RAYLEIGH TUTORIAL

MODULE 3: CONTROLLING PHYSICS IN RAYLEIGH

COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

IN THIS MODULE:

- Physical control flags
- Boundary Conditions
- Initial Conditions
- Overview of available background states
- Exercises:
    - Initiate a Boussinesq simulation
    - Initiate a nondimensional anelastic simulation
    - Initiate a dimensional anelastic simulation

BEFORE WE BEGIN:

- Create a subdirectory named module3
- Create these 3 sudirectories:
  - module3/bous -- this will contain a Boussinesq Run
  - module3/anelastic -- a dimensional anelastic run
  - module3/anelastic_nd -- a nondimensional anelastic run

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- softlink rayleigh into each SUBdirectory:

  ln –s rayleigh/build/rayleigh module3/bous/.

  ln –s ../../rayleigh/build/rayleigh .

- Copy the following inputs to "main_input" in indicated directory

  from Rayleigh/input_examples

  c2001_case0_input → bous/main_input

  main_input_sun → anelastic/main_input

  main_input_Jupiter → anelastic_nd/main_input

REMINDER: A NOTE ABOUT NAMELISTS

- Namelists override default values in the code
- Throughout this tutorial, we will be editing many namelist values, while leaving others untouched.
- Only modify indicated values. This means:

You hear, “set these : ”

```
&problemsize_namelist
 n_theta = 96
 n_r = 64
 rmin = 9.0
 rmax = 10.0
/
```

You see:

```
&problemsize_namelist
 n_theta = 192
 n_r = 32
 rmin = 2.0
 rmax = 10.0
 nprow = 2
 npcol = 4
/
```

You need:

```
&problemsize_namelist
 n_theta = 96
 n_r = 64
 rmin = 9.0
 rmax = 10.0
 nprow = 2
 npcol =4
/
```

i.e., leave nprow and npcol alone in this example.
Omission does not imply deletion!

A NOTE ON BENCHMARK_MODE

- Several of the benchmark input examples contain:

  benchmark_mode = X

- This setting means that:
  - All user inputs are overwritten by those appropriate for benchmark X
  - Benchmark analyses are performed (expensive)

- DELETE benchmark_mode = X if:
  - You want to modify the benchmark inputs in any way
  - You do not want to perform benchmark analyses

BEFORE WE BEGIN (CONTINUED):

- DELETE LINE: bous/main_input “benchmark_mode = 1”
- For all 3 main_inputs, set the following values :

```
&problemsize_namelist
 n_theta = 48
 n_r = 64
 nprow = 2
 npcol = 2
/
```

```
&temporal_controls_namelist
 max_iterations = 10
/
```

GENERAL PHYSICS CONTROLS IN RAYLEIGH

- Several physical "switches" found in physical_controls namelist.
- These switches and their DEFAULT values are:

```
&physical_controls_namelist
 magnetism = .false.            Turns induction equ. off/on
 rotation = .false.             Turns rotation off/on
 lorentz_forces = .true.        Turns Lorentz forces off/on
 viscous_heating = .true.       Turns viscous_heating off/on
 ohmic_heating = .true.         Turns ohmic heating off/on
/
```

BOUNDARY CONDITIONS

- Rayleigh allows some choice over boundary conditions
- Boundaries are ALWAYS impenetrable (zero radial flow)
- Magnetic field ALWAYS matches onto a potential field (zero curl) (but other options in development)
- Thermal, horizontal-flow boundary conditions are left to the user

BOUNDARY CONDITIONS: THERMAL

- "T", "tvar", "S", and "Entropy" are interchangeable
- Meaning depends on reference state
- Value or gradient set at each boundary

```
&Boundary_Conditions_Namelist
 fix_tvar_top = .true.
 fix_dtdr_top = .false.
 T_top = 0.0
 T_bottom = 1.0
 fix_tvar_bottom = .true.
 fix_dtdr_bottom = .false.
 dTdr_top = 0.0
 dTdr_bottom = 0.0
/
```

