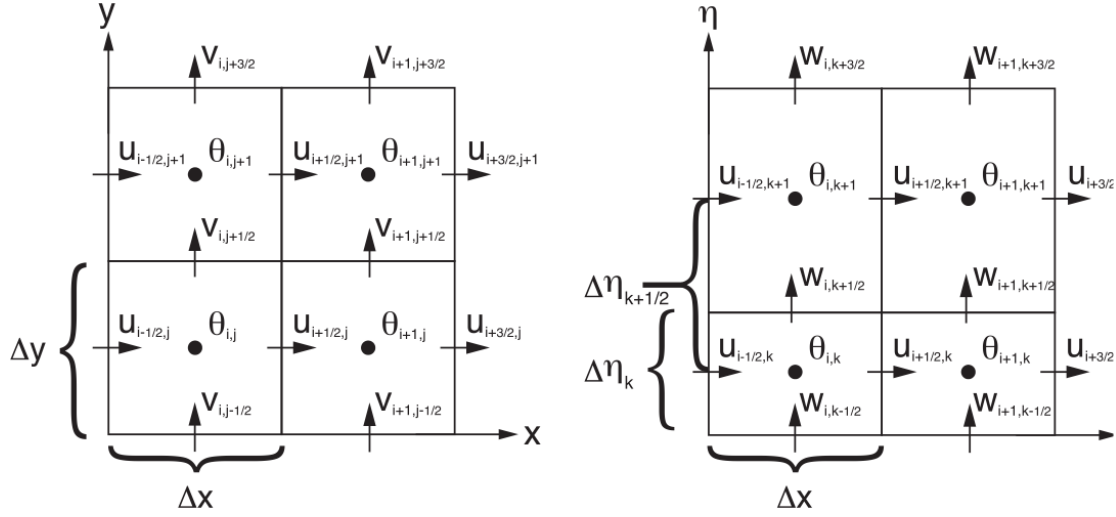


Figure 2.2: Horizontal and vertical finite difference grids of the ARW solver, adapted from [39]

values can be specified by the user. These values should lie within $[0,1]$ interval and monotonically decrease from surface to model top. The horizontal and vertical grids are illustrated in Fig. 2.2. Time discretization of ARW solver uses time-split integration. This approach splits numerical computations into low and high-frequency modes. Low-frequency mode is slowly moving and meteorologically significant mode whereas high-frequency mode contains the acoustic oscillations. Low-frequency mode integration uses third order Runge-Kutta (RK3) method and high-frequency mode integrations use small time steps for numerical stability. The RK3 method used in ARW has third order accuracy for linear equations and second accuracy for non-linear equations. Time splitting methods used in ARW solver is described in detail in [40]. The derivation of the variation of the RK3 method used for time integration is given in [41].

2.1.2 Model Physics

WRF model was developed for both operational and research studies therefore variety of different physics schemes are present in the model. These schemes range from simple and computationally cheap while others are more sophisticated and computationally costly accordingly. Physics package of the WRF model contains microphysics, cumulus, PBL, land-surface and radiation parameterizations. While these parameterization schemes are supported in all of the atmospheric models, the specialty of WRF is these physics packages are isolated from the numerical core of the model as

can be seen in Fig. 2.7. Moreover, the users can also provide their own parameterization schemes and the implementation interface is described in [42]. Physics schemes are described in [39]. Model physics options are listed in Table 2.1.

2.1.3 Model Software Infrastructure

WRF model is a community model and obtained as a package. The package contains the model source code, configuration files (namelists), compilation scripts and some useful utility programs. Fig. 2.3 shows the WRF modeling system package. WRF modeling

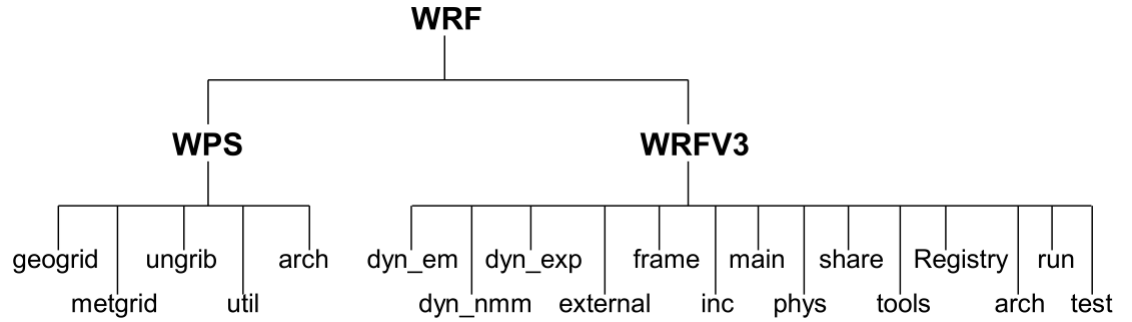


Figure 2.3: Directory tree of the WRF modeling system package

system consists of many independent programs. The flowchart of the whole system is illustrated in Fig. 2.4. However not all of these programs are needed for a regional climate study. In this study the following flowchart was used (Fig. 2.5). Here WPS stands for WRF Preprocessing System and it is used to prepare the simulation domain and the meteorological data. WPS consists of three stand alone programs, namely geogrid, ungrib, and metgrid. Program geogrid sets up the simulation domain; ungrib unpacks the meteorological data in GRIB format and metgrid horizontally interpolates this data to the simulation domain. These programs are configured with a namelist file called namelist.wps. Fig. 2.6 shows how preprocessing mechanism works. Next step is the real.exe program which performs the vertical interpolation of the outputs of the metgrid program and creates the initial and boundary conditions. These resulting files contain the initial state of the atmosphere and tendencies of the field variables at the boundaries which are required for the dynamical core. The later step is running the dynamical core. It performs the numerical computations and outputs the results in NetCDF format. However since these outputs are not CF-compliant, they can not be processed with all softwares that can read NetCDF. The files should be converted with ARWpost package or they can be accessed with special software such as NCL, RIP4 or

Table 2.1: WRF Model Physics, adapted from [39]

Model Physics	Scheme
Microphysics	Kessler scheme
	Purdue Lin scheme
	WRF Single-Moment 3-class (WSM3) scheme
	WSM5 scheme
	WSM6 scheme
	Eta grid scale cloud and precipitation scheme
	Thompson scheme
	Goddard cumulus ensemble model scheme
Cumulus	Morrison 2-moment scheme
	Kain-Fritsch scheme
	Betts-Miller-Janjic scheme
	Grell-Devenyi ensemble scheme
Surface Layer	Grell-3 scheme
	Similarity theory (MM5)
	Similarity theory (Eta)
Land Surface Model (LSM)	Similarity theory (PX)
	5-layer thermal diffusion
	Noah LSM
	RUC LSM
	Pleim-Xiu LSM
	Urban canopy model
	Ocean mixed layer model
	Specified lower boundary conditions
Planetary Boundary Layer (PBL)	MRF PBL
	YSU PBL
	MYJ PBL
	ACM2 PBL
Radiation	RRTM longwave scheme
	GFDL longwave scheme
	CAM longwave scheme
	GFDL shortwave scheme
	MM5 shortwave scheme
	Goddard shortwave scheme
	CAM shortwave scheme

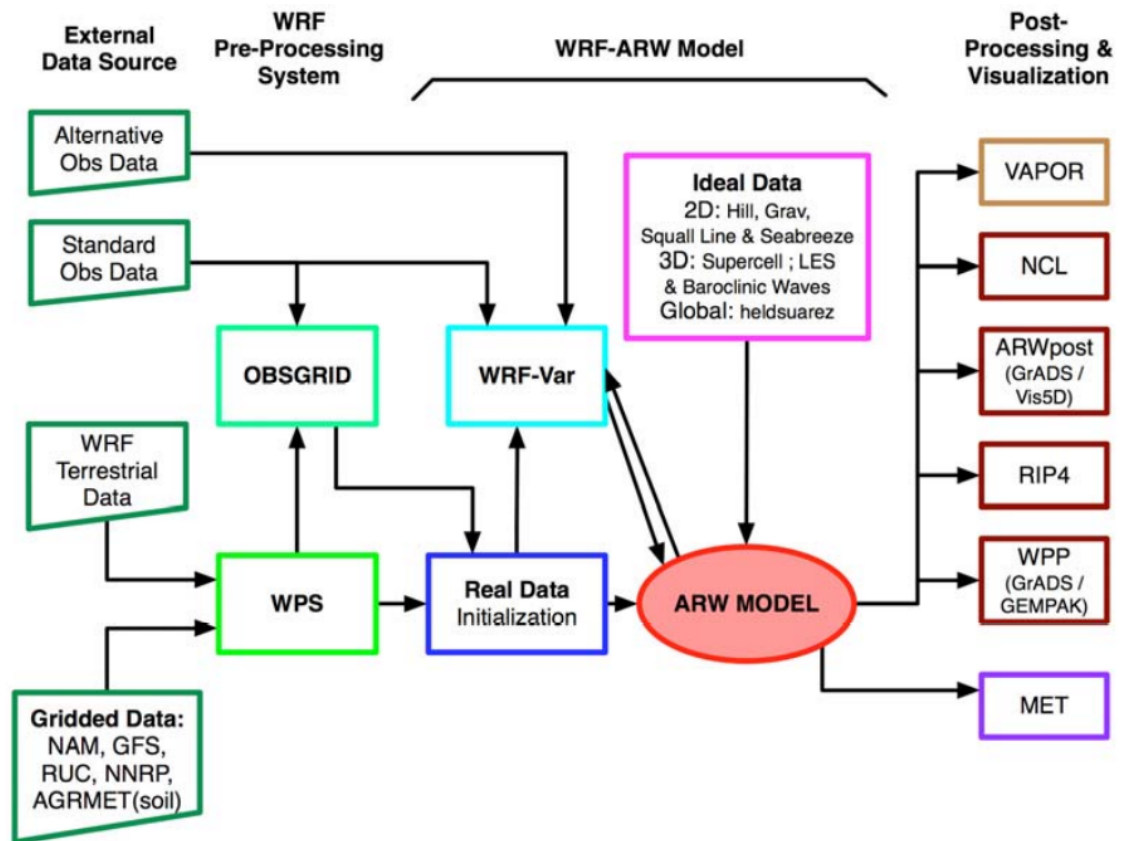


Figure 2.4: WRF modeling system flowchart, adapted from [43]

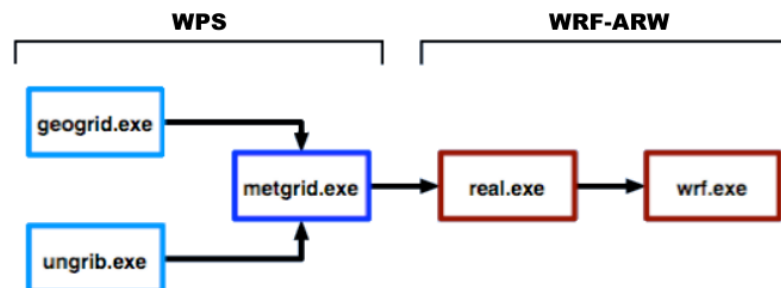


Figure 2.5: Flowchart of the simulations performed in this study, adapted from [43]

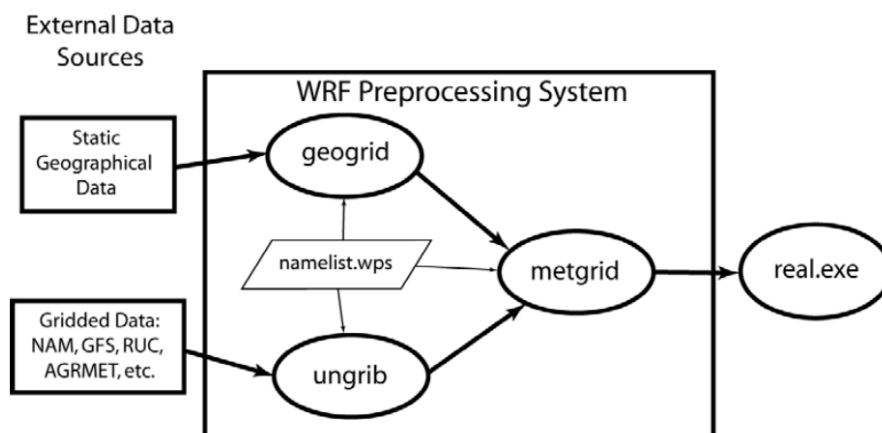


Figure 2.6: Flowchart of the WRF Preprocessor, adapted from [43]

VAPOR.

WRF model has a very modular software infrastructure called *WRF Software Framework* (Fig. 2.7). This framework enables WRF code to be easily developed conveniently. It isolates the dynamical cores and physics packages from the actual software components like an abstract layer. This makes model code to be highly portable and efficient. Along with the software architecture, the parallelization of WRF

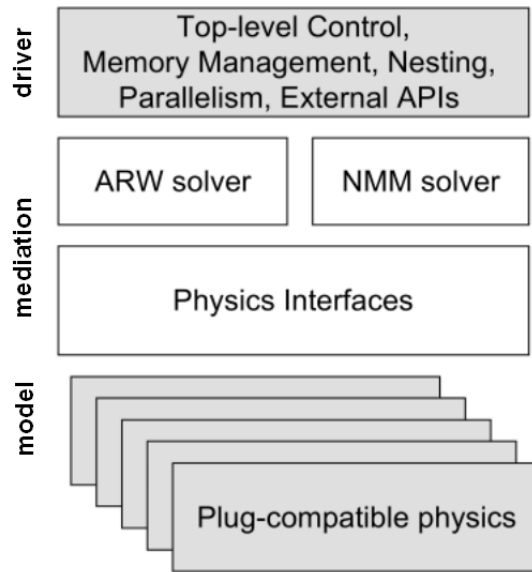


Figure 2.7: WRF Software Framework, adapted from [43]

is also very efficient. WRF code supports both shared memory, distributed memory and hybrid shared-distributed memory parallelizations. Shared memory parallelization is based on OpenMP, distributed memory parallelization is based on MPI and the hybrid parallelization is the combination of two. Both of these are based on domain decomposition which has two levels. In the first level model domain is decomposed into 1-D or 2-D rectangular subdomains called patches and processes are assigned to the patches. If shared memory threading is also available then these patches are further divided into subregions called tiles and threads are assigned to these tiles. This is shown in Fig. 2.8 In addition to CPU level parallelization, WRF also uses GPU level parallelization based on CUDA. Several physics and dynamics subroutines are parallelized for GPU and the benchmark results show a great acceleration (Fig. 2.9).

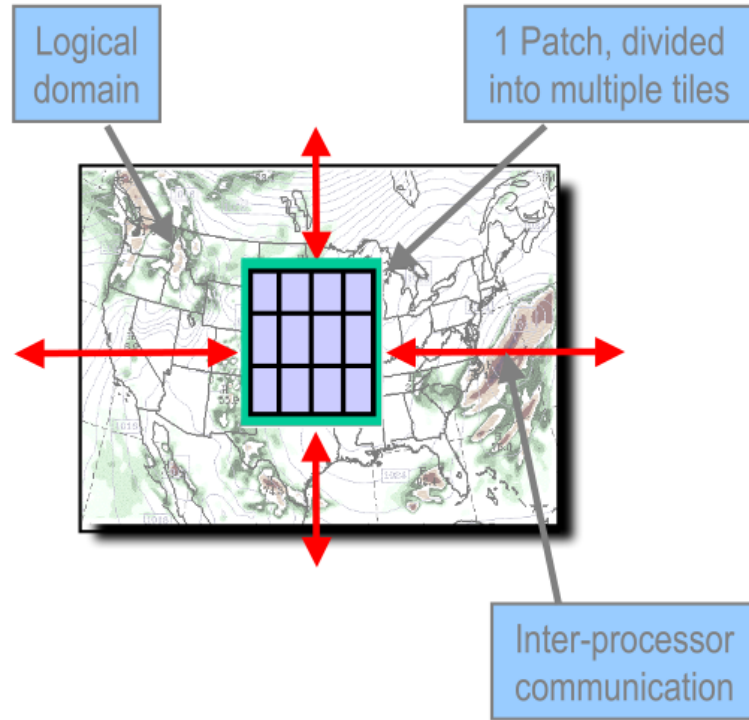


Figure 2.8: Parallelization of WRF model, adapted from [39]

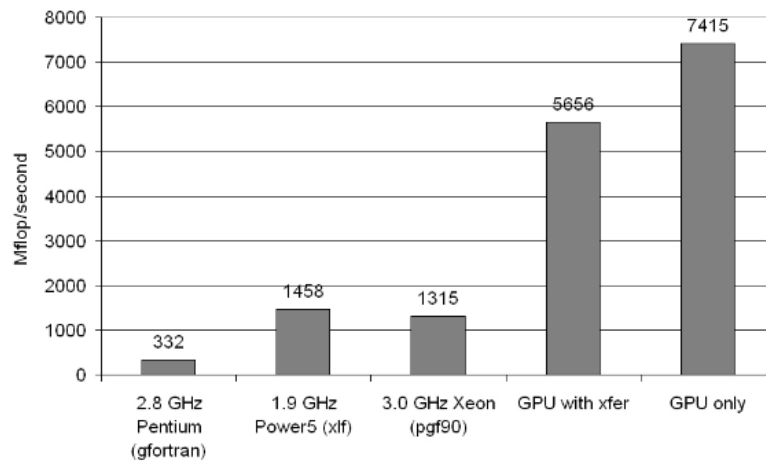


Figure 2.9: Benchmark results of the GPU parallelization of WRF model

2.2 Description of RegCM3

RegCM3 is the second regional climate model that was used in this study. RegCM3 is a regional climate model developed in ICTP. It is one of the first limited area models that is used in regional climate studies. RegCM was first built upon MM4, a NWP model, in late 1980s. However, with the addition of improved numerical schemes RegCM made very similar to the hydrostatic version of MM5. Moreover to make it more suitable for

long term climate simulations several physic packages were integrated to RegCM. These packages consists of radiative, PBL, cumulus convection, moisture and land-surface parameterization schemes. Later on, second version RegCM2 was introduced in 1992. This version included parameterization schemes from NCAR's Community Climate Model and MM5 model as well as new PBL and cumulus schemes to the BATS. The last major version RegCM3 was finalized in 2006 and since then it has been used worldwide for both regional climate downscaling, sensitivity analyses, and climate projections. RegCM3 includes improved physic schemes, embedded lake models and atmospheric aerosol and chemistry modules. The software also contains major developments such user interfaces, input modules that support common reanalysis and GCM data, and parallel computing. More recently, in 2011, the final version RegCM4 is introduced. RegCM4 code was completely rewritten in FORTRAN 95 with new pre and postprocessors. RegCM4 also contains improved SST, sea-ice and dust-chemistry modules. For the future versions it is expected that model will be reformulated with a non-hydrostatic dynamical core and wil incorporate advanced numerical schemes.

2.2.1 Model Formulation and Dynamics

Dynamical core of RegCM3 is a based on compressible, hydrostatic primitive equations. The formulations are based on MM5's dynamical core which are described in detail in [44]. These equations are discretized with staggered finite differences and integrated over terrain following σ coordinates in the vertical. This coordinate system is constructed with the equation **2.9**

$$\sigma = \frac{(p - p_t)}{(p_s - p_t)} \quad (2.9)$$

This transformation results in the value of σ to take values from $[0, 1]$ interval and lower model levels to follow the terrain and higher model levels to flatten. The resulting interpolation is illustrated in Fig. 2.10 In the horizontal direction model equations are discretized with Arakawa-Lamb B staggering [46]. This finite difference grid is shown in Fig. 2.11. Furthermore since the simulation domain only covers a limited area on the globe the model variables must be mapped to this area with map projection methods. RegCM supports Lambert Conformal, Polar Stereographic, Normal Mercator, and Rotated Mercator projections. The map scale factor m used for this transformation

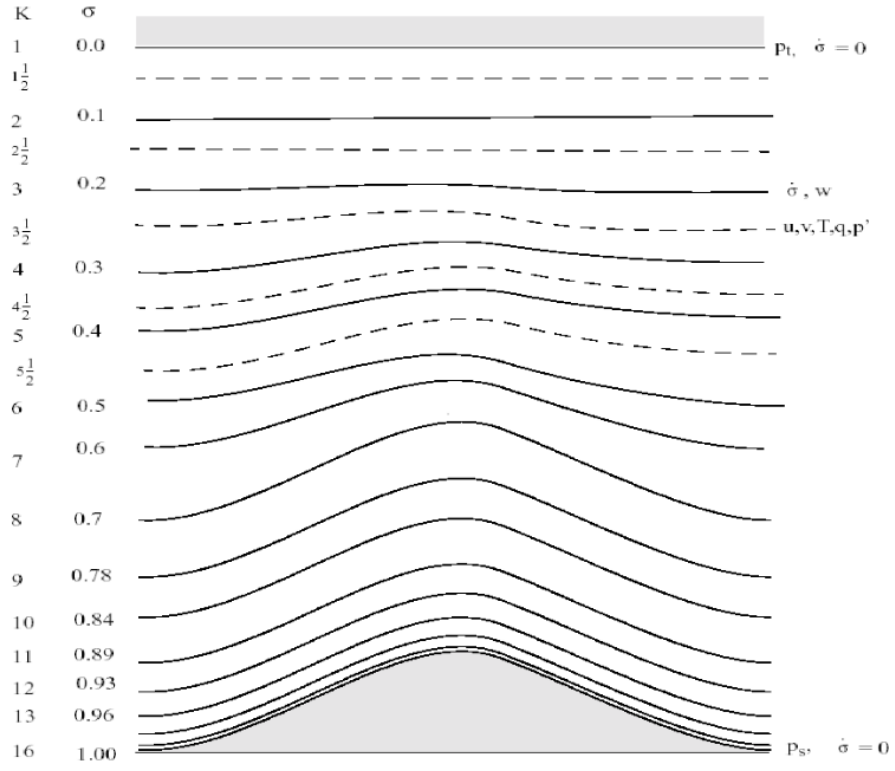


Figure 2.10: Vertical coordinate system used in RegCM3, adapted from [45]

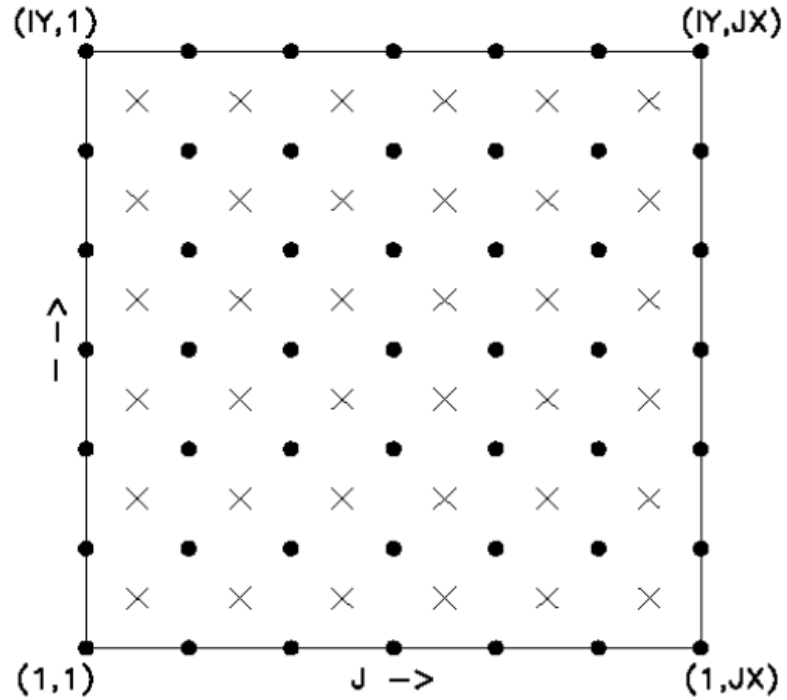


Figure 2.11: Horizontal finite difference grid used in RegCM3, adapted from [45]

is defined as the ratio of distance on grid box to the actual distance on the earth.

The governing equations the dynamical solver a given as follows.

Horizontal Momentum Equations

$$\begin{aligned} \frac{\partial p^* u}{\partial t} = & -m^2 \left(\frac{\partial p^* u u / m}{\partial x} + \frac{\partial p^* v u / m}{\partial y} \right) - \frac{\partial p^* u \dot{\sigma}}{\partial \sigma} \\ & - m p^* \left[\frac{RT_v}{(p^* + p_t / \sigma)} \frac{\partial p^*}{\partial x} + \frac{\partial \phi}{\partial x} \right] + f p^* v + F_H u + F_V u \end{aligned} \quad (2.10)$$

$$\begin{aligned} \frac{\partial p^* v}{\partial t} = & -m^2 \left(\frac{\partial p^* u v / m}{\partial x} + \frac{\partial p^* v v / m}{\partial y} \right) - \frac{\partial p^* v \dot{\sigma}}{\partial \sigma} \\ & - m p^* \left[\frac{RT_v}{(p^* + p_t / \sigma)} \frac{\partial p^*}{\partial y} + \frac{\partial \phi}{\partial y} \right] + f p^* u + F_H v + F_V v \end{aligned} \quad (2.11)$$

Continuity and Sigmadot ($\dot{\sigma}$) Equations

$$\frac{\partial p^*}{\partial t} = -m^2 \left(\frac{\partial p^* u / m}{\partial x} + \frac{\partial p^* v / m}{\partial y} \right) - \frac{\partial p^* \dot{\sigma}}{\partial \sigma} \quad (2.12)$$

$$\dot{\sigma} = -\frac{1}{p^*} \int_0^\sigma \left[\frac{\partial p^*}{\partial t} + m^2 \left(\frac{\partial p^* u / m}{\partial x} + \frac{\partial p^* v / m}{\partial y} \right) \right] d\sigma' \quad (2.13)$$

Thermodynamic Equation and Omega Equation

$$\begin{aligned} \frac{\partial p^* T}{\partial t} = & -m^2 \left(\frac{\partial p^* u T / m}{\partial x} + \frac{\partial p^* v T / m}{\partial y} \right) - \frac{\partial p^* T \dot{\sigma}}{\partial \sigma} + \frac{RT_v \omega}{c_{pm}(\sigma + P_t / p_{ast})} \\ & + \frac{p^* Q}{c_{pm}} + F_H T + F_V T \end{aligned} \quad (2.14)$$

$$\omega = p^* \dot{\sigma} + \sigma \frac{dp^*}{dt} \quad (2.15)$$

$$\frac{dp^*}{dt} = \frac{\partial p^*}{\partial t} + m \left(u \frac{\partial p^*}{\partial x} + v \frac{\partial p^*}{\partial y} \right) \quad (2.16)$$

Hydrostatic Equation

$$\frac{\partial \phi}{\partial \ln(\sigma + p_t / p^*)} = -RT_v \left[1 + \frac{q_c + q_r}{1 + q_v} \right]^{-1} \quad (2.17)$$

2.2.2 Model Physics

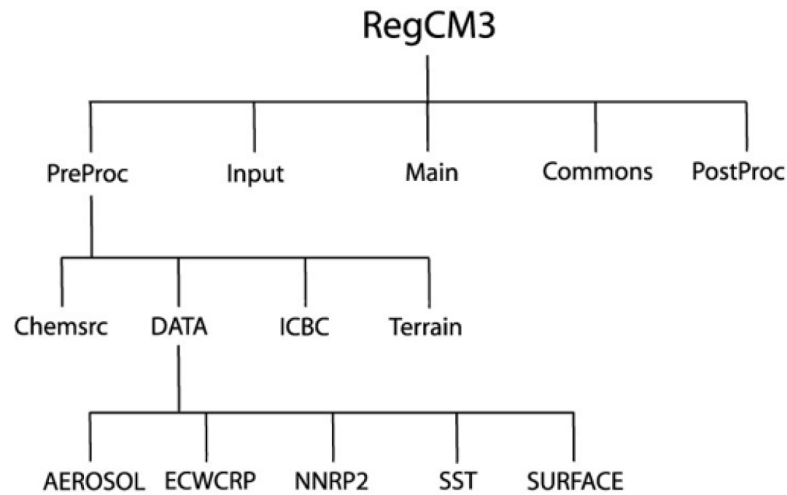
RegCM is intended for regional climate simulation therefore the physics package is focused on climatologically significant schemes. The list of physics options are listed in Table 2.2.

Table 2.2: RegCM3 Model Physics, adapted from [45]

Model Physics	Scheme
Convective Precipitation	Modified-Kuo scheme
	Grell scheme
	MIT-Emanuel scheme
Large Scale Precipitation	Subgrid Explicit Moisture Scheme (SUBEX)
LSM	Biosphere-Atmosphere Transfer Scheme (BATS)
PBL	Holtslag
Radiation	NCAR CCM3
Ocean Flux	BATS
	Zeng
Lake Model	Hostetler
Aerosol and Dust – Chemistry Model	Based on [47] and [48]

2.2.3 Model Software Infrastructure

RegCM is also an open source community model and it is maintained as a single package. This package contains the preprocessor, dynamical core and the postprocessor. The model is written in FORTRAN 77 therefore the modularity and memory allocation is very primitive. It is required to rebuild the model when changes are performed in the configuration. The model code directory is given in Fig. 2.12. RegCM contains a two

**Figure 2.12:** Directory tree of the RegCM3 modeling system, adapted from [49]

level preprocessor called Terrain and ICBC. First is used to define the simulation domain and interpolate the geographical data to this domain, where latter is used to generate the initial and boundary conditions to the dynamical core. This program supports various reanalysis dataset and GCMs such as ECMWF and NNRP dataset and NASA-NCAR GCM and ECHAM. Domain setup and ICBC generation configurations are handled with domain.param and icbc.param files. Next step is running the model. Model

configurations are set in the regcm.in file. The work flow of the RegCM simulation is illustrated in Fig. 2.13. RegCM3 package also contains a parallel version of the

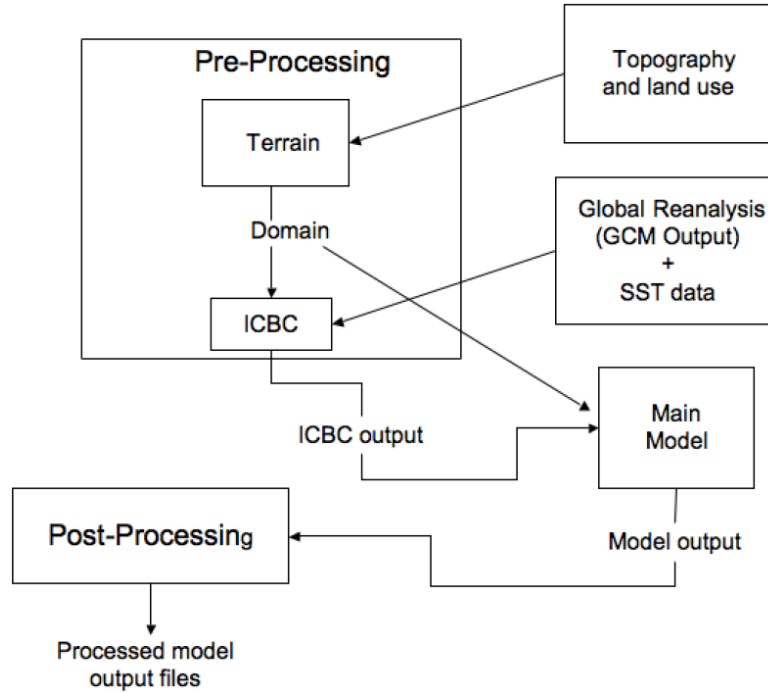


Figure 2.13: Flow chart of the RegCM simulation, adapted from [49]

dynamical solver. It uses only distributed memory parallelization with MPI library. The domain decomposition is only 1-D therefore it is not very efficient. Along with that, the number of grid points in x direction must be an integer multiple of the number of processors used. Consequently this puts a limit to the flexibility of the model. Moreover, I/O is also done serially, only from the master node. In the future versions of the model it is announced that 2-D decomposition and parallel I/O will be provided.

