Gravity Waves in Polar Mesosphere and Lower Thermosphere Revealed in Whole-atmospheric Global Atmospheric Model

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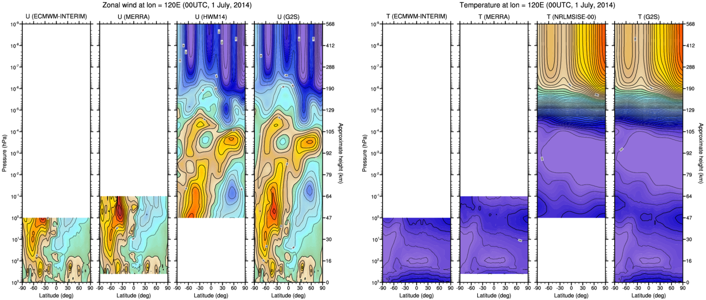
Motivation and Methodology

- Explicit simulation of gravity waves from the troposphere to the lower thermosphere using a whole atmosphere global model initialized at specific date and time
- Understanding of the propagation of gravity waves throughout the whole atmosphere and identification of wave sources for dynamically interesting events, especially in the polar regions
- Method
  1. Atmospheric states at specific date and time using reanalyses and empirical models (HWM14 and NRLMSISE-00)
  2. Dynamically balanced initial condition generated using a stand-alone CAM spectral element (SE) dynamical core on the cubed-sphere grid
  3. Horizontally and vertically high-resolution global model based on SC-WACCM with the SE dycore

Atmospheric states from ground to space

- Data fusion
  - ECMWF Interim reanalysis (0.75°, Ground – 1 hPa)
  - MERRA reanalysis (0.66°, 400 hPa – 0.1 hPa)
  - HWM14 and NRLMSISE-00 (0.75°, 1 hPa – 10^{-9} hPa)
- Contiguous vertical profiles
  - Fitting of a smooth curve represented by cubic-spline basis function to the above-mentioned wind and temperature data



- Surface pressure correction for model topography

Dynamical balance using mechanistic model

- Mechanistic model
  - Local time variations of wind and temperature are specified
  - Same horiz. and vert. resolutions as in full atmospheric model
  - Same topography as in full atmospheric model
  - Model is run until a steady state is reached

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\zeta + f)\,\widehat{\boldsymbol{k}} \times \boldsymbol{v} + \nabla_\eta \left(\frac{1}{2} \boldsymbol{v} \cdot \boldsymbol{v} + \Phi \right) + \dot{\eta} \frac{\partial \boldsymbol{v}}{\partial \eta} + \frac{R_d T_v}{p} \nabla_\eta p = \boldsymbol{D}_{\boldsymbol{v}} - \left(\frac{\partial \boldsymbol{v}}{\partial t} \right)_{\text{specified}}$$

$$\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \nabla_\eta T + \dot{\eta} \frac{\partial T}{\partial \eta} - \frac{R_d T_v}{c_{pd} p} \omega = D_T - \left(\frac{\partial T}{\partial t} \right)_{\text{specified}}$$

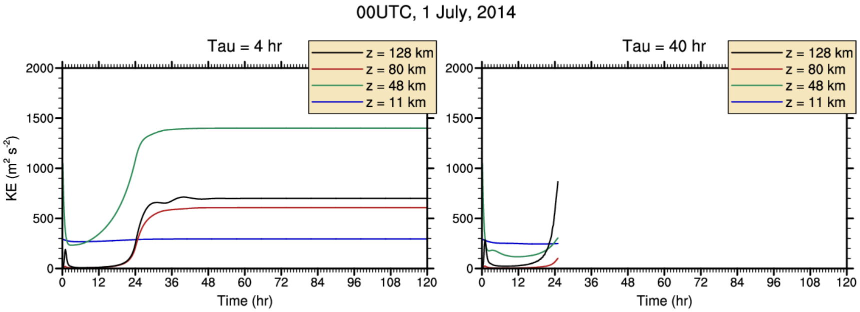
$$\frac{\partial p}{\partial \eta} \dot{\eta} + \frac{\partial p}{\partial t} + \int_{\eta_t}^{\eta} \nabla_{\eta'} \cdot \left(\frac{\partial p}{\partial \eta'} \boldsymbol{v} \right) d\eta' = 0$$

