

1 INTRODUCTION AND MOTIVATION

Climate change is one of the most important societal concerns for the 21th century. Climate system and atmospheric chemistry interactions need to be understood in order to optimise any measures for the preservation to slow down climate changes, as required in the Kyoto protocol and others. The air composition may change due to natural variations (volcanoes, natural biomass burning, lightning, etc.) or due to anthropogenic emissions (e.g., from surface and from air traffic). These emissions affect the concentration of radiatively active gases (such as methane, ozone), aerosols and clouds, and, hence, impact climate. Atmospheric chemistry plays a role in climate by controlling the abundances and distributions of natural and anthropogenic agents described above. On the other hand, climate change affects atmospheric composition. For example, increased greenhouse gases cool the stratosphere and may lead to enhanced ozone depletion. Also, climate changes in the troposphere may cause more thunderstorms, more lightning, more nitrogen oxides formation, more upper tropospheric ozone, and hence enhanced radiative forcing. Regional changes in climate, for example, changes in precipitation, storm patterns, and the level of the oceans definitely lead to the changes of people's life quality in the region. Just a few of many interaction processes in climate system are mentioned here. The system and most processes in it are presently far from being understood and require further research. These interactions between physical and chemical processes in climate system are intricate, can be non-linear and often involve feedback. Those interacting components have to be understood both individually and as an ensemble in order to understand and predict how each of the constituents will affect climate and climate change. In particular, good policy decisions rest on understanding how changes in these species sources will affect climate. Unfortunately, these interactions and feedback processes are complex and poorly understood so far. So a detailed level of understanding is needed to deal with the climate system.

There is a great deal of attention being given to short-lived species (such as NO_x , SO_x , O_3 , and black carbon or soot) because of the possibility of a "quick return" as a result of some policy action. Furthermore, these short-lived species are pollutants that need to be addressed for human health and other concerns. Therefore clear understanding of the processes that connect sources (i.e. emissions and precursors) to abundances and the processes that connect the abundances to the climate forcing are essential for an accurate prediction of the future climate and an assessment of the impact of climate change on the earth system. However, because of the variability in space and time for short-lived species, even the current contributions to the climate forcing are not easily evaluated using atmospheric observations alone. Model calculations, especially scaling down to regional scale with higher temporal and spatial resolution, are required.

Tropospheric ozone, one of the important indicator of climate-chemistry interaction, is a significant greenhouse gas with an infrared absorption band in the atmosphere window region, centred at $9.6 \mu m$. Although the amount of ozone in the troposphere is only about 10% of that of the stratosphere, the effective long-wave optical depth of tropospheric ozone is larger on the one hand. The hydroxyl radicals (OH) could also be produced in the troposphere by the

1 INTRODUCTION AND MOTIVATION

action of solar ultraviolet radiation on ozone on the other hand (Levy, 2000). Despite very low atmospheric concentrations, currently estimated at 10^6 mole cm^{-3} (Spivakovsky et al., 2000), OH is responsible for the oxidation of almost all compounds emitted into the atmosphere by natural processes and anthropogenic activities. The lifetimes of most atmospheric gases are, therefore, largely determined by the concentrations of OH and the corresponding photochemical reactions driven by ozone (Levy, 2000). Therefore the regional even local air quality and climate are interconnected. Of greatest importance would be any changes that might take place in the ozone concentration in the tropopause regions as a result of human activities, such as those caused by H_2O , NO_x , SO_2 and particulate emissions from expanding fleets of civil aircraft flying in the stratosphere and upper troposphere. Despite the great importance of tropospheric ozone in atmospheric chemistry, there are still major uncertainties concerning its budget and both global and regional concentration distribution. In Europe the long history records of ozone observation in the time scale of climate are only available for quite a few individual stations. Trends in ozone are hard to detect via observations because of large inter-annual variations and for this reason long time series are needed (Jonson, 2005). This is why the state-of-the-art regional chemistry transport models on European scale are reliable tools to investigate climate chemistry interaction by reproducing meaningful distribution and trends of tropospheric ozone.

