Overview of GCMs

David Randall

What is a GCM?

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  - By definition, aimed at climate.
  - Must include both ocean and atmosphere.

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- **General Circulation Model**
  - **What does "general" mean, anyway?**
  - **Can be either ocean or atmosphere, or both.**
  - **Can be aimed at climate or NWP.**

What is a GCM?

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  - **Can be either ocean or atmosphere, or both.**
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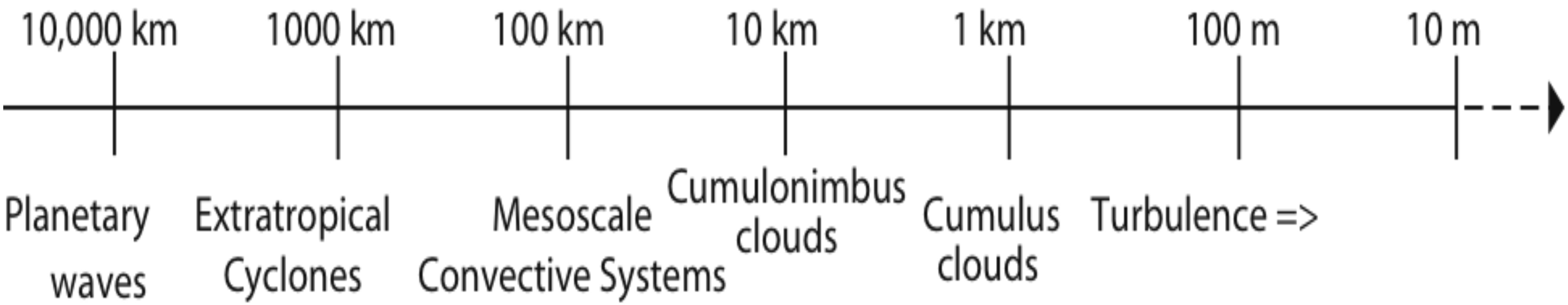
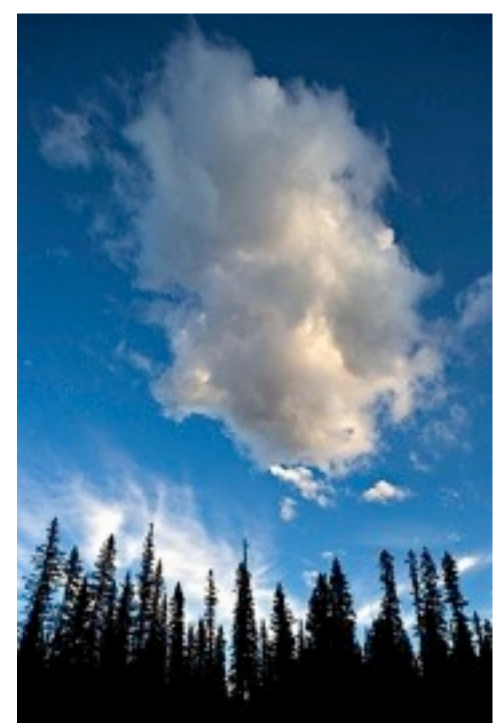
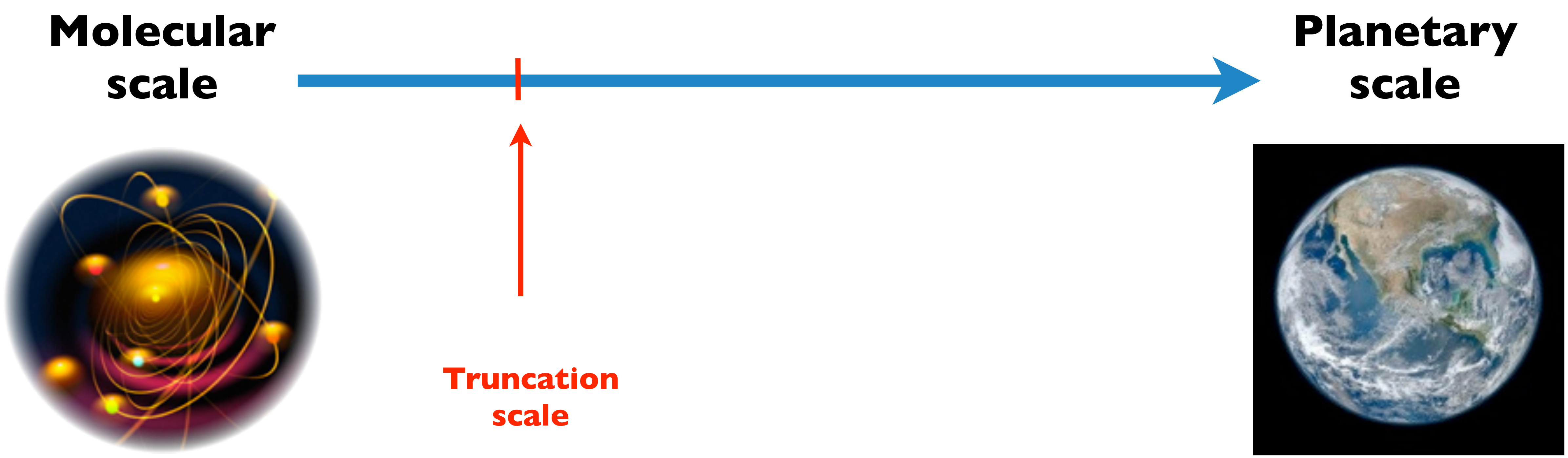
- **Global Circulation Model**
  - **Accurate and flexible.**
  - **May be the best use of the acronym.**

Range of scales

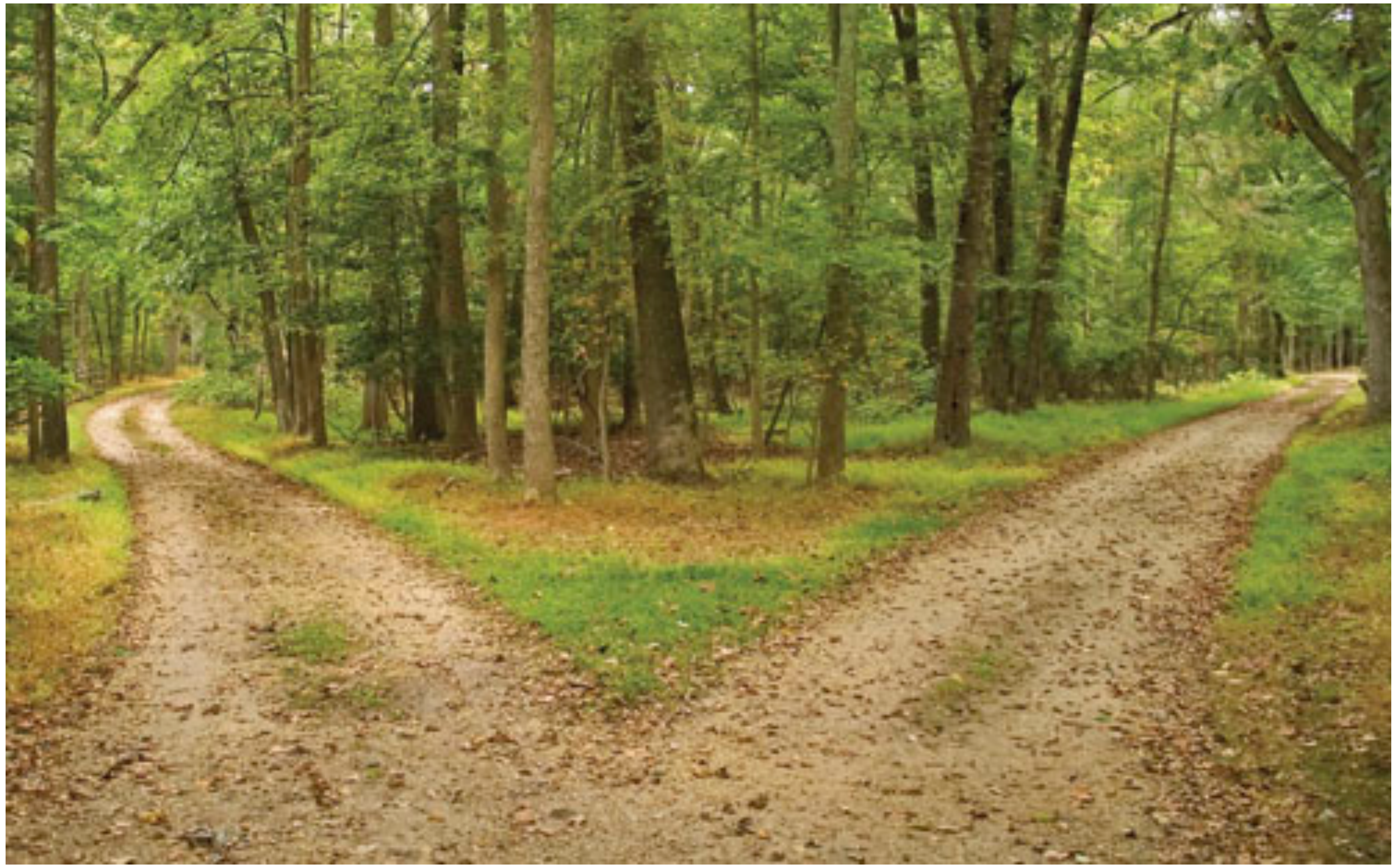






The Earth System starts at the molecular scale and works up.

Modelers start at the planetary scale and work down.

