Portable University Model of the Atmosphere (PUMA)

Dynamical core of the PlanetSimulator (University Hamburg)

Original version

- Global spectral general circulation model of the dry atmosphere
- Numerical solution of hydrostatic EULER equations for an ideal gas on a rotating sphere
- Diabatic, dissipative processes: only Newtonian Cooling and Rayleigh friction

Simple physics extension

- Inclusion of a vapor vapor transport equation
- Boundary layer and condensation scheme by Reed and Jablonowski (2011)

Summary of the governing PUMA equations

$$\text{Vorticity}: \frac{\partial \eta}{\partial t} = \nabla_h \cdot \left(\mathbf{k} \times \mathbf{F}_{\mathbf{v}_h}\right) + D_\eta$$

$$\text{Divergence}: \frac{\partial D}{\partial t} = -\nabla_h \cdot \mathbf{F}_{\mathbf{v}_h} + \nabla^2{}_h \left(\frac{\mathbf{v}_h^{\,2}}{2} \cos^2(\varphi) + \phi + RT \ln(p_s) \right) + D_D$$

$$\text{Temperature}: \frac{\partial T}{\partial t} = -\nabla_h \cdot (\mathbf{v}_h T) + DT - \dot{\sigma} \frac{\partial T}{\partial \sigma} + \frac{\kappa T}{p} \frac{Dp}{Dt} + D_T$$

$$\text{Water vapor}: \frac{\partial}{\partial t}\left(p_s q\right) = -\nabla_h \cdot (\mathbf{v}_h p_s q) - \frac{\partial}{\partial \sigma}\left(\dot{\sigma} p_s q\right) + D_q$$

$$\text{Surface pressure}: \frac{\partial \ln p_s}{\partial t} + \int_0^1 \frac{1}{p_s} \nabla_h \cdot \left(p_s \mathbf{v}_h\right) d\sigma = 0$$

$$\text{Geopotential}: \frac{\partial \phi}{\partial \sigma} = -\frac{RT}{\sigma}$$

$$\text{Vertical velocity}: \dot{\sigma} = \sigma \int_0^1 \frac{1}{p_s} \nabla_h \cdot \left(p_s\, \mathbf{v}_h\right) d\sigma - \int_0^\sigma \frac{1}{p_s} \nabla_h \cdot \left(p_s\, \mathbf{v}_h\right) d\sigma$$

$\sigma = p/p_s$ is the vertical coordinate, D_x irreversible Processes

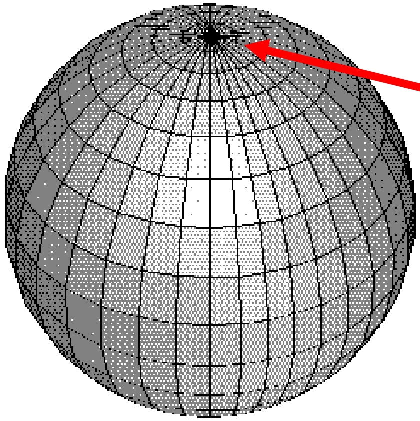
Level arrangement for a five layer model ($\Delta\sigma = 1/N = 1/5 = 0.2$)

σ-value	Index	Variable
$\sigma=0$	½	$\dot{\sigma}_{1/2} = 0$
$\sigma=½\,\Delta\sigma=0.1$	1	$\mathbf{v}_{h1}, \phi_1, T_1$
$\sigma=\Delta\sigma=0.2$	1½	$\dot{\sigma}_{1+1/2}$
$\sigma=1½\,\Delta\sigma=0.3$	2	$\mathbf{v}_{h2}, \phi_2, T_2$
$\sigma=2\Delta\sigma=0.4$	2½	$\dot{\sigma}_{2+1/2}$
$\sigma=2½\,\Delta\sigma=0.5$	3	$\mathbf{v}_{h3}, \phi_3, T_3$
$\sigma=3\Delta\sigma=0.6$	3½	$\dot{\sigma}_{3+1/2}$
$\sigma=3½\,\Delta\sigma=0.7$	4	$\mathbf{v}_{h4}, \phi_4, T_4$
$\sigma=4\Delta\sigma=0.8$	4½	$\dot{\sigma}_{4+1/2}$
$\sigma=5½\,\Delta\sigma=0.9$	$N=5$	$\mathbf{v}_{h5}, \phi_5, T_5$
$\sigma=1$	$N+½$	$\dot{\sigma}_{5+1/2} = 0$

PUMA

Spectral method (Hoskins and Simmons 1975)

PUMA is based on a longitude-latitude grid. However, with spherical coordinates singularities occur at the poles. These singularities induce a collapse of coordinate lines into a single point.



Convergence of meridians near the pole

Source: http://www.personal.umich.edu/~cjablono/project.html

With the spectral method this problem can be solved. All fields are represented by the expansion

$$\boxed{G(\lambda,\varphi,t)=\sum_{n=0}^{\infty}\sum_{m=-n}^{m=n} Y_n^m(\lambda,\mu(\varphi))\hat{G}_n^m(t)}$$

Linear terms are evaluated in spectral space while for nonlinear terms the spectral transform method is applied.

Spectral triangular truncation

The condition that at least (3M+1) longitudes must be used leads to typical values for the spectral truncation wavenumber.
The fastest performance of a Fast FOURIER Transform results when 2^n (n integer) longitudes are given in the model.