Our belief that climate will inexorably change is driven by the very clear evidence of chemical abundance changes in the atmosphere during the last decades. In the past, this belief has led to the development of two separate efforts: to understand and build models to describing the physical climate system and to understand and build models of the chemical climate system. The interaction of two systems has been systematically investigated in community of global climate chemistry modeling since 70s' (Wang et al., 1995). However regional climate chemistry models (chemistry transport model - CTM suitable for long term simulation) become necessary because spatio-temporal distributions are not described accurately in global climate chemistry simulations. Furthermore, regional climate chemistry models are needed for the description of regional climate structures. Regional climate chemistry models help for the evaluation of impact of photochemical pollution on human health and natural ecosystems as well. Consequently it allows the assessment of appropriate emission reduction strategies on a national/continental scale. Significant progress in the development of global and regional CTMs has been obtained from the EUROTRAC-2 sub-project GLOREAM. Over 30 numerical models have been developed and maintained in the framework of GLOREAM. A detailed information list about basic features and examples of studies and scenarios these models have been applied to is given in the GLOREAM final report (Buttiltjes et al., 2003). Let us briefly recall the basic features of some central models widely used in Europe. They are (1) the three-dimensional (3-D) long-range transport model named EUROpean Air Pollution Dispersion (EURAD) covering Europe. EURAD consists of three sub-models for the treatment of meteorology (NCAR/Pennstate University; MM5: Mesoscale model, Version 5), chemistry and transport (EURAD-CTM: Chemistry-Transport-Model) and emission (EEM: EURAD Emission Model). It has been applied to the simulation of a large number of air pollution episodes. The majority of cases has been focusing on ozone and other photo-oxidants, yet aerosols and additional pollutants like sulphur and ammonia have also been analyzed. The module in EURAD for photolysis frequency calculations is described by Madronich (1987) and Chang et al. (1987). Now this system has been involved in chemical weather forecasting. (2) the 3-D chemistry transport model CHIMERE, with which Schmidt et al. (2001), Monteiro et al (2005) performed seasonal simulations of ozone and nitrogen dioxide in summer of 1998

1 INTRODUCTION AND MOTIVATION

and summer of 2001 over West Europe and Portugal, respectively; (3) The EMEP Eulerian Photochemistry Model, which has a horizontal resolution of $50 \times 50 \text{ km}^2$, allows several options with regard to the chemical schemes used. It currently includes two chemistry mechanisms, UNI-ACID and UNI-OZONE, derived from the earlier acidification and oxidant applications of the model (Simpson et al., 2003); (4) A model hierarchy of GEOS-CHEM-REMO-GESIMA in order to interpret results of a global model on regional scales (Langmann, 2000). Its CTM is realized by REMO coupled with RADM2 (Regional Acid Deposition Model, version 2). The photolysis calculation in the chemistry module of this model is still determined off-line with climatological model. This nested model system has focused on Europe, Germany and Brandenburg as well as two episodes FLUMOB 1994 and BERLIOZ 1998 (Langmann et al., 2002; Buttiltjes et al., 2003). The two important differences between RECCM and above models are their treatment of photolysis rate parameters and application of different chemistry mechanisms.

The evaluation and validation about these models in an anonymous way was carried out in GLOREAM model inter comparison studies. The evaluation studies reveal that more research is needed in order to obtain reliable spatial and temporal distributions of atmospheric parameters for the right reasons. The latter criterion is obligatory for forecasting changes in air quality and climate on the longer time scales (Schaller, 2003). This study implies that atmospheric chemistry and transport models are far from being complete. Therefore many aspects of long-term CTM development still require further research. Except to substantially improve model performance one of important direction for this effort is to develop a fully-coupled model which allows chemical-dynamical feedback is able to be examined and investigated quantitatively. On the other hand high performance computers (HPC) are developing so fast that nowadays it is possible to determine chemical and meteorology processes directly together every model time step which allows to assess interaction between all processes of interest. Acceptable CPU time and computing cost for long term simulation allows this kind of fully-coupled climate-chemistry model to reach climate time scale. For the motivation of improving understanding of climate change via a CTM and for the reason of taking advantage of computer technologies this research attempts to develop, evaluate, and validate a new REgional Climate and Chemistry Model (RECCM) on a European scale which should be the third generation of CTM (Peters et al., 1995).