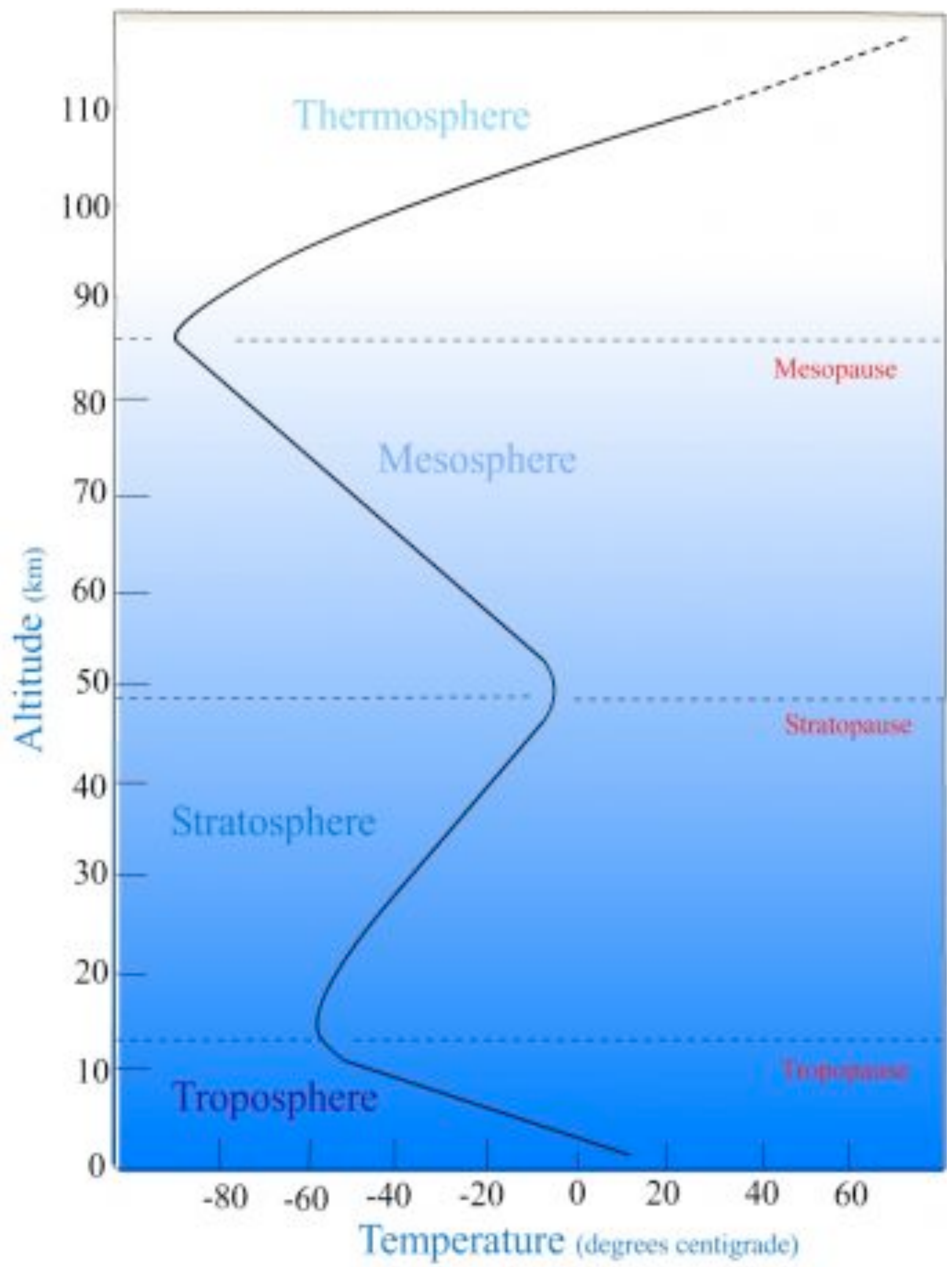


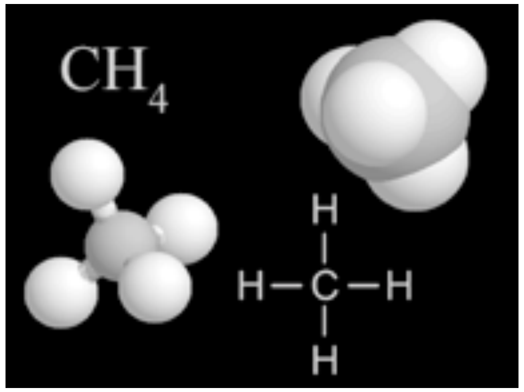
Building a GCM involves an ordered sequence of choices.

Choices I

- Scope
  - Stratosphere?
  - Chemistry?
  - Range of scales (target resolution)?
- Equation set
- Prognostic variables
- Vertical coordinate

Scope


Thermosphere
Mesopause
Mesosphere
Stratopause
Stratosphere
Tropopause
Troposphere
Altitude (km)
0
10
20
30
40
50
60
70
80
90
100
110
-80
-60
-40
-20
0
20
40
60
Temperature (degrees centigrade)


CH_4
H
H—C—H
H

Choices 2

- **Grid point or spectral**

Choices 2

- Grid point or spectral
- Grid type

Choices 2

- Grid point or spectral
- Grid type
- Discretization method
  - Finite volume
  - Spectral element

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- Conservation properties
- Sign preservation, monotonicity, etc.

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These choices are coupled, so the order matters.

Choices 2

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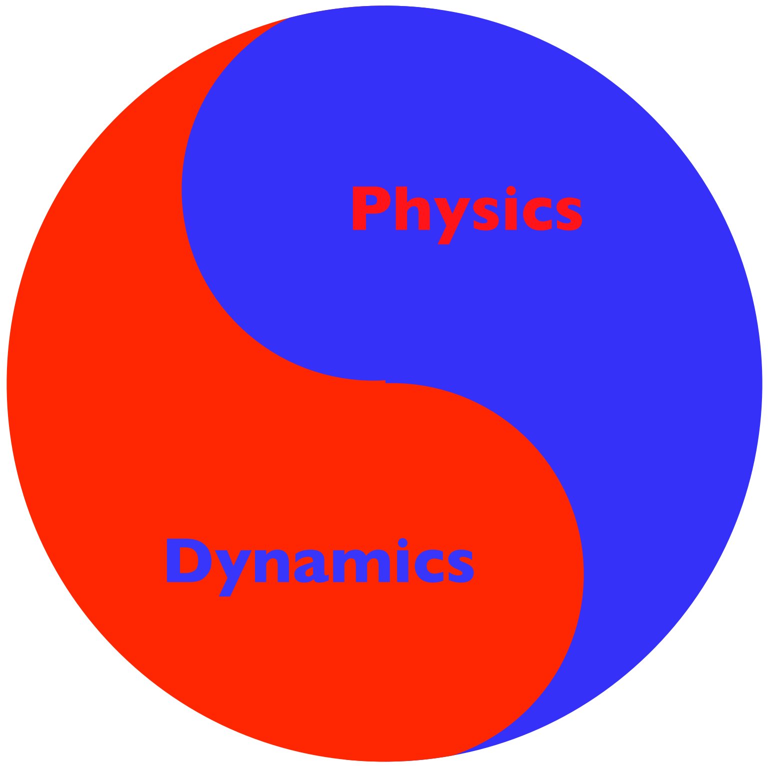
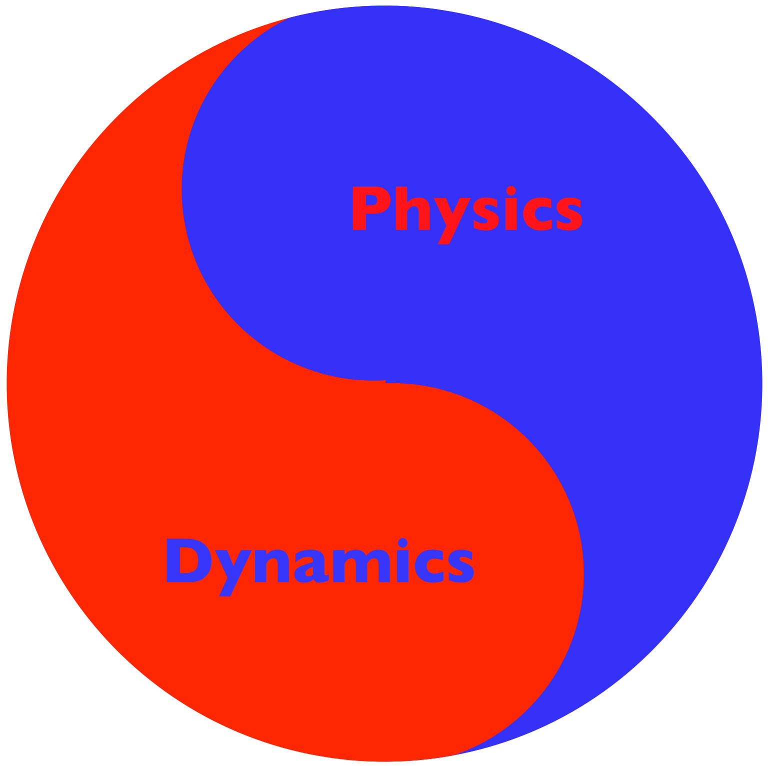
Other speakers will cover the topics listed on this slide.