Longitudes	Truncation	DCMIP denotation	Resolution at equator [km]
32	T10		1250.9
64	T21		625.5
128	T42		312.7
256	T85	LOW	156.4
512	T170	MEDIUM	78.2
1024	T341	HIGH	39.1
2048	T682	ULTRA	19.6

PUMA

Semi implicit time integration scheme

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- Linear part of PUMA can be solved without spectral transform method.
- This part describes high frequency gravity wave oscillations.

With the semi-implicit scheme the tendency is also a function of the "unknown" new state vector $\mathbf{X}^{q+1}$

$$\boxed{\mathbf{X}^{q+1} = \mathbf{X}^{q-1} - i\Delta t\, \mathbf{A} \cdot (\mathbf{X}^{q-1} + \mathbf{X}^{q+1})}$$

where $\mathbf{A}$ is the linear tendency operator of the linear part.
This scheme gives unconditional numerical stability

Hyperdiffusion

To dampen small-scale spatial noise a hyperdiffusion term of the form

$$\boxed{(-1)^{n_h - 1} k_h \nabla_h^{2n_h} F}$$

is added to the vorticity, divergence and temperature equations
where n_h is the order of hyperdiffusion and k_h the coefficient.

Flow diagram of the PUMA model code

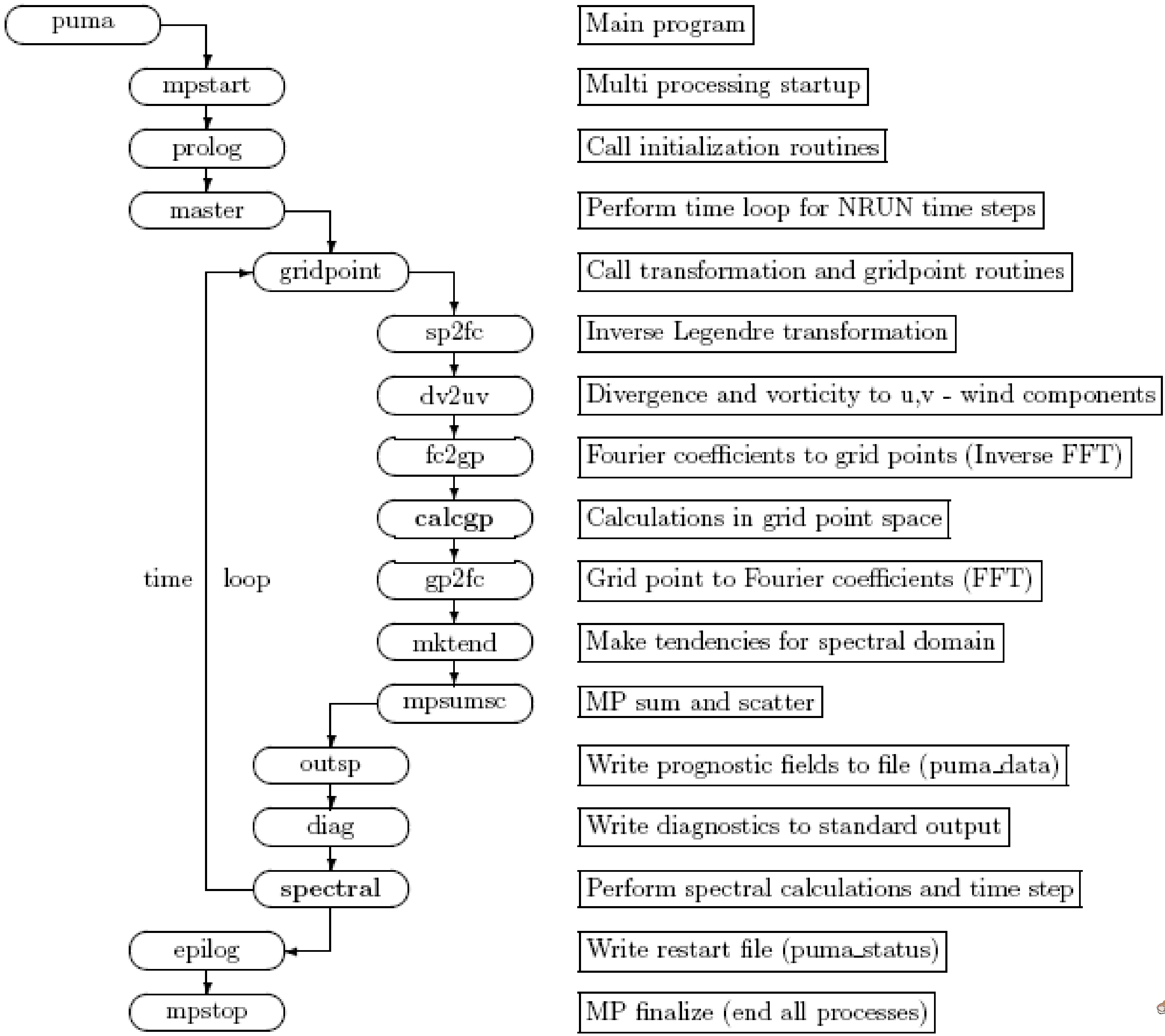

Figure 8.4: Flow diagram of main routines