The research was carried out during the period December 2002 to December 2006. The first two years as spin up phase of this research, the author invested time to get insight into the core structure of typical European regional climate model REMO, and review the latest advance of regional CTMs. The following three years the author concentrated on developing, evaluating and validating a new fully coupled CTM model RECCM independently. In order to ensure the model performance and simulation results to be reliable, a great deal of efforts were given to verification and validation of the program code. This thesis principally provides the model development, evaluation and its primary application.

This thesis contains six chapters. After the overview and background introduction the motivation of this study is highlighted in the first chapter. As a review of the physical processes and their governing equations as well as sub-grid parametrization in the model a brief introduction to Regional Model (REMO) is given in Chapter 2. The chemical module and its key components including chemistry mechanism specification, ODEs solver qualification, are discussed in details in Chapter 3. In Chapter 4, based on integration of the prognostic mass conservation equation in each grid cell of a given grid the 3-D chemical transport model is assembled. The methodology and algorithm to deal with horizontal advection, vertical advec-

1 INTRODUCTION AND MOTIVATION

tion and turbulent diffusion, re-distribution caused by large scale convection system, chemical transformation, dry deposition, emission are introduced. An interface between REMO and chemical transport model is proposed and numerically solved. As one of important characteristics of this model the calculation of photolysis rates by using FAST-J algorithm is also discussed in this chapter. Chapter 5 provides the detailed information about the model evaluation and validation based on pre-defined model quality objectives. The baseline simulation of the year 1999 for ozone, nitrogen dioxide and carbon monoxide are discussed, analysed through comparing against observations. With scores derived from MQO the comparison with other model results is also discussed. The model reproduction of one case of early spring ozone in Spain in 1999 is analysed. A high ozone episode in summer 1999 pronounced by European Environment Agency (EEA) is reproduced by RECCM and the results is discussed as well. The Chapter 6 makes a summary of the thesis and describes the remaining problems and limitations. Suggestions for future research focusing on critical open questions are proposed at the end of this chapter.

2 PHYSICAL DESCRIPTION OF RECCM MODEL

The RECCM is a chemical transport model system coupled to the regional climate model REMO. The main features of REMO are introduced first. As the interface between meteorological part and chemical module continuity equation of chemical species is set up. The relevant transport processes are discussed.

2.1 Background about development of REMO

The REMO model was developed 10 years ago to perform the downscaling of the results of global climate simulations to the regional scales. REMO was developed upon the request of the reviewers within the BMBF-Förderschwerpunkt Wasserkreislauf as the atmospheric component of the coupled atmospheric-hydrology model system. Development and application of this system was considered a central task within the international BALTEX (Baltic Sea Experiment). Max-Planck Institute for Meteorology (MPIfM) then was asked to develop the German BALTEX model on the basis of the former numerical weather prediction model Europa Model (EM, (Majewski, 1991)) of the German Weather Service (DWD) in co-operation with DKRZ (Deutsches Klimarechenzentrum), DWD (Deutscher Wetterdienst) and GKSS (Forschungszentrum Geesthacht). These parties agreed in Nov. 93 to develop a regional model suitable for climate modelling and weather forecast mode whilst DKRZ and MPIfM focused on developments needed for the use of REMO (REgional MOdel) in climate mode. REMO runs on various platforms including scalar and vector computers. A parallel version (MPI) is also in use. Horizontal resolutions between $1/10^\circ$ and 1° are currently used for simulations covering time ranges from days to decades. Therefore REMO can be integrated in the weather forecast mode as well as in the climate mode. The parallel version of REMO suitable for high performance computers (HPC) is also available. The following regions have been investigated with REMO: Europe, Arctic, Antarctic, Siberia, Indonesia, India, Brazil, Peru, Africa, North America, Baltic Sea, North Sea, North Atlantic, Pacific Ocean. As a climate research model REMO is also used by about 15 institutes in Germany, France, Switzerland, Greece and China. REMO is coupled to three different hydrology models and three ocean/sea-ice models (Jacob and Podzun, 1997). On evaluation of REMO performance one can refer to results of project QUIRCUS (Quantification of Uncertainties In Regional Climate and climate change Simulations) which is available at QUIRCUS <http://www-1.tu-cottbus.de/BTU/Fak4/Umwmeteo/Quircs/home.html>.