Physics and dynamics



Physics and dynamics

- "Physics" refers to parameterized processes:
  - Radiation
  - Vertical fluxes due to turbulence, especially in the boundary layer
  - Cumulus convection
  - Stratiform clouds & microphysics
  - Gravity-wave drag
  - Chemistry, including aerosols
  - Horizontal diffusion due to unresolved scales



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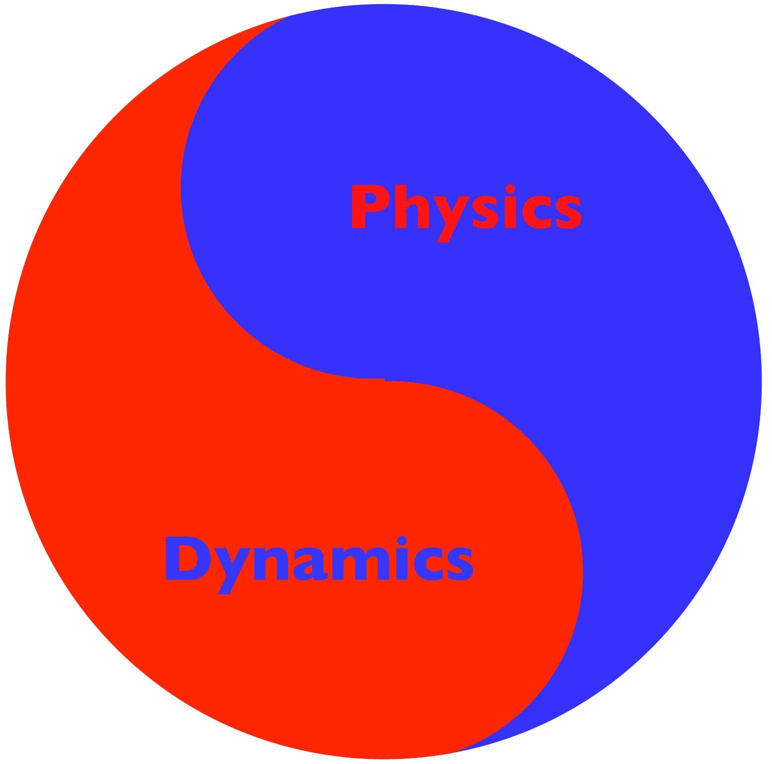
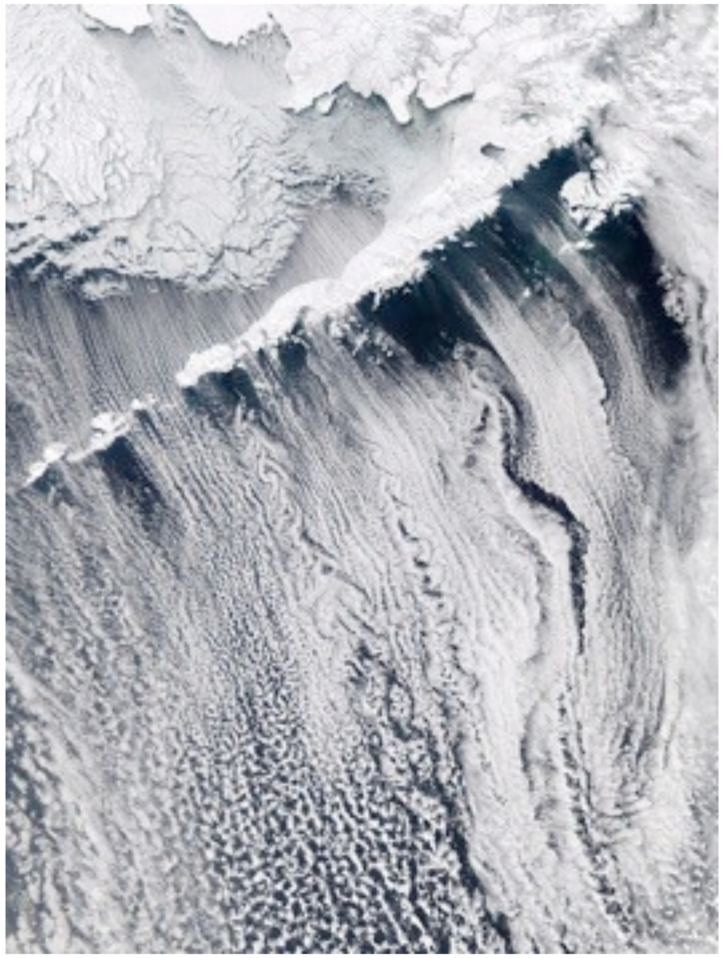
- "Dynamics" refers to everything else.



Dry dynamical cores

- The equation of motion
- The continuity equation
- The thermodynamic energy equation
- Tracer equations



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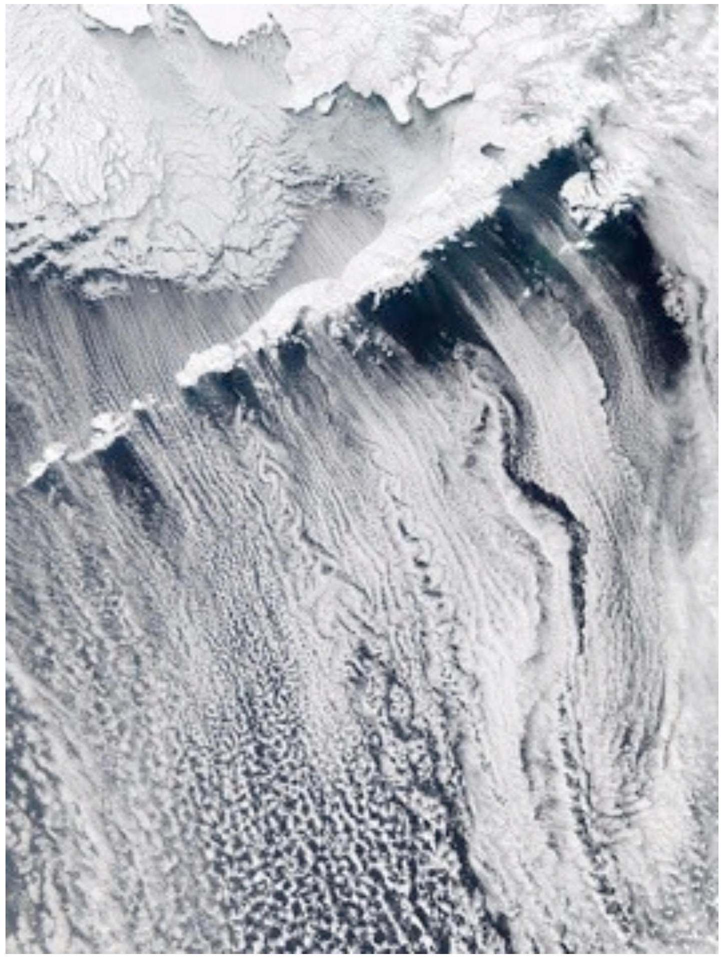

Can be tested to some extent using the shallow water system.

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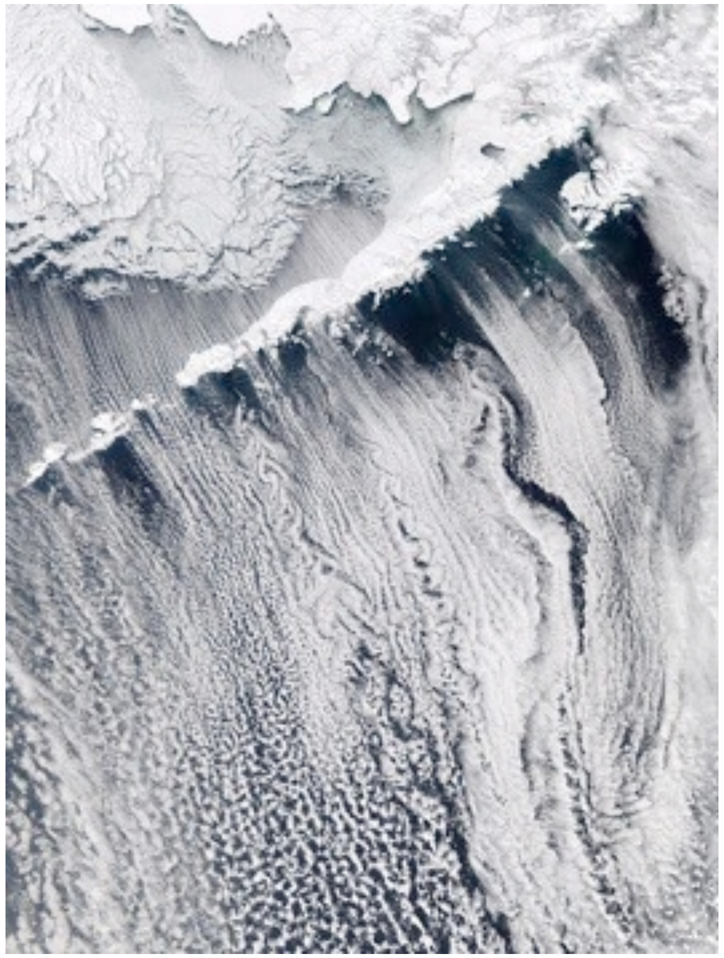

Can be tested to some extent using the shallow water system.

Results cannot be compared with observations, or with exact solutions except for highly idealized special cases.