$$\frac{\partial p_s}{\partial t} + \int_{\eta_t}^{\eta_s} \nabla_{\eta'} \cdot \left(\frac{\partial p}{\partial \eta'} \boldsymbol{v} \right) d\eta' = 0$$

$$\boldsymbol{D}_{\boldsymbol{v}} = -\frac{\boldsymbol{v} - \boldsymbol{v}_{\text{ini}}}{\tau} \quad D_T = -\frac{T - T_{\text{ini}}}{\tau}, \quad \tau = 4 \text{ hr}$$

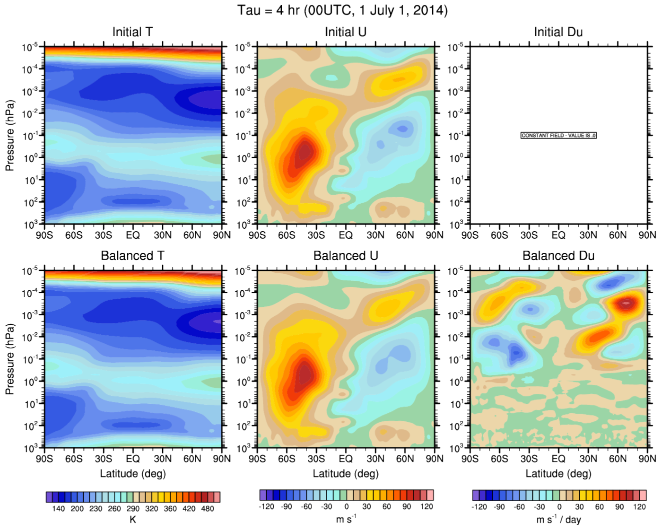
Time series of global-mean KE

- 5-day run of mechanistic model
- Strong and deep Rayleigh damping for initial 1 hr
    - Fast initial spurious gravity waves are damped
- Mechanistic model does not converge for weak $\boldsymbol{D_v}$
    - $\boldsymbol{D_v}$: diffusive momentum forcing
        - $\boldsymbol{D_v}$ = GWD + tidal forcing + turbulent diffusion + etc
    - Balanced wind requires diffusive momentum forcing