2.2 Model domain and coordinates

As described above REMO is based on EM. The originally dynamic structure of REMO is therefore similar to the EM/DM system (Majewski, 1991). It includes the new physical parametrization package of the global model ECHAM-4 (Roeckner et al., 1996). This approach with the same physics as in global climate model is preferable to assess the scale dependence of physical parametrization within the same dynamical framework. REMO con-

2 PHYSICAL DESCRIPTION OF RECCM MODEL

Orographie

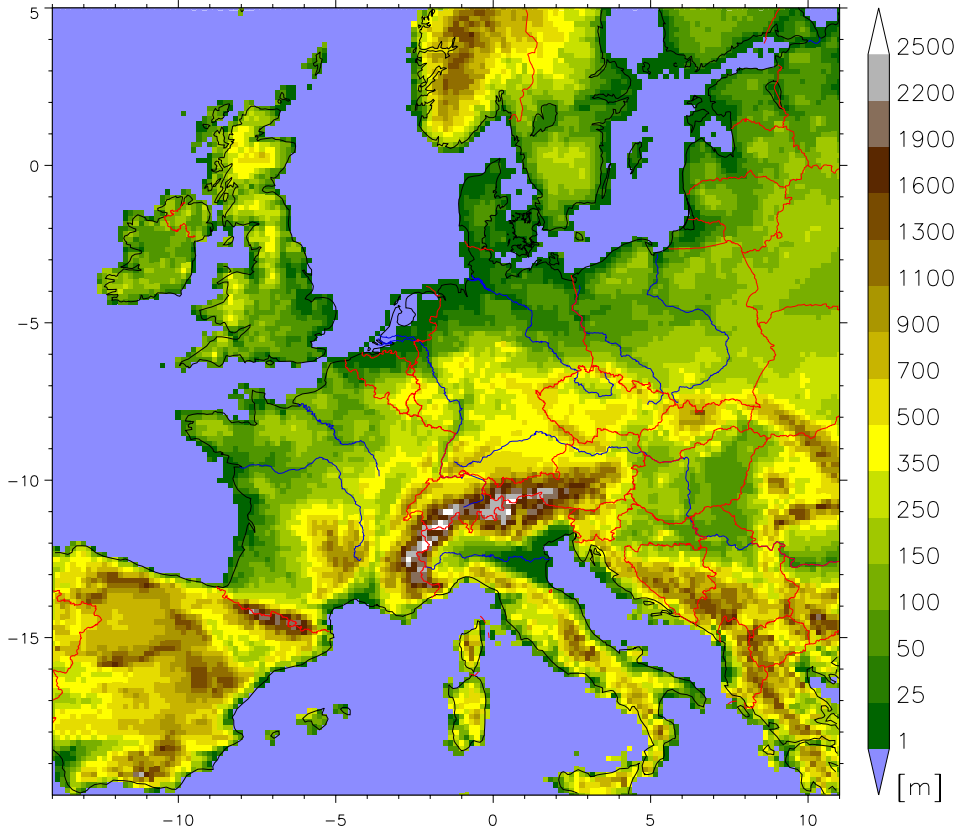


Figure 2.1: The REMO model domain and orography. Ordinate value denotes φ , and abscissa value is λ .

sists 20 vertical layers of unequal depth between the ground and the 25 hPa pressure level. It is based on the primitive equations in a terrain-following hybrid pressure- η coordinate system. Rotated geographical coordinates are used in the horizontal direction. The origin grid point of north polar coordinate is located at -170° E and 32.5° N after rotation. The model grid begins at geographical 6.28° W and 35.82° N as the lower left corner. The horizontal resolution for this research is $1/6^\circ \times 1/6^\circ$ corresponding to approximately $18.5 \text{ km} \times 18.5 \text{ km}$ at 60° N. The number of horizontal grid points is 151×151 . The model domain covered central Europe as shown in Figure 2.1 in rotated coordinate : $\lambda = -14, 11$, $\varphi = -20, 5$. The prognostic variables are surface pressure p , temperature T , horizontal wind components u , v , cloud water content q_{mw} and water vapour content q_m . The model uses the Arakawa C grid for the spatial discretizations with these variables defined on the staggered grid illustrated in Figure 2.2. In vertical direction these variables except surface pressure are defined at full level. Vertical velocity and geopotential height are defined at half level. The pressure at full level is defined as full level pressure, it is termed as half level pressure otherwise. The meteorology at boundaries is updated every 6 hours by ECMWF reanalysis data (ERA40). ECMWF/ERA40 time-dependent fields consist of surface pressure, horizontal velocities, temperature and spe-