3. EXPERIMENT DESIGN AND SETUP

3.1 Simulation Domain

The simulation domain used in this study spans over 13° E - 55° E and 28° N - 51° N. In order to map this area on the globe to the computational domain, Lambert Conformal projection is used. This projection is defined with true latitudes located at 30° N and 60° N; reference latitude and longitude 40° N and 32° E; and standard longitude at 32° E. The topography of this region is shown in Fig. 3.1 There are various considerations for



Figure 3.1: Topography of the simulation domain

the choice of domain. As discussed in [50] domain choice can greatly affect the quality of the climate simulations. Other sensitivity studies regarding domain choice are done in [51] and [52]. As discussed by Önoğlu [53], the simulation domain should

- include the meteorological and climatological phenomenon that forces the climatology of the domain,
- not include complex topography on the boundaries, and

- main analysis region inside the domain should be kept away from the lateral buffer regions.

Moreover, Önoğlu has performed sensitivity analyses over EM region as given in detail in [11] and [23] and his domain was chosen in this study. According to this there are 144 and 100 grid points in W-E and S-N directions respectively. The horizontal grid resolution in both direction is chosen as 27 km. In the vertical direction RegCM3 uses 18 levels whereas WRF uses 35. The use of higher vertical resolution in WRF is mainly due to its non-hydrostatic computations and the choice of the radiation schemes. In the initial runs WRF was also tried to be run with 18 vertical levels however these runs crashed on account of insufficient number of vertical levels required by the physics package.

3.2 Model Data

The regional climate modeling is a boundary value problem therefore we need to specify the sufficient conditions at the boundaries and inside the simulation domain. The mandatory data sets are static geographical information and time-dependent meteorological data set. In addition, for long simulations the effect of the seas are also important therefore SST data set should also be used.

3.2.1 Geographical Data

Geographical data set contains both the topography of the Earth and the land use information. In RegCM simulations 10 minute resolution GTOPO30 topography and GLCC land use data sets were used. In WRF simulations 30 second resolution MODIS topography and land use data set was used. Topographies of WRF and RegCM are shown in Fig. 3.2 and Fig. 3.3 respectively. It can be clearly seen that geographical data used in WRF represents the simulation domain finer than of RegCM's. Mountain heights are higher in WRF data set and regional features are better represented.

Land use is another important case for representation of the geography. Land use categories of WRF and RegCM are shown in Fig. 3.4 and Fig. 3.5 respectively. WRF represents the domain with a larger land use data set. It uses 24 variables while RegCM uses 20 variables. Moreover, WRF is more successful in representing fine variabilities in the domain. The landuse categories of WRF and RegCM are given in Table 3.1 and

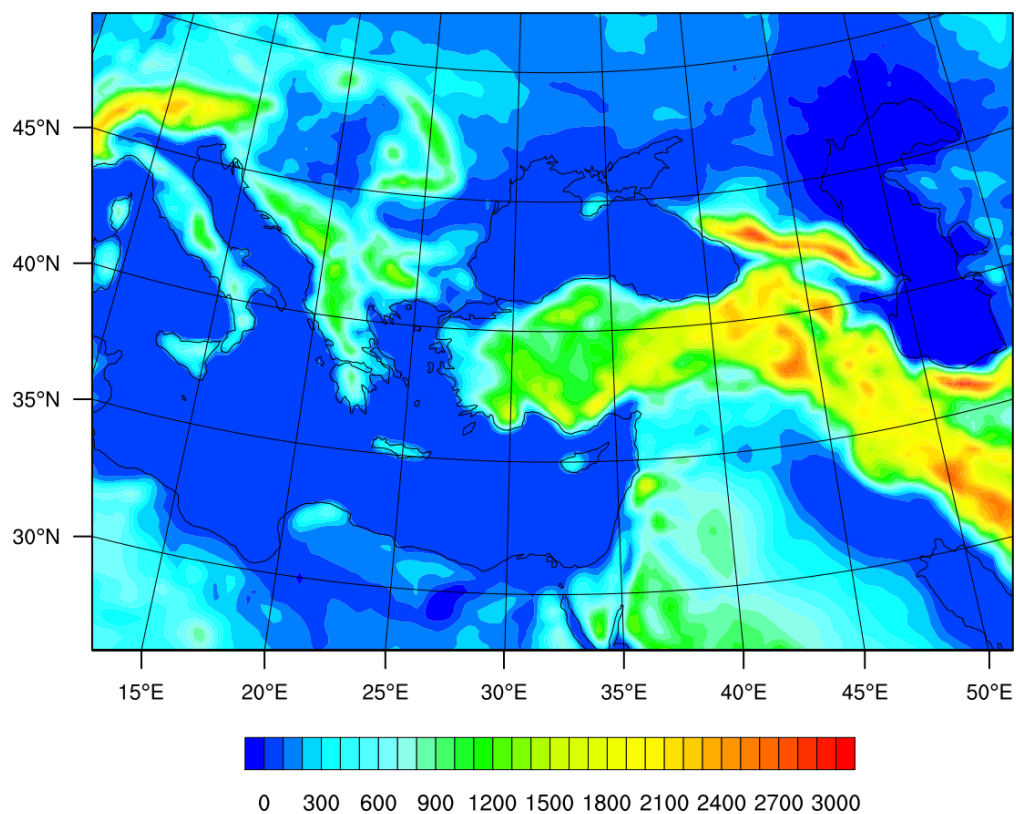


Figure 3.2: Topography of the WRF model, mean sea level height is colored at every 100 meters

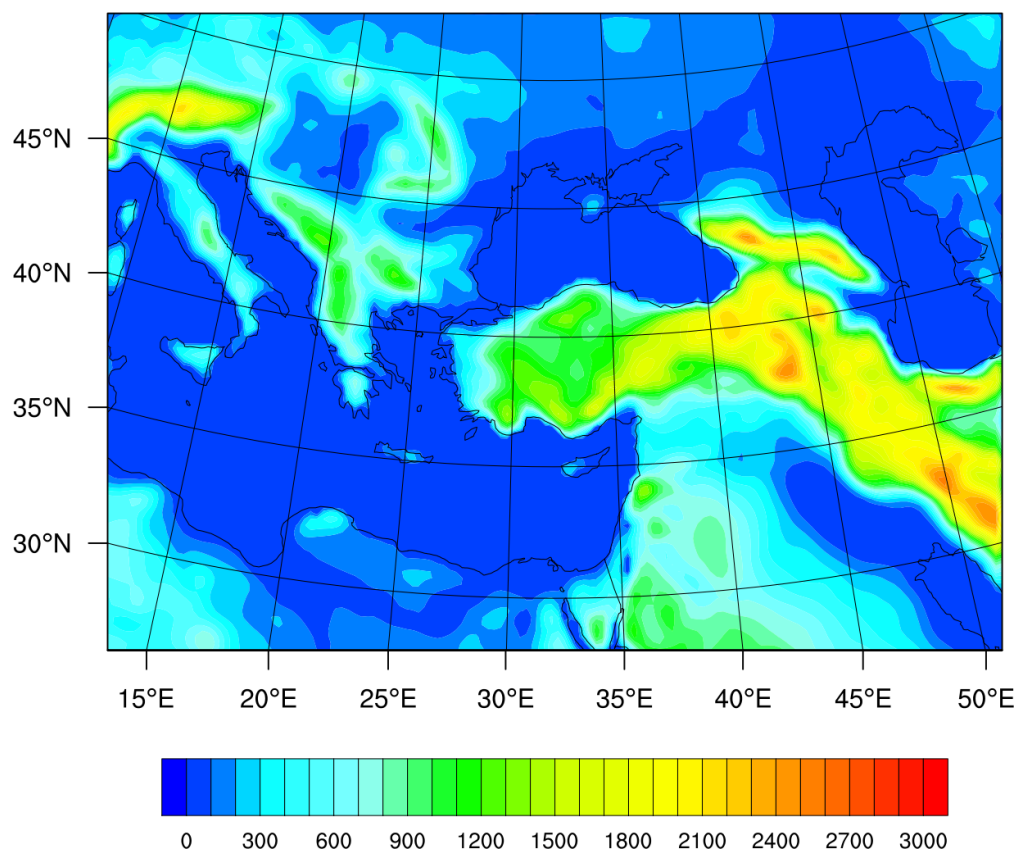


Figure 3.3: Topography of the RegCM model, mean sea level height is colored at every 100 meters

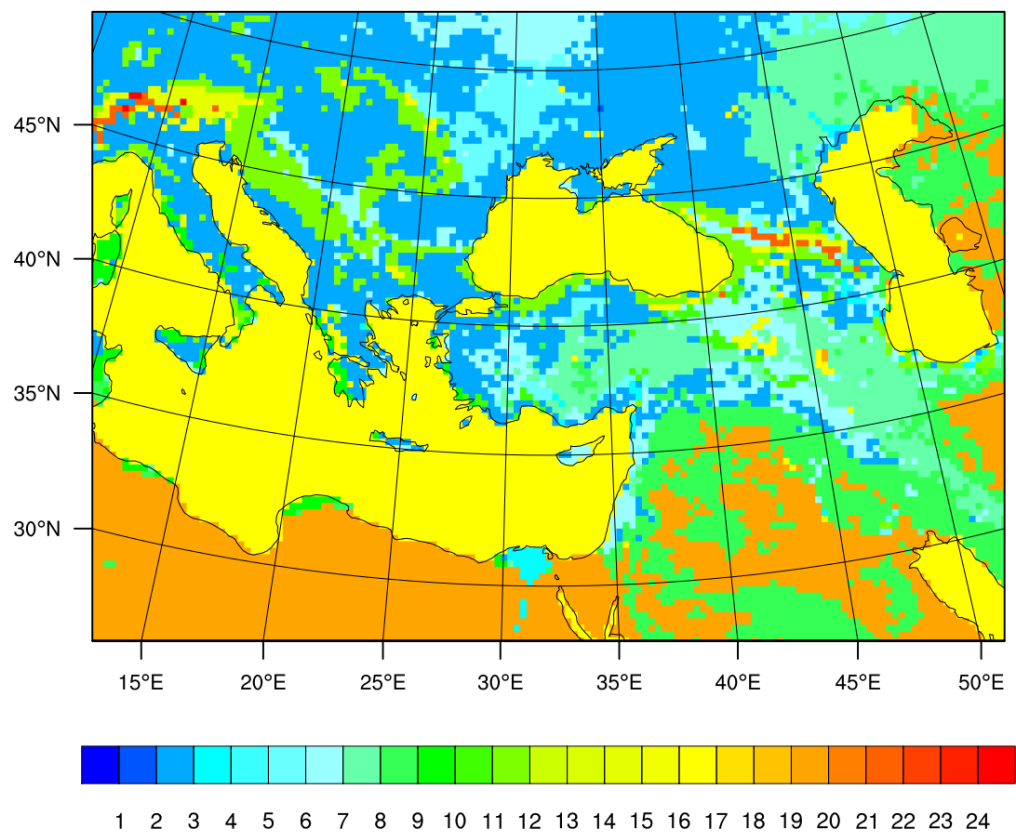


Figure 3.4: Land use of the WRF model

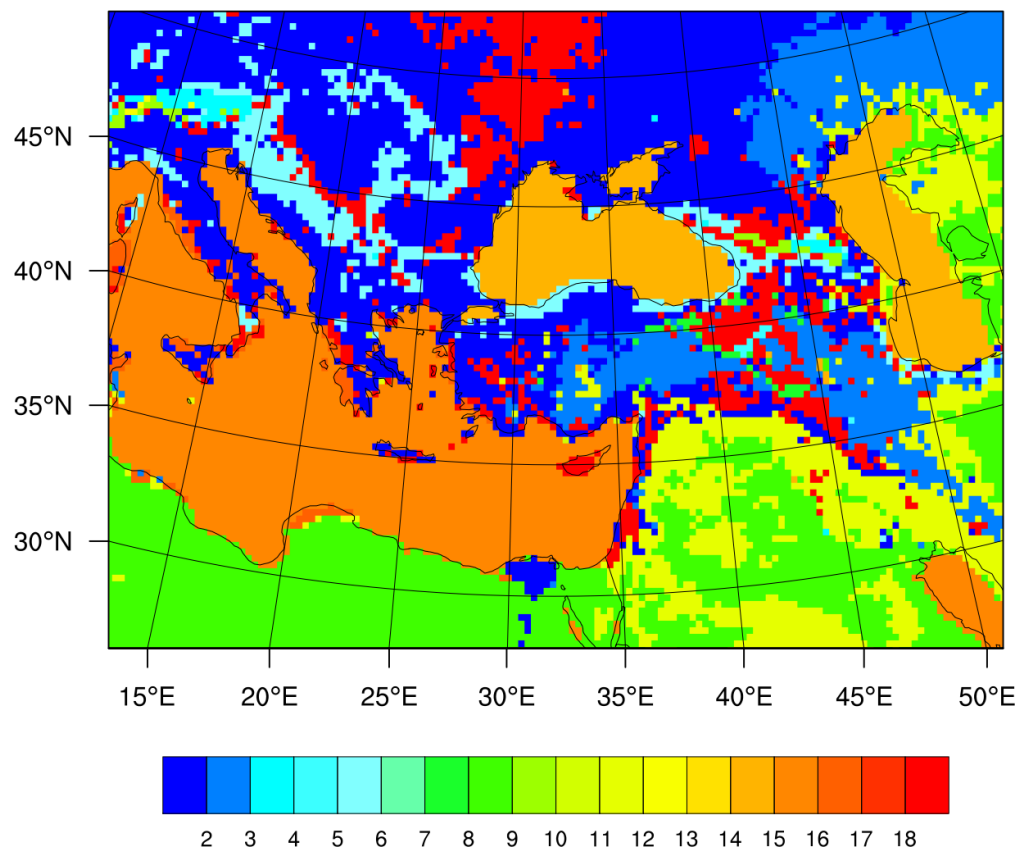


Figure 3.5: Land use of the RegCM model

Table 3.1: Land use representation of WRF model, adapted from [43]

Land Use Category	Land Use Description
1	Urban and Built-up Land
2	Dryland Cropland and Pasture
3	Irrigated Cropland and Pasture
4	Mixed Dryland/Irrigated Cropland and Pasture
5	Cropland/Grassland Mosaic
6	Cropland/Woodland Mosaic
7	Grassland
8	Shrubland
9	Mixed Shrubland/Grassland
10	Savanna
11	Deciduous Broadleaf Forest
12	Deciduous Needleleaf Forest
13	Evergreen Broadleaf
14	Evergreen Needleleaf
15	Mixed Forest
16	Water Bodies
17	Herbaceous Wetland
18	Wooden Wetland
19	Barren or Sparsely Vegetated
20	Herbaceous Tundra
21	Wooded Tundra
22	Mixed Tundra
23	Bare Ground Tundra
24	Snow or Ice

Table 3.2 respectively.

Additionally, MODIS data set contains gravity wave drag (GWD) fields. GWD is generated over the topography where the amplitude of the waves grow and break, causing a turbulent forcing over mean zonal flow. This can alter short term as well as long term climatological flows. [54]. Kim et al. shows that only models that are run with 1-10 km spatial resolutions can fully resolve GWD and those with coarser resolutions must parameterize GWD. GWD parameterization is present ARW solver but it is optional to use it. Shin et al. found that using GWD parameterization in WRF increases the model's performance in tropospheric wind and temperature fields [55]. Consequently GWD option is activated in the WRF run.

3.2.2 Meteorological Data

Meteorological data constitutes the most important part in the whole data sets. NCEP-NCAR Reanalysis ds090.0 data set (NNRP) was used to provide the initial and

Table 3.2: Land use representation of RegCM model, adapted from [45]

Land Use Category	Land Use Description
1	Crop/mixed farming
2	Short grass
3	Evergreen needleleaf tree
4	Deciduous needleleaf tree
5	Deciduous broadleaf tree
6	Evergreen broadleaf tree
7	Tall grass
8	Desert
9	Tundra
10	Irrigated Crop
11	Semi-desert
12	Ice cap/glacier
13	Bog or marsh
14	Inland water
15	Ocean
16	Evergreen shrub
17	Deciduous shrub
18	Mixed Woodland
19	Forest/Field mosaic
20	Water and Land mixture

boundary conditions. Since this study consists of comparison of two model, same data set was used. This data set contains more than 80 variables over 192x94 global Gaussian grid ($2.5^\circ \times 2.5^\circ$) and 17 vertical pressure level. The data is available from 1948 with 6 hour intervals. The details of the data set is given in [56].

3.2.3 SST Data

In long term climate simulations atmosphere-ocean interactions become very important. Since the atmospheric data set does not contain the SST and sea-ice fields they must be included from a global SST data set. In this study, GISST data set was used in both models. GISST data set contains monthly SST values from 1871 to 2003 over a $1^\circ \times 1^\circ$ grid. This data set was first converted to NetCDF format and interpolated to 6 hours and then read by the model preprocessor. However, since WRF preprocessor is not able to read the GISST dataset an external preprocessor, `gisst2wrf` was written to convert it into a readable format. Details of this program is given in the appendix.

3.3 Model Configurations

Model configurations consist of the choice of dynamical & numerical methods and physics packages. The optimum choice is very important and it is a subject to an independent study. Önoğlu has performed sensitivity studies with the RegCM3 over EM region found the most appropriate dynamical and physical configurations [11]. Consequently, his findings provided a road map for RegCM and WRF runs. However, it is important to note that two models are not formulated in the same way and do not offer the same physics schemes. Therefore, in case of the WRF configuration time tested and recommended schemes were chosen.

3.3.1 Dynamics

Integration time step for both models are chosen as 60 seconds. This is a reasonable choice to avoid CFL violations since the spatial resolution is 27 km. In RegCM3 runs no CFL violations were encountered however in WRF simulations few CFL violations caused model to crash. Since a smaller time step would increase the simulation time, adaptive time step was chosen so that model increases the time resolution where the solutions become unstable and continues with the normal time step where it is not needed. These time step options are given below.

```
use_adaptive_time_step = .true.,  
step_to_output_time = .true.,  
target_cfl = 1.2
```

```

max_step_increase_pct = 5
starting_time_step = 60
min_time_step = 10
max_time_step = 60

```

The options are written to the model configuration file (namelist.input) and it adapts the model's time step according to the target CFL number. If the computations become unstable the time step is decreased continuously with the given percentage until the solution becomes stable. Similarly, time step increased back to its normal value.

LBC options are very important as mentioned before that climate modeling is a boundary value problem. Consequently, buffer zones at the boundaries are kept larger than default and boundary values are smoothed exponentially. The LBC zones used in WRF are illustrated in Fig. 3.6

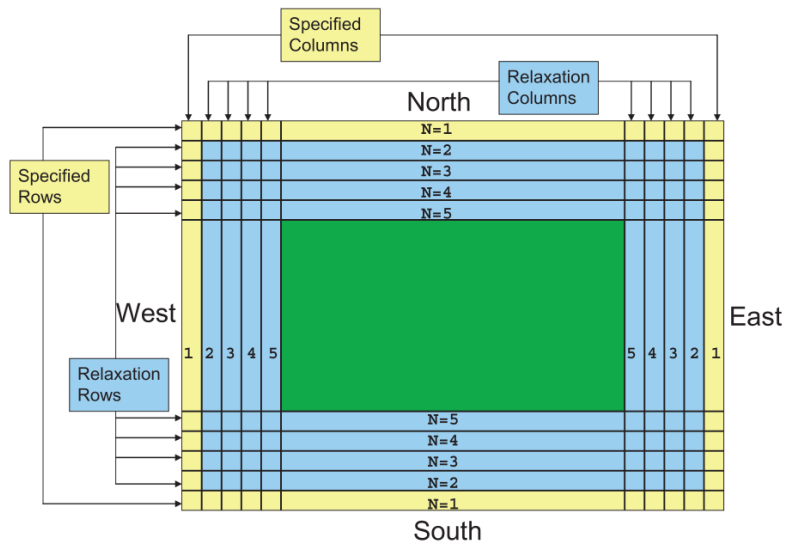


Figure 3.6: LBC zones in WRF model, adapted from [39].

3.3.2 Physics

The physics options are tried to be chosen as similar as possible since the aim is on the comparative performance of the models. Physics options of RegCM have already been configured for regional climate simulations and optimum schemes have been found by Önoğlu [11]. On the other hand, physics schemes of WRF are mainly focused on short term simulations but starting with version 3 schemes for regional climate simulations are implemented into WRF. These schemes come from CAM3 model (Community Atmosphere Model, version 3) of NCAR's CCSM Model (Community Climate System

Table 3.3: Physics schemes used in WRF simulations

Model Physics	Parameterization Scheme
Microphysics	WSM 6-class graupel microphysics
Cumulus convection	New Grell Cumulus
Surface layer	MM5 similarity
LSM	Noah LSM
PBL	YSU PBL
Radiation	CAM radiation with time step = 30 minutes

Table 3.4: Physics schemes used in RegCM simulations

Model Physics	Parameterization Scheme
Microphysics	SUBEX
Cumulus convection	Grell
LSM	BATS
PBL	Holtslag
Radiation	CCM3 radiation with time step = 30 minutes

Model). The suggested schemes and parameters given in [43] has been used WRF runs. Physics options of WRF and RegCM models are given in Table 3.3 and Table 3.4 respectively.

3.3.3 Model Outputs

In WRF simulations, the model outputs are written to the disk as a NetCDF file at every three hours and a new file is generated when model begins computing the next day. Each output file contains the three dimensional atmospheric field variables and computed diagnostic fields. These field variables are still on the computational grids and velocity components are on staggered grids. Therefore for statistical analysis and visualization the required fields must be processed. Since the WRF output files are not CF compliant, the users have to write their own postprocessing scripts. It should be noted that in this 30 year simulation study more than 11 000 files were generated and the postprocessing takes as much time as the model computations.

In RegCM3 simulations, the surface fields are written to the disk at every three hours and upper atmospheric fields are written at every 6 hours. The output file format is simple binary form and the RegCM3 postprocessor converts these binary files to CF compliant NetCDF files. Since there are many command-line based programs such as NCO (NetCDF operators) and CDO (climate data operators) which can compute

climate indices and various diagnostics, the RegCM outputs are easier to work with than WRF outputs for climate studies. Although a conversion script `wrfout_to_cf.ncl`¹ that converts WRF NetCDF outputs to CF compliant NetCDF outputs, the speed of conversion was so low that it was not applicable to convert 11 000 files.

3.4 Computing Environment and Performance Analysis

Multi-year regional climate simulations require a vast amount of computational resources. Typically, computing speed, memory and harddisk capacity of PCs and even current state-of-the-art scientific workstations are not enough for a 30 year climate run. Clusters of computers provide a 10-1000 order more computational resource than a single PC. Consequently, simulations performed in this study was run on the clusters at National Center for High Performance Computing(UYBHM).

UYBHM consists of five main computing clusters, namely, Anadolu, Trakya, Ege, and Karadeniz; a high performance parallel run space (RS); a high capacity data storage system (Akdeniz) and two data backup systems. The system architecture is illustrated in Fig. 3.7. In this study Akdeniz cluster and Anadolu disk system was used because of their higher performance.

Anadolu cluster consists of 192 compute nodes. These are Intel Xeon 2.33 GHz dual and quad core systems and whole cluster contains 1004 cores. There are 8 GB memory for dual core and 16 GB memory for each quad core system. Each compute node runs 64 bit Red Hat Enterprise Linux (RHEL) 5.1 operating system and connected to each other with 20 Gpbs Infiniband network. RS system, on the other hand, is a special parallel disk system which is mounted by compute nodes and reserved for submitted jobs. RS has 128 TB of storage space and uses Lustre file system (LFS). LFS is a massively parallel file system designed for distributed supercomputers and clusters. The file system structure of the UYBHM is illustrated in Fig. 3.8 In this architecture, all computers which are mounted to file system of UYBHM that runs LFS system become a LFS client. User data are stored in the distributed disks called OST (Object Storage Target). The access from clients to OSTs are managed by OSSs (Object Storage Server). However, this distributed physical structure must be mapped to a single logical structure since the users manage their data as if they reside in a single computer. This is handled by MDS

¹Availiable from http://www.mmm.ucar.edu/wrf/src/utils/wrfout_to_cf.ncl

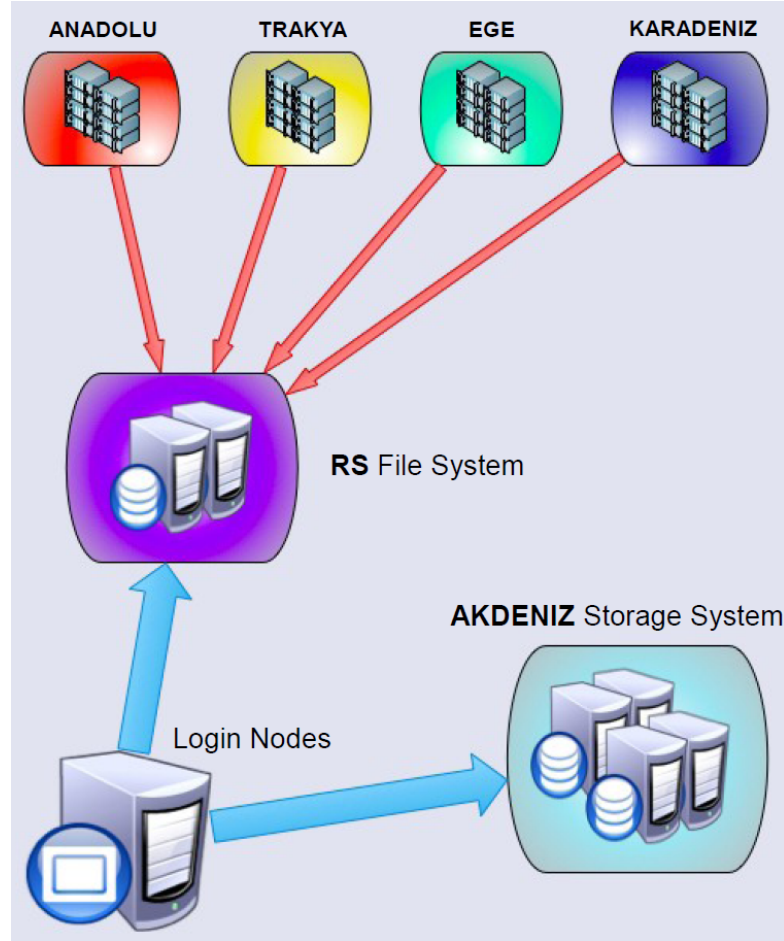


Figure 3.7: Architecture of the UYBHM computing system, adapted from [57].

(Metadata Server) and the unique informations of each file in the system is stored in MDT (Metadata Target).

Before running the WRF model in UYBHM clusters several benchmarks were performed to analyze its performance on multiple cores. In parallel computing there are several performance metrics for analyzing the scalability of a parallel program. The most important metrics are speedup($S(p)$) and efficiency(E). These are defined as

$$S(p) = \frac{\text{execution time of the program with one processors}}{\text{execution time of the parallel program with } p \text{ processors}} = \frac{t_s}{t_p} \quad (3.1)$$

$$E(p) = \frac{\text{Speed up with } p \text{ processors}}{\text{number of processors}} = \frac{S(p)}{p} \quad (3.2)$$

respectively in [58]. Accordingly, WRF was run with 8, 16, 24, 32, 48, 60, and 120 cores and these metrics were calculated. The results of these calculations are given in Fig. 3.9, Fig. 3.10, and Fig. 3.11. These results show that WRF runs faster as the number of computing cores increase however its parallel efficiency is not very desirable. This is

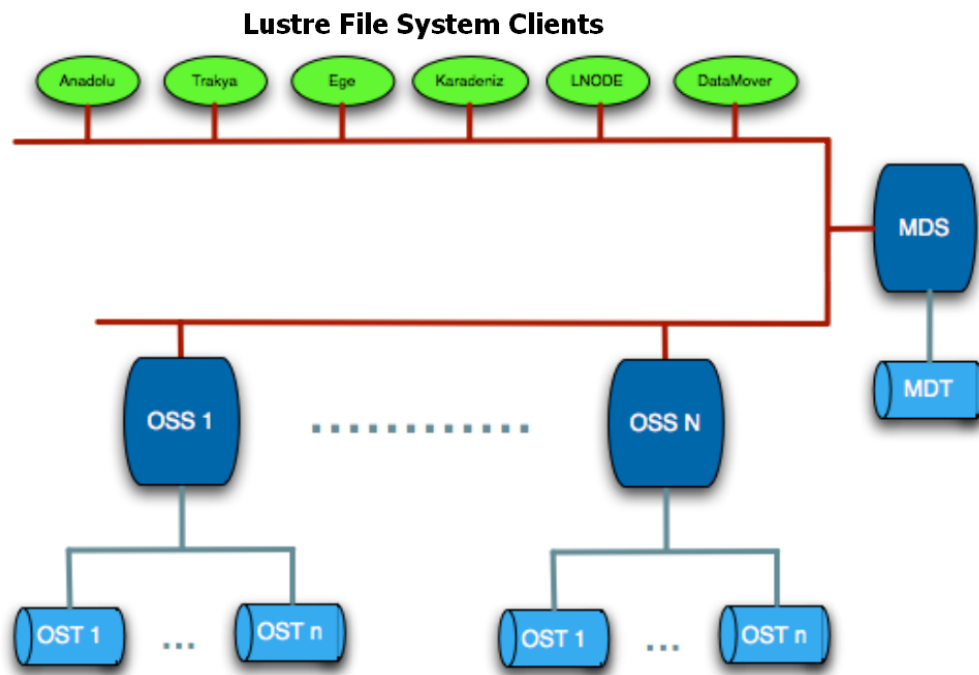


Figure 3.8: Architecture of the UYBHM file system, adapted from [57].