Initial and balanced states

- Zonal-mean T, U, D_u in 00UTC, 1 July, 2014

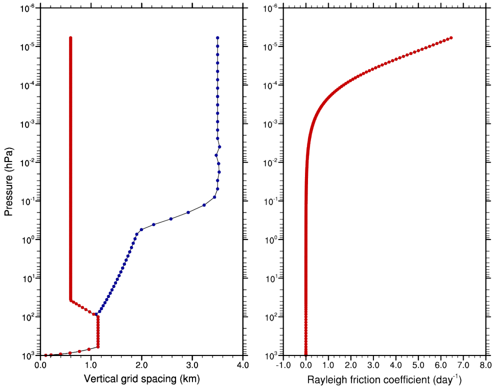


High-resolution SC-WACCM

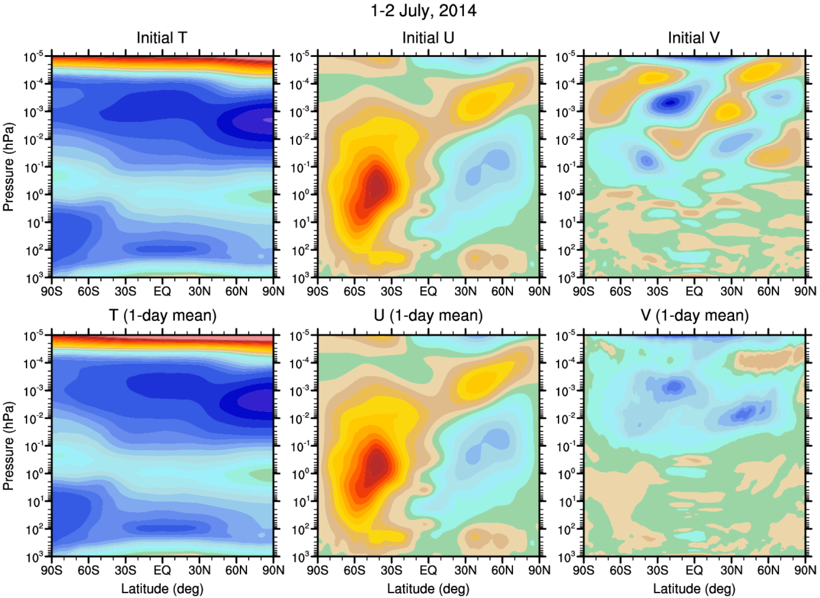
- SC-WACCM (Specified Chemistry WACCM)
  - Spectral element dynamical core on the cubed-sphere grid
  - Prognostic variables : U, V, T, δp
  - Specified radiatively active chemical constituent distributions
  - Specified non-LTE solar radiation
- Resoluton
  - Horizontally 0.5° resolution (ne60np4)
  - 210 vertical layers from the ground to the WACCM top
  - Dynamical time step : 7.5 s
- Hyperviscosity (4th-order linear diffusion)
  - $\nu_{\mathrm{vort}} = 1.0 \times 10^{14}\ \mathrm{m}^4\ \mathrm{s}^{-1}$, and $\nu_{\mathrm{div}} = 2.5 \times 10^{14}\ \mathrm{m}^4\ \mathrm{s}^{-1}$
- Physics modification (mostly called every 600 s)
  - RRTMG is used for faster computation (called every 1 hr)
  - Holtslag and Boville (93) vertical mixing (modified *Ri* criteria)
  - Rayleigh damping to handle lack of damping mechanism
  - GWD efficiency factors are reduced to 25%

Model layers and Rayleigh damping

- Model layers
  - Vertical grid spacing for $p > 90$ hPa is unchanged
  - For $p < 40$ hPa, $\Delta z \approx 600$ m (for scale height of 7 km)
- Rayleigh damping
  - Strong damping above the mesopause ($p < 10^{-3} - 10^{-4}$ hPa)