2 PHYSICAL DESCRIPTION OF RECCM MODEL

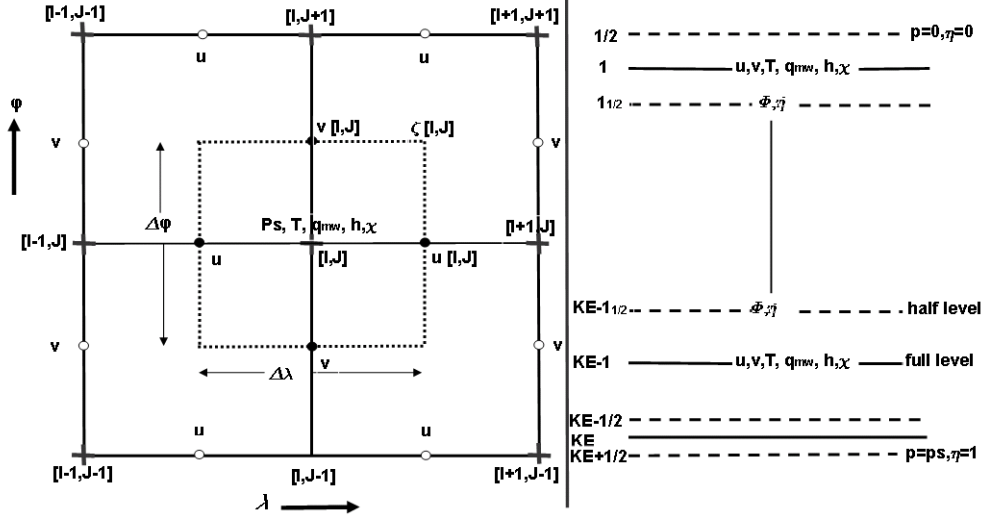


Figure 2.2: The Arakawa C grid cell (left panel) for horizontal arrangement of variables (u , v , p_s , T , q_{mw} , h , and vorticity ζ), large cross is C-grid point at cell center for pressure and other scalar variables. The advection velocities (u , v) are at C-grid points on cell faces. The vertical grid configuration of η system (right panel). There are KE+1 interfaces defined as half levels (dashed lines) including top and bottom, and KE full levels (solid lines) which are regarded as mid-layer of vertical grid cell. In this study KE=20. η denotes vertical velocity and p denotes pressure.

cific humidity. Therefore the model atmosphere stays close to the real-weather situation. In addition horizontal distributions for four climatological types of aerosols (oceanic, desert, urban, and stratospheric background) are defined.

2.3 Governing equations in REMO

Vertical coordinate and pressure

The vertical coordinate η defined as

$$\eta = \frac{p}{p_0}; \quad 0 \leq p \leq p_T$$

$$\eta = \frac{p-p_T}{p_s-p_T} + \frac{p_T}{p_0} \cdot \frac{p_s-p}{p_s-p_T}; \quad p_T \leq p \leq p_s \quad (2.1)$$

$$\frac{\partial p}{\partial \eta} = p_0; \quad 0 \leq p \leq p_T$$

$$\frac{\partial p}{\partial \eta} = \frac{p_0(p_s-p_T)}{p_0-p_T}; \quad p_T \leq p \leq p_s \quad (2.2)$$

$$p = A(\eta) + p_s B(\eta) \quad (2.3)$$

$$A(\eta) = p_0 \eta \quad B(\eta) = 0; \quad 0 \leq \eta \leq \eta_T$$

$$A(\eta) = \frac{p_0 p_T}{p_0 - p_T} (1 - \eta) \quad B(\eta) = \frac{p_0 \eta - p_T}{p_0 - p_T}; \quad \eta_T \leq \eta \leq 1 \quad (2.4)$$