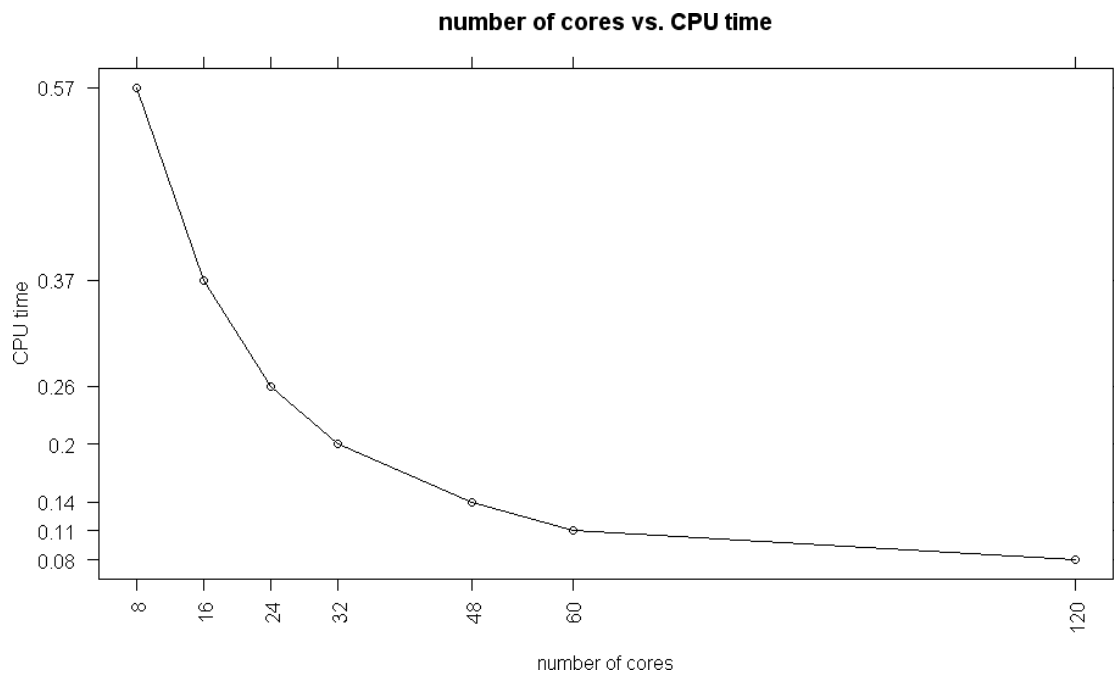


Figure 3.9: Number of cores versus average CPU time consumed at each time step integration in WRF run

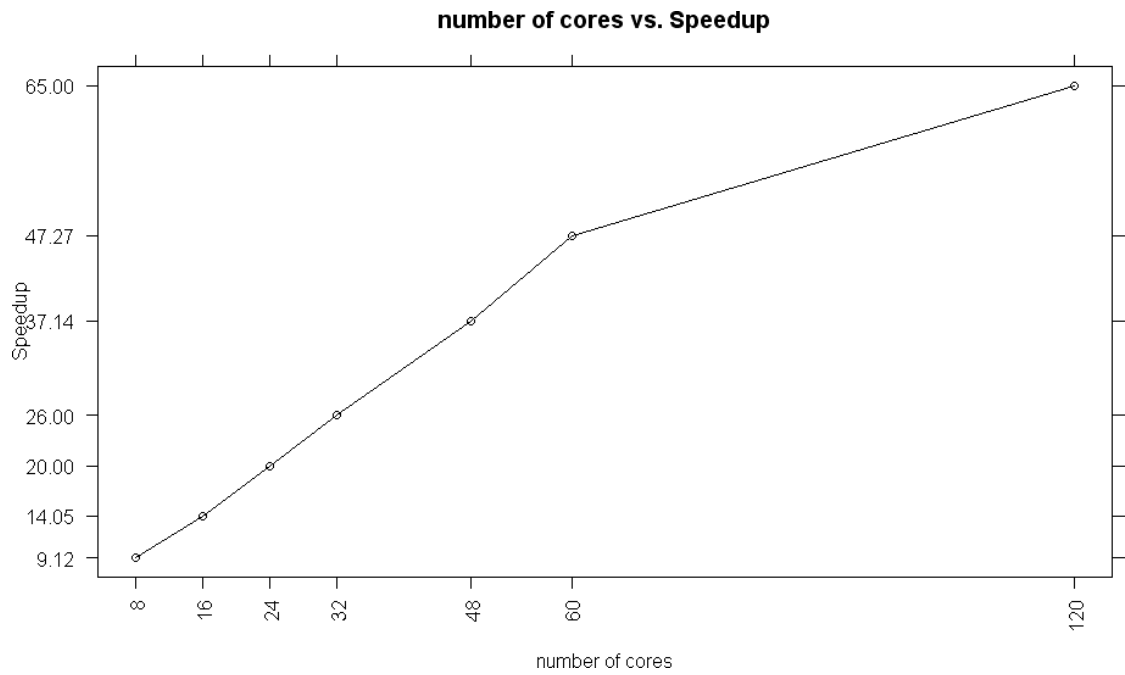


Figure 3.10: Number of cores versus speedup of WRF

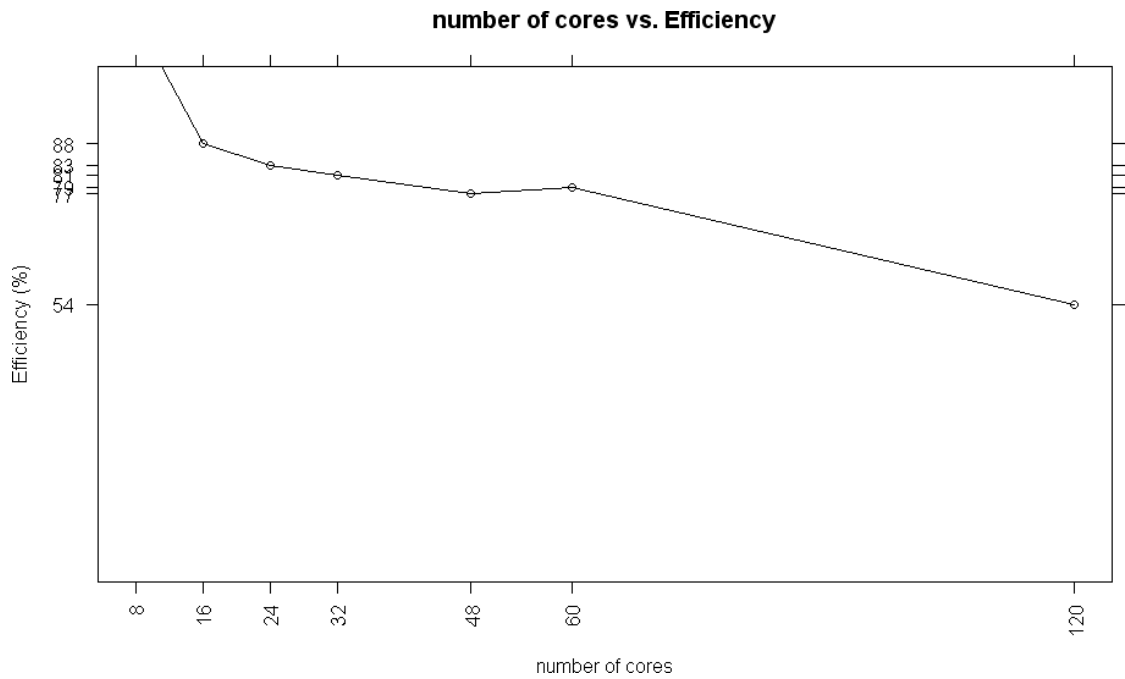


Figure 3.11: Number of cores versus parallel efficiency of WRF

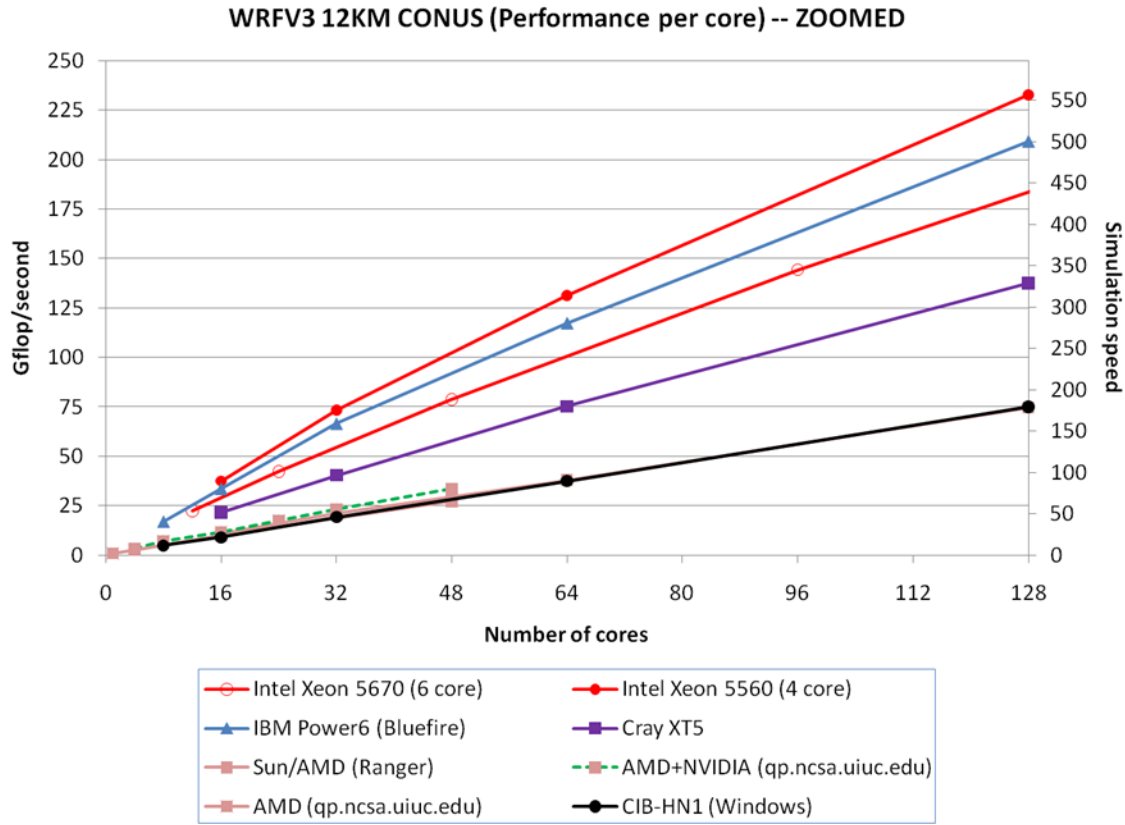


Figure 3.12: An official benchmark result of WRF model on various different architectures

mainly due to the traffic in UYBHM's network and complex physical and dynamical schemes which are not very efficiently parallelized. The official WRF benchmark results are announced at <http://www.mmm.ucar.edu/wrf/WG2/benchv3/> and a sample result is given in Fig. 3.12 In this figure the *simulation speed* parameter was defined as the model time step (60 seconds) divided by average time per time step. Simulation speed is computed for our case and is depicted in Fig. 3.13. This result shows that the performance of WRF on UYBHM is better than the official benchmark results. However fine-tuning the parallel performance of the model requires more performance analysis.

In addition, LFS allows users to configure the stripe sizes and counts for fine-tuning the OSTs for a particular parallel application. Each WRF output file contains a daily output at written at every 3 hours. These files contain 8 chunks that are approximately 43 MB. Therefore LFS stripe count of the model run directory was changed to 8 and stripe size was changed to 43 MB. After these modifications the model run time performance increased by 7.14%.

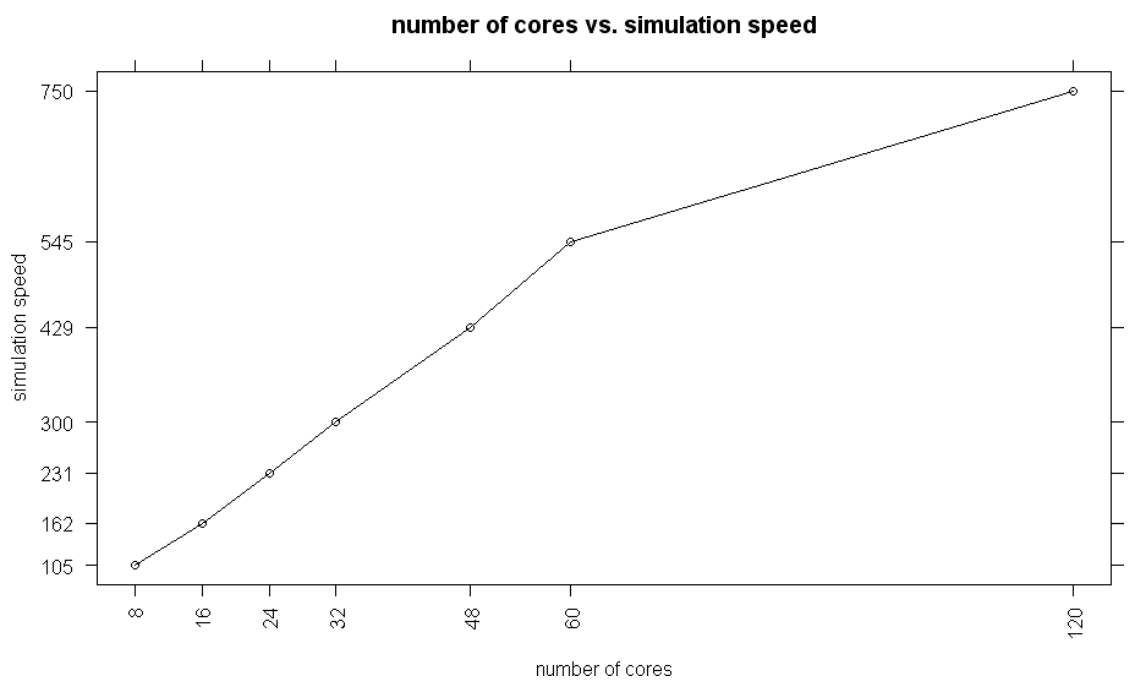


Figure 3.13: Number of cores versus simulation speed of WRF

4. SIMULATION RESULTS

Model performances are tested with respect to observations and meteorological input data. First, large scale fields such as middle and lower atmospheric fields are analyzed to investigate the performances of simulating general flow fields and patterns. The reference data used here is NNRP dataset. Model results and NNRP dataset is seasonally averaged over 61-90 period. Monthly average results are given in the appendix.

Next, two important climate variables, 2 meter temperature and monthly average precipitation, are analyzed both visually and statistically. CRU dataset is used as the reference field. CRU dataset is a monthly average global dataset with a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$. For the statistical computations this dataset was interpolated to the model grids. Both the model results and the CRU dataset is seasonally averaged over 61-90 period. Monthly average results are given in the appendix. The model performance evaluations are based on seasonal and monthly model results.

4.1 Large Scale Fields

4.1.1 500 hPa Field

In winter season the height patterns are very similar in all three cases however RegCM simulates slightly lower heights on the Northern boundary of the domain. WRF generated wind field is consistent with the reanalysis however RegCM is biased towards north-west and south-west on the upper left and lower right parts of the domain respectively. In spring the height distribution is sharper in RegCM whereas there is a better match between WRF and NNRP. RegCM simulated fields illustrate more dominant low heights in the northern side of the domain. The north-west bias in wind field is very clear in the RegCM outputs in addition with the strong south-west wind on the lower left part of the domain. In summer, the bias towards lower heights in RegCM results are again visible. On the other hand, WRF generates greater height values on the southern part and a smooth wind field that is in a better agreement with the NNRP wind field.

500 hPa Geopotential Height and Wind Field

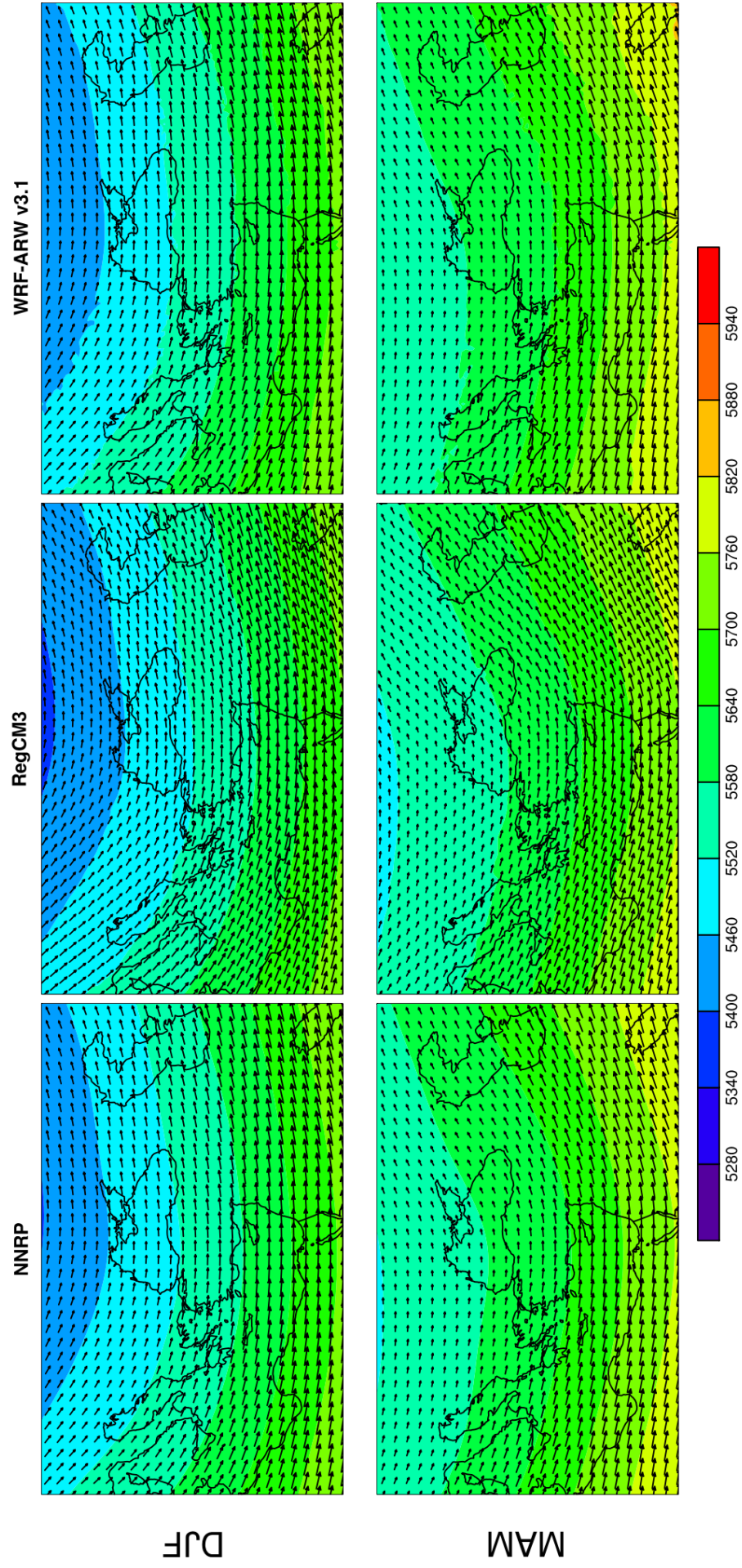


Figure 4.1: 500 hPa geopotential height (gpm) and wind field for winter and spring seasons

500 hPa Geopotential Height and Wind Field

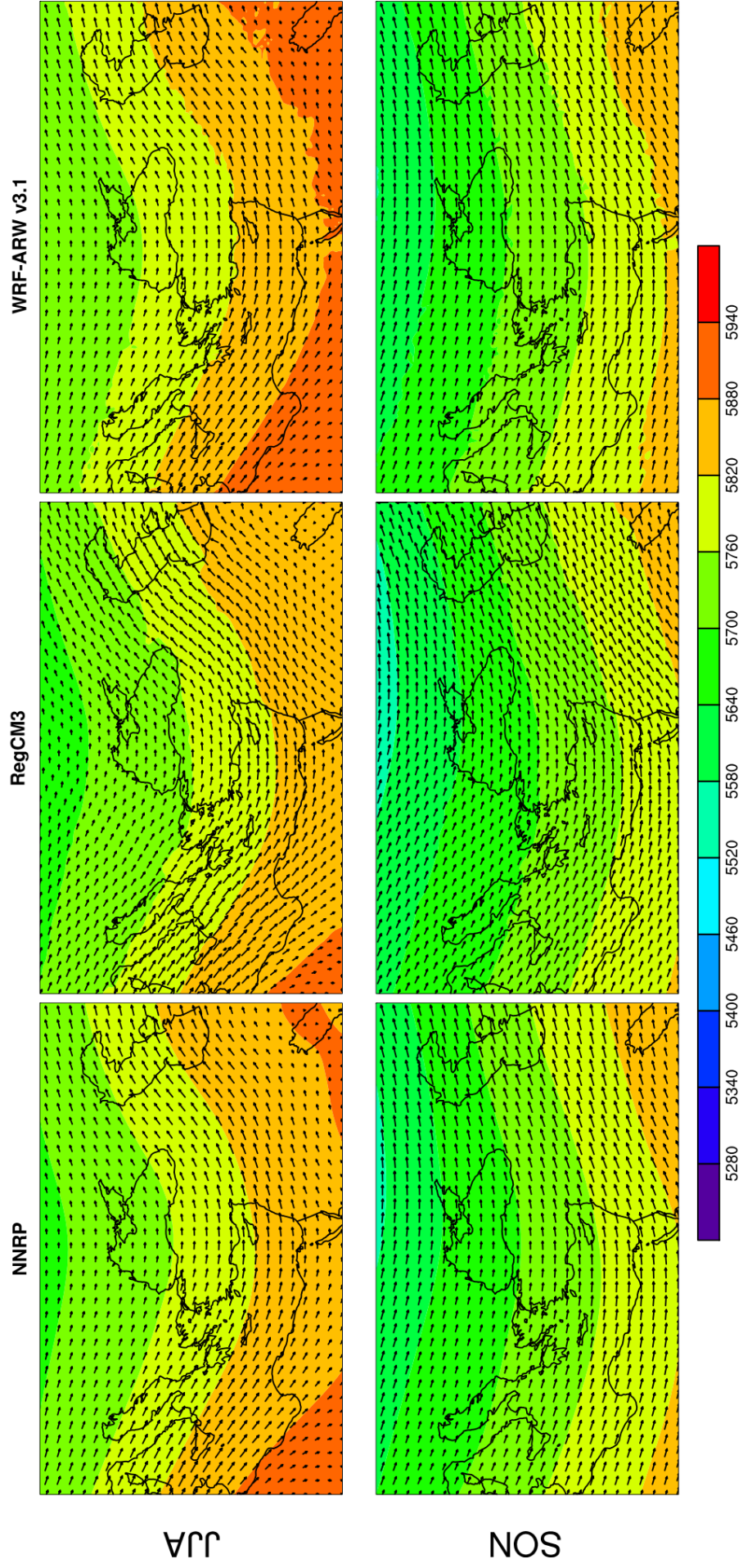


Figure 4.2: 500 hPa geopotential height (gpm) and wind field for summer and autumn seasons

In autumn the low bias in RegCM simulated height field is still very clear with the tendency to cyclonic rotation in the wind field where NNRP and WRF depict a nearly zonal flow.

4.1.2 700 hPa Field

In winter the RegCM simulated height fields are again biased towards the lower values however not as much as in the 500 hPa field. However the wind field is stronger than NNRP and WRF on the boundaries. On the parts on domain where a zonal flow is encountered in NNRP and WRF, RegCM has simulated cyclonic rotations. Also there are some disturbances in the wind field in RegCM outputs over the mountainous parts of the eastern Turkey. In spring the WRF and NNRP agrees on the height patterns whereas RegCM overpredicts the lower height field. RegCM simulates cyclonic flow over where zonal flow in NNRP and WRF. This indicates the bias of the cyclonic circulation in the RegCM dynamic computations. In summer the overprediction of cyclonic system extends over the whole domain in RegCM outputs. The anticyclonic circulation on the southern boundary matches both in WRF, RegCM, and NNRP; however RegCM simulates greater gradients in the wind field. Also the strong north-west winds on the top boundary is very apparent in RegCM results. WRF and NNRP are in much better agreement in the wind field. In autumn both the wind and height fields match in NNRP and WRF. RegCM on the other hand, still has sharp gradients especially between the cyclonic and anticyclonic patterns. However the dominance of the cyclonic system is not as much as in the previous seasons.

700 hPa Geopotential Height and Wind Field

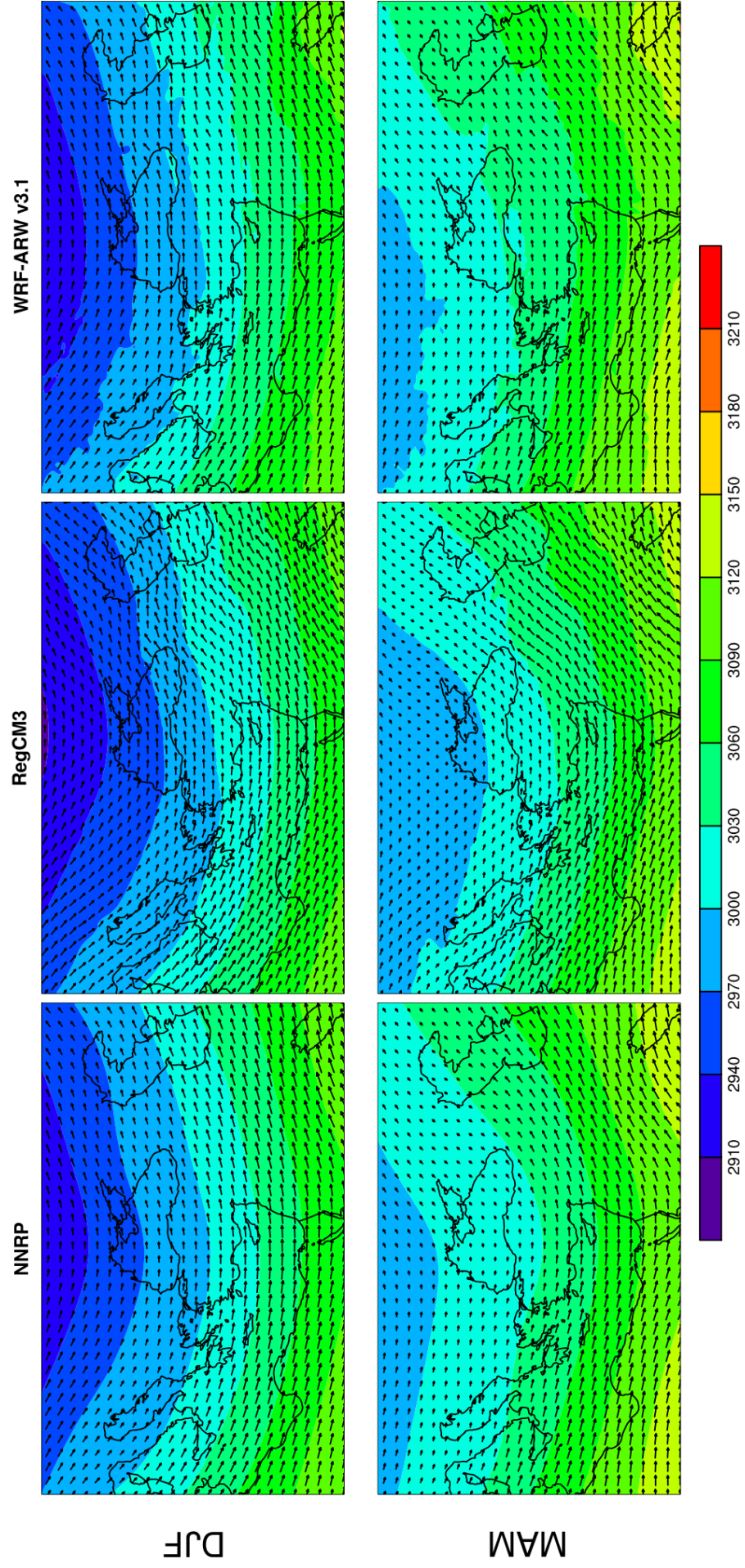


Figure 4.3: 700 hPa geopotential height (gpm) and wind field for winter and spring seasons

700 hPa Geopotential Height and Wind Field

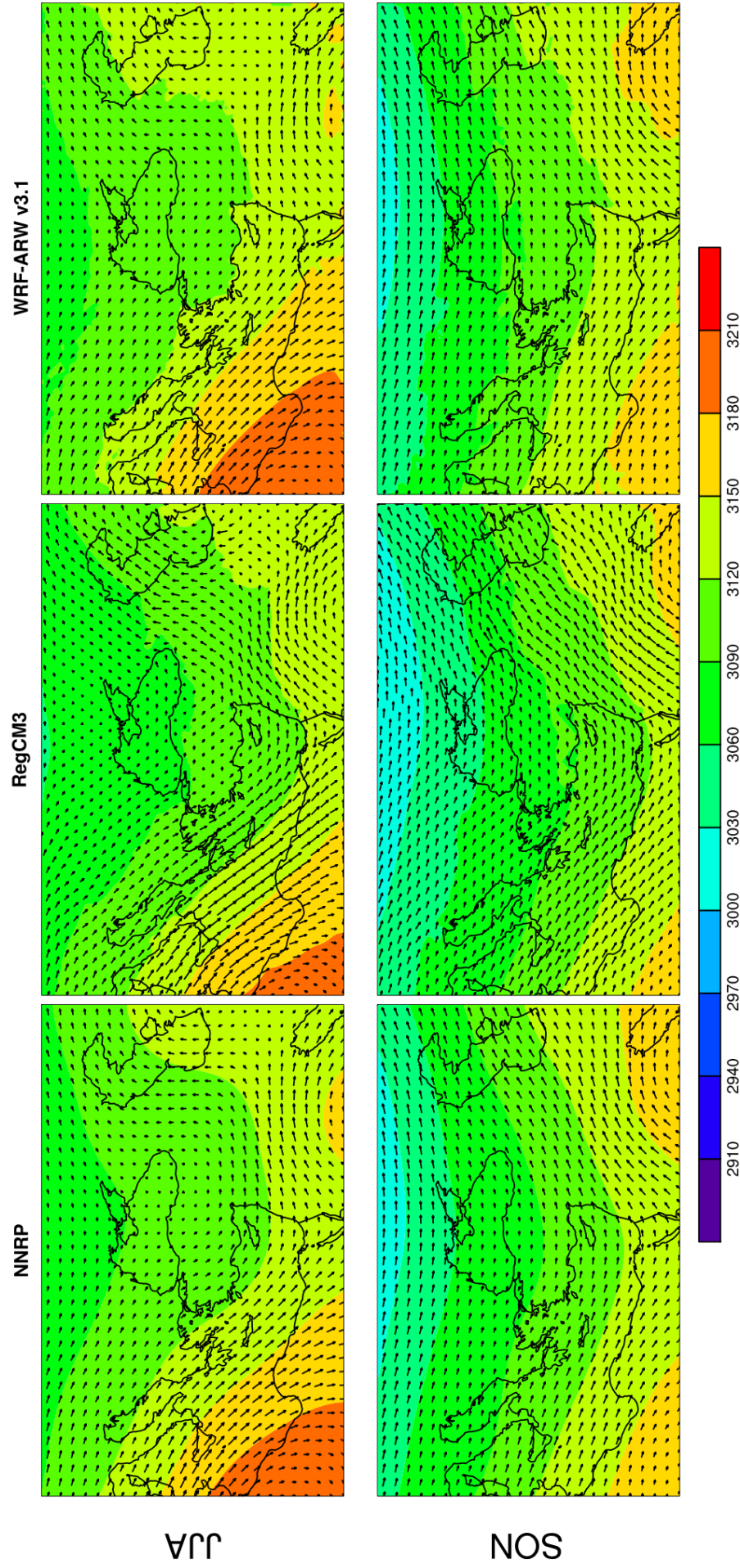


Figure 4.4: 700 hPa geopotential height (gpm) and wind field for summer and autumn seasons

4.1.3 850 hPa Field

In all seasons RegCM simulates a very strong wind field over Mediterranean Sea. WRF simulated wind fields match better with the reanalysis data. WRF can generate circulation patterns over the regions where RegCM generates large wind velocities in a single direction. The geopotential height fields of both models are in a better agreement. In summer RegCM underestimated the pattern of the geopotential height field simulated northerly wind flow over Black Sea. Similar but weaker flow pattern is also present in WRF results. The same high geopotential field over Africa is better simulated by WRF in autumn. In autumn both models simulated lower height over the northern part of the domain and a related flow pattern while a zonal flow is seen in the reanalysis.

4.1.4 Sea Level Pressure and Surface Winds

In surface level the models are more correlated within each other. In winter WRF simulates lower pressure values over Europe especially over mountainous areas. WRF also simulates a weak anticyclonic circulation over south east. RegCM has outflowing wind field over the bottom boundary which is not seen in NNRP or WRF. In spring the all fields are very similar in addition to stronger wind field in RegCM results. In summer both models simulate the strong wind patterns over the Aegean Sea. Models also simulate northerly flow over the top boundary where it is not seen in NNRP. In autumn the wind patterns of WRF and RegCM agree with each other. RegCM simulates higher pressure values over Europe.

