



Utrecht University



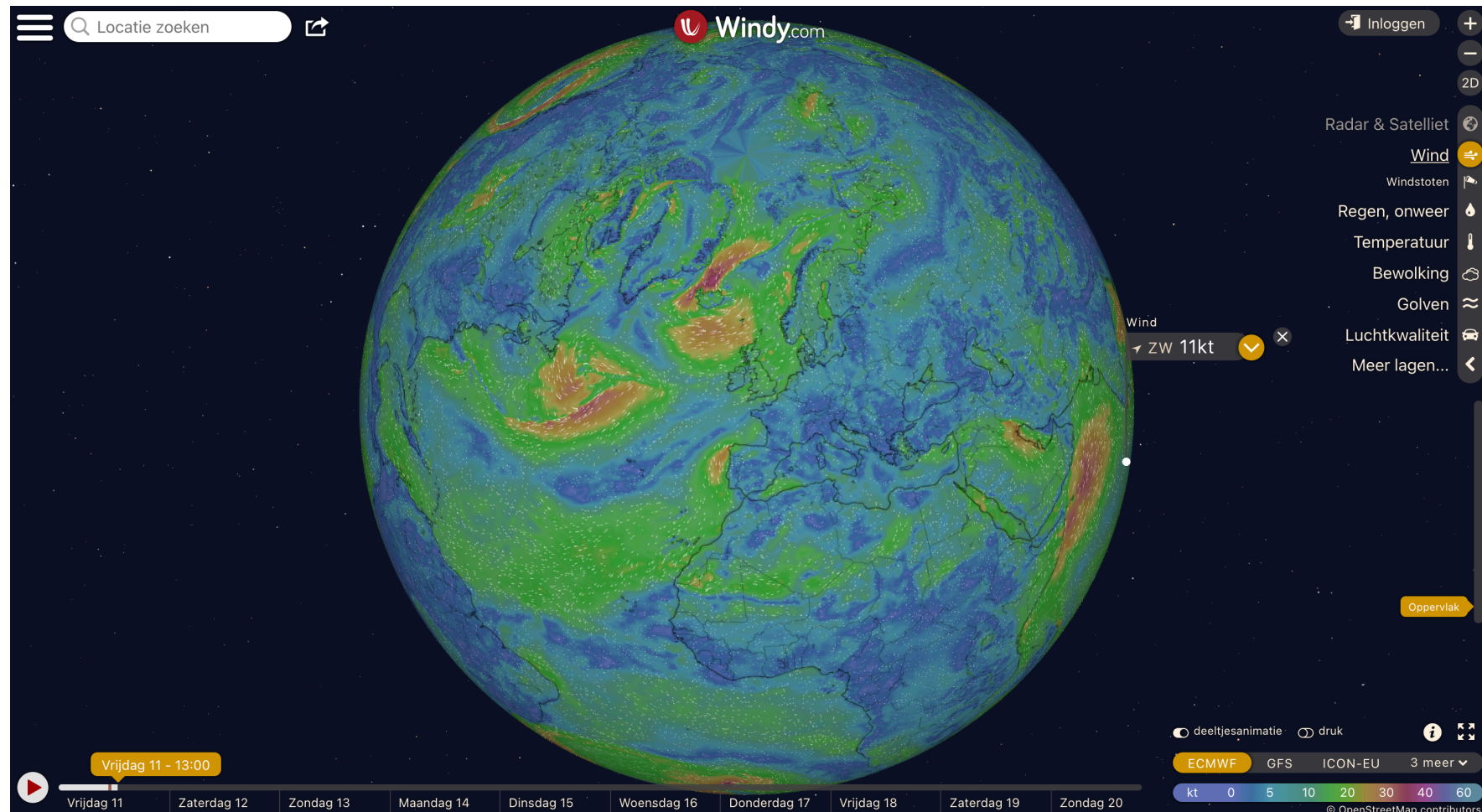
Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Waterstaat