2 PHYSICAL DESCRIPTION OF RECCM MODEL

where $p_0 = 1000 \text{ hPa}$ a standardization constant, p is air pressure; p_s is the surface pressure. $p_T = 220 \text{ hPa}$ is defined as a reference pressure with the level η_T below which a hybrid vertical coordinate is used, above which horizontally homogeneous pressure coordinate is utilized. $\eta_T = p_T/p_0 = 0.220$ in this application. Then $\eta = 1$ when $p = p_s$ and $\eta \sim p/p_0$ as $p \rightarrow 0$. η is a fraction ≤ 1 and varies monotonically from 1 when $p = p_s$ to 0 when $p = 0$.

Continuity equation and vertical boundary conditions

The continuity equation for air in spherical- η coordinates is

$$\frac{\partial}{\partial t} \left(\frac{\partial p}{\partial \eta} \right) + \frac{1}{a \cos \varphi} \left\{ \frac{\partial}{\partial \lambda} \left(u \frac{\partial p}{\partial \eta} \right) + \frac{\partial}{\partial \varphi} \left(v \cos \varphi \frac{\partial p}{\partial \eta} \right) \right\} + \frac{\partial}{\partial \eta} \left(\dot{\eta} \frac{\partial p}{\partial \eta} \right) = -\mu_R \left(\frac{\partial p}{\partial \eta} - \frac{\partial p_R}{\partial \eta} \right) \quad (2.5)$$

where t is time, $a = 6371229 \text{ m}$ the earth radius, u and v are zonal and meridional wind components in rotated coordinates and $\dot{\eta}$ is vertical velocity in η coordinate system. No air mass flux at the model top is assumed, and no air mass penetrates the ground surface. $\dot{\eta} = 0$ at the model top $\eta = 0$ and $\dot{\eta} = 0$ at model surface $\eta = 1$. μ_R is relaxation coefficient, which is non-zero only in the boundary zone, the time step-dependent values of μ_R is derived according to Davies' lateral boundary scheme. p_R is an externally specified field of pressure from reanalysis data ECMWF/ERA40 interpolated to the grid of REMO.

Equations for surface pressure p_s and vertical velocity $\dot{\eta}$

Explicit expression for the rate of change of surface pressure p_s , and for $\dot{\eta}$, are obtained by integrating 2.5 using the boundary condition $\dot{\eta} = 0$ at both $\eta = 0$ and $\eta = 1$:

$$\frac{\partial p_s}{\partial t} = -\frac{1}{a \cos \varphi} \int_0^1 \left\{ \frac{\partial}{\partial \lambda} \left(u \frac{\partial p}{\partial \eta} \right) + \frac{\partial}{\partial \varphi} \left(v \cos \varphi \frac{\partial p}{\partial \eta} \right) \right\} d\eta - \mu_R (p_s - p_{sR}) \quad (2.6)$$

Integration 2.5 from $\eta = 0$ to a specified level η_k . Equation for vertical velocity $\dot{\eta}$ defined as modified vertical velocity $\dot{\eta}^*$:

$$\begin{aligned} \dot{\eta}^*|_{\eta_k} &= \left(\dot{\eta} \frac{\partial p}{\partial \eta} \right)_{\eta_k} = - \left(\frac{\partial p}{\partial p_s} \right)_{\eta_k} \left(\frac{\partial p_s}{\partial t} + \mu_R (p_s - p_{sR}) \right) \\ &\quad - \frac{1}{a \cos \varphi} \int_0^{\eta_k} \left\{ \frac{\partial}{\partial \lambda} \left(u \frac{\partial p}{\partial \eta} \right) + \frac{\partial}{\partial \varphi} \left(v \cos \varphi \frac{\partial p}{\partial \eta} \right) \right\} d\eta \end{aligned} \quad (2.7)$$