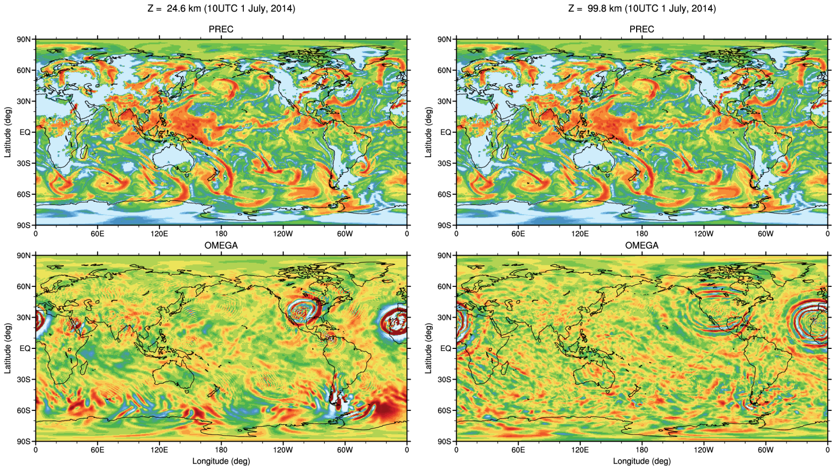


Result after 1 day: Zonal-mean



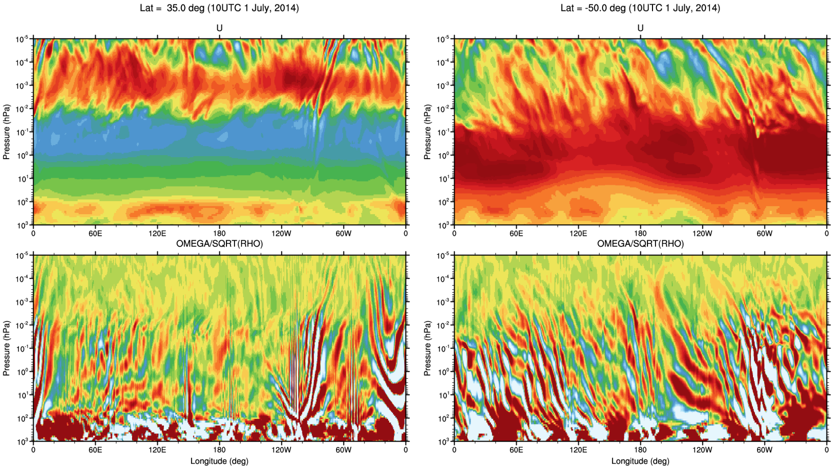
Result at 10 hr: Precipitation and ω

- Precipitation and ω at 25 km and 100 km
  - Convective GWs in the northern hemisphere
  - Mountain and frontal GWs in the southern hemisphere



Result at 10 hr: U and $\omega/\sqrt{\rho_0}$

- U and $\omega/\sqrt{\rho_0}$ at latitude = 35N and 50S
  - Convective GWs in the northern hemisphere
  - Mountain and frontal GWs in the southern hemisphere



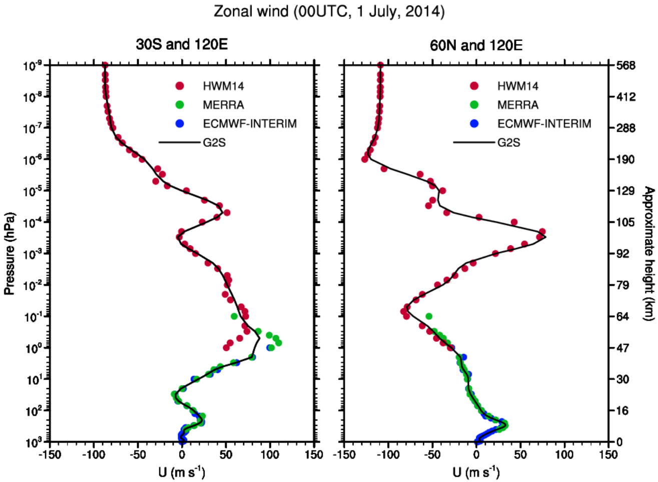
Summary and future plans

- Summary
  - Hindcast simulation using hi-res SC-WACCM
    - L210 with $\Delta z \approx 600m$ for $p < 40$ hPa
    - 0.5 deg simulations from 00UTC, July 1, 2014
    - Initial states obtained from reanalyses and empirical models
    - Dynamically balanced initial states are generated using mechanistic model
  - Explicitly simulated gravity waves (GWs) in the MLT region
    - High-frequency convective GWs in the NH high latitudes
    - Mountain and frontal GWs in the SH high latitudes
- Future plans
  - $1/4^\circ$ simulations
  - Comparison with GW observations
    - Meteor radar observations at around $z = 90$ km at King Sejong Station, Antarctica, operated by KOPRI
  - Case study for stratospheric sudden warming (SSW) events
    - GW propagation and interaction with large-scale flow when SSWs occur