Choice of equation set

- **Fully compressible ("exact") system of equations**

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- **Quasi-static system with the "traditional" approximations**

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- **Various anelastic systems**

Choice of equation set

- Fully compressible ("exact") system of equations
- Quasi-static system with the "traditional" approximations
- Various anelastic systems
- Alternative forms of the pressure-gradient force

Choice of prognostic variables

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  - **Normal and/or tangential components on grid cell edges**

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- Thermodynamic energy

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- **Thermodynamic energy**
  - **Temperature**

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- **Thermodynamic energy**
  - **Temperature**
  - **Potential temperature**

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  - Temperature
  - Potential temperature
  - Entropy
  - Moist entropy

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  - Moist entropy
- Moisture

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- **Moisture**
  - **Water vapor mixing ratio**

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  - **Total water mixing ratio**

Choice of prognostic variables

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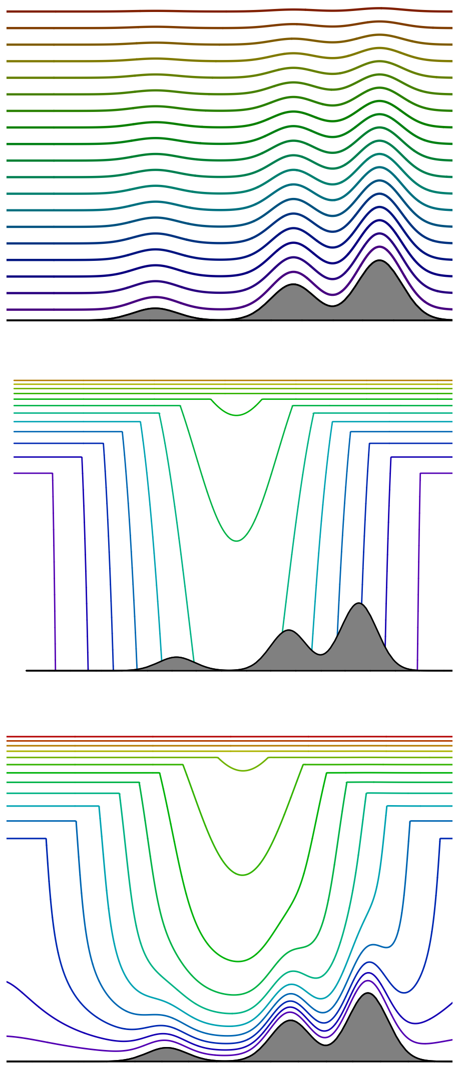
- Thermodynamic energy
  - Temperature
  - Potential temperature
  - Entropy
  - Moist entropy
- Moisture
  - Water vapor mixing ratio
  - Total water mixing ratio
  - Condensed water species

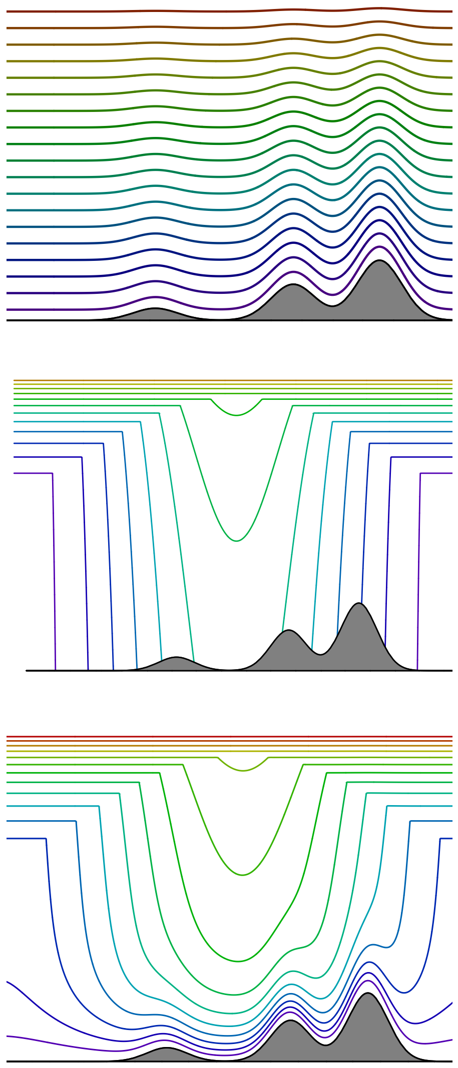
Choice of vertical coordinates

- **Height**



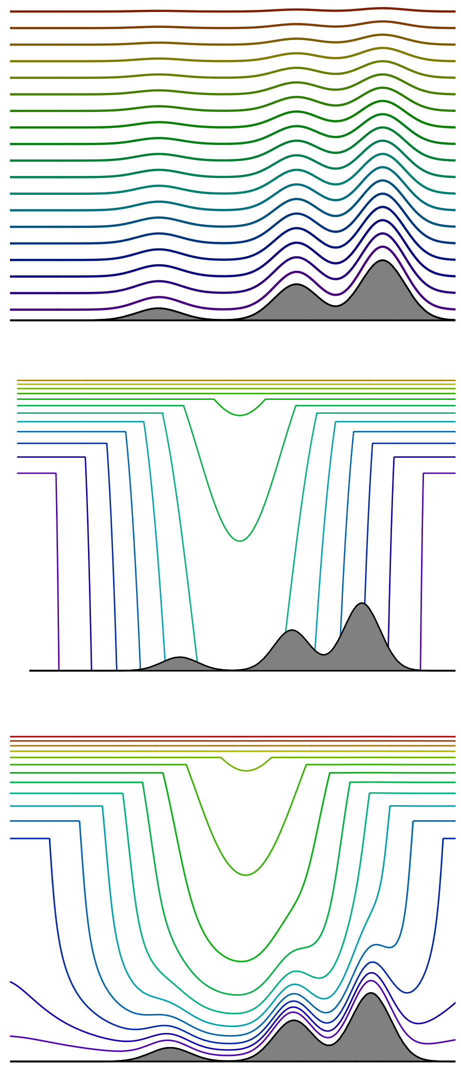
Choice of vertical coordinates

- **Height**
- **Sigma**



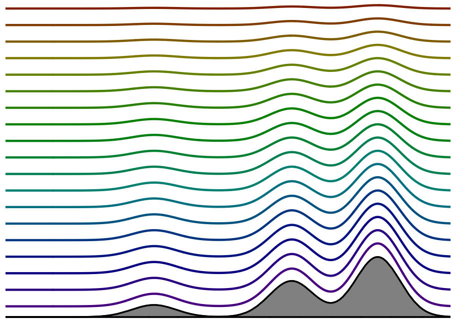
Choice of vertical coordinates

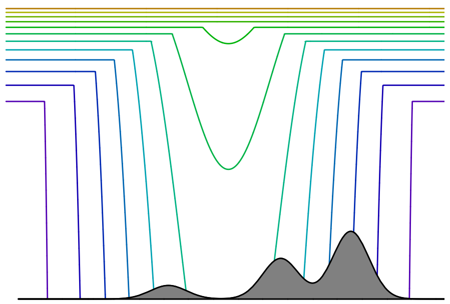
- **Height**
- **Sigma**
- **Theta**

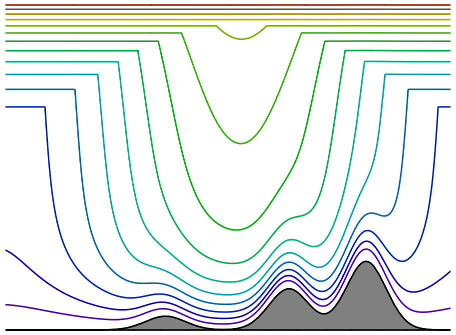


Choice of vertical coordinates

- Height
- Sigma
- Theta
- Various hybrids
  - Sigma-pressure
  - Theta-sigma







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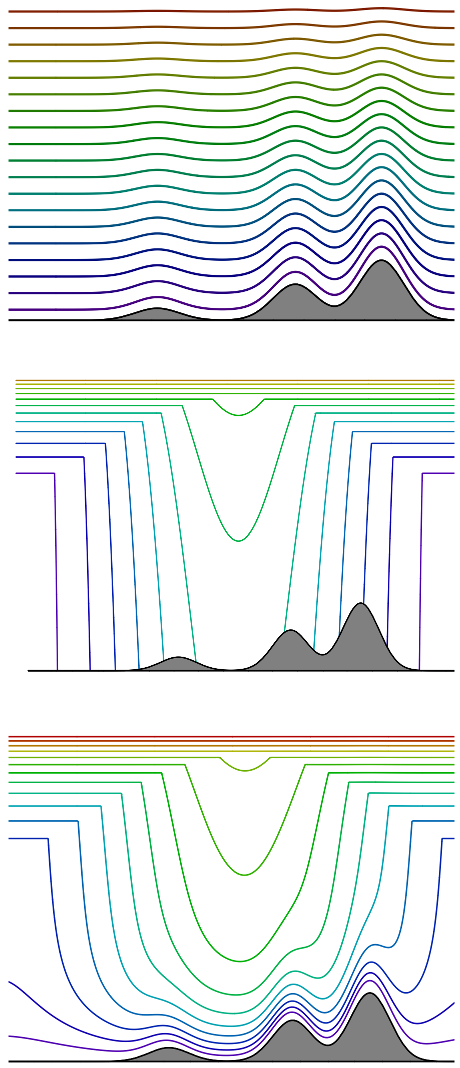


Mike Toy will discuss these topics on Wednesday.