Equation for wind components u and v

$$\begin{aligned} \frac{\partial u}{\partial t} - \frac{1}{\cos \varphi} Q \frac{\partial p}{\partial \eta} v \cos \varphi + \frac{1}{a \cos \varphi} \frac{\partial}{\partial \lambda} (\Phi + K) + \frac{RT_v}{a \cos \varphi} \frac{\partial}{\partial \lambda} \ln p + \dot{\eta} \frac{\partial u}{\partial \eta} \\ = F_H^u - g \left(\frac{\partial p}{\partial \eta} \right)^{-1} \frac{\partial \tau_\lambda}{\partial \eta} + \left(\frac{\partial u}{\partial t} \right)_{sub} - \mu_R (u - u_R) \end{aligned} \quad (2.8)$$

2 PHYSICAL DESCRIPTION OF RECCM MODEL

$$\begin{aligned} \frac{\partial v}{\partial t} + Q \frac{\partial p}{\partial \eta} u + \frac{1}{a} \frac{\partial}{\partial \varphi} (\Phi + K) + \frac{RT_v}{a} \frac{\partial}{\partial \varphi} \ln p + \dot{\eta} \frac{\partial v}{\partial \eta} \\ = F_H^v - g \left(\frac{\partial p}{\partial \eta} \right)^{-1} \frac{\partial \tau_\varphi}{\partial \eta} + \left(\frac{\partial v}{\partial t} \right)_{sub} - \mu_R (v - v_R) \end{aligned} \quad (2.9)$$

here Q is potential absolute vorticity

$$Q = \frac{\zeta + f}{\partial p / \partial \eta} = \left(\frac{\partial p}{\partial \eta} \right)^{-1} \left\{ f + \frac{1}{a \cos \varphi} \left(\frac{\partial v}{\partial \lambda} - \frac{\partial}{\partial \varphi} (u \cos \varphi) \right) \right\} \quad (2.10)$$

with the Coriolis parameter f

$$f = 2\Omega (\sin \varphi \sin \varphi_{GN} + \cos \varphi \cos \varphi_{GN} \cos(\lambda - \lambda_{GN})) \quad (2.11)$$

K is the mass specific kinetic energy

$$K = \frac{1}{2} \left(\bar{u}^2 + \frac{1}{\cos^2 \varphi} \overline{v^2} \right) \quad (2.12)$$

the virtual temperature T_v is defined as:

$$T_v = T \left\{ 1 + \left(\frac{R_m}{R} - 1 \right) q_m \right\} \quad (2.13)$$

Equations for specific volume α and ω

$$p\alpha = RT_v \quad (2.14)$$

$$(\alpha\omega)_{\eta_k} = (RT_v)_{\eta_k} \left(\frac{\omega}{p} \right)_{\eta_k} \quad (2.15)$$

ω is originally given in vertical η coordinate by (Simmons and Burridge, 1981)

$$\omega \equiv \frac{dp}{dt} = - \int_0^\eta \nabla \cdot \left(\mathbf{V} \frac{\partial p}{\partial \eta} \right) d\eta + \mathbf{V} \cdot \nabla p$$

which is converted into REMO rotated sphere coordinate by

$$\begin{aligned} \left(\frac{\omega}{p} \right)_{\eta_k} = \frac{1}{p_{\eta_k}} \left[- \left(\frac{\partial p}{\partial p_s} \right)_{\eta_k} \mu_R (p_s - p_{sR}) - \frac{1}{a \cos \varphi} \int_0^{\eta_k} \left\{ \frac{\partial}{\partial \lambda} \left(u \frac{\partial p}{\partial \eta} \right) + \frac{\partial}{\partial \varphi} \left(v \cos \varphi \frac{\partial p}{\partial \eta} \right) \right\} d\eta \right] \\ + \frac{1}{a \cos \varphi} \left(u \frac{\partial}{\partial \lambda} \ln p + v \cos \varphi \frac{\partial}{\partial \varphi} \ln p \right)_{\eta_k} \end{aligned} \quad (2.16)$$

while geopotential Φ is given by integrating hydrostatic equation with $\Phi|_{\eta=1} = \Phi_s$ and Equation 2.14, Φ_s is the surface geopotential.