850 hPa Geopotential Height and Wind Field

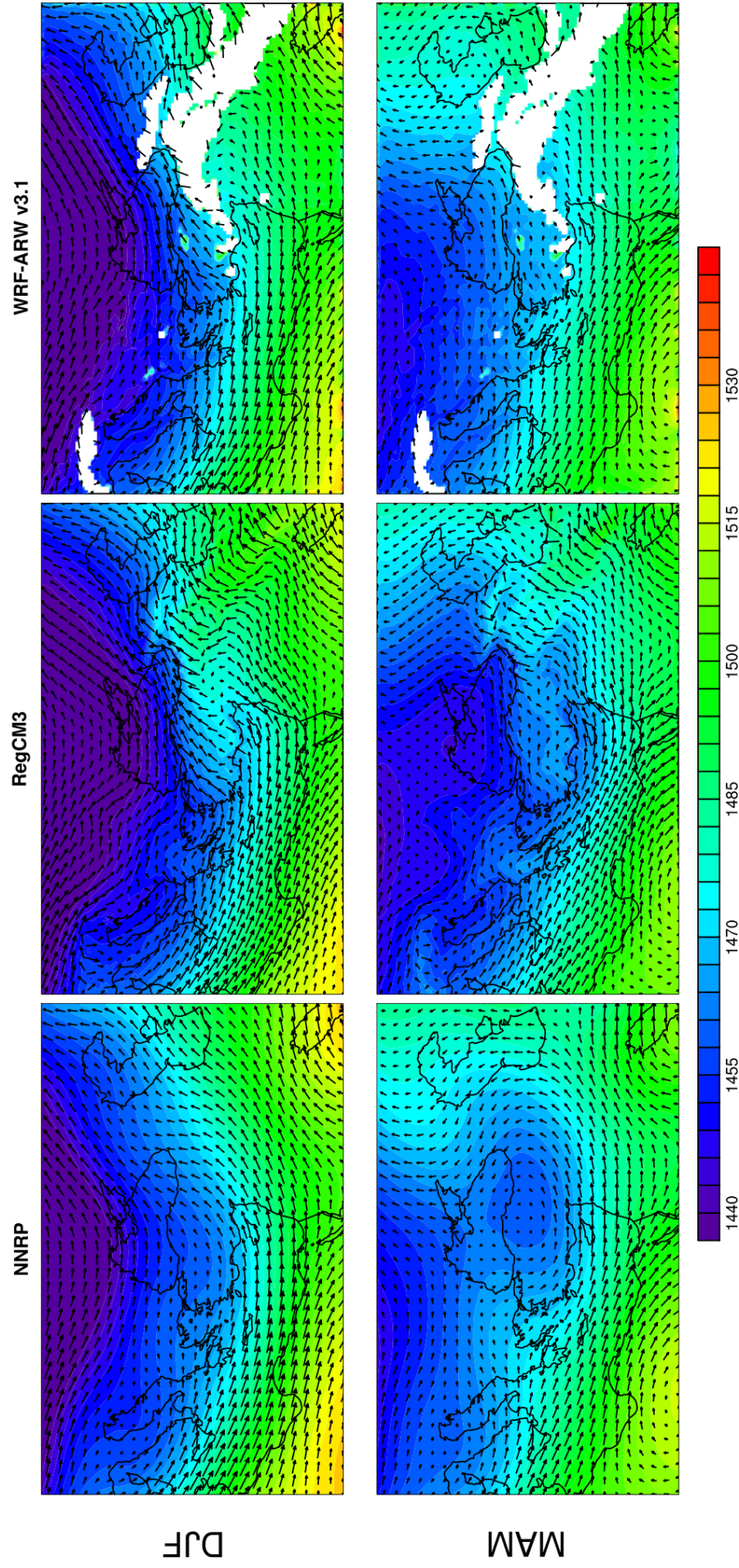


Figure 4.5: 850 hPa geopotential height (gpm) and wind field for winter and spring seasons

850 hPa Geopotential Height and Wind Field

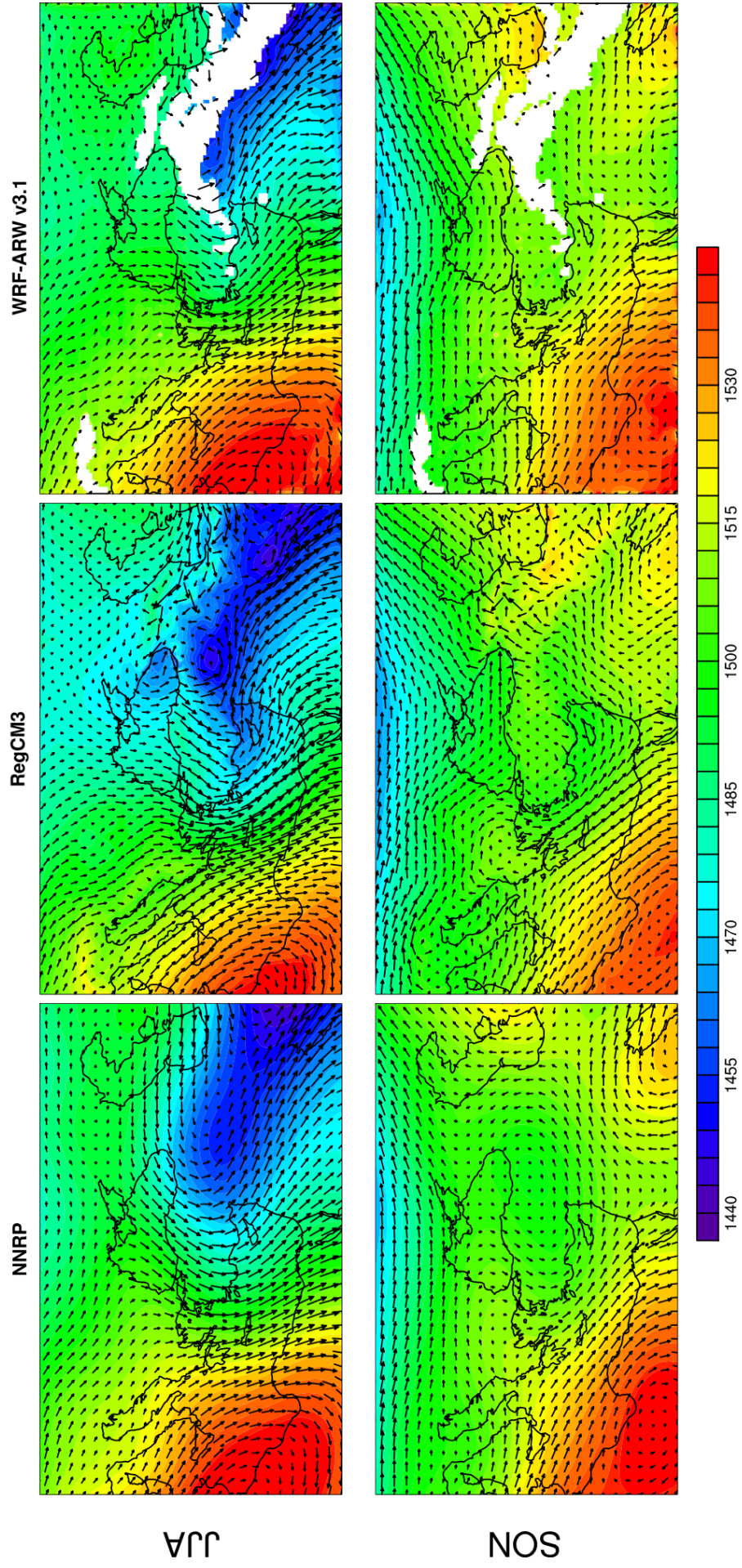


Figure 4.6: 850 hPa geopotential height (gpm) and wind field for summer and autumn seasons

10 m Wind Field and SLP

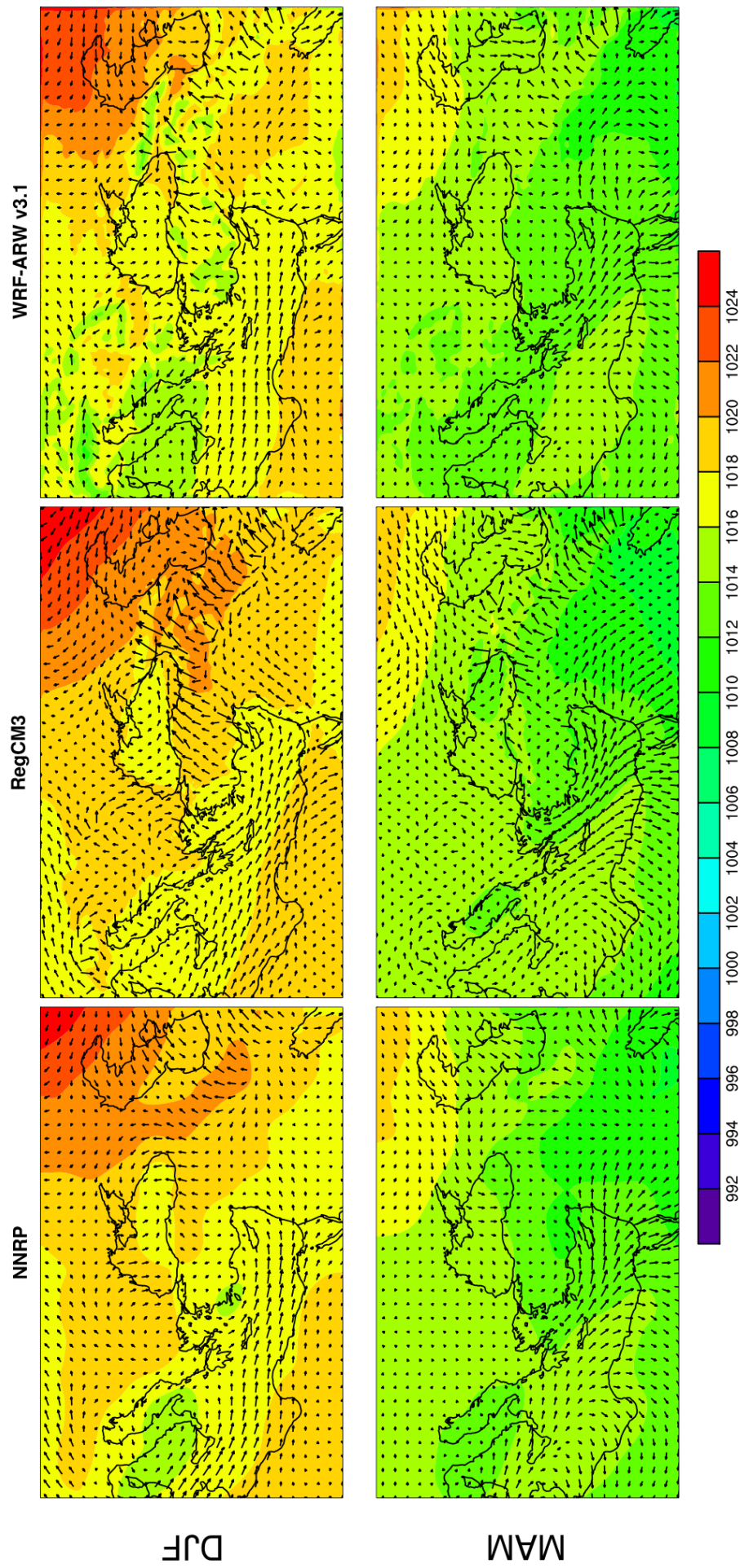


Figure 4.7: Surface field for winter and spring seasons

10 m Wind Field and SLP

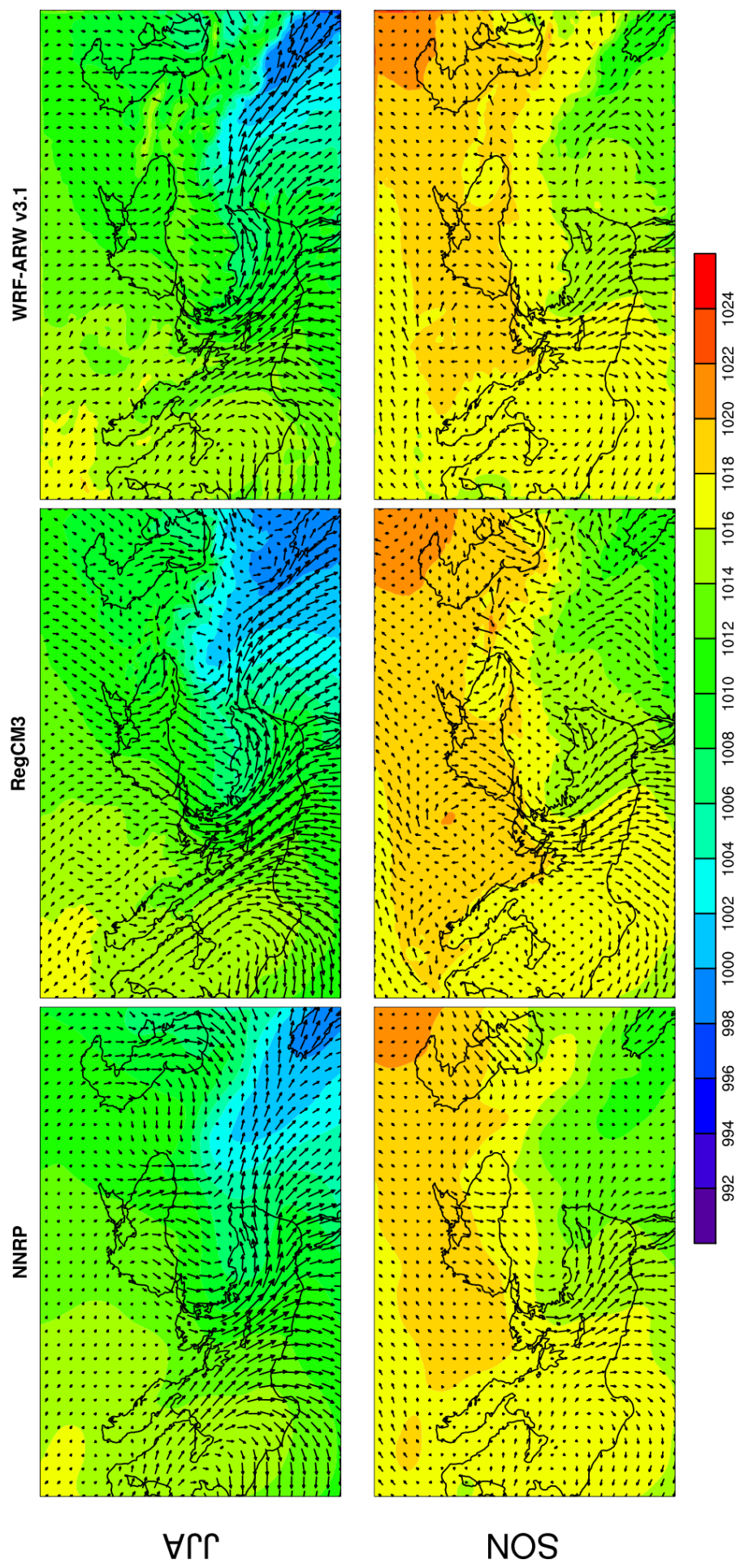


Figure 4.8: Surface field for summer and autumn seasons

4.2 Climate Variables

4.2.1 2 Meter Temperature Field

In all seasons WRF simulates colder temperatures over mountainous regions. On account of the higher resolution geographical data used in WRF runs, it can represent the complex terrain over Turkey better than RegCM. RegCM also simulates higher bias over Northern Africa. Over the seas both models simulated nearly the same temperature values and distributions. WRF generally has a cold bias with respect to RegCM simulations.

4.2.2 Monthly Mean Precipitation

Precipitation is the most difficult climate variable to be successfully simulated. Both models simulate higher precipitation values over Europe and steep orography. WRF simulated precipitation distribution seems to be smoother than the RegCM simulated distributions. WRF generates unrealistic values near the boundaries, especially on the northern boundary but since these are the buffer zones, they can be neglected. Over north eastern part of Turkey and southern part of the Caspian Sea, RegCM generates higher precipitation values.

Surface Temperature [C]

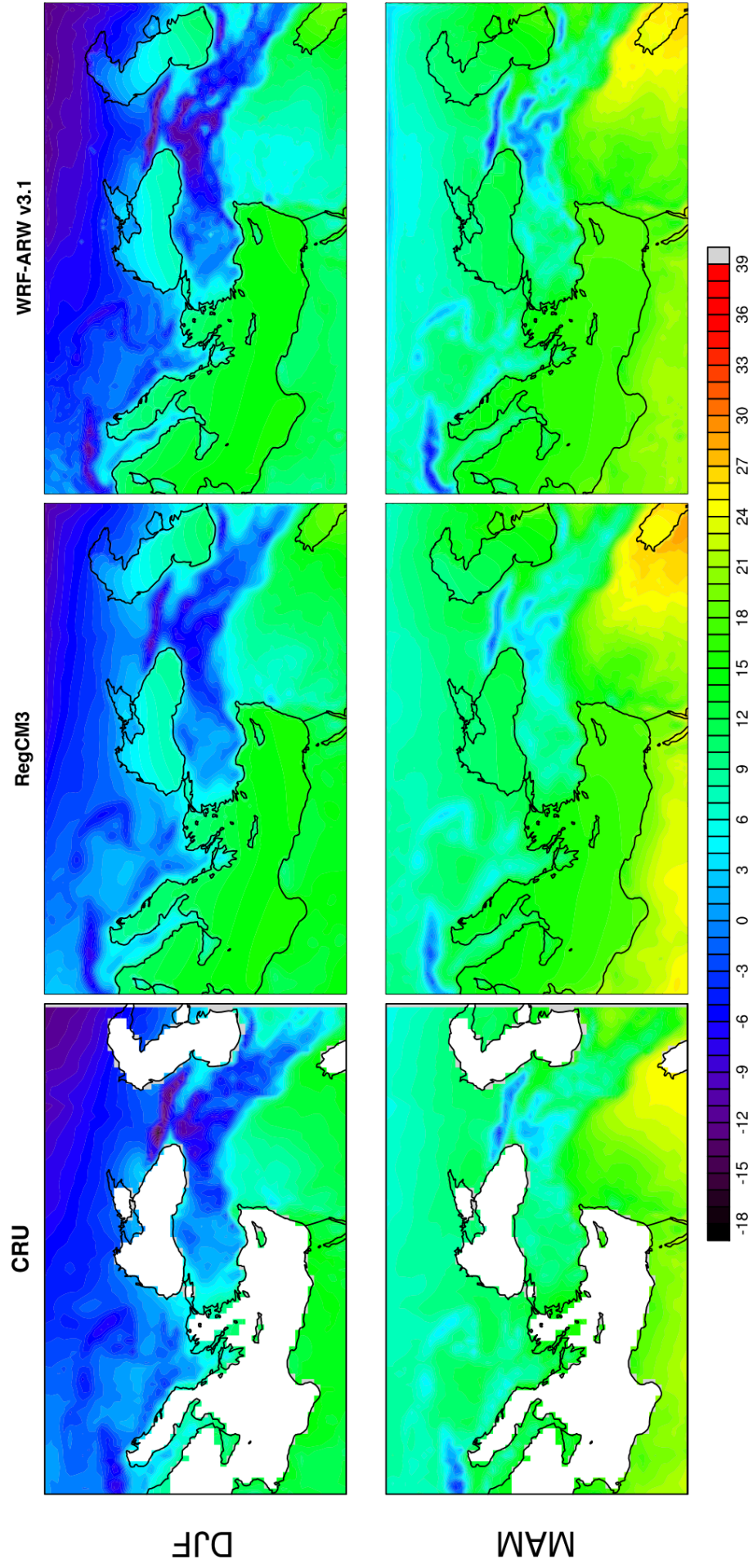


Figure 4.9: 2 Meter temperature field (°C) for winter and spring seasons

Surface Temperature [C]

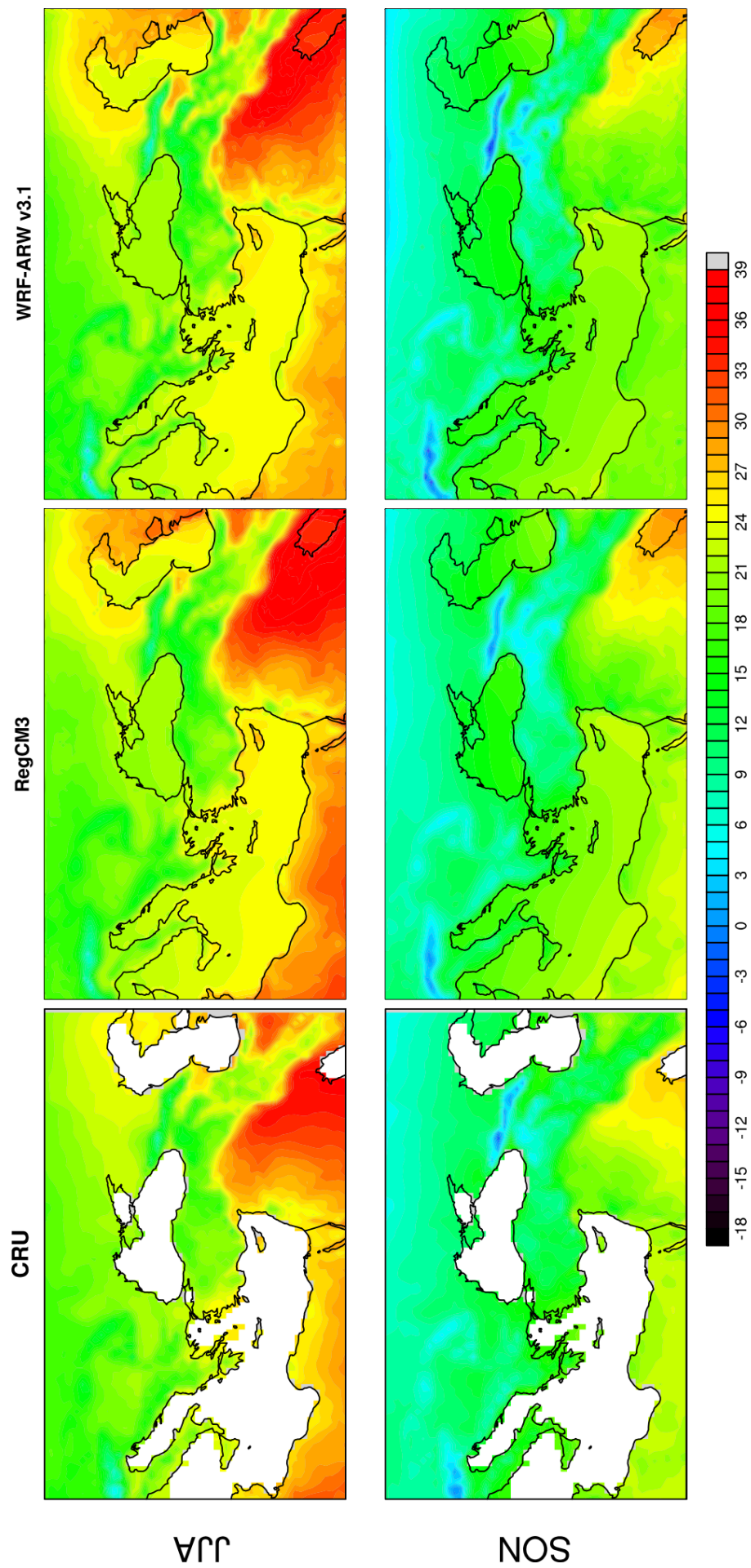


Figure 4.10: 2 Meter temperature field ($^{\circ}\text{C}$) for summer and autumn seasons

Monthly Precipitation [mm/day]

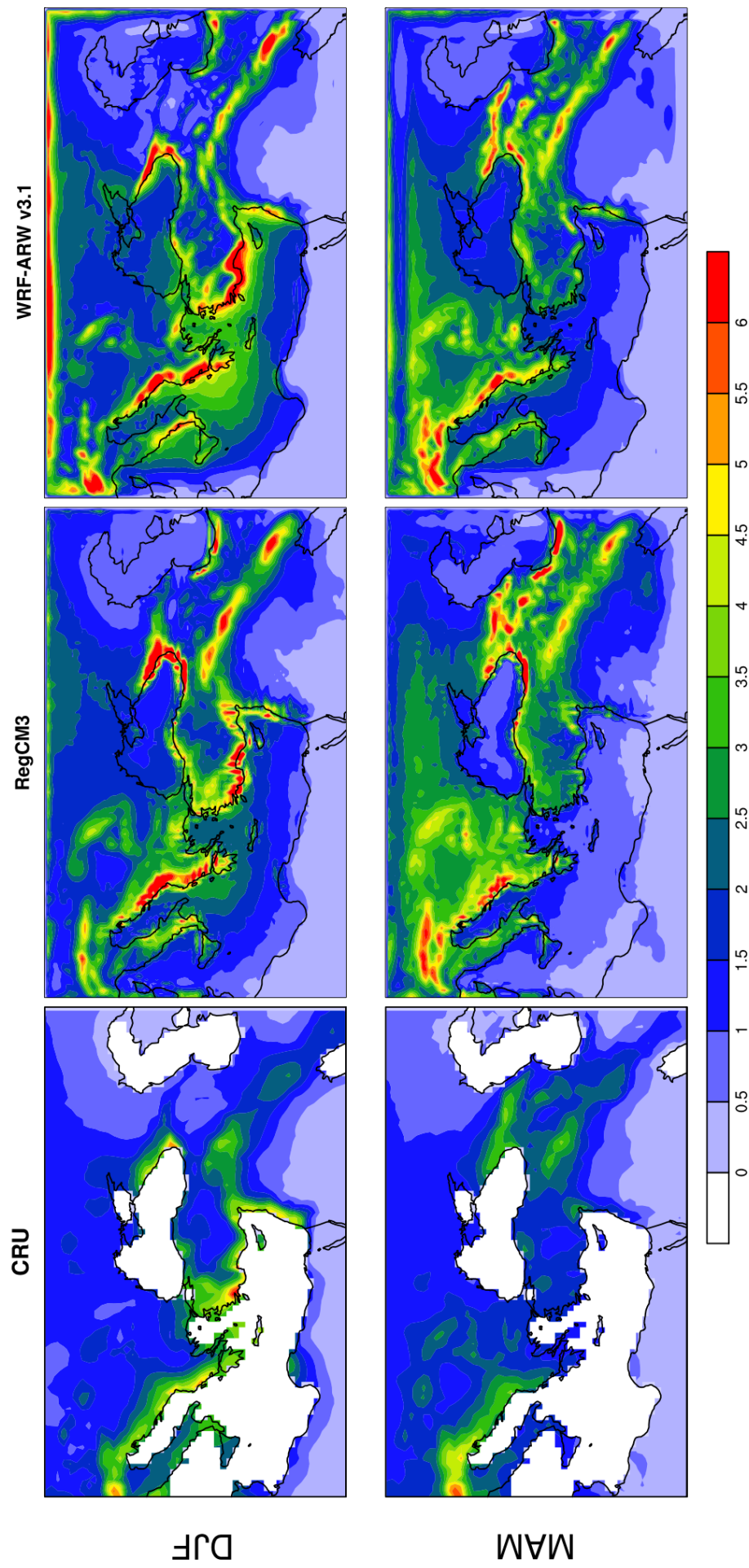


Figure 4.11: Monthly mean precipitation distribution (mm/day) for winter and spring seasons

Monthly Precipitation [mm/day]

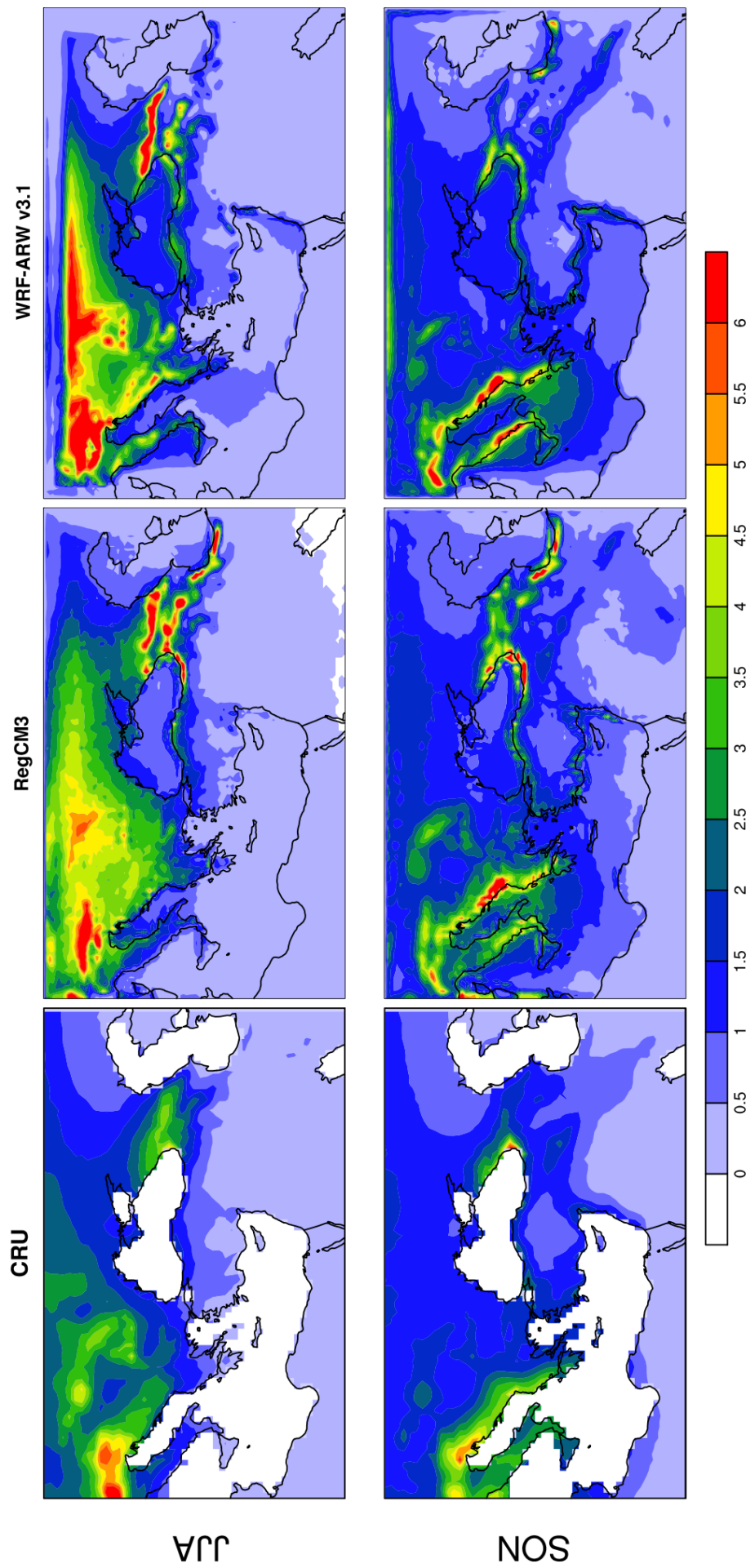


Figure 4.12: Monthly mean precipitation distribution (mm/day) for summer and autumn seasons

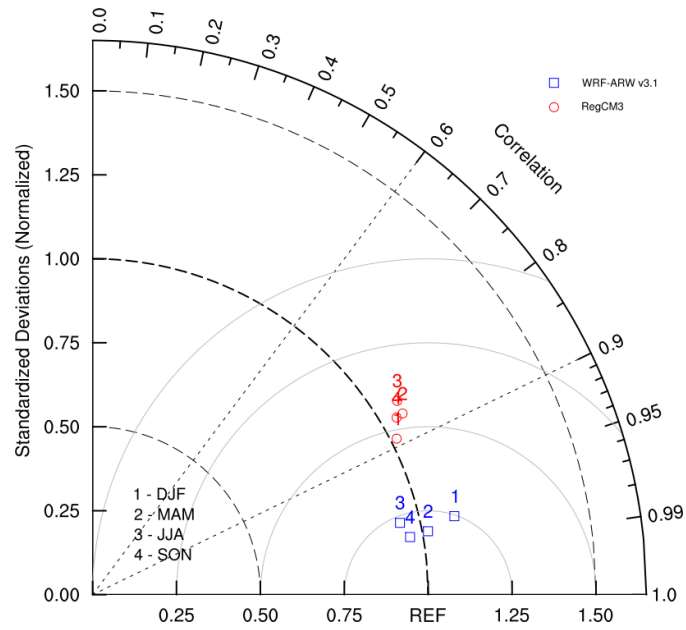


Figure 4.13: Taylor diagram of the precipitation distribution for winter and spring seasons

4.2.3 Statistical Analysis

In the following Taylor diagrams, pattern correlation, standard deviation, and root mean square error (RMSE) are depicted. Both models are tested against CRU observations as in the previous plots. The results for the surface temperature shows that WRF is spatially better correlated with lower RMSE than RegCM however their standard deviations are very similar. RegCM exhibits greater variation in summer where it has a warm temperature bias.