Common approximations

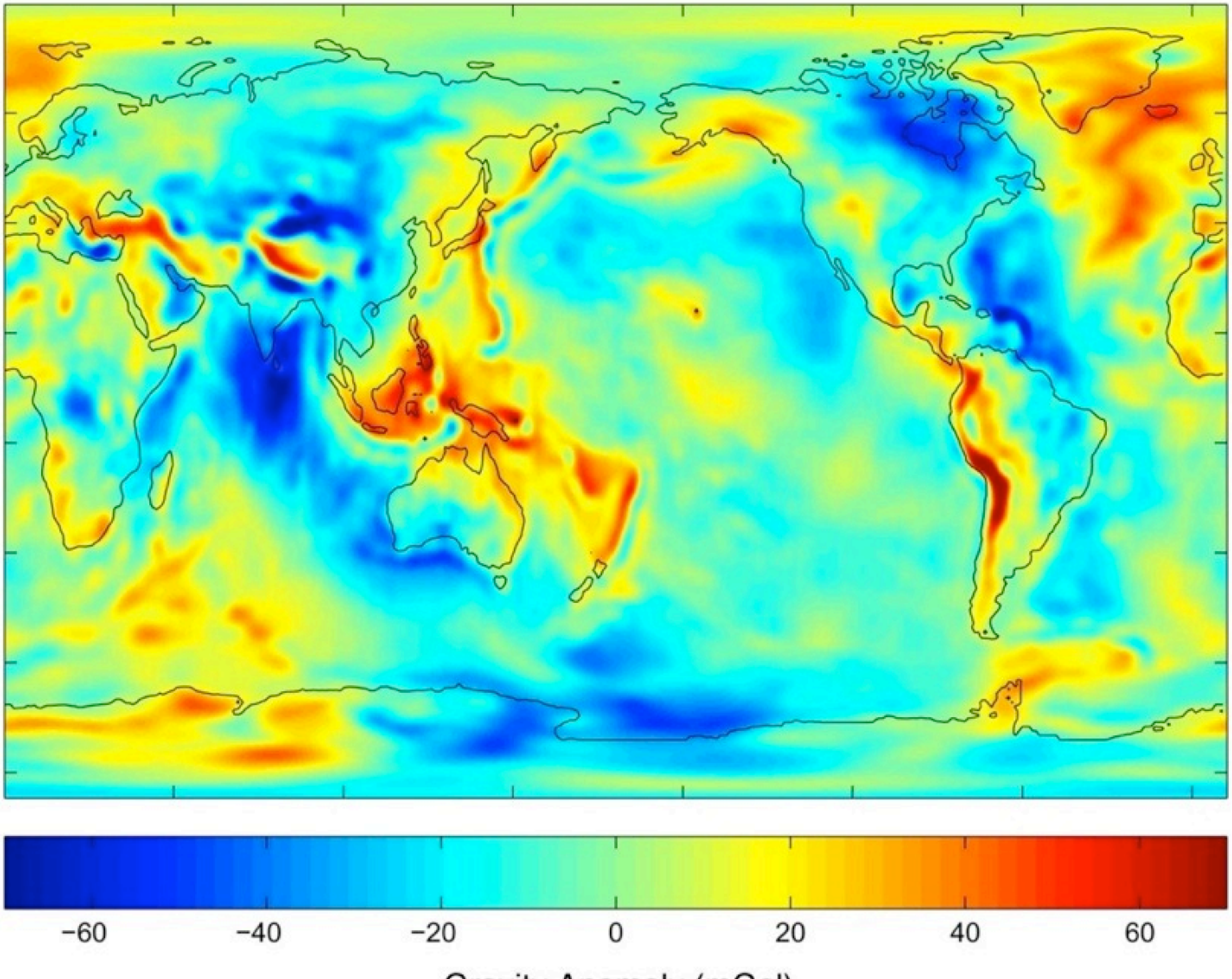
- Quasi-static approximation
- Thin atmosphere approximation
- Neglect of some Coriolis terms
- Neglect of the centrifugal acceleration
- Spherical Earth approximation
- Uniform gravity approximation

We are gradually eliminating these approximations.

The quasi-static approximation is the most useful, and will be the first to go.

In reality, the Equatorial radius is only about 20 km larger than the polar radius.


−60
−40
−20
0
20
40
60
Gravity Anomaly (mGal)

The “exact” equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0$$

$$\frac{D\mathbf{V}}{Dt} = -2\mathbf{\Omega} \times \mathbf{V} - \mathbf{\Omega} \times \left(\mathbf{\Omega} \times \mathbf{r}\right) - \nabla \phi_a - \alpha \nabla p - \alpha \nabla \cdot \mathbf{F}$$

$$\frac{D}{Dt}\left(c_v T\right) + p\frac{D\alpha}{Dt} = -\alpha \nabla \cdot \left(\mathbf{R} + \mathbf{F}_S\right) + LC + \delta$$

$$\frac{Dq_v}{Dt} = g\frac{\partial F_{q_v}}{\partial p} - C$$

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No coordinate system is used here.

Using spherical coordinates:

$$\frac{\partial \rho}{\partial t}+\frac{1}{r\cos\varphi}\frac{\partial}{\partial\lambda}(\rho u)+\frac{1}{r\cos\varphi}\frac{\partial}{\partial\varphi}(\rho v\cos\varphi)+\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho w r^2\right)=0$$

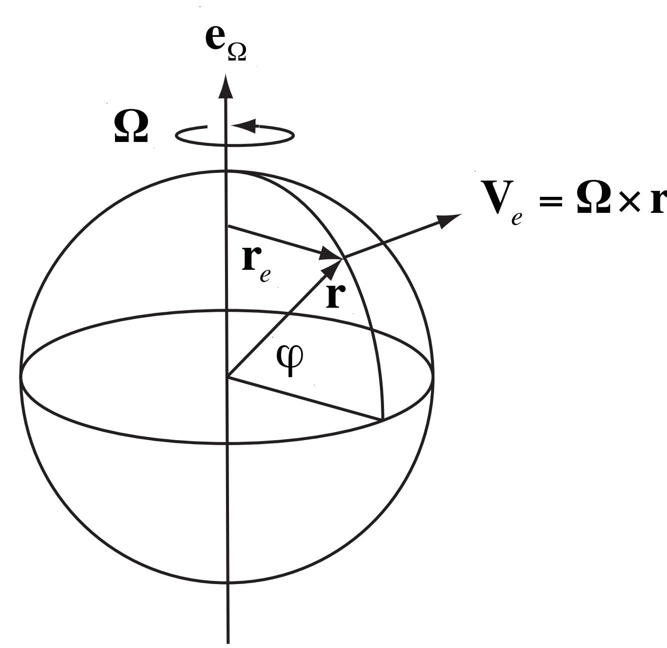
$$\frac{Du}{Dt}-\left(2\Omega+\frac{u}{r\cos\varphi}\right)(v\sin\varphi-w\cos\varphi)=-\frac{\alpha}{r\cos\varphi}\frac{\partial p}{\partial\lambda}-\alpha(\nabla\cdot\mathbf{F})_\lambda$$

$$\frac{Dv}{Dt}+\left(2\Omega+\frac{u}{r\cos\varphi}\right)u\sin\varphi+\frac{vw}{r}+\Omega^2 r\sin\varphi\cos\varphi=-\frac{\alpha}{r}\frac{\partial p}{\partial\varphi}-\alpha(\nabla\cdot\mathbf{F})_\varphi$$

$$\frac{Dw}{Dt}-\left(2\Omega+\frac{u}{r\cos\varphi}\right)u\cos\varphi-\frac{v^2}{r}-\Omega^2 r\cos^2\varphi+g_a=-\alpha\frac{\partial p}{\partial r}-\alpha(\nabla\cdot\mathbf{F})_r$$

$$\frac{D}{Dt}(c_v T)+p\frac{D\alpha}{Dt}=-\alpha\nabla\cdot\left(\mathbf{R}+\mathbf{F}_S\right)+LC+\delta$$

$$\frac{Dq_v}{Dt}=g\frac{\partial F_{q_v}}{\partial p}-C$$



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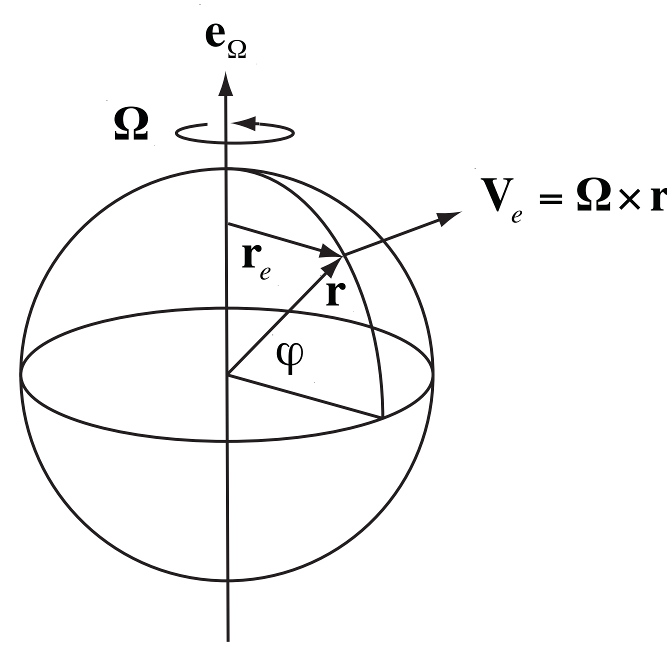


The components of the equation of motion contain “metric” terms that come from the coordinate system.

Widely used approximations

- **Thin atmosphere**
- **Neglect of some Coriolis and metric terms**
- **Variable gravity and centrifugal acceleration replaced by constant "effective gravity".**

$$\nabla \cdot \mathbf{H} = \frac{1}{r\cos\varphi}\frac{\partial H_\lambda}{\partial \lambda} + \frac{1}{r\cos\varphi}\frac{\partial}{\partial \varphi}\left(H_\varphi \cos\varphi\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(H_r r^2\right)$$

$$\nabla \cdot \mathbf{H} = \frac{1}{r\cos\varphi}\frac{\partial H_\lambda}{\partial \lambda} + \frac{1}{r\cos\varphi}\frac{\partial}{\partial \varphi}\left(H_\varphi \cos\varphi\right) + \frac{\partial H_r}{\partial r} + \cancel{\frac{2H_r}{r}}$$

$$r \rightarrow a$$

$$\nabla \cdot \mathbf{H} = \frac{1}{a\cos\varphi}\frac{\partial H_\lambda}{\partial \lambda} + \frac{1}{a\cos\varphi}\frac{\partial}{\partial \varphi}\left(H_\varphi \cos\varphi\right) + \frac{\partial H_r}{\partial r}$$

This leads to

$$\frac{\partial\rho}{\partial t}+\frac{1}{a\cos\varphi}\frac{\partial}{\partial\lambda}(\rho u)+\frac{1}{a\cos\varphi}\frac{\partial}{\partial\varphi}(\rho v\cos\varphi)+\frac{\partial}{\partial r}(\rho w)=0$$

$$\frac{Du}{Dt}-\left(2\Omega+\frac{u}{a\cos\varphi}\right)v\sin\varphi=-\frac{\alpha}{a\cos\varphi}\frac{\partial p}{\partial\lambda}-\alpha(\nabla\cdot\mathbf{F})_{\lambda}$$