$$\frac{\partial \Phi}{\partial \eta} = - \frac{RT_V}{p} \frac{\partial p}{\partial \eta} \quad (2.17)$$

2 PHYSICAL DESCRIPTION OF RECCM MODEL

Equations for temperature T , specific humidity q_m and cloud water content q_w

$$\begin{aligned} & \frac{\partial T}{\partial t} + \frac{1}{a \cos \varphi} \left(u \frac{\partial T}{\partial \lambda} + v \cos \varphi \frac{\partial T}{\partial \varphi} \right) + \dot{\eta} \frac{\partial T}{\partial \eta} \\ &= \frac{\alpha \omega}{c_p} + F_H^T - g \left(\frac{\partial p}{\partial \eta} \right)^{-1} \frac{\partial \eta_T}{\partial \eta} + \left(\frac{\partial T}{\partial t} \right)_{sub} + \frac{L_v}{c_p} C_{MW}^q - \mu_R (T - T_R) \end{aligned} \quad (2.18)$$

$$\begin{aligned} & \frac{\partial q_m}{\partial t} + \frac{1}{a \cos \varphi} \left(u \frac{\partial q_m}{\partial \lambda} + v \cos \varphi \frac{\partial q_m}{\partial \varphi} \right) + \dot{\eta} \frac{\partial q_m}{\partial \eta} \\ &= F_H^{q_m} - g \left(\frac{\partial p}{\partial \eta} \right)^{-1} \frac{\partial \eta_{q_m}}{\partial \eta} + \left(\frac{\partial q_m}{\partial t} \right)_{sub} - C_{MW}^q - \mu_R (q_m - q_{mR}) \end{aligned} \quad (2.19)$$

$$\begin{aligned} & \frac{\partial q_w}{\partial t} + \frac{1}{a \cos \varphi} \left(u \frac{\partial q_w}{\partial \lambda} + v \cos \varphi \frac{\partial q_w}{\partial \varphi} \right) + \dot{\eta} \frac{\partial q_w}{\partial \eta} \\ &= F_H^{q_w} - g \left(\frac{\partial p}{\partial \eta} \right)^{-1} \frac{\partial \eta_{q_w}}{\partial \eta} + \left(\frac{\partial q_w}{\partial t} \right)_{sub} + C_{MW}^q - \mu_R (q_w - q_{wR}) \end{aligned} \quad (2.20)$$

Equations for specific enthalpy h and specific water content q_{mw}

$$h = c_p T - L_v q_m \quad (2.21)$$

$$q_{mw} = q_m + q_w \quad (2.22)$$

$$\begin{aligned} & \frac{\partial h}{\partial t} + \frac{1}{a \cos \varphi} \left(u \frac{\partial h}{\partial \lambda} + v \cos \varphi \frac{\partial h}{\partial \varphi} \right) + \dot{\eta} \frac{\partial h}{\partial \eta} \\ &= \alpha \omega + F_H^h - g \left(\frac{\partial p}{\partial \eta} \right)^{-1} \frac{\partial \eta_h}{\partial \eta} + \left(\frac{\partial h}{\partial t} \right)_{sub} - \mu_R (h - h_R) \end{aligned} \quad (2.23)$$

$$\begin{aligned} & \frac{\partial q_{mw}}{\partial t} + \frac{1}{a \cos \varphi} \left(u \frac{\partial q_{mw}}{\partial \lambda} + v \cos \varphi \frac{\partial q_{mw}}{\partial \varphi} \right) + \dot{\eta} \frac{\partial q_{mw}}{\partial \eta} \\ &= F_H^{q_{mw}} - g \left(\frac{\partial p}{\partial \eta} \right)^{-1} \frac{\partial \eta_{q_{mw}}}{\partial \eta} + \left(\frac{\partial q_{mw}}{\partial t} \right)_{sub} - \mu_R (q_{mw} - q_{mwR}) \end{aligned} \quad (2.24)$$

where p_R , p_{sR} , T_R , h_R , u_R , v_R , q_{mR} , q_{wR} and q_{mwR} are initial boundary fields specified by ECMWF reanalysis data (ERA40) and updated every six hours.