Thank you for your attention

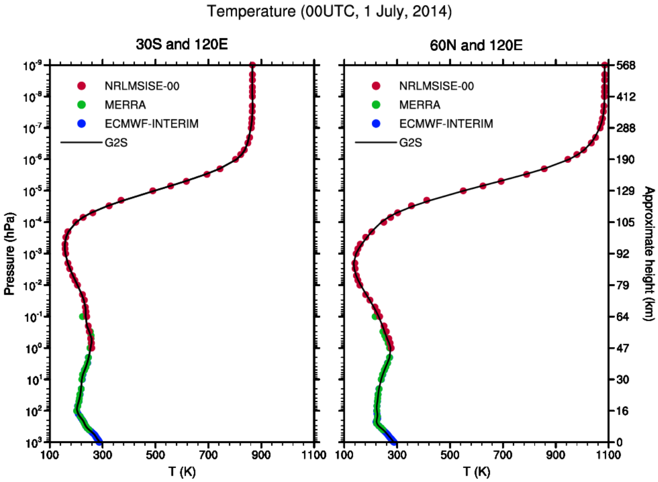
Backup: Ground to space - I

- Vertical profiles of fitting curves for U



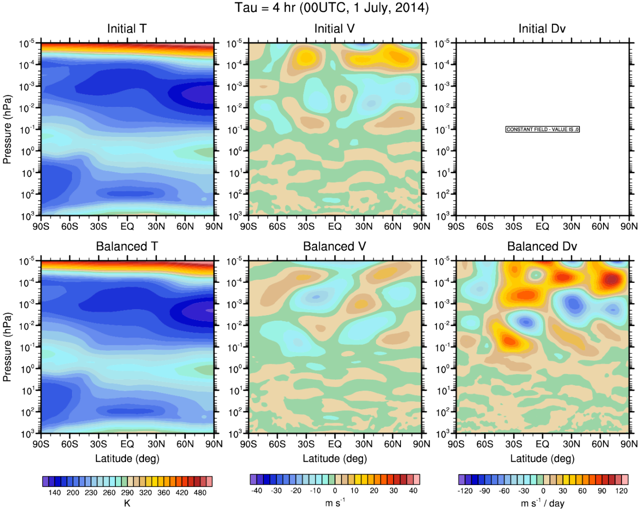
Backup: Ground to space - II

- Vertical profiles of fitting curves for T



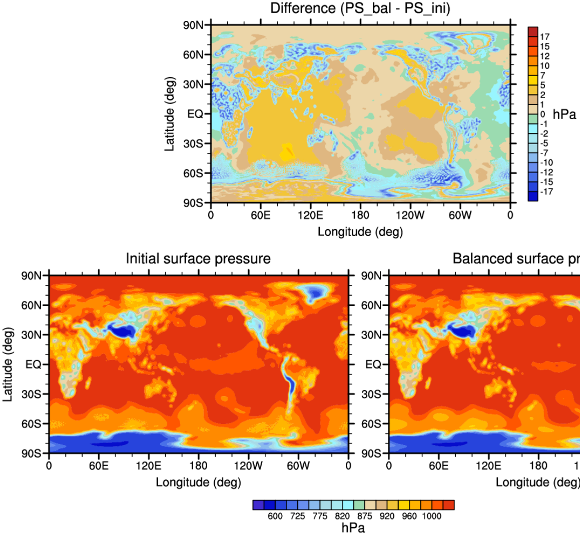
Backup: Balanced state - I

- Zonal-mean T, V, D_v in 00UTC, 1 July, 2014



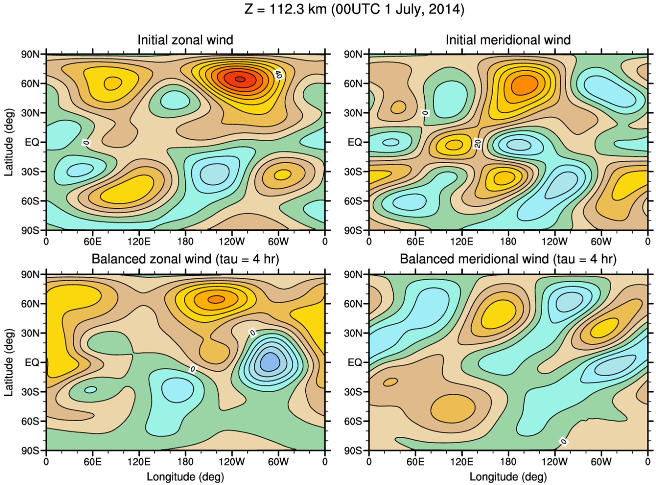
Backup: Balanced state - II

- Surface pressure difference in 00UTC, 1 July, 2014



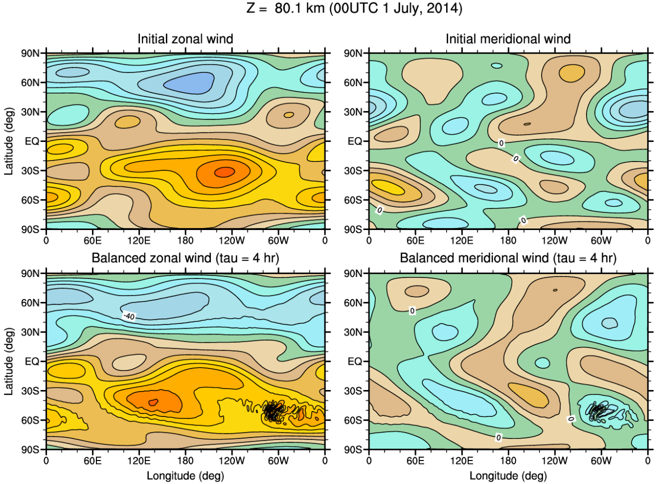
Backup: Balanced state - III