LAURENS STOOP

CLIMATE PHYSICS

NUMERICAL PREDICTION BASED ON NAVIER-STOKES EQUATIONS

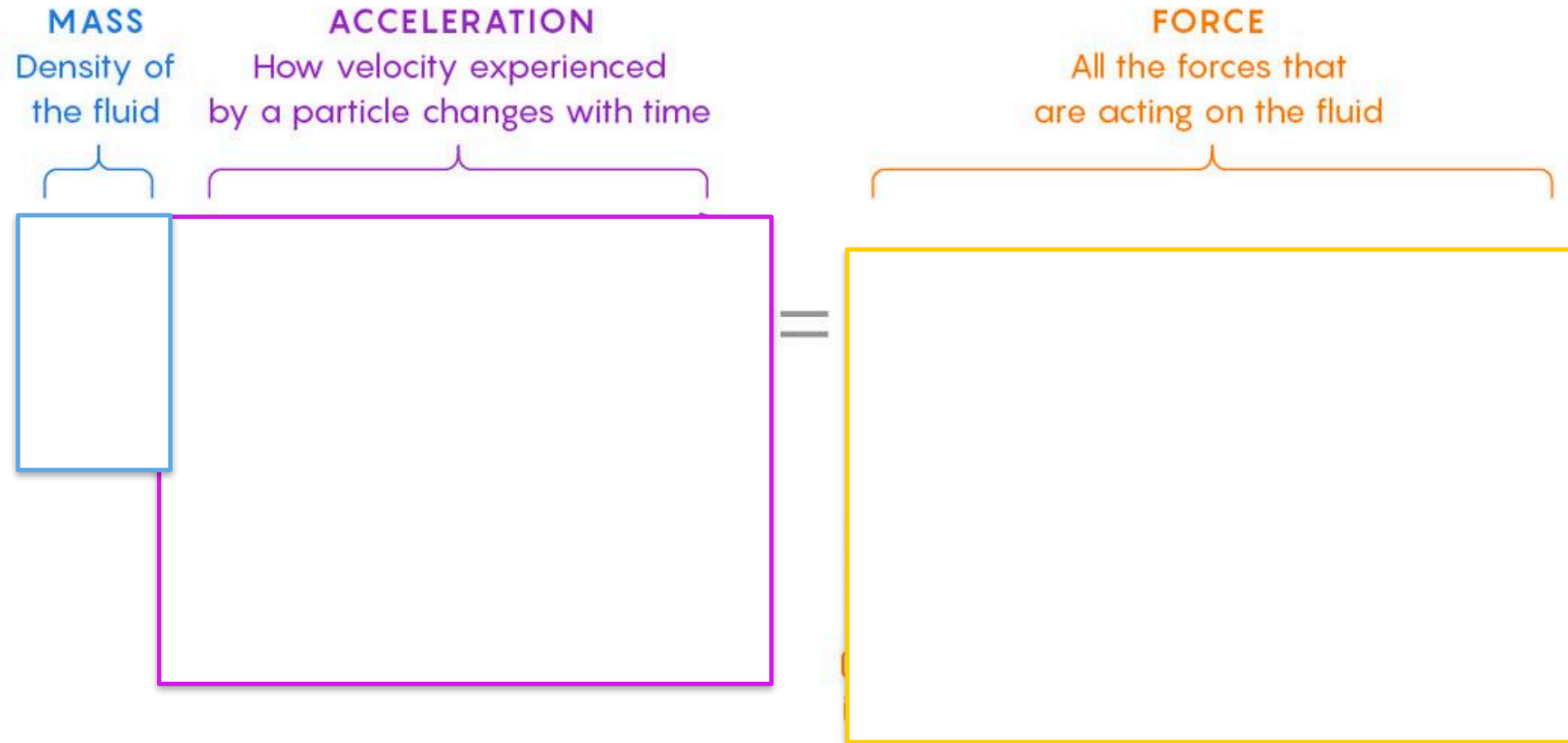


THE NAVIER-STOKES EQUATIONS — ORIGIN

Four equations that determine the properties and behaviour

- ▶ Conservation of Energy
- ▶ **Conservation of Momentum**
- ▶ Conservation of Mass
- ▶ Ideal Gas Law

THE NAVIER-STOKES EQUATIONS



THE NAVIER-STOKES EQUATIONS

The diagram illustrates the structure of the Navier-Stokes equation, showing the relationship between mass, acceleration, and force. It consists of three main parts: a mass term, an acceleration term, and a force term, separated by an equals sign.