Defaults indicated

Only one set
needs to be specified

Fix_dtdr overrides Fix_tvar

Exercise (Boussinesq example

```
&Boundary_Conditions_Namelist
 fix_tvar_top = .true.
 fix_dtdr_top = .false.
 T_top = 0.0
 T_bottom = 1.0
 fix_tvar_bottom = .true.
 fix_dtdr_top = .false.
 dTdr_top = 0.0
 dTdr_bottom = 0.0
/
```

Edit bous/main_input

Assign a temperature contrast of 2 (instead of 1)

Run the code (we will build on this)

BOUNDARY CONDITIONS: HORIZONTAL FLOW

- Horizontal flow can be no-slip or stress-free

```
&Boundary_Conditions_Namelist
 stress_free_top = .true.
 stress_free_bottom = .true.
 no_slip_top = .false.
 no_slip_bottom = .false.
 no_slip_boundaries = .false.
/
```

Defaults indicated

Only one set needed

no_slip overrides stress_free

no_slip_boundaries sets top and bottom simultaneously

Exercise

```
&Boundary_Conditions_Namelist
 stress_free_top = .true.
 stress_free_bottom = .true.
 no_slip_top = .false.
 no_slip_bottom = .false.
 no_slip_boundaries = .false.
/
```

Edit bous/main_input

Give the simulation stress-free boundaries

Run the code (we will build on this)

INITIALIZATION

- Initial conditions have their own namelist
- Magnetic fields have a separate init flag

Typical init scheme:

randomized thermal field
(max amplitude 10)

randomized magnetic field
(max amplitude 1)

zero velocity field

```
&Intial_Conditions_Namelist
 init_type = 7
 magnetic_init_type = 7
 temp_amp = 10.0
 mag_amp = 1.0
/
```

INITIALIZATION

- Spherically symmetric component of entropy can be initialized to a conductive profile
- Other modes are randomized

```
&Intial_Conditions_Namelist
 init_type = 7
 magnetic_init_type = 7
 temp_amp = 10.0
 mag_amp = 1.0
 conductive_profile = .true.
/
```

INITIALIZATION

- Magnetic fields can be added to evolved hydro runs

Typical init scheme:

randomized B-field (max amplitude 1)

Everything else from checkpoint

```
&Intial_Conditions_Namelist
 init_type = -1
 magnetic_init_type = 7
 mag_amp = 1.0
 restart_iter = 0
/
```

INITIALIZATION

- Or everything can be resumed

Typical init scheme:

Everything from last checkpoint

Everything from same checkpoint

```
&Intial_Conditions_Namelist
 init_type = -1
 magnetic_init_type = -1
 restart_iter = 0
/
```

- Several other init_types available for the benchmark runs (see input_examples)

INITIALIZATION EXERCISE

- Edit bous/main_input
- Initialize using a random thermal field with a conductive profile
- Run the code

```
&Intial_Conditions_Namelist
 init_type = 7
 temp_amp = 0.01
 conductive_profile = .true.
/
```

INITIALIZATION EXERCISE

- Edit bous/main_input
- Turn magnetism on
- Initialize a random magnetic field
- Run the code (we will revisit this run soon)

REFERENCE/BACKGROUND STATES IN RAYLEIGH

- Nondimensionalization in Rayleigh is controlled through the reference state.
- There are three available reference states, selected through the Reference Namelist:

```
&reference_namelist
 reference_type = 1     Boussinesq
Or
reference_type = 2      Anelastic (dimensional)
Or
reference_type = 3      Anelastic (nondimensional)
/
```

- Each type of run is controlled slightly differently

BOUSSINESQ RUNS

$$\frac{D\boldsymbol{v}}{Dt} = -\frac{2}{E}\hat{\boldsymbol{z}} \times \boldsymbol{v} - \frac{1}{E}\boldsymbol{\nabla}P + \frac{Ra}{Pr}\left(\frac{r}{r_o}\right)^n T\hat{\boldsymbol{r}} + \frac{1}{Pm\,E}(\boldsymbol{\nabla} \times \boldsymbol{B}) \times \boldsymbol{B} + \nabla^2\boldsymbol{v}$$

$$\frac{DT}{Dt} = \frac{1}{Pr}\nabla^2 S$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \frac{1}{Pm}\nabla^2\,\boldsymbol{B}$$

```
&reference_namelist
 reference_type = 1                    Boussinesq
 Ekman_number = 1.0d-3
 Rayleigh_Number = 1.0d5
 Prandtl_Number = 1.0
 Magnetic_Prandtl_Number = 5.0
 Gravity_power = 1.0        "n" in momentum eq.
/
```