- Horizontal wind at z = 112 km in 00UTC, 1 July, 2014



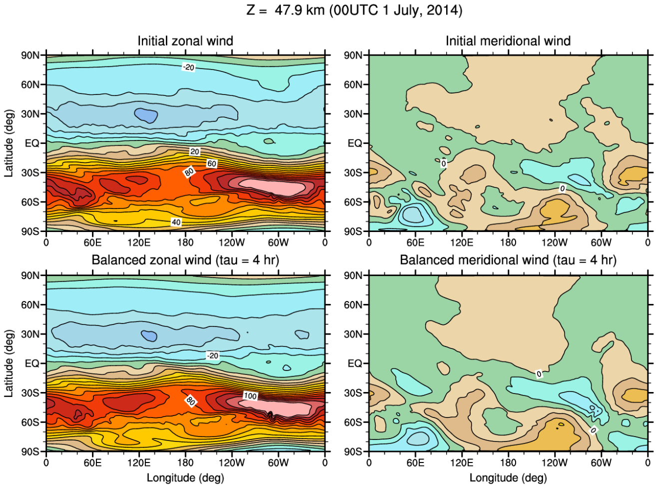
Backup: Balanced state - IV

- Horizontal wind at z = 80 km in 00UTC, 1 July, 2014

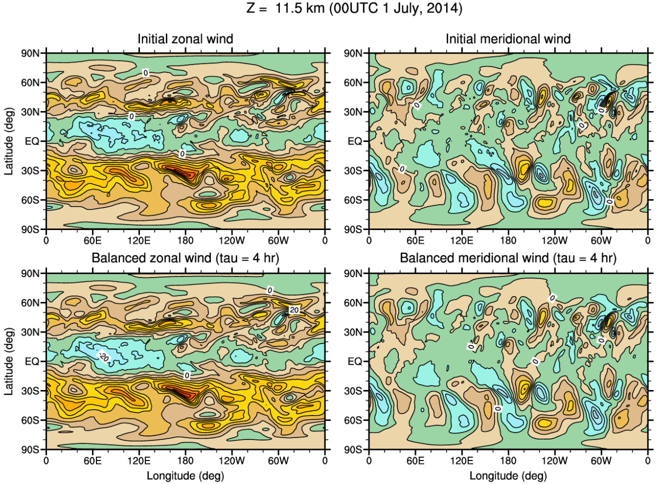


Backup: Balanced state - V

- Horizontal wind at z = 48 km in 00UTC, 1 July, 2014



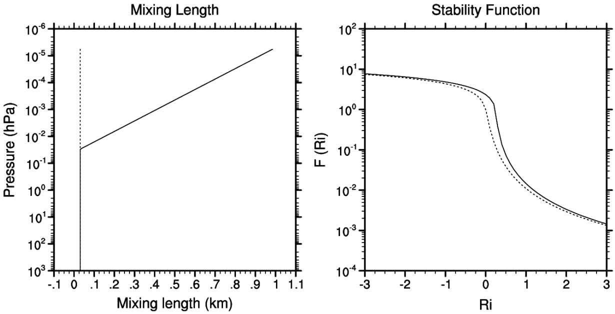
- Horizontal wind at z = 12 km in 00UTC, 1 July, 2014



Backup: Modification in vertical mixing

- Mixing length (l_m)
  - $l_m = 30$ m for $p > 0.03$ hPa
  - Vertical increase of l_m for $p < 0.03$ hPa
- Critical Richardson number for stability function