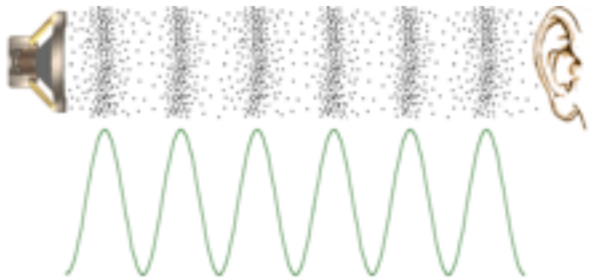
$$\frac{Dv}{Dt}+\left(2\Omega+\frac{u}{a\cos\varphi}\right)u\sin\varphi=-\frac{\alpha}{a}\frac{\partial p}{\partial\varphi}-\alpha(\nabla\cdot\mathbf{F})_{\varphi}$$

$$\frac{Dw}{Dt}+g=-\alpha\frac{\partial p}{\partial r}-\alpha(\nabla\cdot\mathbf{F})_{r}$$

$$\frac{D}{Dt}(c_vT)+p\frac{D\alpha}{Dt}=-\alpha\nabla\cdot(\mathbf{R}+\mathbf{F}_S)+LC+\delta$$

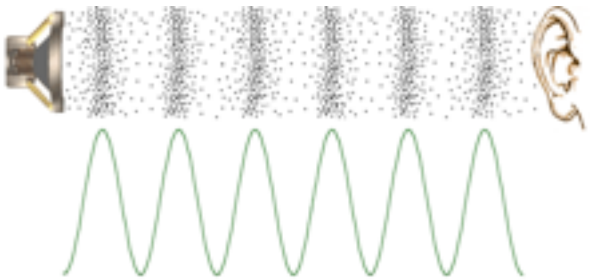
$$\frac{Dq_v}{Dt}=g\frac{\partial F_{q_v}}{\partial p}-C$$

Vertically propagating sound waves are bad.



In the Earth's atmosphere, the speed of sound is about 300 m/s.

Vertically propagating sound waves are bad.



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If vertically propagating sound waves are simulated with explicit time differencing, the time step required for computational stability can be as small as one second, because the vertical grid spacing can be on the order of 300 m.

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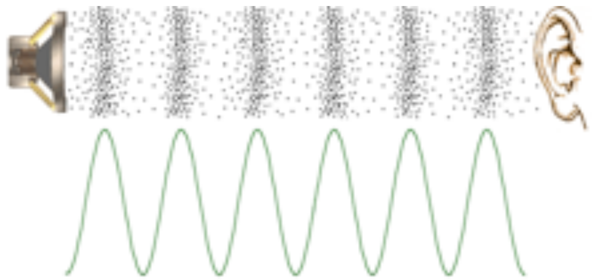

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Horizontally propagating sound waves are not so bad if the grid cells are much wider than they are tall.

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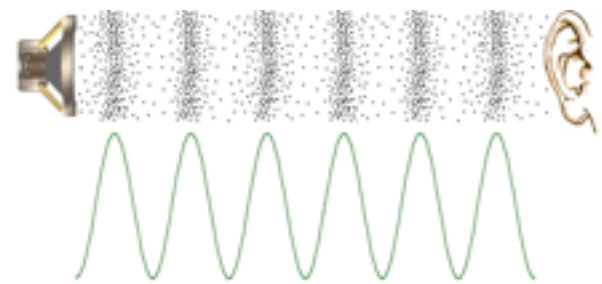

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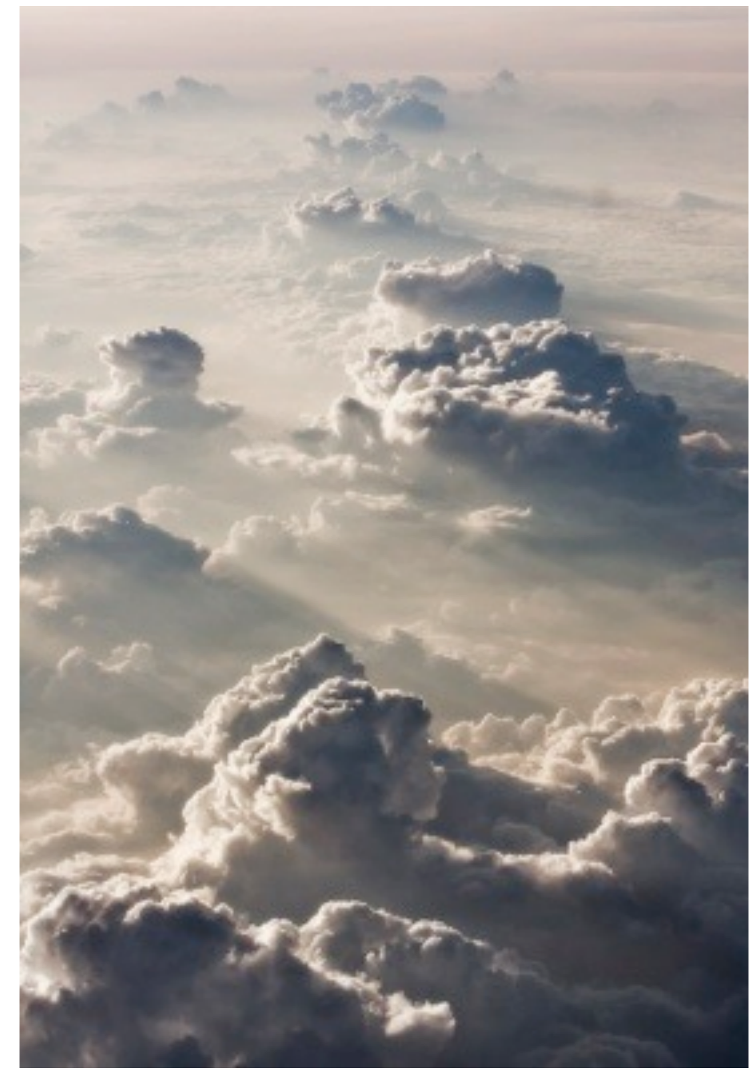
300 m

100 km

Four ways to deal with vertically propagating sound waves

- **Take small time steps (bad).**



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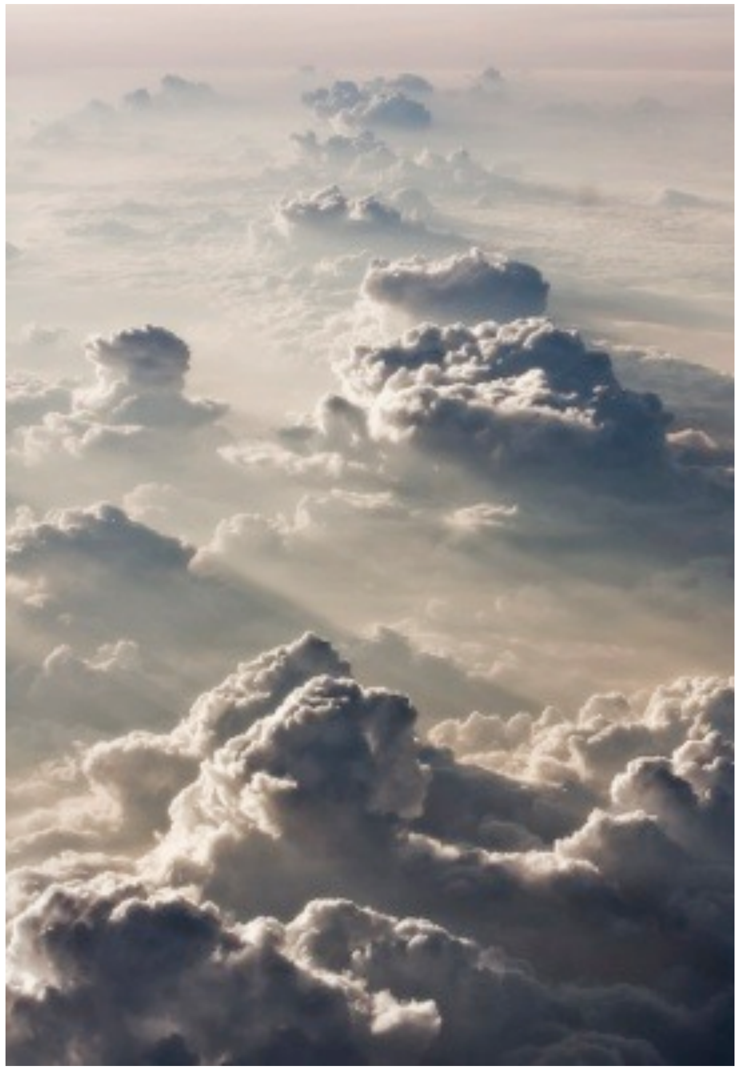