WRF is in a better agreement in precipitation distributions than RegCM in all months. In all months WRF has a better correlation and lower RMSE values. The deviations for winter and summer are very close but especially in spring RegCM has larger deviations

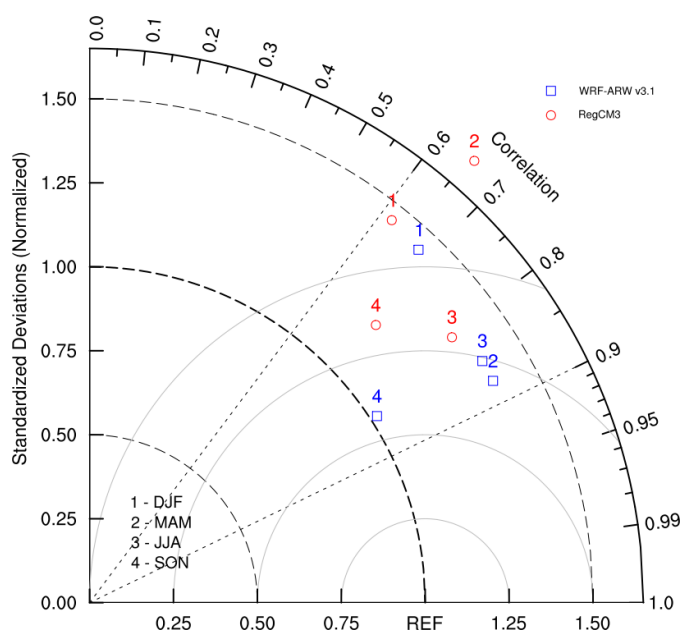


Figure 4.14: Taylor diagram of the precipitation distribution for summer and autumn seasons

5. CONCLUSION AND FURTHER STUDIES

5.1 Conclusion

In this study we compared two important regional models on the EM domain. Due to the duration of the simulation period and choice of the domain, this study is expected to provide a road map to future studies. Model results show that WRF simulations are better than RegCM simulations especially over complex terrain. Statistical comparisons show that the spatial correlation of WRF simulated fields match better with the observations than of RegCM's. These results conclude that WRF model is adequate for regional climate studies and it can be used for further studies. The following sections briefly summarizes some possible improvements and further studies.

5.2 Further Studies

5.2.1 Data Sets

For long term regional climate studies the performance of the LAM is very strongly dependent of the LBC. A further study could investigate the performance of these models using a higher resolution meteorological dataset such as ERA-40 and ERA-Interim. On the other hand, monthly SST dataset can be replaced by a higher resolution dataset such as weekly OISST dataset.

Similar rules also apply to observational dataset which is used to compute the validity of the models. High resolution observations from state meteorological service can be used for a more detailed validation. Another interesting outcome is the performance of WRF over steep mountainous regions. Since the observation dataset is not very reliable over these regions, mountain station data should be used to validate the performance of WRF.

5.2.2 Couple Model Applications

Couple model applications provide a better representation to the climate system and recent studies incorporate couple model applications even more with the advances in the computational power. Both RegCM and WRF has been run with ocean models. WRF has a very sophisticated coupling mechanism and it can be run be several different ocean models. Application of a coupled system is expected to give very interesting outcomes about the air sea interaction in Mediterranean region.

5.2.3 Nesting

Using a nested domain with a resolution of 9 km can help us to generate a high resolution climatology which is require in many areas such as agricultural studies. Horizontal resolutions such as 9 km is not applicable with RegCM because of its hydrostatic limitations. The advanced dynamical core of WRF enables it to be successfully applied to horizontal resolutions even below 1 km. In addition it provides more complex nesting techniques such as two-way nesting. Two-way nesting provides an interactive two-way data flow between coarse and fine domains but it is computationally more expensive than one-way nesting. A sensitivity analysis can be performed to compare the model results for one-way and two-way nesting.

5.2.4 Sensitivity Analysis

In every version new set of physics parameterizations are added to models. These new packages have to be tested for a better regionalization of the models to our domain. However, due to the number of physics packages the are many different combinations and the validation is not a trivial process.

5.2.5 Model Modifications for Climate Modeling

Both RegCM and WRF are open-source, community models. They can be further modified for a better performance or new physics schemes can be embedded. A possible study could be the improvement of the LBC scheme of WRF since especially in simulation of the precipitation it generates unrealistic distributions near the boundaries.

5.2.6 Climate Projections

One of the most important goals of using LAMs in climate modeling is climate projections and climate change scenarios. RegCM has been applied simulate the future climates of the world under various emission scenarios and with different GCMs. Similar studies has to be performed with WRF since its performance is found to be satisfactory in regional climate modeling.

5.2.7 Computational Studies

In addition, UYBHM system contains a NVIDIA Tesla GPU systems that consists of 1920 core in total, having a peak performance at 4.14 TFlops. This GPU system can also be activated to examine the GPU acceleration of WRF. A further study could also investigate the parallel performance of WRF by using the advanced profiling tools available at UYBHM. Parallel profiling is an important analysis method for finding the bottlenecks and hotspots in parallel programs.

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6. APPENDICES

Appendix A : WRF Model Configuration Files

Appendix B : RegCM Model Configuration Files

Appendix C : SST Preprocessor for WRF (gisst2wrf)

Appendix D : WRF Code Modifications

Appendix E : 1961-1990 Monthly Model Outputs

APPENDIX A

namelist.wps – domain configuration file

```
&share
  wrf_core = 'ARW',
  max_dom = 1,
  start_date = '1960-01-01_00:00:00',
  end_date   = '1990-12-31_00:00:00',
  interval_seconds = 21600
  io_form_geogrid = 2,
/

&geogrid
  parent_id          = 1,
  parent_grid_ratio  = 1,
  i_parent_start     = 1,
  j_parent_start     = 1,
  e_we              = 144,
  e_sn              = 100,
  geog_data_res      = '30s',
  dx = 27000,
  dy = 27000,
  map_proj = 'lambert',
  ref_lat  = 40.00,
  ref_lon  = 32.00,
  truelat1 = 30.0,
  truelat2 = 60.0,
  stand_lon = 32.0,
  geog_data_path = '/AKDENIZ/HOME005/users/doktk.ural/rs/WRF_TEZ/geog'
/

&ungrib
  out_format = 'WPS',
  prefix = 'NNRP_2D',
/

&metgrid
  fg_name = 'NNRP_2D', 'NNRP_3D', 'SST'
  io_form_metgrid = 2,
/
```

namelist.input – model run-time options file

```

&time_control
run_days              = 11322,
run_hours             = 0,
run_minutes           = 0,
run_seconds           = 0,
start_year            = 1960,
start_month           = 01,
start_day             = 01,
start_hour            = 00,
start_minute          = 00,
start_second          = 00,
end_year              = 1990,
end_month             = 12,
end_day               = 31,
end_hour              = 00,
end_minute            = 00,
end_second            = 00,
interval_seconds      = 21600
input_from_file       = .true.,
history_interval      = 180,
frames_per_outfile    = 8,
restart               = .false.,
restart_interval      = 10080,
io_form_history       = 2,
io_form_restart      = 2,
io_form_input         = 2,
io_form_boundary      = 2,
debug_level           = 0,
auxinput4_inname      = "wrflowinp_d<domain>",
auxinput4_interval    = 360,
io_form_auxinput4     = 2,
/

&domains
nproc_x               = -1,
nproc_y               = -1,
time_step             = 60,
time_step_fract_num   = 0,
time_step_fract_den   = 1,
max_dom               = 1,
e_we                  = 144,
e_sn                  = 100,
e_vert                = 35,
p_top_requested       = 1000,
num_metgrid_levels    = 18,
num_metgrid_soil_levels = 2,
dx                    = 27000,
dy                    = 27000,
grid_id               = 1,
parent_id             = 0,
i_parent_start        = 1,
j_parent_start        = 1,
parent_grid_ratio      = 1,
parent_time_step_ratio = 1,
feedback              = 1,
smooth_option         = 0,
use_adaptive_time_step = .true.,
step_to_output_time   = .true.,
target_cfl            = 1.2
max_step_increase_pct = 5
starting_time_step    = 60
min_time_step         = 10
max_time_step         = 60
/

&physics
mp_physics            = 6,
ra_lw_physics         = 3,
ra_sw_physics         = 3,
levsiz                = 59,
paerlev               = 29,
cam_abs_dim1          = 4,
cam_abs_dim2          = 35,

```

```

radt                                = 30,
sf_sfclay_physics                   = 1,
sf_surface_physics                   = 2,
bl_pbl_physics                       = 1,
bldt                                = 0,
cu_physics                           = 5,
cudt                                = 5,
isfflx                               = 1,
ifsnow                               = 0,
sst_skin                             = 1,
sst_update                           = 1,
bucket_mm                            = 100,
bucket_J                             = 1.e9,
tmn_update                           = 1,
icloud                               = 1,
surface_input_source                 = 1,
num_soil_layers                      = 4,
sf_urban_physics                     = 0,
maxiens                              = 1,
maxens                               = 3,
maxens2                              = 3,
maxens3                              = 16,
ensdim                               = 144,
/

&fdda
/

&dynamics
w_damping                           = 0,
diff_opt                             = 1,
km_opt                               = 4,
diff_6th_opt                         = 0,
diff_6th_factor                      = 0.12,
base_temp                            = 290.,
damp_opt                             = 0,
zdamp                                = 5000.,
gwd_opt                              = 1,
dampcoef                             = 0.2,
khdif                                = 0,
kvdif                                = 0,
non_hydrostatic                      = .true.,
moist_adv_opt                        = 1,
scalar_adv_opt                       = 1,
/

&bdy_control
spec_bdy_width                       = 10,
spec_zone                            = 1,
relax_zone                           = 9,
specified                            = .true.,
spec_exp                             = 0.33
nested                               = .false.,
/

&grib2
/

&namelist_quilt
nio_tasks_per_group = 0,
nio_groups = 1,
/

```


APPENDIX B

domain.param – domain configuration file

```

c
c the following parameter must be given for the model domain settings.
c
    character*6 iproj ! Map projection choice,
c                      iproj='LAMCON', Lambert conformal
c                      iproj='POLSTR', Polar stereographic
c                      iproj='NORMER', Normal Mercator (ROTMER w/ plat=0)
c                      iproj='ROTMER', Rotated Mercator
    integer iy          ! number of grid points in y direction (i)
    integer jx          ! number of grid points in x direction (j)
    integer kz          ! number of vertical levels (k), 18, 14, or 23
    integer nsq         ! number of subgrid in x (y) direction
    real ds             ! grid point separation in km
    real ptop           ! pressure of model top in cb.
    real clat           ! Central latitude of model domain in degrees,
c                      (north hemisphere, positive)
    real clon           ! Central longitude of model domain in degrees,
c                      (western hemisphere, negative)
    real plat           ! Pole latitude (only for rotated Mercator Proj)
    real plon           ! Pole longitude (only for rotated Mercator Proj)
    real truelatL       ! Lambert true latitude (low latitude side)
    real truelatH       ! Lambert true latitude (high latitude side)
    integer ntypec       ! which resolution of the global terrain and
c                      landuse data be used,
c                      (ntypec= 60, for 1 degree resolution,
c                      ntypec= 30, for 30 minutes resolution,
c                      ntypec= 10, for 10 minutes resolution,
c                      ntypec= 5, for 5 minutes resolution,
c                      ntypec= 3, for 3 minutes resolution,
c                      ntypec= 2, for 2 minutes resolution)
    integer ntypec_s     ! same as ntypec, except for subgrid.
    real h2opct         ! If the water percentage is less than h2opct, then
c                      ! the gridpoint is considered land. Water if greater.

    logical ifanal       ! TRUE=Perform cressman-type objective analysis
c                      ! FALSE=16-point overlapping parabolic interpolation
    logical smthbdy      ! TRUE=Perform extra smoothing in boundaries
    logical lakadj        ! TRUE=Adjust Great Lakes Levels according to obs

    integer igrads       ! output GrADS control file, 1 Yes (0 No)
    integer ibigend      ! 1 for big-endian binary computer (SUN, SGI, IBM)
c                      ! 0 for little-endian binary computer (PC LINUX, DEC)
c                      ! Note: After you use '-byteswapio' or
c                      ! '-convert big_endian' compiler option,
c                      ! you need set ibigend=1
    integer ibrace       ! For direct access open statements,
c                      ! 1 for SGI, DEC and IFC8
c                      ! 4 for SUN, IBM, PGI and IFC7

    LOGICAL FUDGE_LND    ! Landuse fudge?
    LOGICAL FUDGE_TEX    ! Texture fudge?
    LOGICAL FUDGE_LND_s  ! Landuse fudge? for subgrid
    LOGICAL FUDGE_TEX_s  ! Texture fudge? for subgrid

    character*50 filout  ! Terrain Output filename
    character*50 filctl  ! Grads control filename for output

    integer IDATE1       ! begining date of your experiments
    integer IDATE2       ! ending date of your experiments
    CHARACTER*6 DATTYP   ! which type of global analysis datasets used,
c 'ECMWF','ERA40','ERAHI','NNRP1','NNRP2','NRP2W','FVGCM','FNEST','EH5OM','EH5OM2'
    CHARACTER*6 SSTYP    ! which type of SST datasets used,
c 'GISST' or 'OISST' or 'OI_WK'
c                      ! GISST means Hadley SST in big_endian binary format.

```

```

c          ! OISST means OISST in netCDF format.
c          ! OI_WK means weekly OISST in netCDF format.
c          ! For 'FVGCM' run, SSTTYP = 'FV_RF' or 'FV_A2'
c          ! 'FV_RF' for the reference run, 1960 - 1990;
c          ! 'FV_A2' for A2 Scenario, 2070 - 2100 run.
c          ! For 'EH5OM' run, SSTTYP = 'EH5RF' or 'EH5A2'
c          ! 'EH5RF' for the reference run, 1950 - 2000;
c          ! 'EH5A2' for A2 Scenario, 2050 -2100 run.
c          ! For other method of ECHAM5 Run
c          ! 'EH5OM2' for A2 and 20C control
CHARACTER*4 LSMTYP ! LANDUSE legend, 'BATS' or 'USGS'
integer nveg      ! number of LANDUSE categories, 20 for BATS, 25 for USGS
CHARACTER*7 AERTYP ! which AEROSOL datasets used,
c          ! 'AER00D0': Neither aerosol, nor dust used;
c          ! 'AER01D0', Biomass, SO2 + BC + OC, no dust;
c          ! 'AER10D0', Anthropogenic, SO2 + BC + OC, no dust;
c          ! 'AER11D0', Anthropogenic+Biomass, SO2 + BC + OC, no dust;
c          ! 'AER00D1', No aerosol , with dust;
c          ! 'AER01D1', Biomass, SO2 + BC + OC, with dust;
c          ! 'AER10D1', Anthropogenic, SO2 + BC + OC, with dust;
c          ! 'AER11D1', Anthropogenic+Biomass, SO2 + BC + OC, with dust.
integer ntex      ! Number of SOIL TEXTURE categories, 17
integer NPROC     ! Number of CPU used for parallel run.
! NPROC=0 if just for serial run;
! NPROC > 0 which will prepare regcm.param for serial run;
! and prepare regcm.param2 for parallel run.

parameter(iproj='LAMCON') ! Map projection (LAMCON,NORMER,POLSTR,ROTMER)
parameter(iy=100)        ! number of grid points in y direction (i)
parameter(jx=144)        ! number of grid points in x direction (j)
parameter(kz=18)         ! number of vertical levels (14, 18 or 23)
parameter(nsg=1)         ! number of subgrids in 1 grid (one direction)
parameter(ds=27.0)       ! grid point separation in km
parameter(ptop= 5.0)     ! pressure of model top in cb.

parameter(clat= 40.00)    ! Central latitude (North positive)
parameter(clon= 32.00)    ! Central longitude (East positive)
parameter(plat=clat)     ! Pole latitude (used for ROTMER)
parameter(plon=clon)     ! Pole longitude (used for ROTMER)
parameter(truelatL= 30.) ! LAMCON true latitude (low latitude side)
parameter(truelatH= 60.) ! LAMCON true latitude (high latitude side)

parameter(ntypec=10)     ! Global topo/landuse data resolution (min)
parameter(ntypec_s=10)   ! Global topo/landuse data resolution (min)
parameter(h2opct=75.)    ! Minimum H2O percent to be considered water

parameter(ifanal=.true.) ! Type of interpolation for topography
parameter(smthbdy=.false.) ! Smoothing of boundaries
parameter(lakadj=.false.) ! Adjust Great Lakes levels (for US domain)
parameter(igrads=1)      ! Output GrADS control file?
parameter(ibigend=1)     ! 1=big-endian; (always 1)
parameter(ibyte=1)       ! For direct access open statements (1 or 4)
parameter(FUDGE_LND=.false.) ! LANDUSE adjustments?
parameter(FUDGE_LND_s=.false.) ! Subgrid LANDUSE adjustments?
parameter(FUDGE_TEX=.false.) ! TEXTURE adjustments?
parameter(FUDGE_TEX_s=.false.) ! Subgrid TEXTURE adjustments?

parameter(filout='../../Input/DOMAIN.INFO') ! Location/name of output
parameter(filctl='../../Input/DOMAIN.CTL') ! Location/name of GrADS ctl

c The following parameters can be reset later in RegCM/ICBC/icbc.param
parameter(IDATE1=1960010100) ! First date of simulation
parameter(IDATE2=1999123118) ! Last date of simulation
! DATYP : (ECMWF,ERA40,ERAHI,NNRP1,NNRP2,FVGCM,FNEST,EH5OM,EH5OM2)
parameter(DATYP='CAM85')
! SSTTYP : (GISST,OISST,OI_WK,FV_RF,FV_A2,FV_B2,EH5RF,EH5A2,EH5OM2)
parameter(SSTTYP='CAM85')
parameter(LSMTYP='BATS') ! LANDUSE legend (BATS or USGS)
parameter(nveg=20)       ! Number of LANDUSE categories
! 20 for BATS, 25 for USGS.
parameter(AERTYP='AER00D0') ! AEROSOL TYPE option,
parameter(ntex=17)        ! Number of SOIL TEXTURE categories
parameter(NPROC=36)       ! Number of CPU used for parallel job.

```

regcm.in – model run-time options file

```
$restartparam
ifrest  = .true.,
idate0  = 1960010100,
idate1  = 1961010100,
idate2  = 1990123118,
nslice  =      120,
$
$timeparam
radfrq  =      30.,
abemh   =      18.,
abatm   =     240.,
dt       =      60.,
ibdyfrq =        6,
$
$outparam
ifsave  = .true. ,
savfrq  =     48.,
iftape  = .true. ,
tapfrq  =      6.,
ifrad   = .true. ,
radisp  =      6.,
ifbat   = .true. ,
ifsub   = .true. ,
batfrq  =      3.,
ifprt   = .false.,
prtfrq  =     12.,
kxout   =        6,
jxsex   =       40,
iotyp   =        1,
ibintyp =        1,
ifchem  = .true. ,
chemfrq =      6.,
$
$physicsparam
iboudy  =        5,
ibltyp  =        1,
icup    =        2,
igcc    =        2,
ipptls  =        1,
iocnflx =        2,
ipgf    =        0,
lakemod =        0,
ichem   =        0,
$
$subexparam
ncld    =  3,
qcklland = 0.00025,
qckloce = 0.00025,
cevap   = 1.0e-3,
caccr   = 3.0,
$
$grellparam
$
$emanparam
$
$chemparam
idirect  =  2,
chtrname = 'SO2',
chtrsol  =  0.20,
chtrdpv  = 0.00300,0.00800,
dustbsiz = 0.01, 1.00,
$
```


APPENDIX C

gisst2wrf.f90 – main program

```
!*****
! -FILE: gisst2wrf.f90
! -AUTHOR: Deniz URAL, ITU Informatics Institute , Computational Science and
!           Engineering Department
! -DATE: 27 May 2010
! -DESCRIPTION:
! -USAGE: gisst2wrf <gisst_nc_file>
!           -gisst_nc_file: path to GISST netcdf file
!*****
program gisst2wrf
  use utility !! utility functions and subroutines
  use netcdf
  implicit none

  ! Variable declarations
  integer, parameter :: MAX_FNAME_SIZE = 128 ! maximum permitted file name length
  character(len=MAX_FNAME_SIZE) :: gisst_nc_file
  integer :: gisst_nc_id ! ID of the GISST NetCDF file
  character(len=*,parameter) :: PREFIX = "SST" !! file prefix
  integer, parameter :: DT = 6 !! time interval, 6 hours
  integer :: fname_size ! actual length of the file name
  character(len=MAX_FNAME_SIZE) :: wps_fname ! name of the WPS intermediate file
  integer, parameter :: NDIMS = 4
  ! dimensions of the data
  integer, parameter :: NLON=360, NLAT=180, NLEV=1, NT=79992
  ! # of elements to be read in each dim
  integer, dimension(NDIMS), parameter :: COUNTS = (/ NLON, NLAT, 1, 1 /)
  ! starting indexes in each direction
  integer, dimension(NDIMS) :: starts = (/ 1, 1, 1, 1 /)
  character(len=24) :: hdate ! date in the YYYY:MM:DD_HH:00:00 format
  integer, parameter :: TIME_DIM = 4 ! Time is the 4th dimension of the data

  ! constants, start dates
  integer, parameter :: YEAR_S = 1947
  integer, parameter :: MONTH_S = 12
  integer, parameter :: DAY_S = 01
  integer, parameter :: HOUR_S = 0

  ! constants, end dates
  integer, parameter :: YEAR_E = 2002
  integer, parameter :: MONTH_E = 9
  integer, parameter :: DAY_E = 1
  integer, parameter :: HOUR_E = 0

  ! current dates and their initialization
  integer :: year = YEAR_S
  integer :: month = MONTH_S
  integer :: day = DAY_S
  integer :: hour = HOUR_S

  integer :: i, argc, ierr
  integer :: n, m

  real, dimension(:,,:), allocatable :: data_2d ! 2D data to be written
  allocate(data_2d(NLON,NLAT), stat=ierr)
  if (ierr /= 0) then
    print *, "ERROR: Cannot allocate data, Aborting"
    stop
  end if

  ! Check command line arguments
  argc = command_argument_count()
  if (argc /= 1) then
    print *, "ERROR: Usage: gisst2wrf <gisst_nc_file>"
  end if
```

```

        print *, "          -gisst_nc_file: path to GISST netcdf file"
    stop
end if

! get the netcdf gisst filename from cmd line
call get_command_argument(1, gisst_nc_file)

! get the actual length of the WPS file name
fname_size = len(PREFIX) + len(":YYYY-MM-DD_HH")
if (fname_size > MAX_FNAME_SIZE) then
    print *, "ERROR: length of the file name exceeds MAX_FNAME_SIZE."
    stop
end if

! Open the GISST NetCDF file
call check( nf90_open(gisst_nc_file, NF90_NOWRITE, gisst_nc_id) )
print *, "Opened GISST NetCDF file ", gisst_nc_file

! Begin main time loop, loop through all time available in the file ,
! increment by 6 hours
do i = 1, NT
    ! Construct name of the WPS intermediate file in PREFIX:YYYY-MM-DD_HH format
    call make_fname(PREFIX, year, month, day, hour, wps_fname)

    ! Construct hdate in the YYYY:MM:DD_HH:00:00 format
    call make_hdate(year, month, day, hour, hdate)
    !print *, "Fname: ", wps_fname(:fname_size), "date: ", hdate
    starts(TIME_DIM) = i
    call read_data_2d(gisst_nc_id, "sst", data_2d, NLON, NLAT, starts, COUNTS)
    call write_intermediate(wps_fname(:fname_size), hdate, data_2d)

    !! Construct the next date in YYYY-MM-DD-HH
    if (hour < 24-DT) then
        hour = hour + DT
    else
        hour = hour + DT - 24
        if (day < number_of_days(month,year)) then
            day = day + 1
        else
            day = 1
            if (month < 12) then
                month = month + 1
            else
                month = 1
                year = year + 1
            end if
        end if
    end if
end if
end do ! end of time loop

! Clean up, deallocate arrays and close opened files
deallocate(data_2d)
call check( nf90_close(gisst_nc_id) )
print *, "Closed GISST NetCDF file ", gisst_nc_file

end program gisst2wrf
!!! End of Main Program !!!

```

utility.f90 – utility functions

```

!*****
! -FILE: utility.f90
! -AUTHOR: Deniz URAL, ITU Informatics Institute , Computational Science and
!           Engineering Department
! -DATE: 27 May 2010
! -DESCRIPTION: contains utility functions and subroutines for gisst2wrf
!*****
module utility
!   use netcdf
!   public ndigits , int_to_char , number_of_days , make_fname
contains

!-----
! subroutine check(status)
! => wraps all calls to NetCDF procedures for error handling
! - status: return value of the NetCDF calls , ie. N90_NOERR, ...
!-----
subroutine check(status)
    use netcdf
    implicit none
    integer, intent(in) :: status
    if (status /= NF90_NOERR) then
        print *, "ERROR: ", trim(nf90_strerror(status)), ", Aborting"
        stop
    end if
end subroutine check

!-----
! function ndigits(int_val) result (num_dig)
! => finds the number of digits of an integer number, base 10
! - int_val: integer value
! - num_dig: number of digits
!-----
function ndigits(int_val) result (num_dig)
    implicit none
    integer, intent(in) :: int_val
    integer :: new_val
    integer :: num_dig

    num_dig = 1
    new_val = int_val

    do
        new_val = new_val / 10 ! chop first digit
        if (new_val > 0) then
            num_dig = num_dig + 1
        else
            return
        end if
    end do
end function ndigits

!-----
! subroutine int_to_char(int_val, ndig, res_char)
! => Converts and integer number to character array
! - int_val: integer number to be converted
! - res_char: result character array
!-----
subroutine int_to_char(int_val, res_char)
    implicit none
    integer, intent(in) :: int_val
    character, intent(out), allocatable, dimension(:) :: res_char
    integer :: new_val, digit, i, nd

    new_val = int_val
    nd = ndigits(int_val)
    allocate(res_char(nd))

    do i = 0, nd-1
        digit = mod(new_val,10) !! extract first digit
        !! convert to character and locate

```

```

        res_char(nd-i : nd-i) = char(ichar('0') + digit)
        new_val = new_val / 10  !! throw away the processed digits
    end do
end subroutine int_to_char

!-----
! function number_of_days(month, year) result(ndays)
! => returns the number of days in the given year and month
! - month: number of month, 1-12
! - year: current year
!-----
function number_of_days(month, year) result(ndays)
    implicit none
    integer, intent(in) :: month
    integer, intent(in) :: year
    integer :: ndays

    select case(month)
    case(1)  ! January
        ndays = 31
    case(2)  ! February, check if there is leap year
        if ( mod(year,4) == 0 ) then
            ndays = 29
        else
            ndays = 28
        end if
    case(3)  ! March
        ndays = 31
    case(4)  ! April
        ndays = 30
    case(5)  ! May
        ndays = 31
    case(6)  ! June
        ndays = 30
    case(7)  ! July
        ndays = 31
    case(8)  ! August
        ndays = 31
    case(9)  ! September
        ndays = 30
    case(10) ! October
        ndays = 31
    case(11) ! November
        ndays = 30
    case(12) ! December
        ndays = 31
    case default
        print *, "ERROR: Invalid month: ", month, "Aborting program"
        stop
    end select
end function number_of_days

!-----
! subroutine make_fname(prefix, year, month, day, hour, fname)
! => creates the file name in PREFIX:YYYY-MM-DD_HH format, that is to
! be used in write_intermediate subroutine
! - prefix: file prefix, i.e.: SST, FILE, ...
! - year: current year
! - month: current month
! - day: current day
! - hour: current hour
! - fname: file name in PREFIX:YYYY-MM-DD_HH format
!
! ----- : Y Y Y Y - M M - D D _ H H
! prefix  1 2 3 4 5 6 7 8 9 0 1 2 3 4
!-----
subroutine make_fname(prefix, year, month, day, hour, fname)
    implicit none
    character(len=*), intent(in) :: prefix
    integer, intent(in) :: year, month, day, hour
    integer :: lp, i
    character(len=len(prefix) + len(":YYYY-MM-DD_HH")), intent(out) :: fname
    character, allocatable, dimension(:) :: buffer

```

```

allocate(buffer(len(fname)))

!!! Construct the file name
lp = len(prefix)
fname(1 : lp) = prefix
fname(lp+1 : lp+1) = ':'

call int_to_char(year,buffer)  !! year
do i = 1, 4
    fname(lp+1+i : lp+1+i) = buffer(i)
end do
fname(lp+6 : lp+6) = '-'

call int_to_char(month,buffer)  !! month
if (month < 10) then
    fname(lp+7 : lp+7) = '0'
    fname(lp+8 : lp+8) = buffer(1)
else
    fname(lp+7 : lp+7) = buffer(1)
    fname(lp+8 : lp+8) = buffer(2)
end if
fname(lp+9 : lp+9) = '-'

call int_to_char(day,buffer)  !! day
if (day < 10) then
    fname(lp+10 : lp+10) = '0'
    fname(lp+11 : lp+11) = buffer(1)
else
    fname(lp+10 : lp+10) = buffer(1)
    fname(lp+11 : lp+11) = buffer(2)
end if
fname(lp+12 : lp+12) = '_'

call int_to_char(hour,buffer)  !! hour
if (hour < 10) then
    fname(lp+13 : lp+13) = '0'
    fname(lp+14 : lp+14) = buffer(1)
else
    fname(lp+13 : lp+13) = buffer(1)
    fname(lp+14 : lp+14) = buffer(2)
end if
end subroutine make_fname

!-----
! subroutine make_hdate(year, month, day, hour, hdate)
! => creates the hdate name in YYYY-MM-DD_HH:00:00 format, that is to be
!     used in write_intermediate subroutine
! - year: current year
! - month: current month
! - day: current day
! - hour: current hour
! - hdate: hdate in YYYY-MM-DD_HH:00:00 format
!
!   Y Y Y Y - M M - D D _ H H : 0 0 : 0 0 s s s s s   ('s' stands for space )
!   1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4
!-----
subroutine make_hdate(year, month, day, hour, hdate)
    implicit none
    integer, intent(in) :: year, month, day, hour
    character(len=24), intent(out) :: hdate
    character, allocatable, dimension(:) :: buffer
    integer :: i
    allocate(buffer(len(hdate)))

    call int_to_char(year,buffer)  !! year
    do i = 1, 4
        hdate(i : i) = buffer(i)
    end do
    hdate(5 : 5) = '-'

    call int_to_char(month,buffer)  !! month
    if (month < 10) then
        hdate(6 : 6) = '0'
        hdate(7 : 7) = buffer(1)

```

```

    else
        hdate(6 : 6) = buffer(1)
        hdate(7 : 7) = buffer(2)
    end if
    hdate(8 : 8) = '-'

    call int_to_char(day,buffer)  !! day
    if (day < 10) then
        hdate(9 : 9) = '0'
        hdate(10 : 10) = buffer(1)
    else
        hdate(9 : 9) = buffer(1)
        hdate(10 : 10) = buffer(2)
    end if
    hdate(11 : 11) = '-'

    call int_to_char(hour,buffer)  !! hour
    if (hour < 10) then
        hdate(12 : 12) = '0'
        hdate(13 : 13) = buffer(1)
    else
        hdate(12 : 12) = buffer(1)
        hdate(13 : 13) = buffer(2)
    end if
    hdate(14 : ) = ":00:00"
print *, "HDATE: ", hdate
end subroutine make_hdate

!-----
! subroutine read_data_2d()
! => reads the 2D slab from netcdf file into a temporary buffer
! - ncid: ID of the NetCDF file
! - varname: variable name (eg. "SST")
! - data_2d: variable will be written on this 2D array to be written
! - nx, ny: x and y sizes of the array
! - starts: 1-D array that holds the starting indexes
! - counts: 1-D array that holds the number of elements
!-----
subroutine read_data_2d(ncid, varname, data_2d, nx, ny, starts, counts)
    use netcdf
    implicit none

    integer, intent(in) :: ncid, nx, ny
    character(len=*), intent(in) :: varname
    real, dimension(:,:), intent(out) :: data_2d
    integer, dimension(:), intent(in) :: starts, counts
    integer :: var_id

    call check( nf90_inq_varid(ncid, varname, var_id) )
    call check( nf90_get_var(ncid, var_id, data_2d, start=starts, count=counts) )
end subroutine read_data_2d

!-----
! subroutine write_intermediate(fname, hdate, data)
! => writes the slabs from netcdf file to the WPS intermediate files,
! details on writing intermediate files are described in WRF Users Guide,
! Chapter 3: WRF Preprocessing System (WPS)
! -fname: name of the WPS intermediate file
! -hdate: day to be processed
! -data: 2D data to be written
!-----
subroutine write_intermediate(fname, hdate, data)
    implicit none

    character(len=*), intent(in) :: fname  ! name of the WPS intermediate file
    ! Valid date for data YYYY:MM:DD_HH:00:00
    character(len=24), intent(in) :: hdate
    real, dimension(:,:), intent(in) :: data  ! 2D data to be written
    !integer,parameter :: IFV = 5  ! Format version, must be 5 for WPS format
    integer :: IFV = 5  ! Format version, must be 5 for WPS format
    integer, parameter :: funit = 10 ! file unit number
    integer :: ios  ! file I/O status, must be zero for successful I/O operation