Namelist Controls

ANELASTIC RUNS (DIMENSIONAL)

$$\frac{D\boldsymbol{v}}{Dt} = -2\Omega\hat{\boldsymbol{z}} \times \boldsymbol{v} - \boldsymbol{\nabla}\frac{P}{\bar{\rho}} + \boldsymbol{g}\frac{S}{c_p} + \frac{1}{4\pi\bar{\rho}}(\boldsymbol{\nabla} \times \boldsymbol{B}) \times \boldsymbol{B} + \frac{1}{\bar{\rho}}\boldsymbol{\nabla} \cdot \boldsymbol{D}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times (\eta\boldsymbol{\nabla} \times \boldsymbol{B})$$

$$\mathrm{D}_{ij} \equiv 2\bar{\rho}\nu\left(e_{ij} - \frac{1}{3}(\nabla \cdot v)\delta_{ij}\right)$$

$$\bar{\rho}\bar{T}\frac{DS}{Dt} = \nabla \cdot (\bar{\rho}\bar{T}\kappa\nabla S) + Qi + Qo + Qv$$

$$Q_i \equiv Internal\ Heating$$

$$Q_o \equiv \frac{1}{4\pi}\eta(\boldsymbol{\nabla} \times \boldsymbol{B})^2$$

$$Q_v \equiv 2\bar{\rho}\nu\left(e_{ij}e_{ij} - \frac{1}{3}(\nabla \cdot v)^2\right)$$

```
&reference_namelist
reference_type = 2
/
```

ANELASTIC (DIMENSIONAL): RUN CONTROL

Two namelists

```
&reference_namelist
reference_type = 2                   anelastic setup
Poly_n = 1.5                         polytropic_index
Poly_Nrho = 3.0                      density scaleheights
Poly_mass = 1.989d33                 interior mass
Pressure_specific_heat = 3.5d8
Angular_velocity = 2.6d-6
/
```

Polytropic background assumed

```
&Transport_namelist
nu_top = 2d12
kappa_top = 2d12
eta_top = 2d12
/
```

See Featherstone & Hindman, 2016, ApJ , 818, 32

ANELASTIC RUNS (NONDIMENSIONAL)

$$\frac{D\boldsymbol{v}}{Dt} = -2\hat{\boldsymbol{z}} \times \boldsymbol{v} - \boldsymbol{\nabla}\frac{P}{\bar{\rho}} + Ra^{*}\left(\frac{r}{r_o}\right)^2 S\hat{\boldsymbol{r}} + \frac{E}{\bar{\rho}}\boldsymbol{\nabla}\cdot\boldsymbol{D}$$

$$\bar{\rho}\bar{T}\frac{DS}{Dt} = \frac{E}{Pr}\left[\nabla\cdot\left(\bar{\rho}\bar{T}\nabla S\right) + Qi\right] + \frac{E\ Di}{Ra^{*}}Q_v$$

MHD soon…

```
&reference_namelist
 reference_type = 3      Anelastic ND
 Ekman_number = 1.0d-5
 Modified_Rayleigh_Number = 0.05
 Prandtl_Number = 1.0
 poly_n = 2.0           polytropic index
 poly_Nrho = 5.0      density scaleheights
/
```

See Heimpel et al., 2016, Nature Geoscience 9, 19

EXERCISES

1. Add magnetism to the anelastic/main_input case.
   Specify a magnetic Prandtl number of 2 *by setting eta_top*.
   Run for 10 time steps.

2. Turn off rotation in the anelastic_nd/main_input case.
   Change Pr to 2.
   Run for 10 time steps.

Questions?