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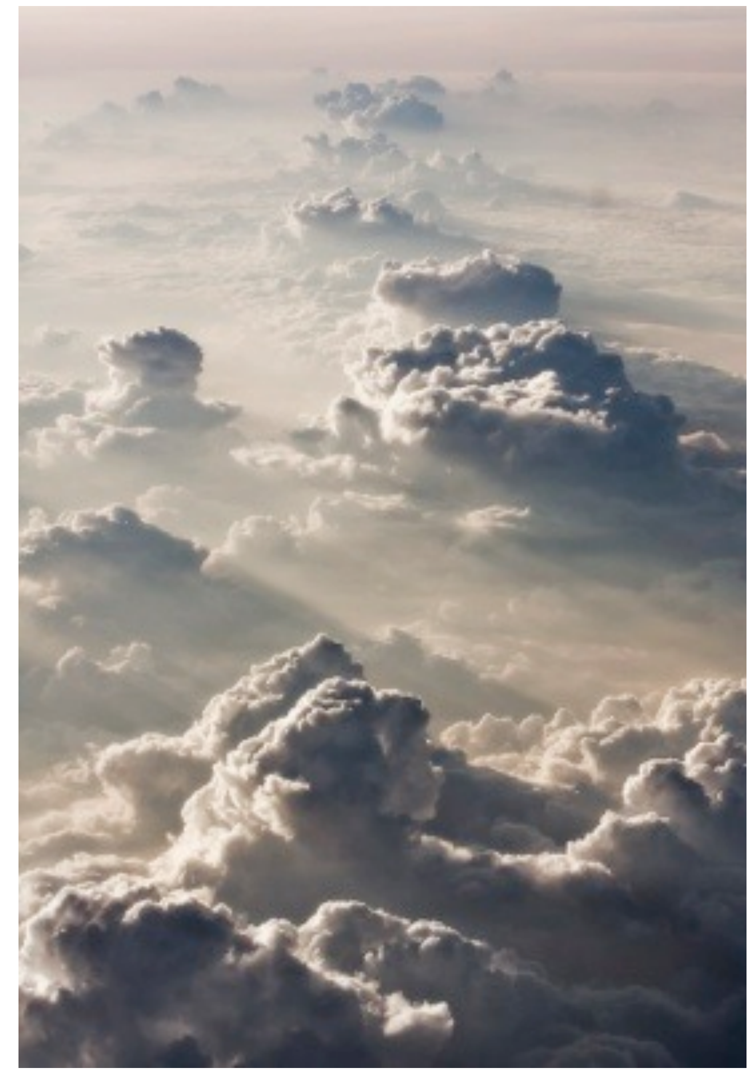

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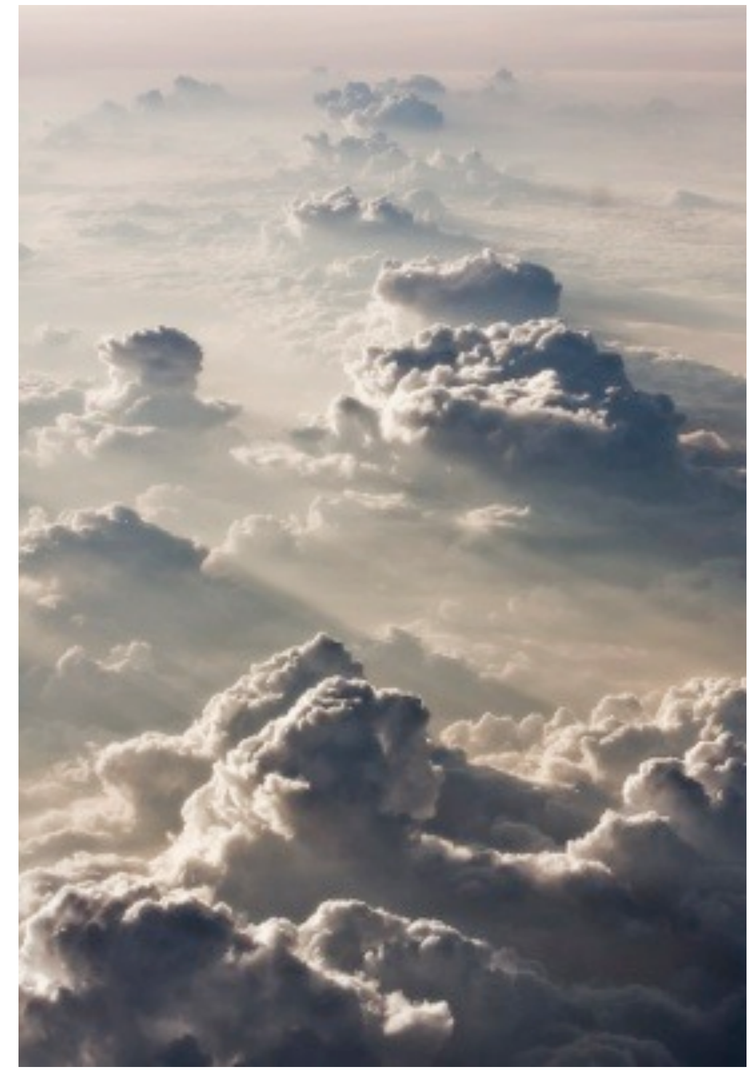

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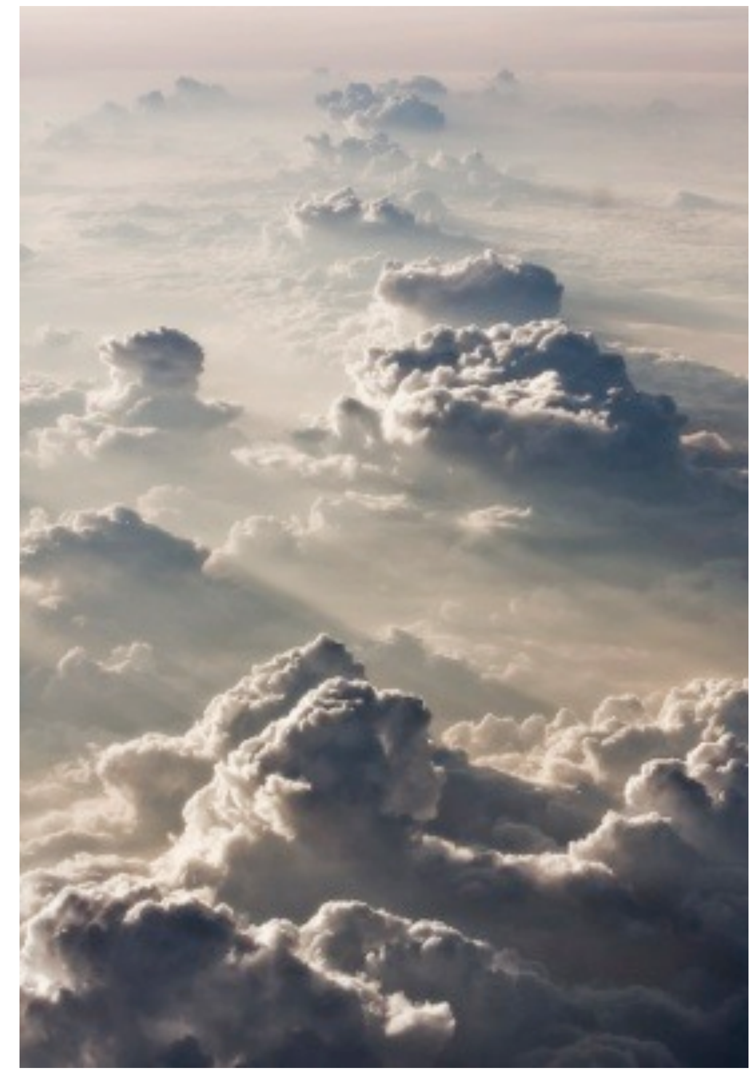

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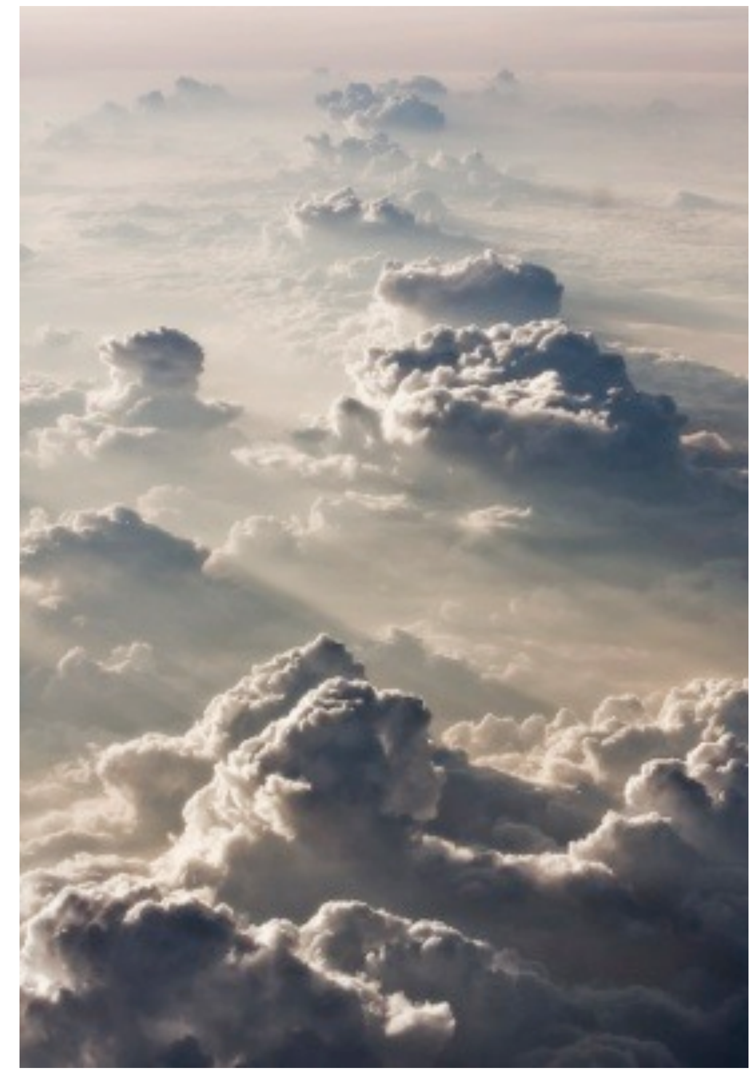

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The fourth method is based on a physical approximation.

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It is *not justified* for vigorous small-scale weather systems.