```

```

real :: xfcst = 0.0      ! Forecast hour of data
character(len=9), parameter :: FIELD = "sst"      ! Name of the field
character(len=25), parameter :: UNITS = "K"
character(len=46), parameter :: DESC = "SST data from GISST netcdf file"
character(len=32), parameter :: MAP_SOURCE = "created by gisst2wrf"
real, parameter :: XLVL = 200100 ! surface data
integer, parameter :: NX = 360 ! x- and y-dimensions of 2-d array
integer, parameter :: NY = 180
integer, parameter :: IPROJ = 4 ! Gaussian projection
! Which point in array is given by startlat/startlon, set either
! to 'SWCORNER' or 'CENTER'
character(len=8) :: startloc = "SWCORNER"
! Lat/lon of point in array indicated by startloc string
real, parameter :: STARTLAT = -89.237
real, parameter :: STARTLON = 0.5
real, parameter :: DELTALAT = 1. ! Grid spacing, degrees
real, parameter :: DELTALON = 1.
! # of latitudes north of equator for Gaussian grids
real, parameter :: NLATS = NY / 2
real, parameter :: EARTH_RADIUS = 6367470. * .001 !! Earth radius, km
logical, parameter :: IS_WIND_EARTH_REL = .FALSE.

! Open WPS file for writing. Make sure that file is in big endian format
open(unit=funit, iostat=ios, form='unformatted', file=fname)
if (ios /= 0) then
    print *, "ERROR: Can not open file ", fname, ", Aborting"
    stop
end if
print *, "Opened WPS intermediate file ", fname, &
    " for writing. Processing date -> ", hdate

! Write the data to the intermediate file
write (unit=funit, iostat=ios) IFV
write (unit=funit, iostat=ios) hdate, XFCST, MAP_SOURCE, FIELD, &
    UNITS, DESC, XLVL, NX, NY, IPROJ
write (unit=funit, iostat=ios) STARTLOC, STARTLAT, STARTLON, &
    NLATS, DELTALON, EARTH_RADIUS
write (unit=funit, iostat=ios) IS_WIND_EARTH_REL
write (unit=funit, iostat=ios) data
if (ios /= 0) then
    print *, "ERROR: Write failed for intermediate file ", fname, &
        ", Aborting"
    stop
end if

close(funit)
end subroutine write_intermediate

end module utility

```


APPENDIX D

Modifications to the METGRIB.TBL file

```
=====
name=sst
  interp_option=sixteen_pt+four_pt
  fill_missing=0.
  missing_value=-9999.
  masked=land
  flag_in_output=FLAG_SST
=====
```

Modifications to the WRF/WPS/ungrib/src/filelist.F file

```
module filelist
!!! BUG: This line is commented-out since more than 10000 files are generated
!!!      Deniz, 27/08/2010
!!! character(len=24), dimension(10000) :: filedates = '0000-00-00 00:00:00.0000'

!!! corrected line, Deniz 27/08/2010
  character(len=24), dimension(46752) :: filedates = '0000-00-00 00:00:00.0000'
  integer :: nfiles = 0
end module filelist
```


APPENDIX E

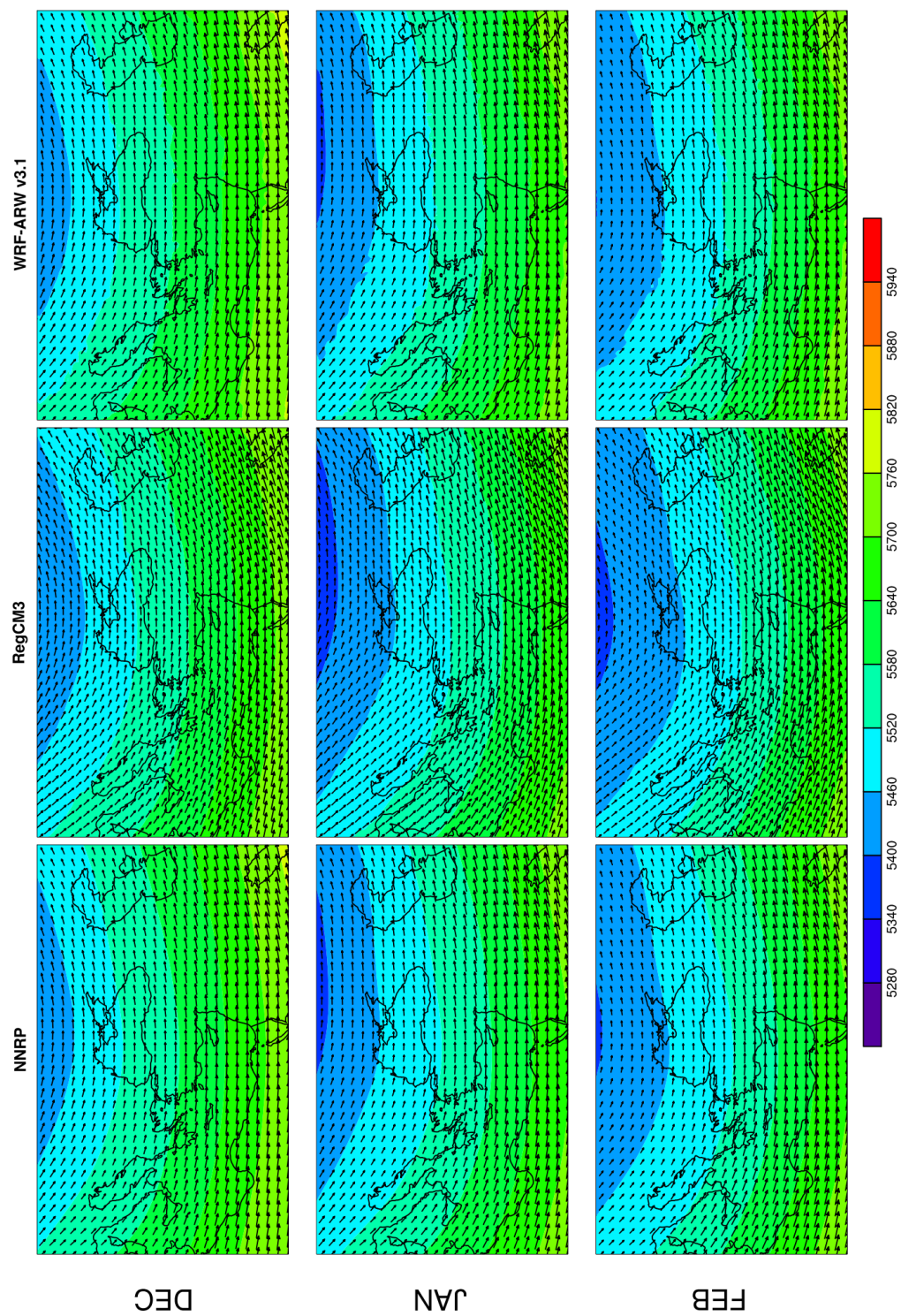


Figure E.1: 500 hPa geopotential height (gpm) and wind field for december, january, and february

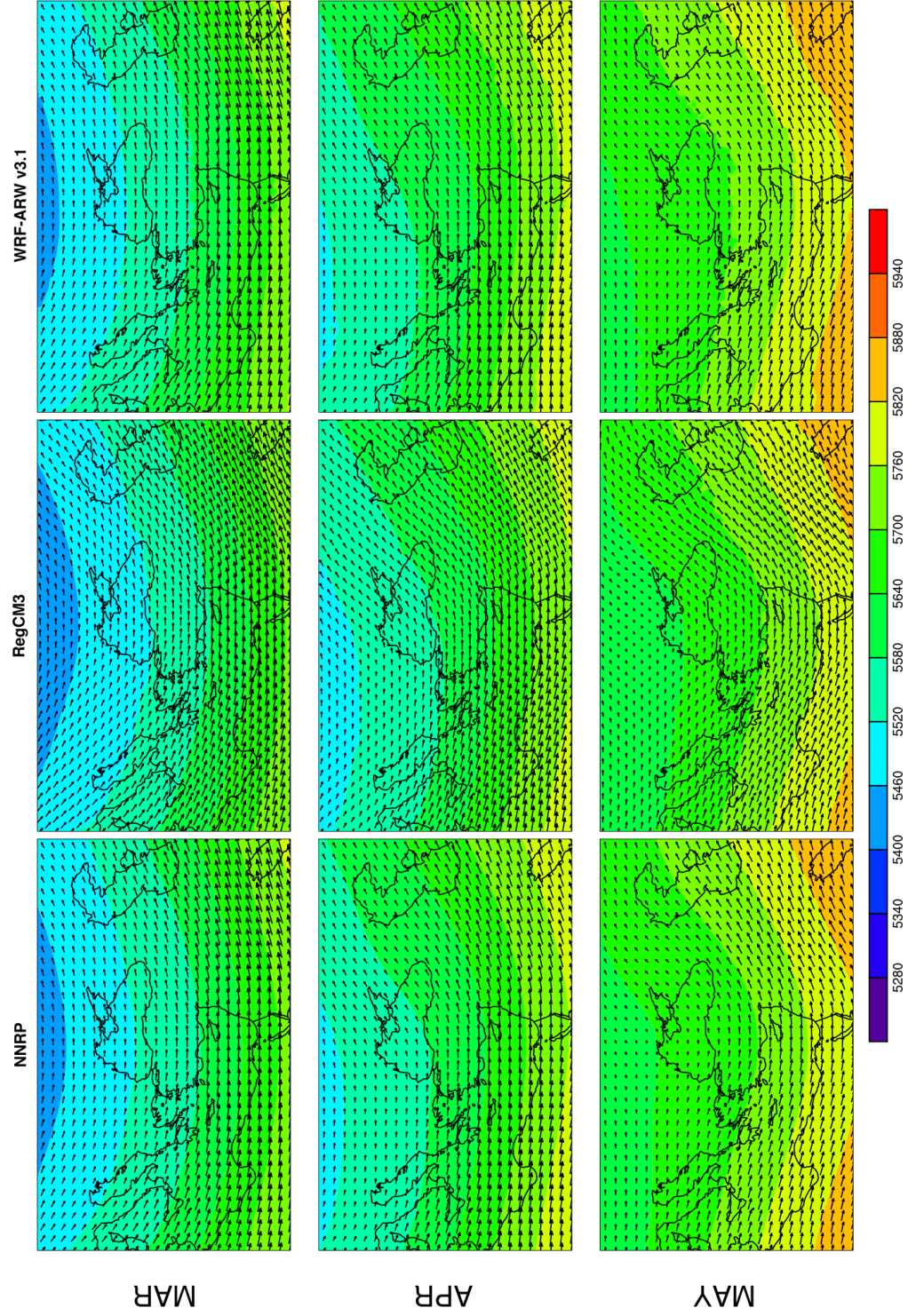


Figure E.2: 500 hPa geopotential height (gpm) and wind field for march, april, and may

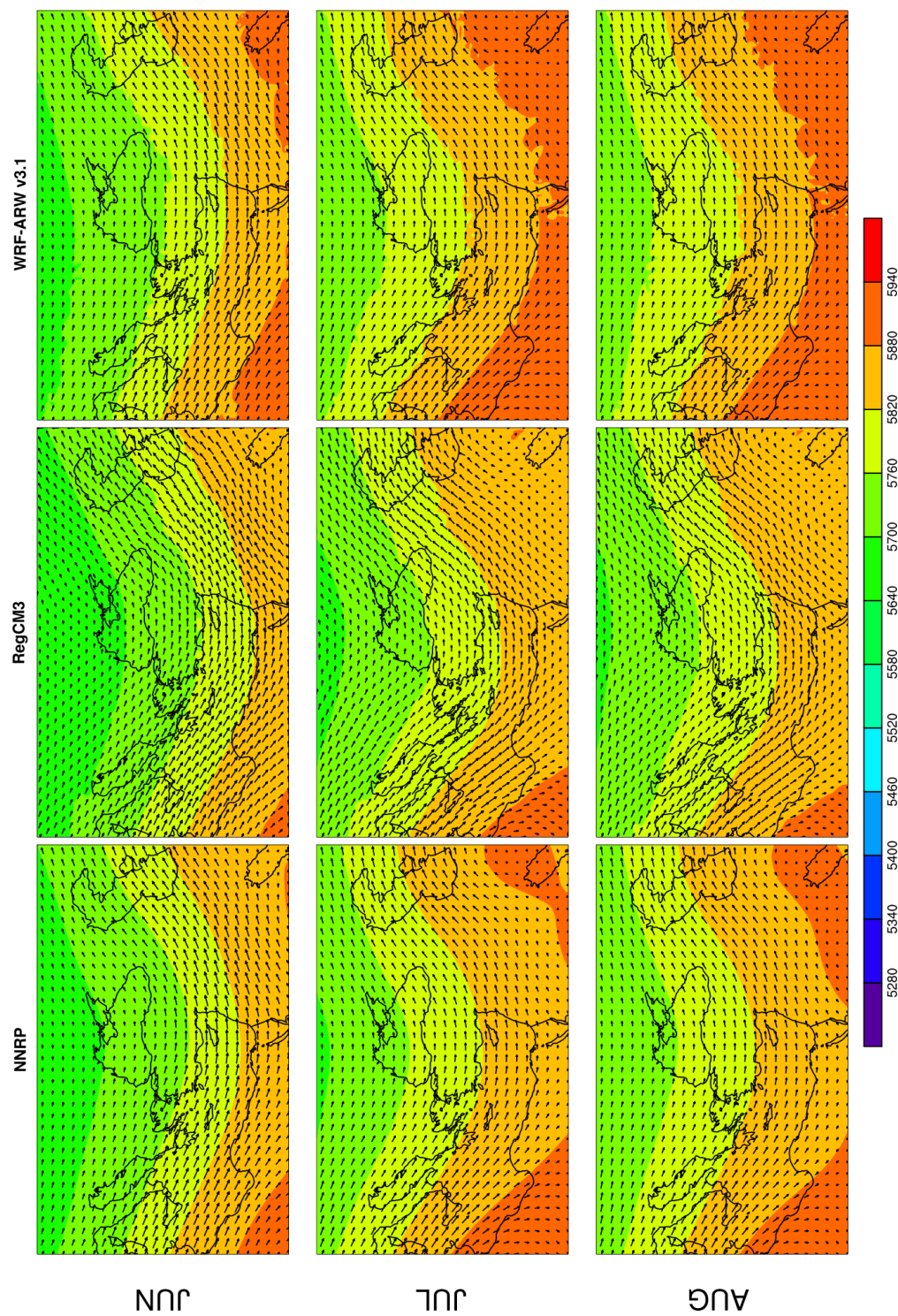


Figure E.3: 500 hPa geopotential height (gpm) and wind field for june, july, and august

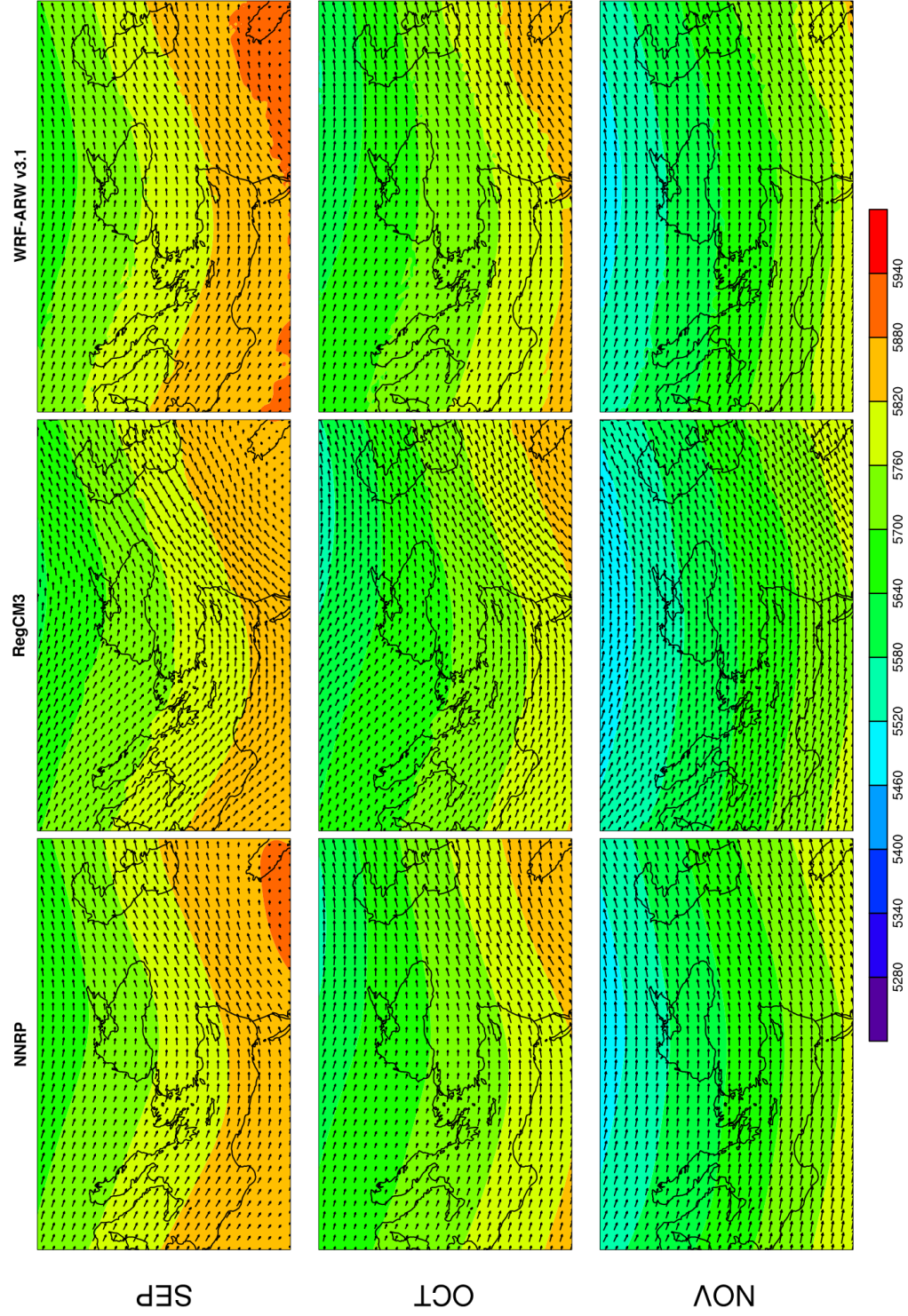


Figure E.4: 500 hPa geopotential height (gpm) and wind field for september, october, and november

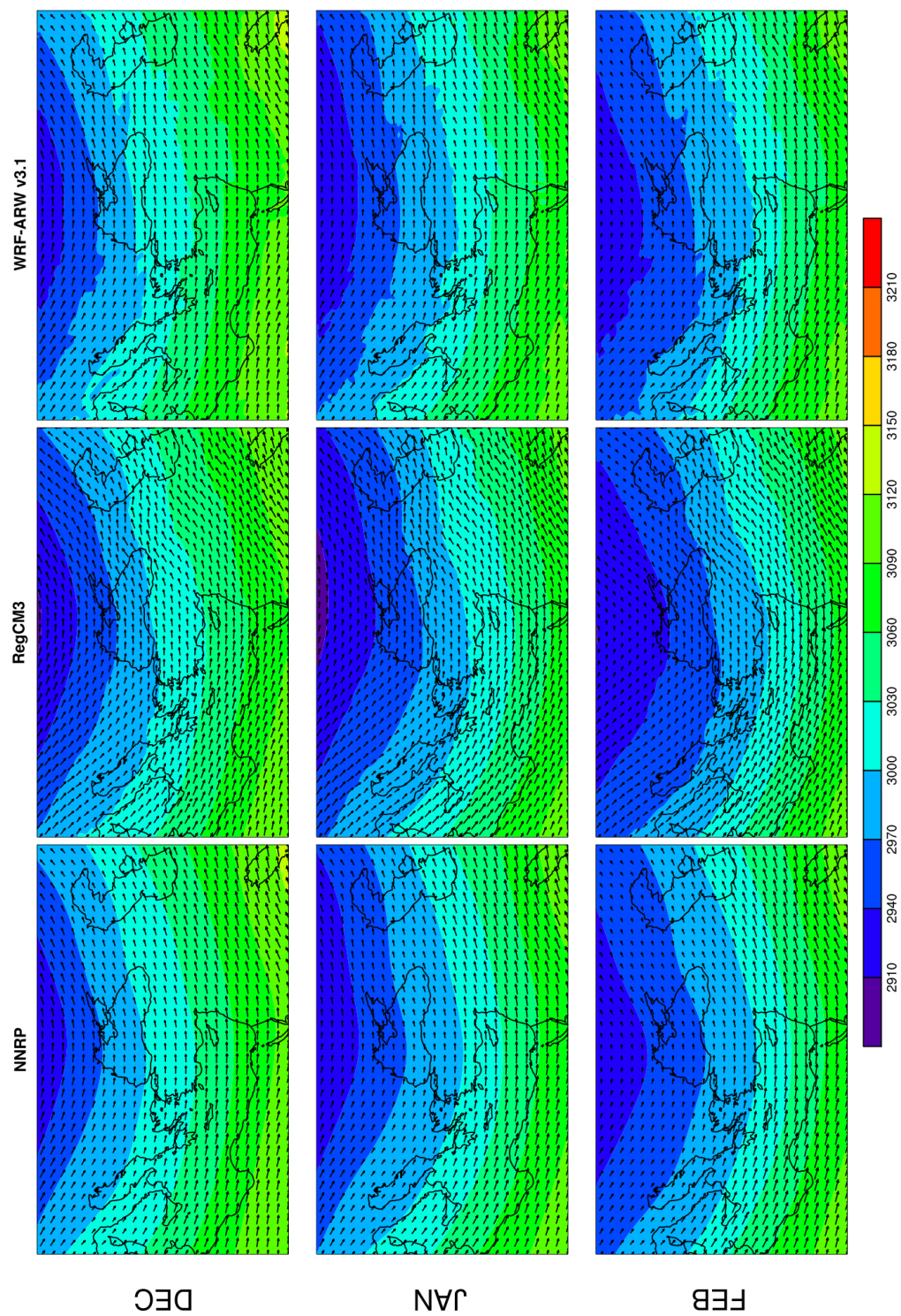


Figure E.5: 700 hPa geopotential height (gpm) and wind field for december, january, and february

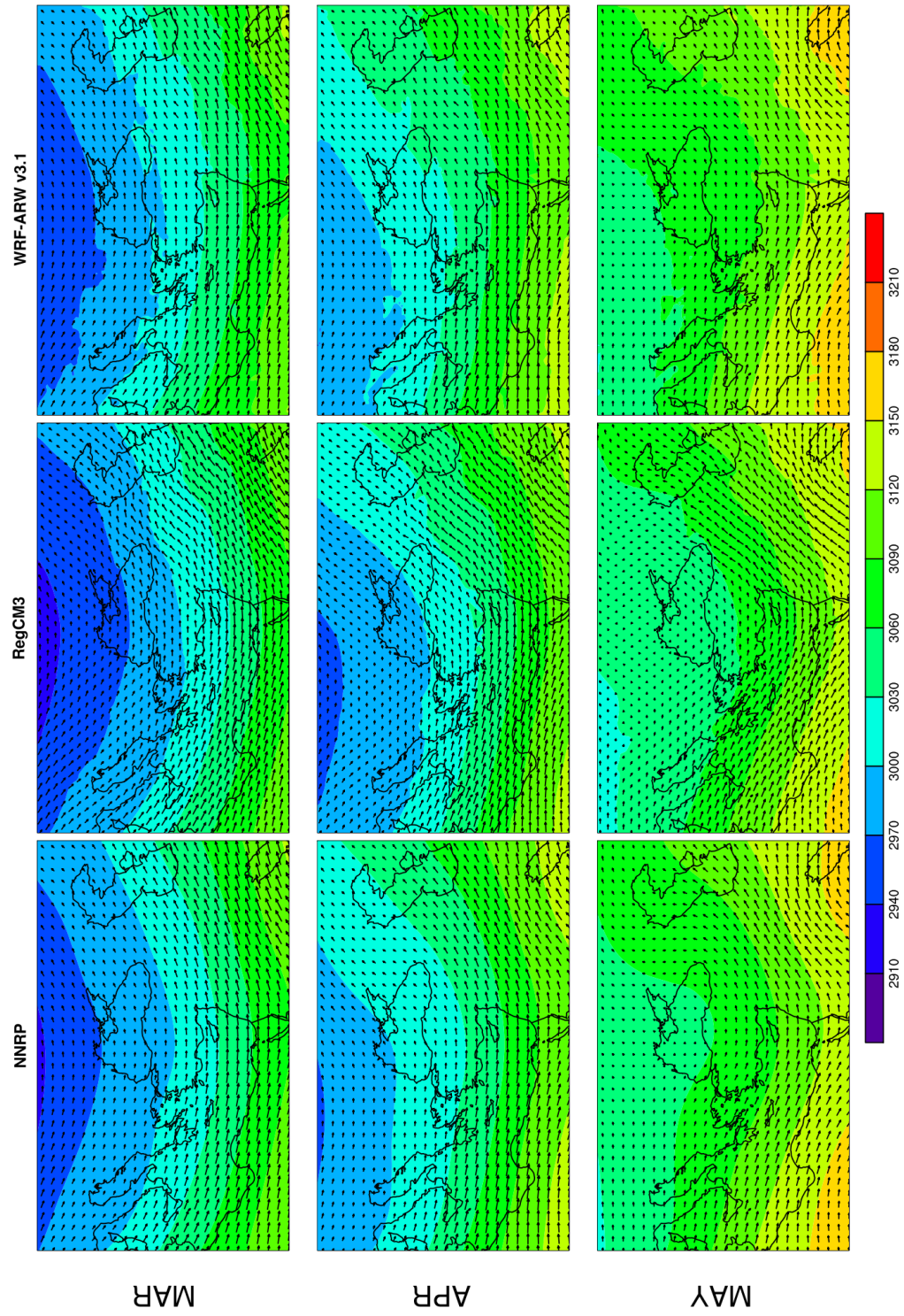


Figure E.6: 700 hPa geopotential height (gpm) and wind field for march, april, and may

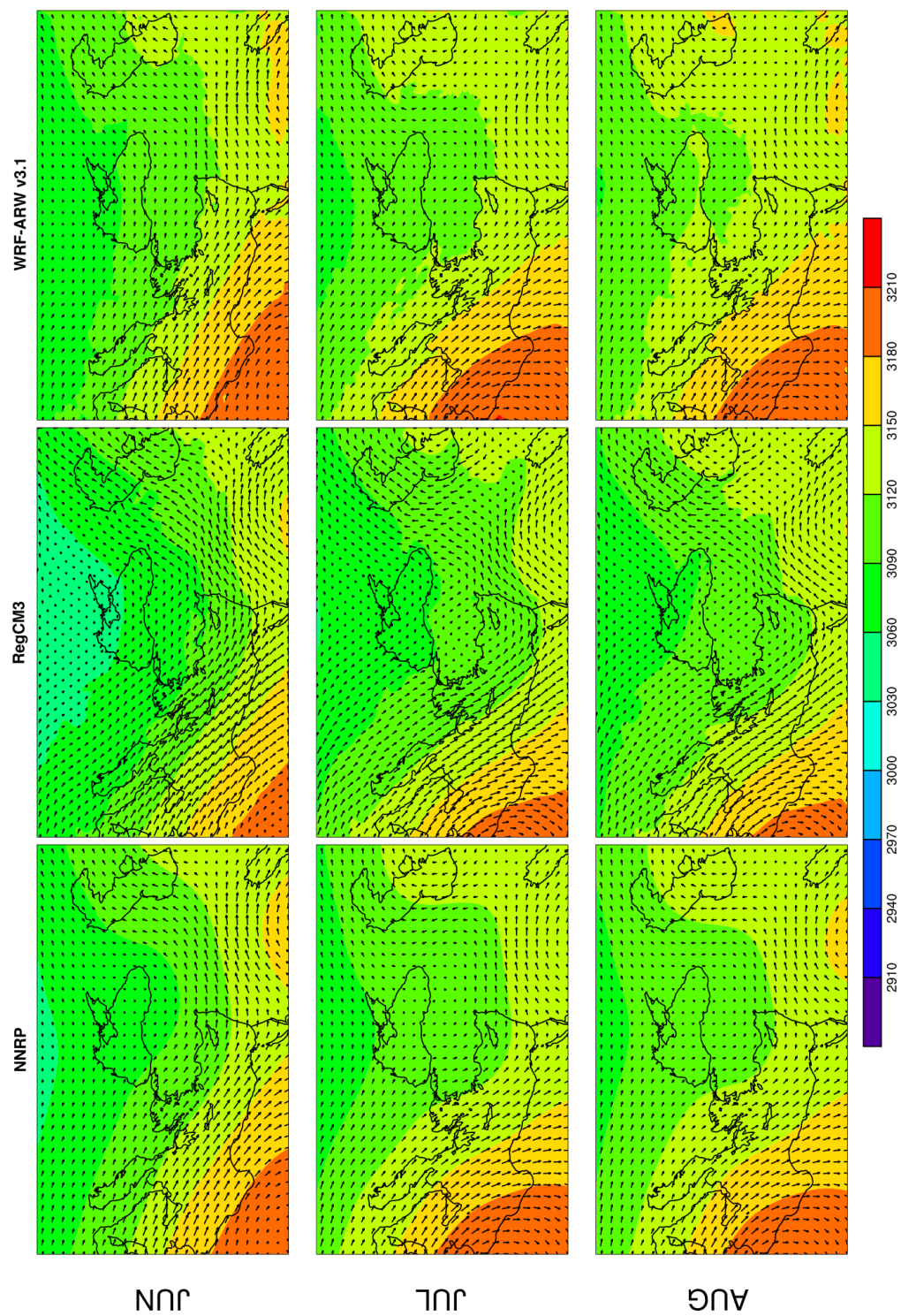


Figure E.7: 700 hPa geopotential height (gpm) and wind field for june, july, and august