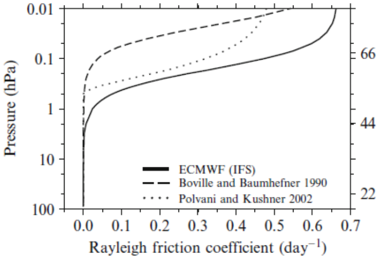
$$F(Ri) = \sqrt{1 - 18(Ri - Ri_c)} \quad \text{for} \qquad Ri \leq Ri_c (= 0.25)$$
$$= [1 + 10(Ri - Ri_c)(1 + 8(Ri - Ri_c))]^{-1} \quad \text{for} \qquad Ri > Ri_c (= 0.25)$$



Backup: Rayleigh damping in other models

- Other models
  - Coefficients for 0.5–0.7 day^{-1} at 0.01 hPa in other models
- Hi-res SC-WACCM
  - 7 day^{-1} at 10^{-5} hPa
  - Not excessive in a sense of vertical extrapolation of Rayleigh coefficients in other models

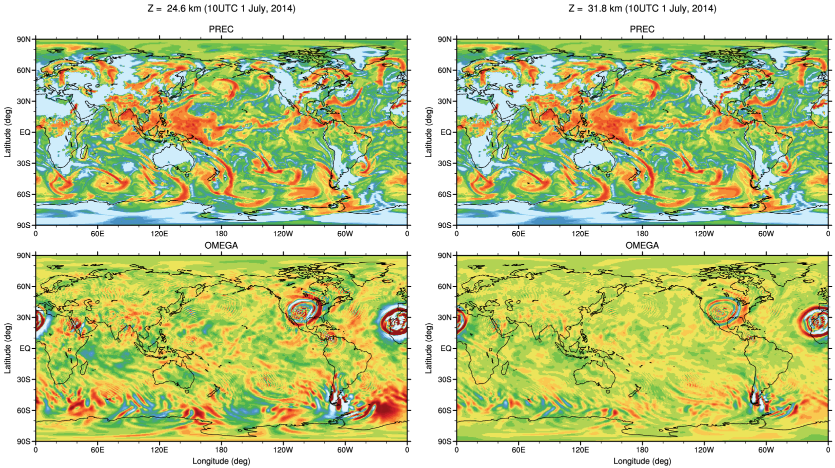
Fig. 13.9 Vertical profiles of three Rayleigh friction coefficients k_R in units day^{-1}



Adapted from Chapter 13 by Jablonowski and Williamson in

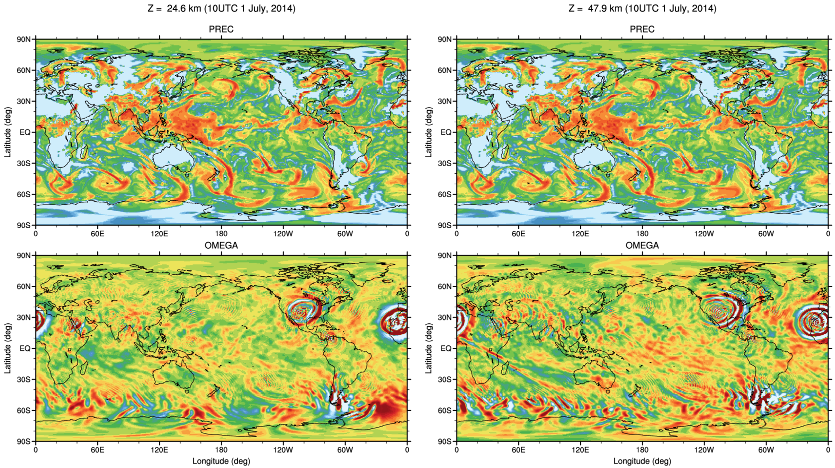
Numerical Techniques for Global Atmospheric Models (Lauritzen et al., Eds., 2011, Springer-Verlag)

- Precipitation and ω at 25 km and 32 km
  - Convective GWs in the northen hemisphere
  - Mountain and frontal GWs in the southern hemisphere



Backup: Result at 10 hr - II

- Precipitation and ω at 25 km and 48 km
  - Convective GWs in the northern hemisphere
  - Mountain and frontal GWs in the southern hemisphere



- Precipitation and ω at 25 km and 64 km
  - Convective GWs in the northern hemisphere
  - Mountain and frontal GWs in the southern hemisphere