The quasi-static system with the traditional approximations

$$\frac{\partial\rho}{\partial t}+\frac{1}{a\cos\varphi}\frac{\partial}{\partial\lambda}(\rho u)+\frac{1}{a\cos\varphi}\frac{\partial}{\partial\varphi}(\rho v\cos\varphi)+\frac{\partial}{\partial r}(\rho w)=0$$

$$\frac{Du}{Dt}-\left(2\Omega+\frac{u}{a\cos\varphi}\right)v\sin\varphi=-\frac{\alpha}{a\cos\varphi}\frac{\partial p}{\partial\lambda}-\alpha(\nabla\cdot\mathbf{F})_\lambda$$

$$\frac{Dv}{Dt}+\left(2\Omega+\frac{u}{a\cos\varphi}\right)u\sin\varphi=-\frac{\alpha}{a}\frac{\partial p}{\partial\varphi}-\alpha(\nabla\cdot\mathbf{F})_\varphi$$

$$g=-\alpha\frac{\partial p}{\partial r}$$

$$\frac{D}{Dt}(c_v T)+p\frac{D\alpha}{Dt}=-\alpha\nabla\cdot(\mathbf{R}+\mathbf{F}_S)+LC+\delta$$

$$\frac{Dq_v}{Dt}=g\frac{\partial F_{q_v}}{\partial p}-C$$

With the quasi-static system, we cannot use the equation of vertical motion to determine the vertical velocity.

The method used to determine the vertical velocity depends on the choice of vertical coordinate system.

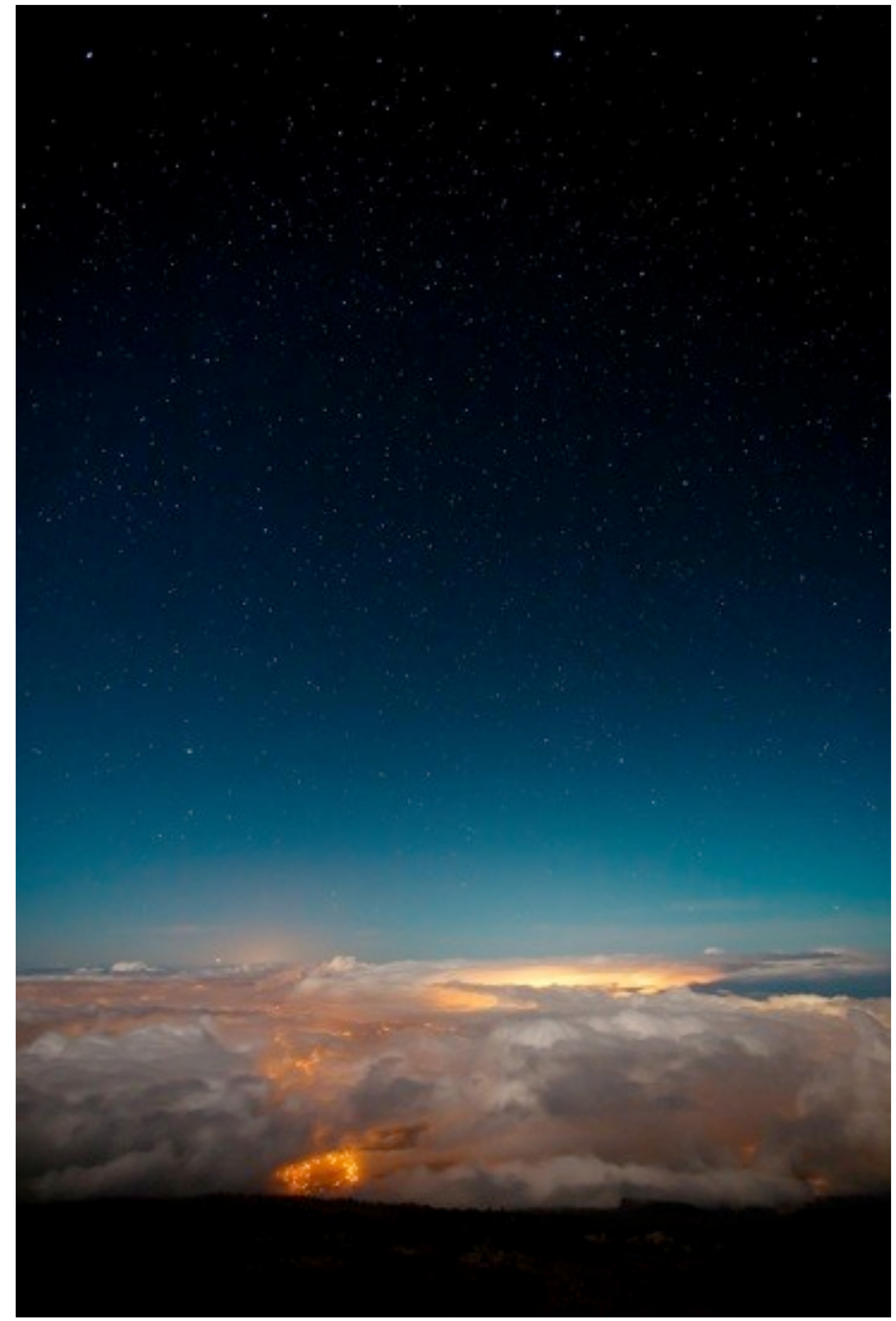
The trend to non-hydrostatic models

Faster, massively parallel computers are allowing us to use finer grids.

Finer grids can resolve weather systems, e.g. thunderstorms, that are not quasi-static.

For this reason, we are now building GCMs that do not use the quasi-static approximation.

These new high-resolution GCMs can borrow ideas from the well established mesoscale modeling community.



Filtering vertically propagating sound waves without using the quasi-static approximation

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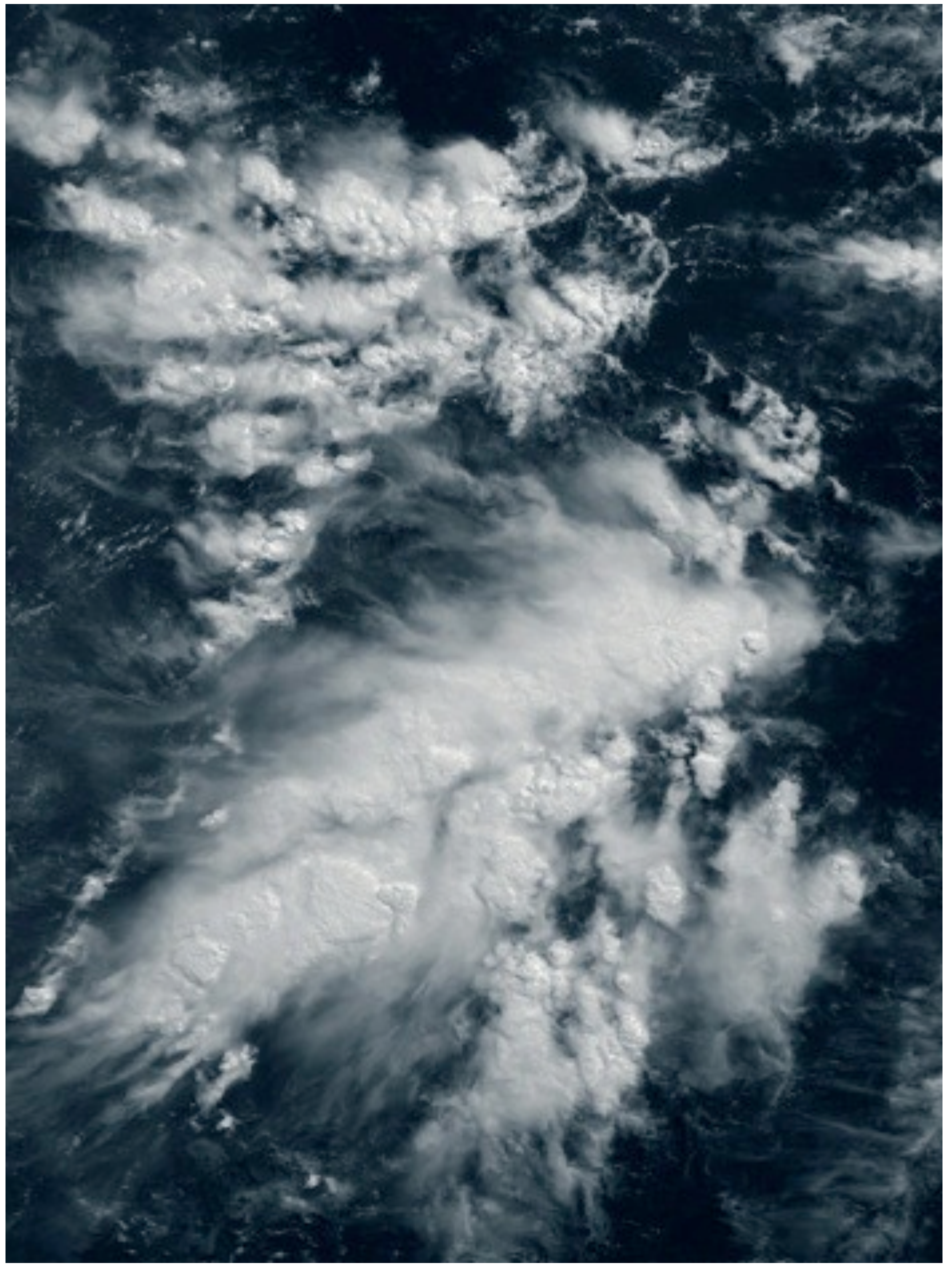
I will discuss this further later in the week.

High-resolution physics

- The nature of the "sub-grid" physical processes depends on the grid size.
- Physics appropriate for low-resolution models is not appropriate for high-resolution models, and vice-versa.
- Can we design intelligent physical parameterizations that can adapt to a wide range of grid spacings?



Conclusions

- GCM design involves an ordered sequence of choices.
- The choice of equation set is determined partly by the intended resolution of the model.
- The new generation of high-resolution models will have to give up the venerable quasi-static approximation.
- The emerging 21st century models may also spurn various other approximations that have been widely used in the past.
- The creation of a new generation of models is an opportunity to re-examine our traditional approaches to physical parameterization.