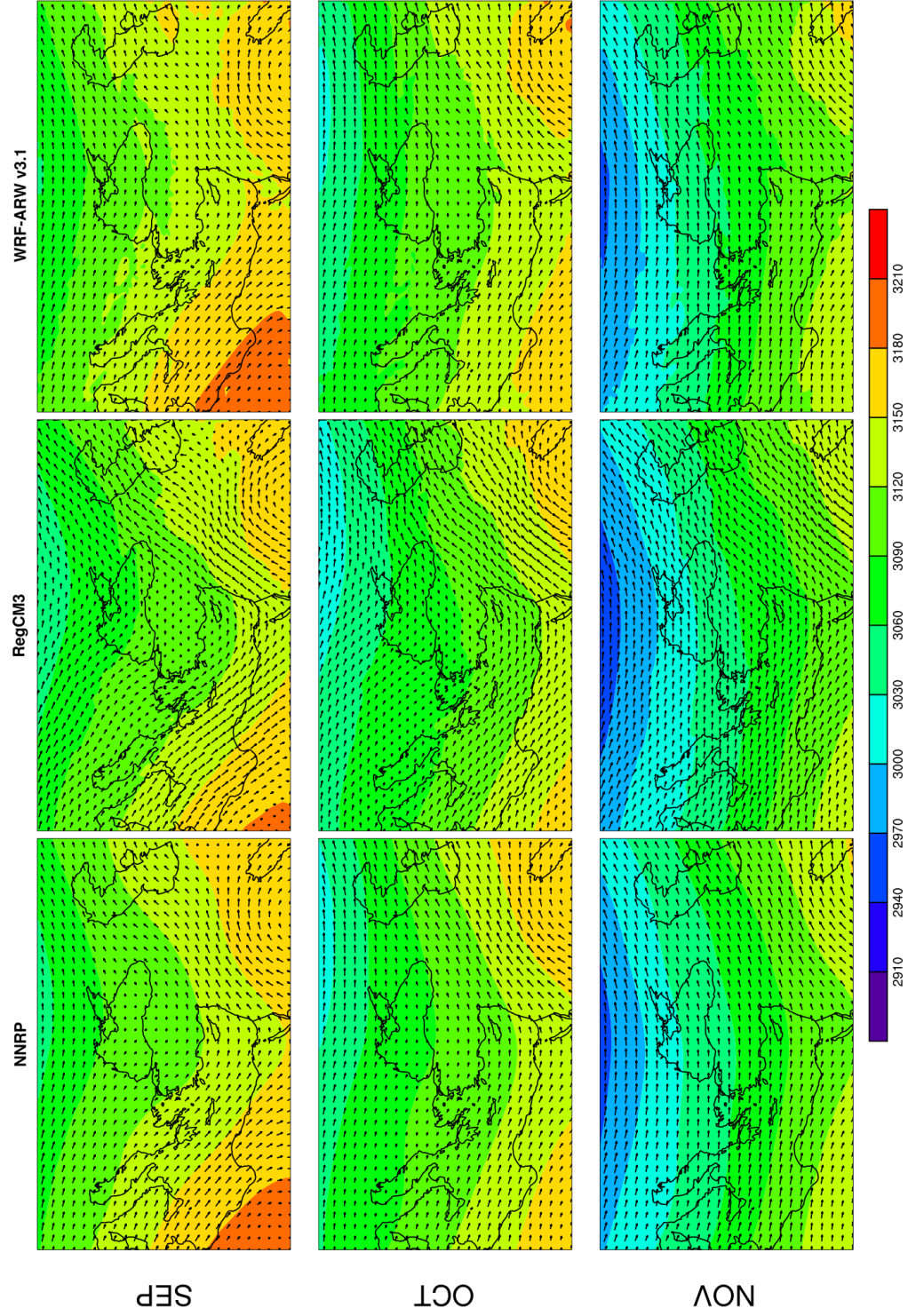


Figure E.8: 700 hPa geopotential height (gpm) and wind field for september, october, and november

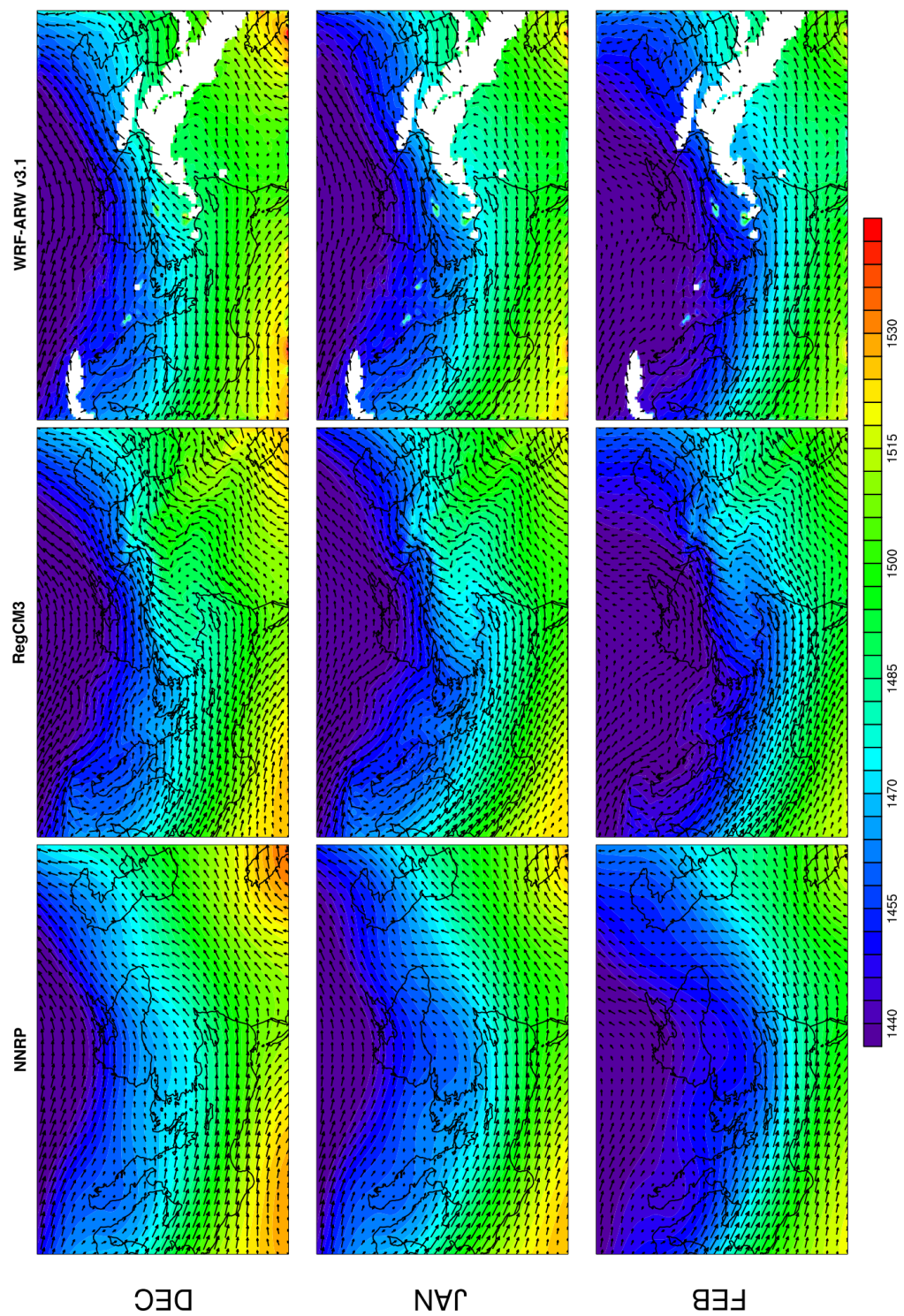


Figure E.9: 850 hPa geopotential height (gpm) and wind field for december, january, and february

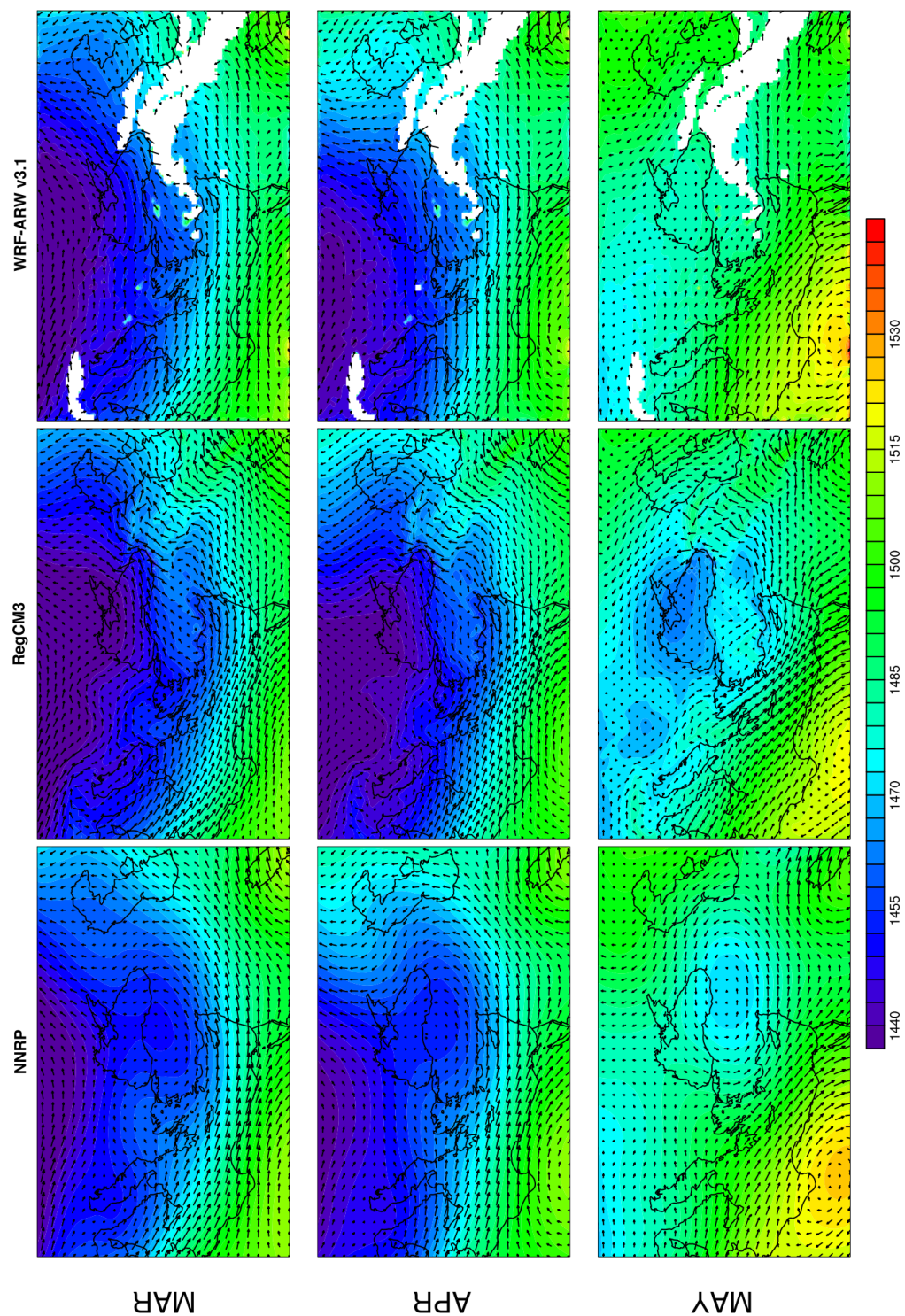


Figure E.10: 850 hPa geopotential height (gpm) and wind field for march, april, and may

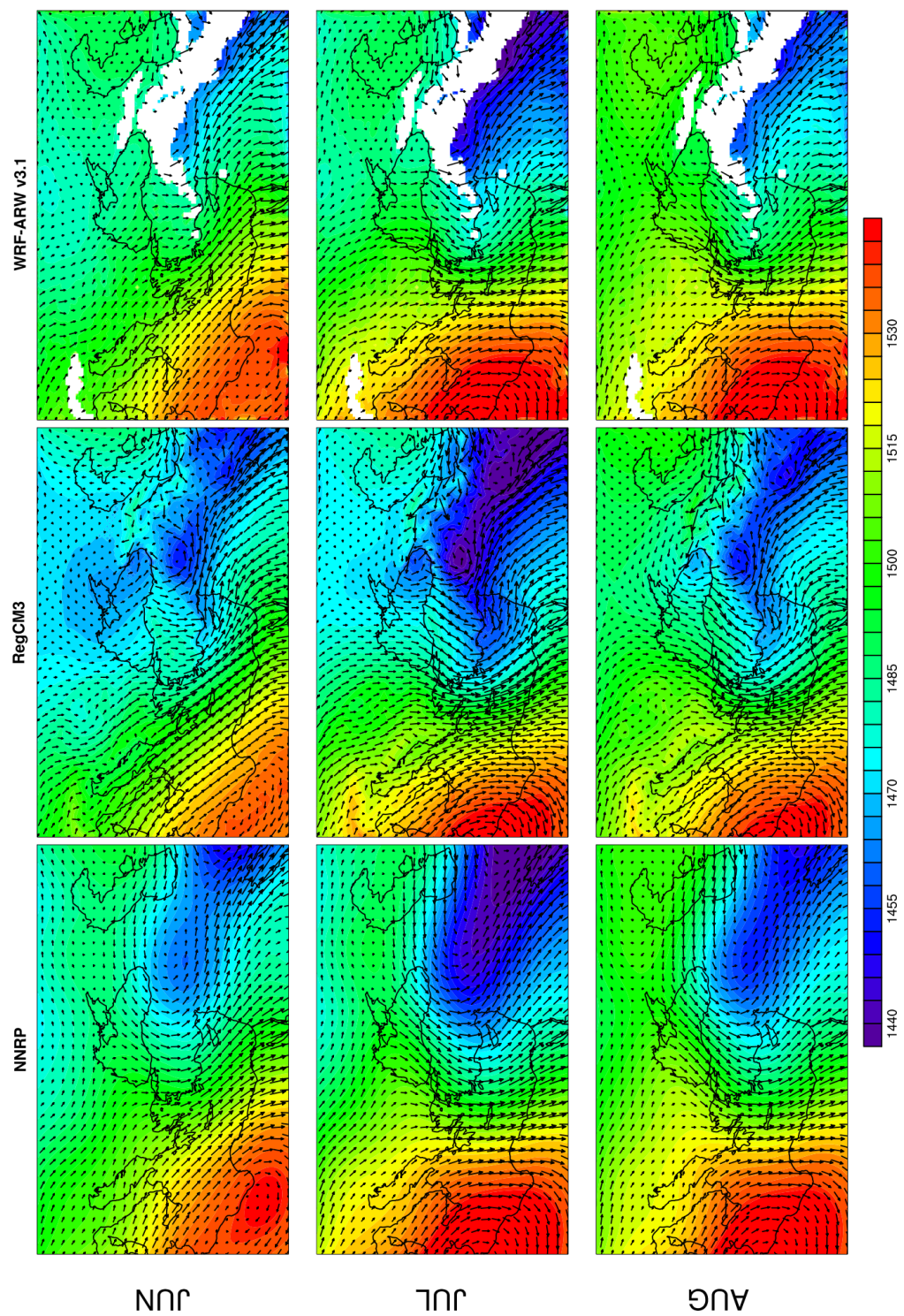


Figure E.11: 850 hPa geopotential height (gpm) and wind field for June, July, and August

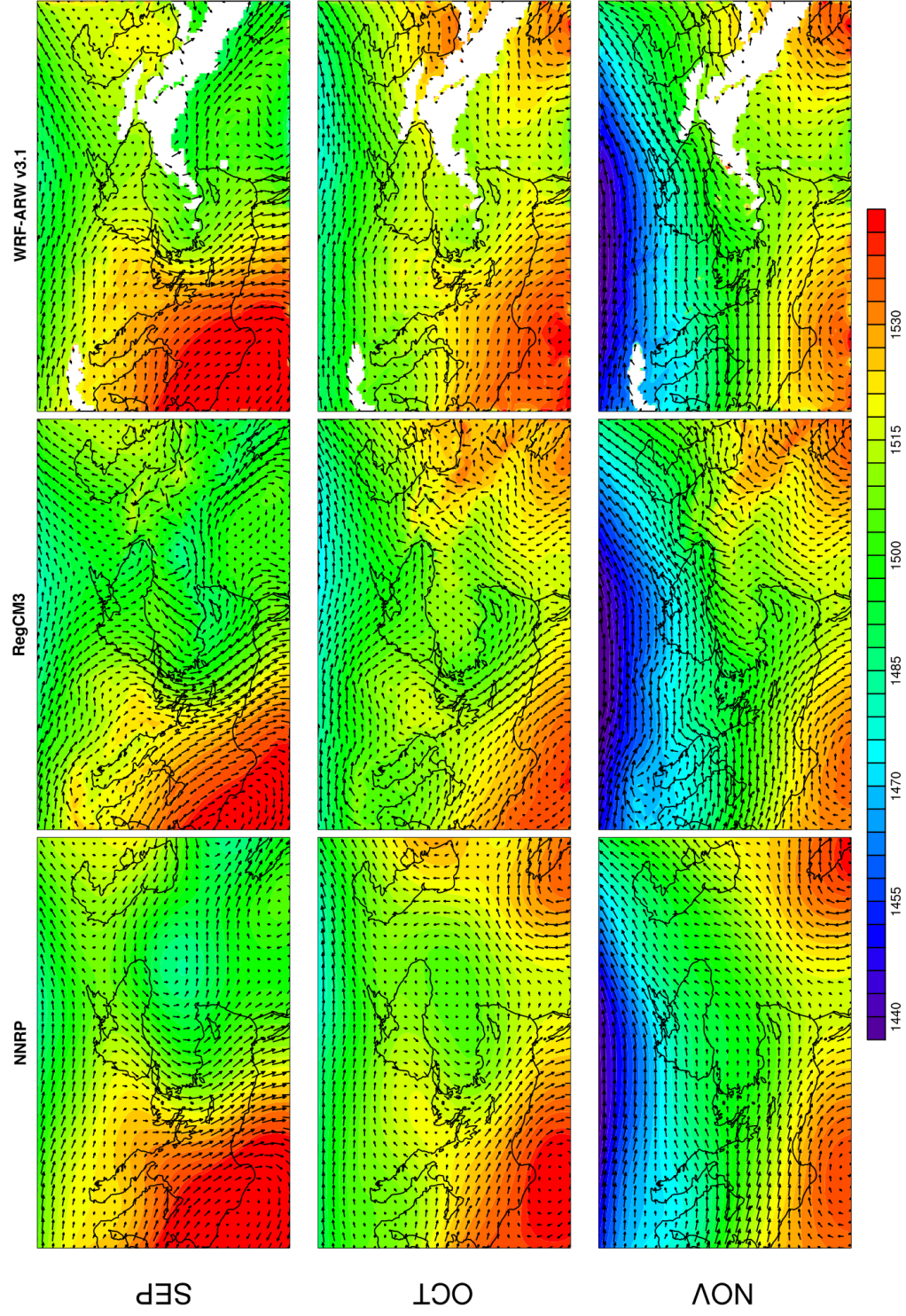


Figure E.12: 850 hPa geopotential height (gpm) and wind field for september, october, and november

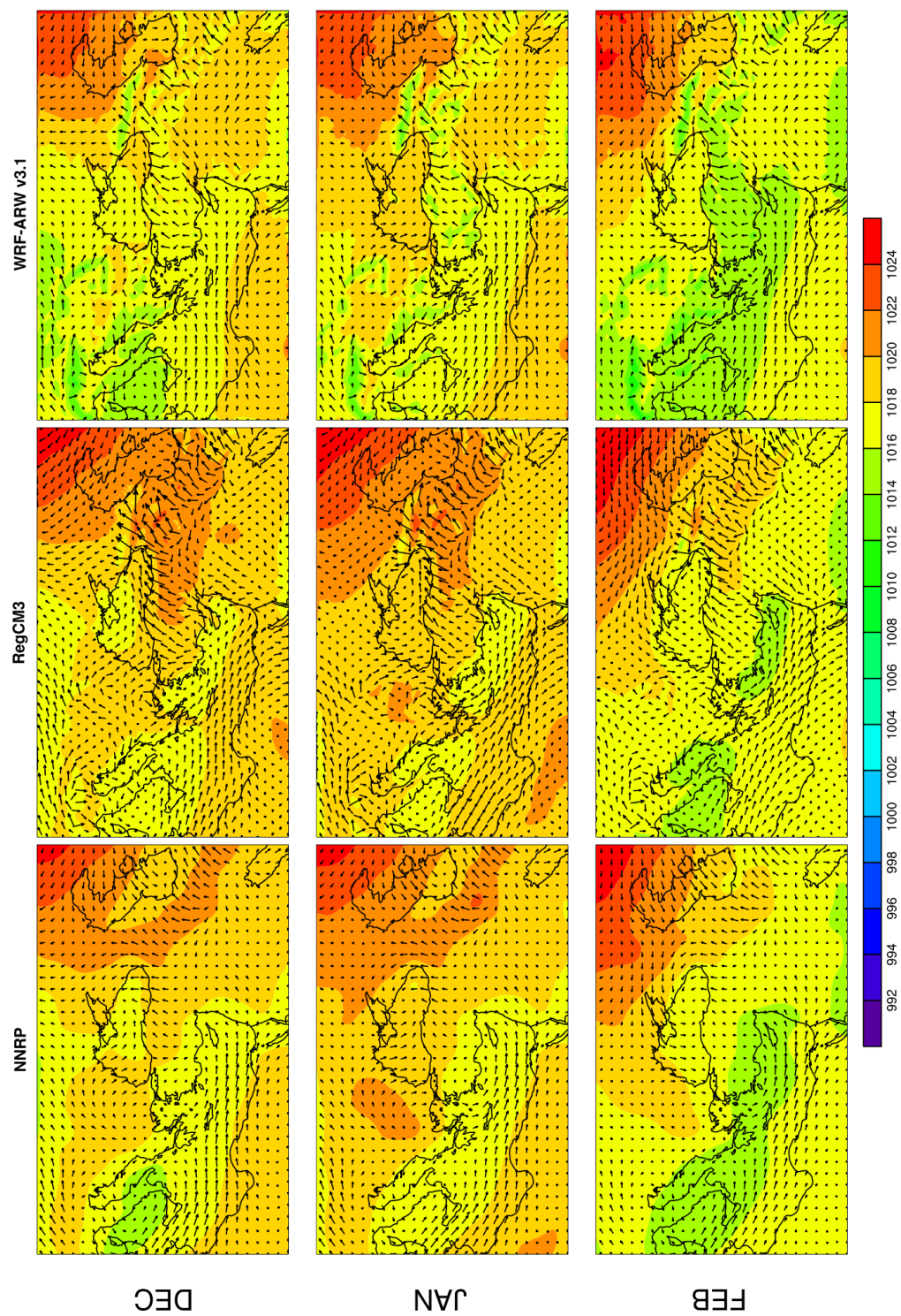


Figure E.13: Sea level pressure and surface wind field for december, january, and february

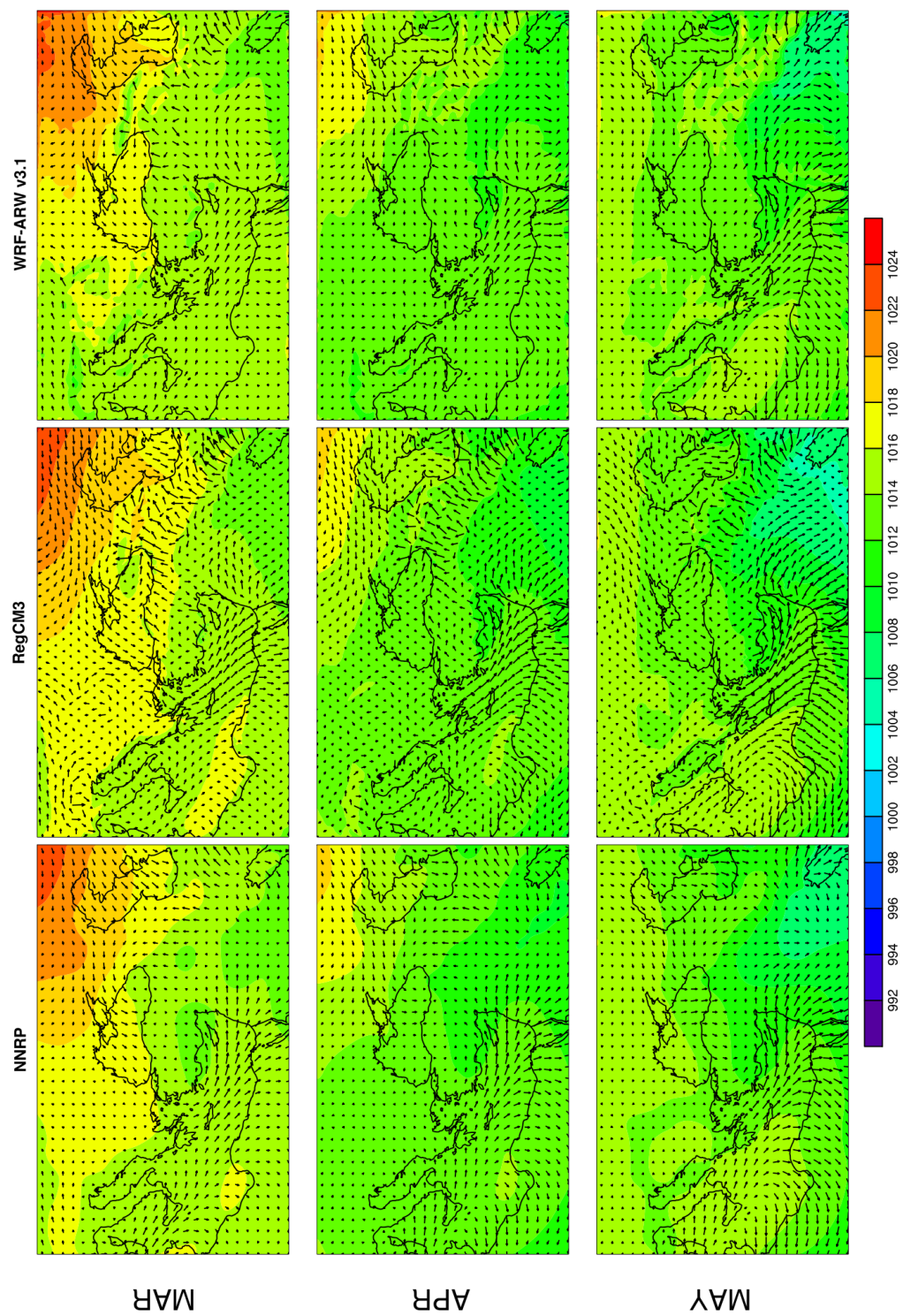


Figure E.14: Sea level pressure and surface wind field for march, april, and may

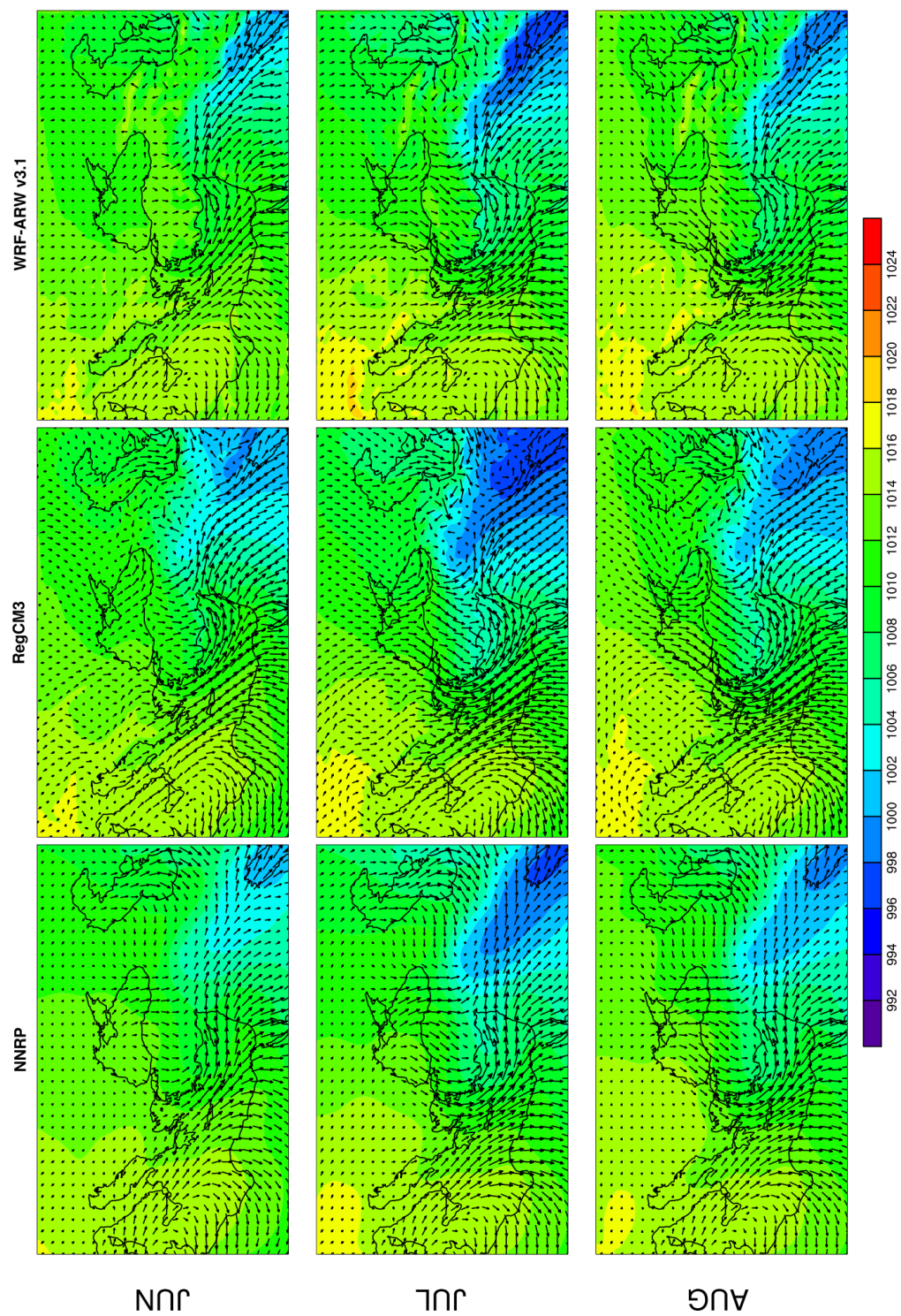


Figure E.15: Sea level pressure and surface wind field for june, july, and august

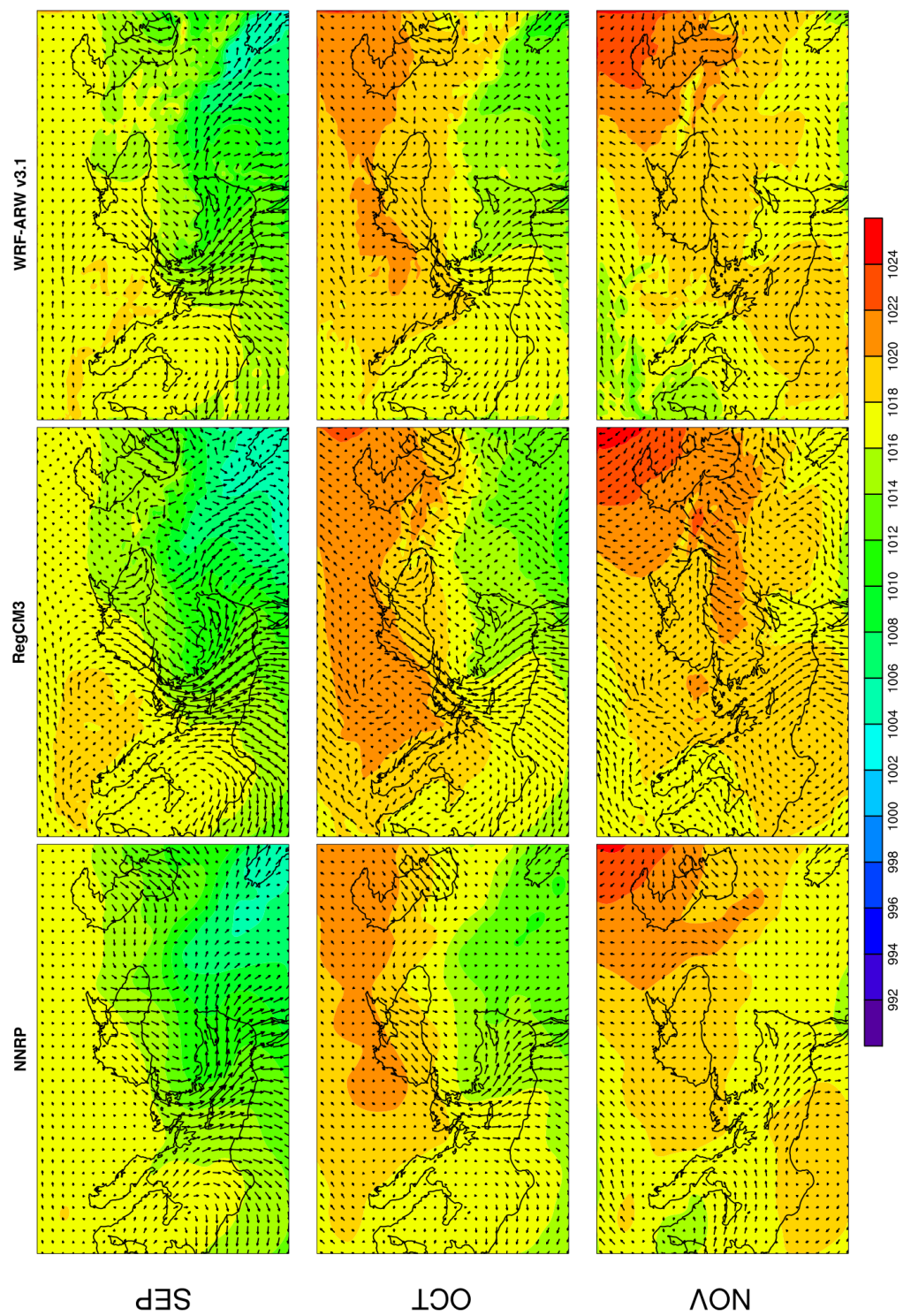


Figure E.16: Sea level pressure and surface wind field for september, october, and november

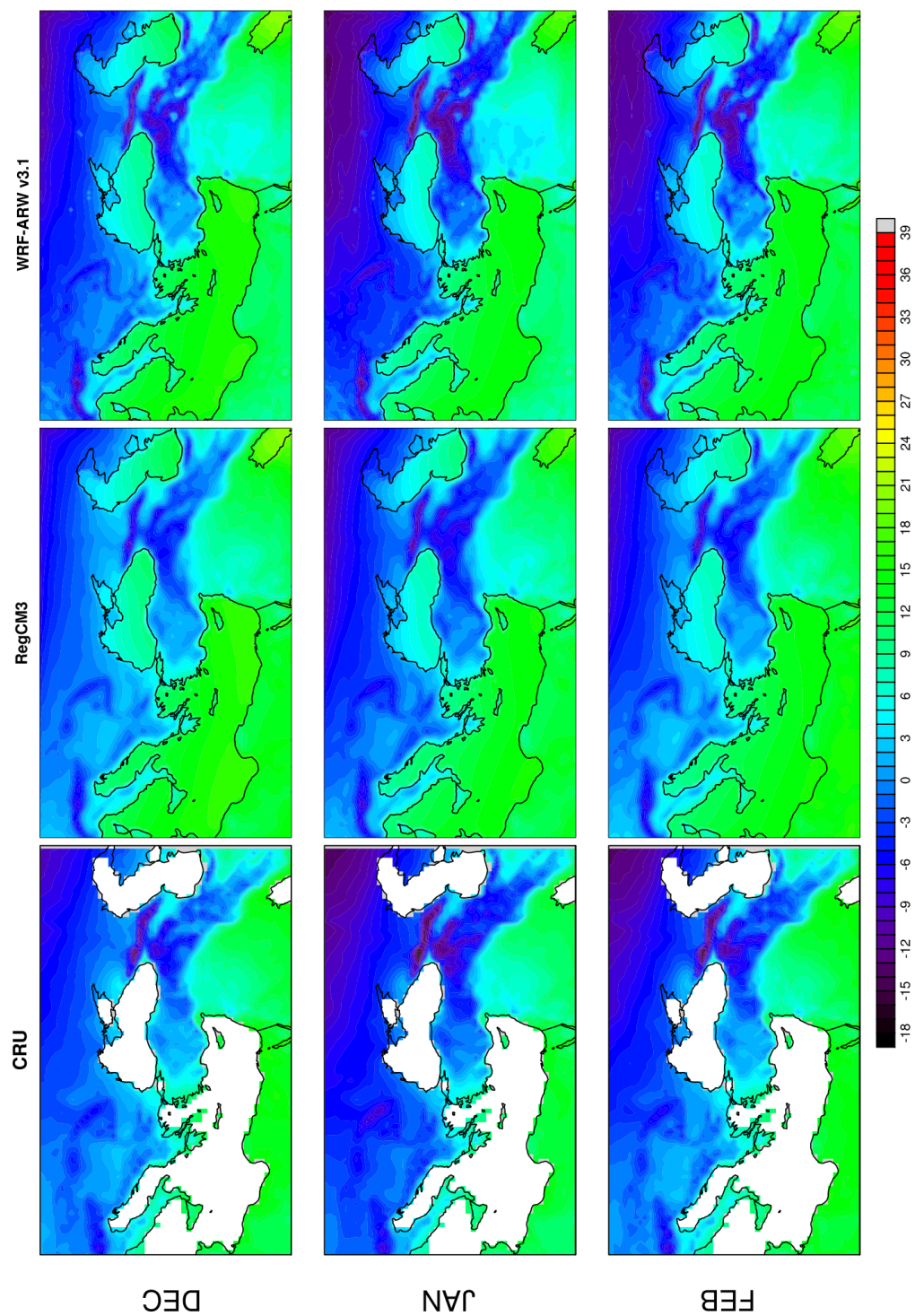


Figure E.17: 2 Meter temperature field ($^{\circ}\text{C}$) for december, january, and february

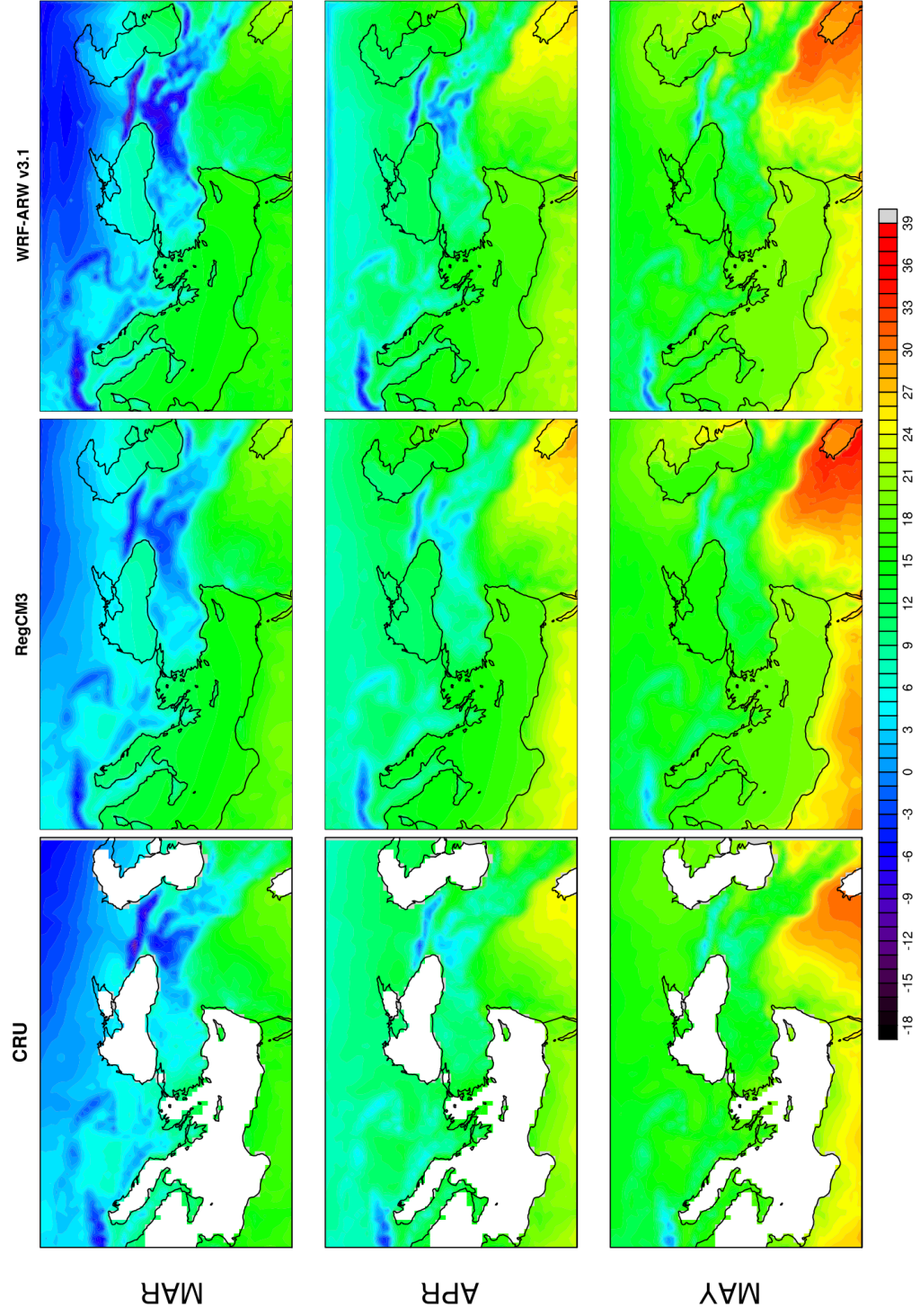


Figure E.18: 2 Meter temperature field ($^{\circ}\text{C}$) for march, april, and may

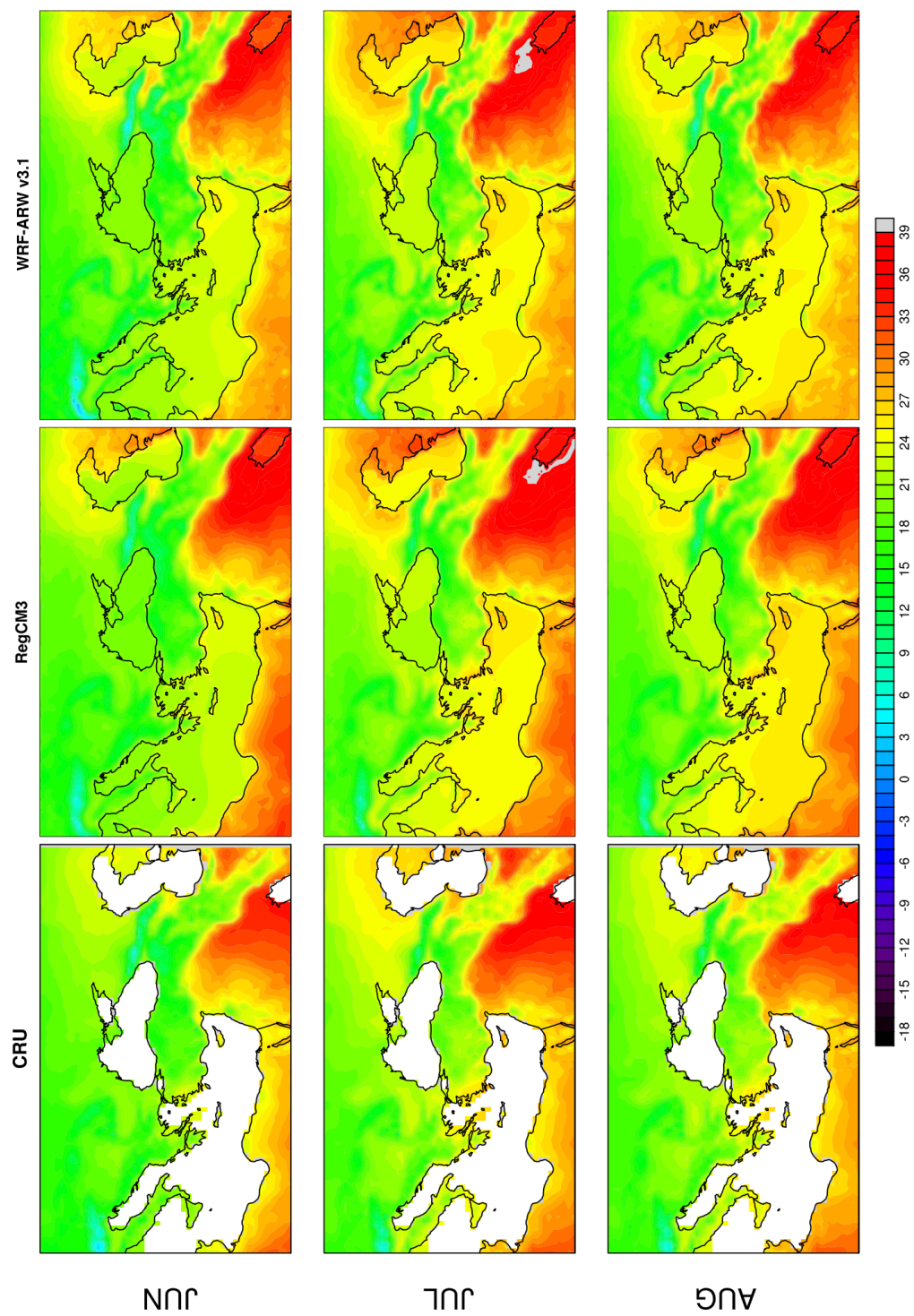


Figure E.19: 2 Meter temperature field ($^{\circ}\text{C}$) for june, july, and august

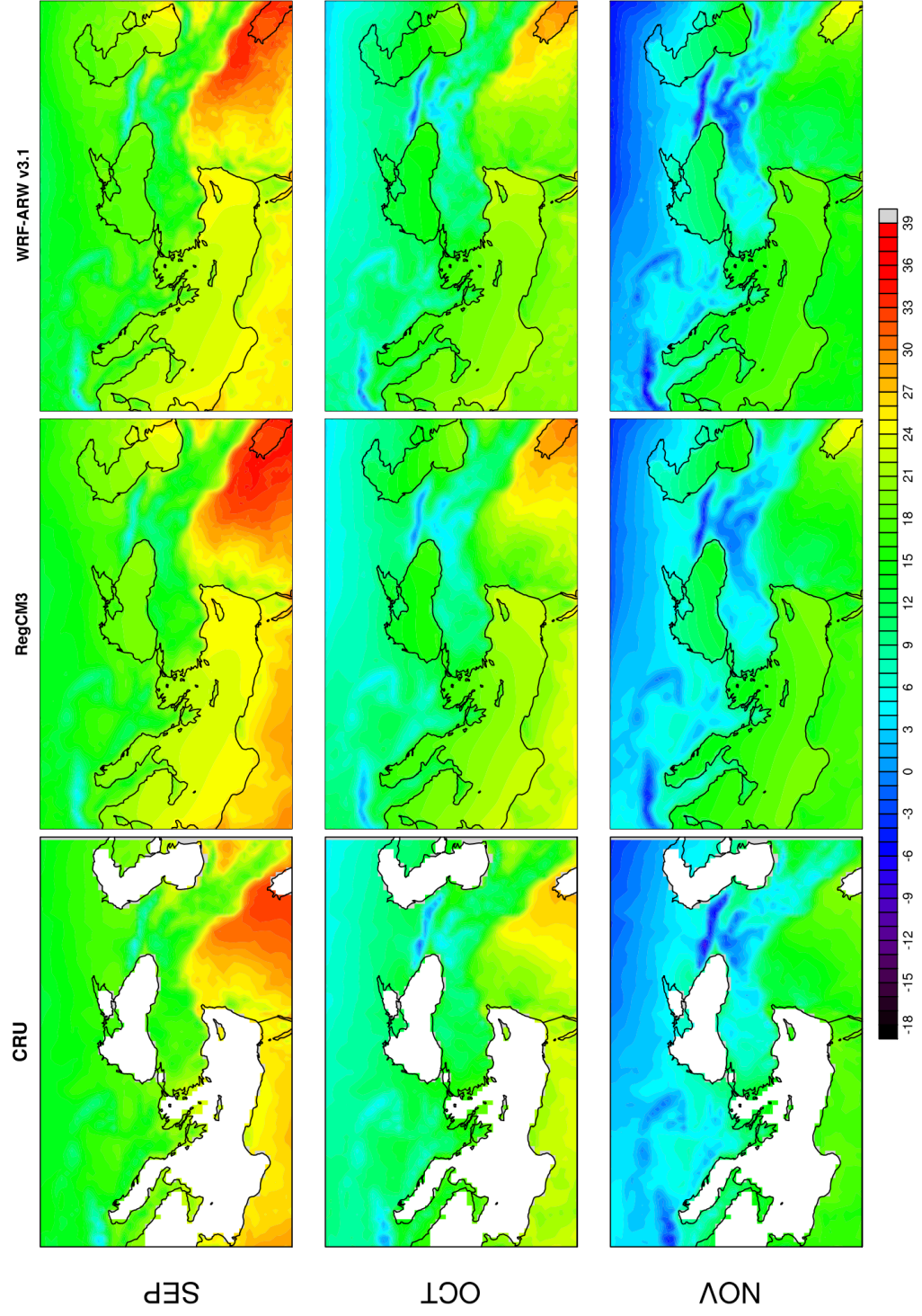


Figure E.20: 2 Meter temperature field ($^{\circ}\text{C}$) for september, october, and november

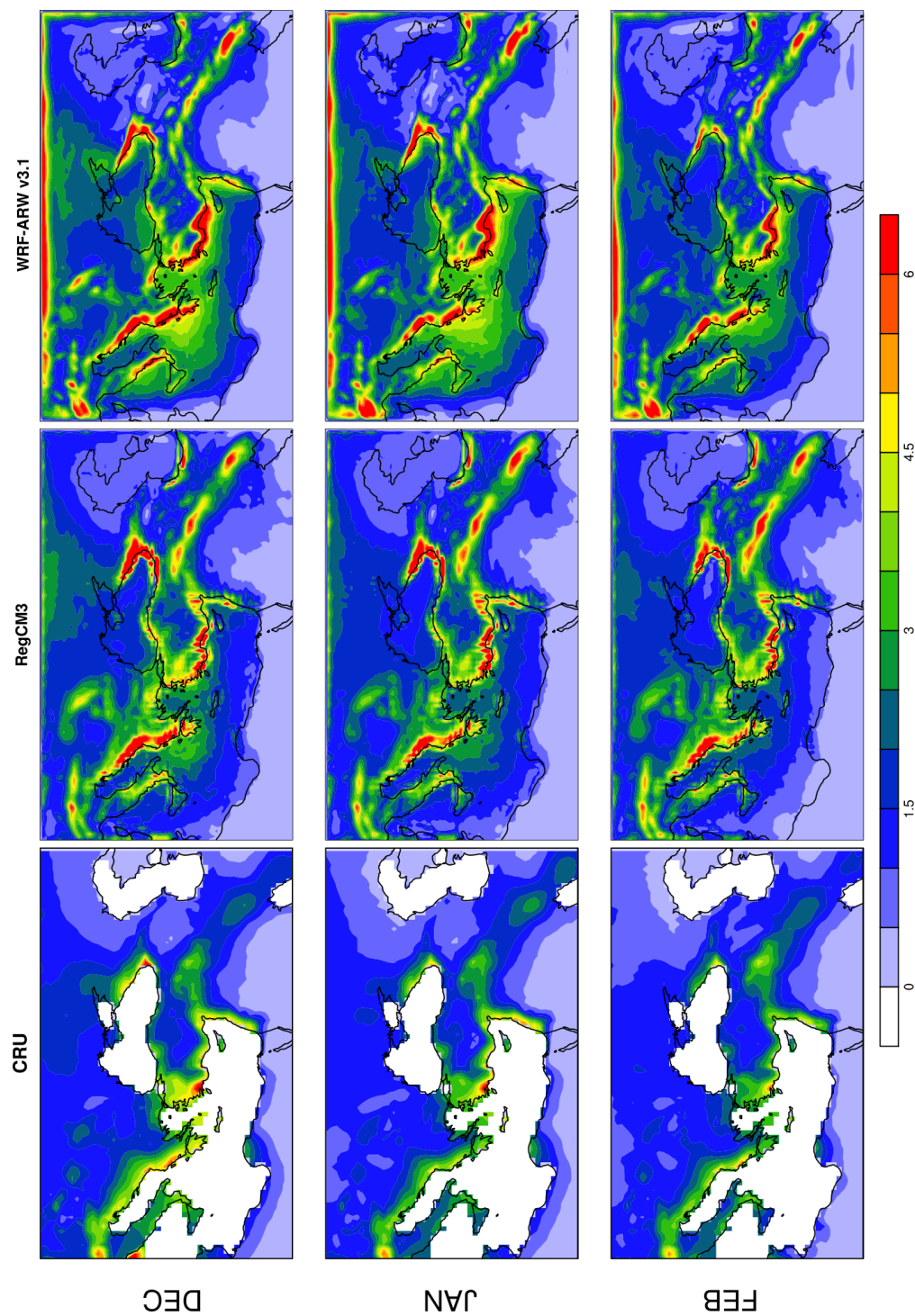


Figure E.21: Monthly mean precipitation distribution (mm/day) for december, january, and february

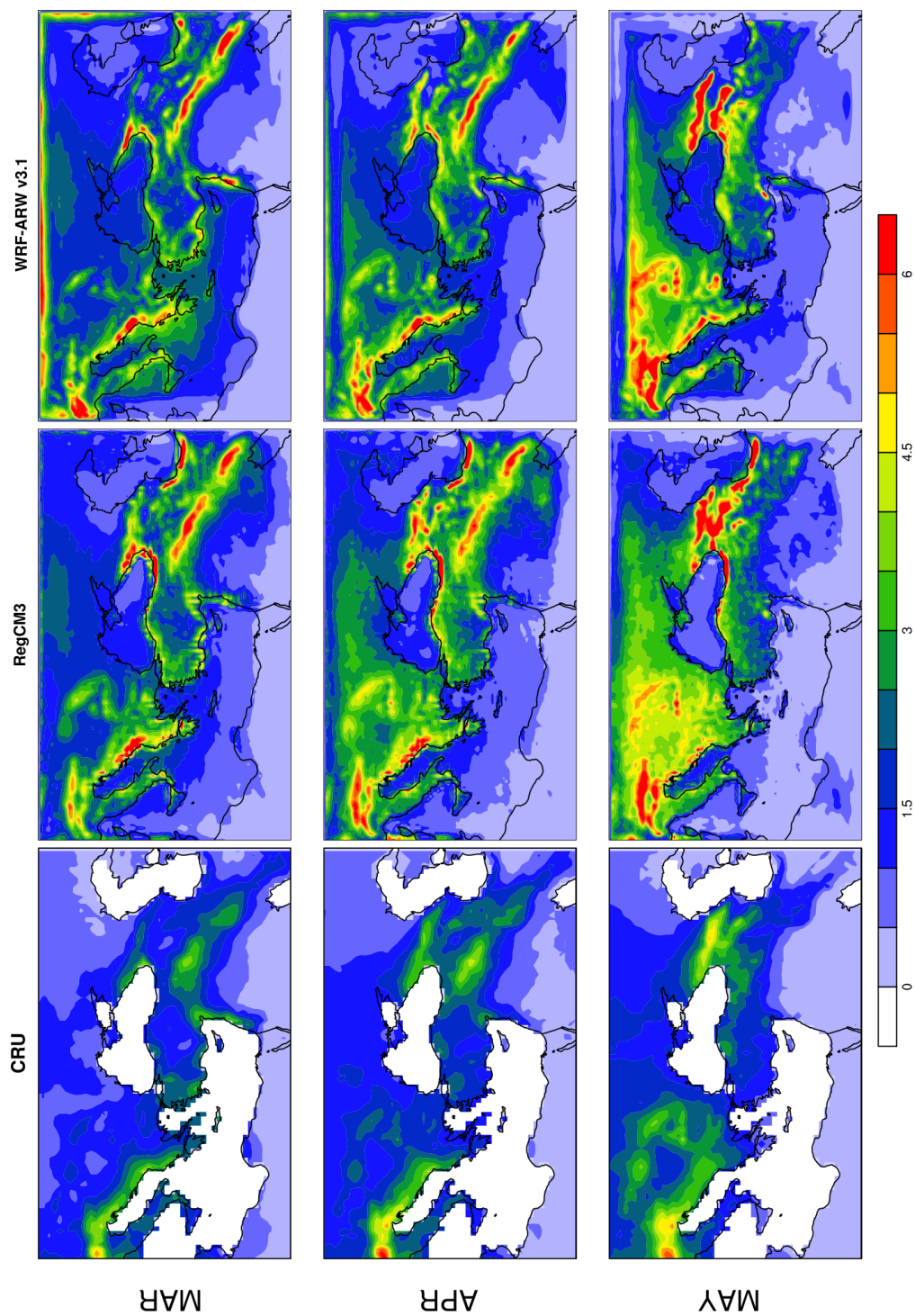


Figure E.22: Monthly mean precipitation distribution (mm/day) for march, april, and may

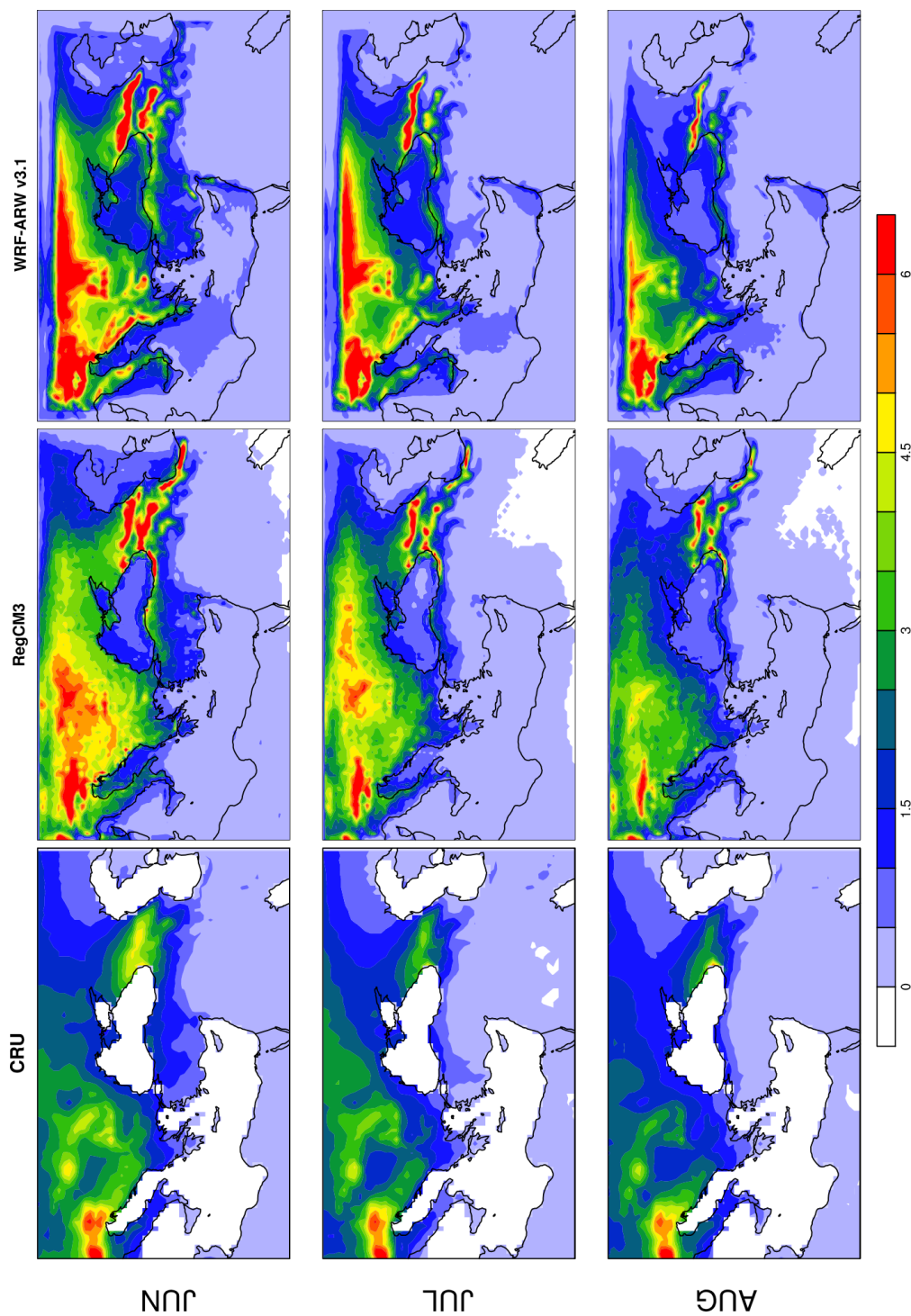


Figure E.23: Monthly mean precipitation distribution (mm/day) for june, july, and august

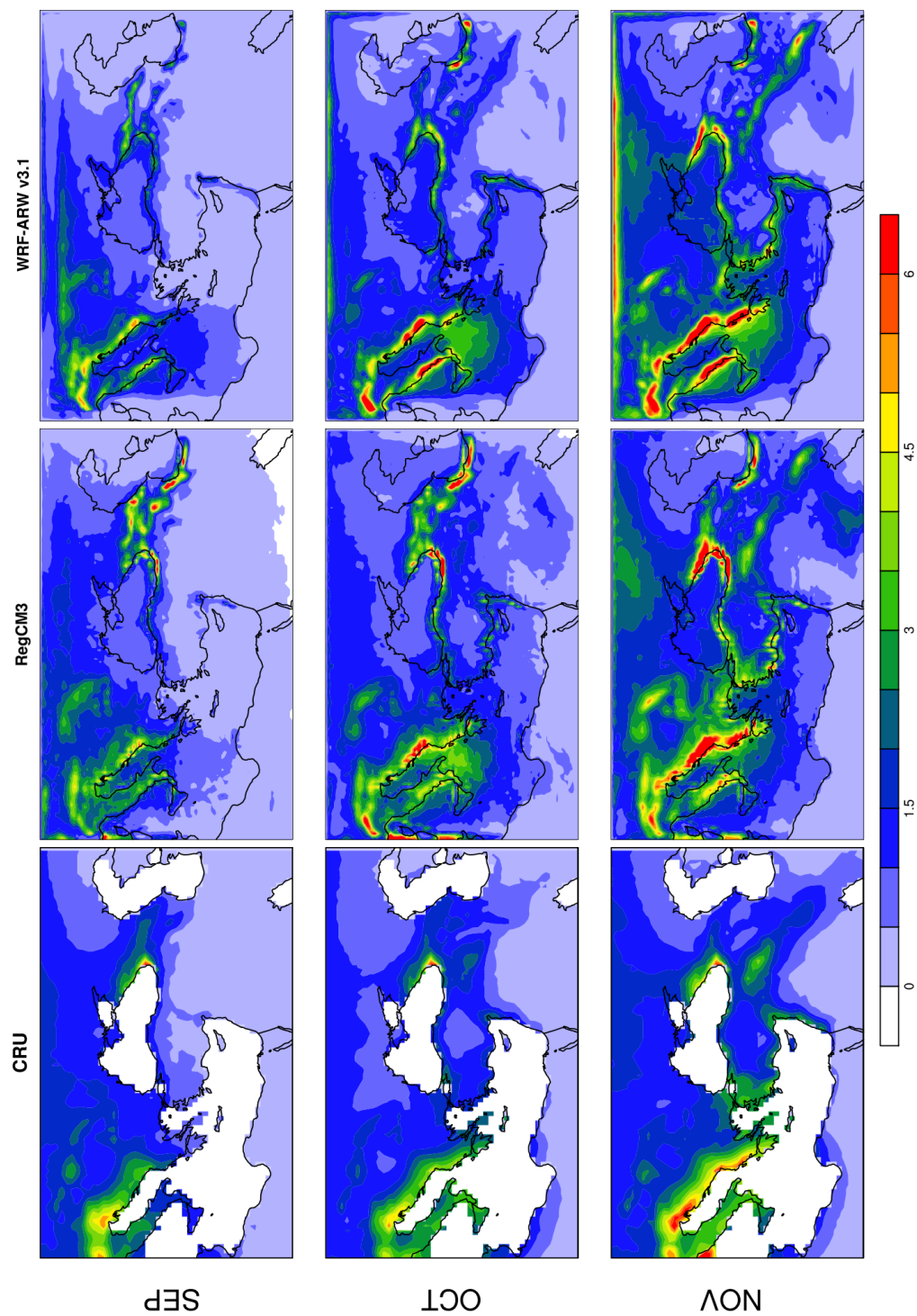


Figure E.24: Monthly mean precipitation distribution (mm/day) for september, october, and november

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- **Ural, D.**, Dalfes, H.N., Sen, O.L., Analysis of the Regional Climate of Turkey with WRF-ARW Model, *European Geosciences Union General Assembly*, April 3–8, Vienna, Austria.