MASS
Density of the fluid
 ρ

ACCELERATION
How velocity experienced by a particle changes with time

FORCE
All the forces that are acting on the fluid

The equation is represented as:

$$\rho \left[\frac{d\mathbf{v}}{dt} \right] = \mathbf{F}$$

where ρ is the density of the fluid, $\frac{d\mathbf{v}}{dt}$ is the acceleration, and \mathbf{F} is the force.

THE NAVIER-STOKES EQUATIONS

MASS
Density of the fluid

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How velocity experienced by a particle changes with time

FORCE
All the forces that are acting on the fluid

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

Change in velocity over time

The speed and direction which the fluid is moving

The diagram illustrates the Navier-Stokes equation with color-coded labels and brackets. The left side of the equation is labeled with 'MASS' (Density of the fluid) in blue and 'ACCELERATION' (How velocity experienced by a particle changes with time) in purple. The acceleration term is further broken down into 'Change in velocity over time' (for the partial derivative) and 'The speed and direction which the fluid is moving' (for the convective term). The right side of the equation is labeled 'FORCE' (All the forces that are acting on the fluid) in orange and is represented by a large empty orange box.

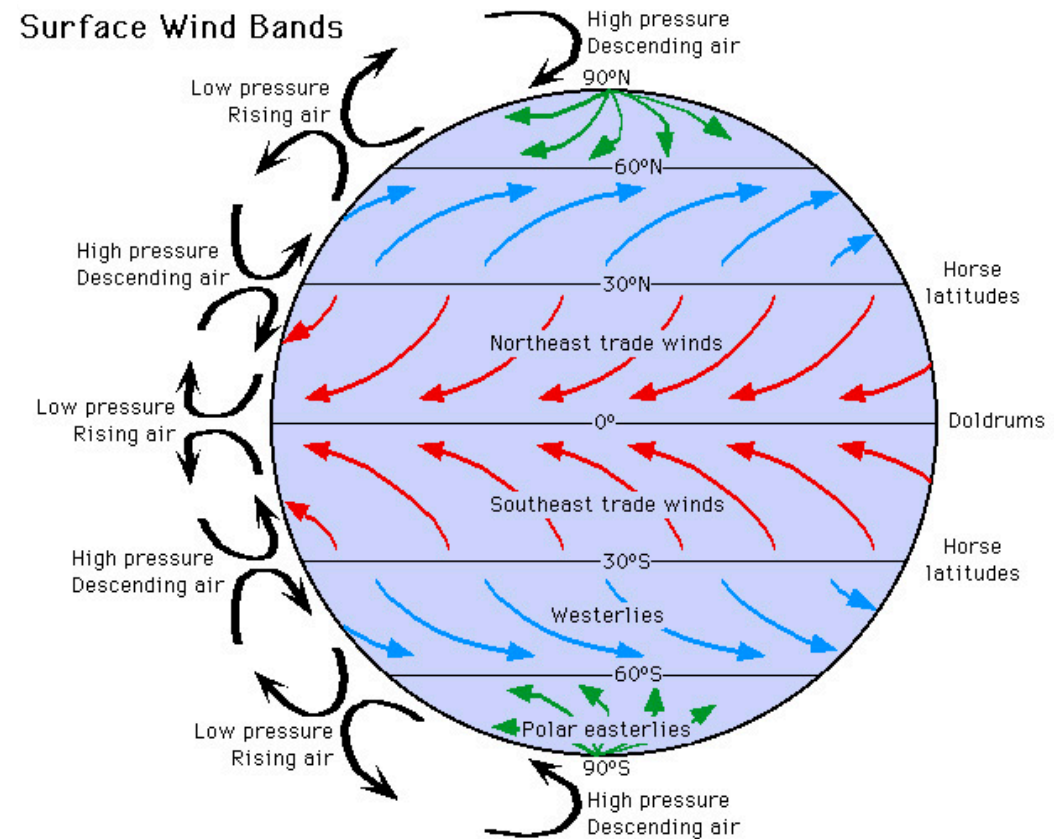
THE NAVIER-STOKES EQUATIONS

The diagram illustrates the Navier-Stokes equation with detailed annotations for each term. On the left, the equation is written as $\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \nabla P + \rho \mathbf{g} + \mu \nabla^2 \mathbf{V}$. Brackets and labels explain each part:

- MASS**: Density of the fluid (ρ)
- ACCELERATION**: How velocity experienced by a particle changes with time. This is represented by the terms in the large parentheses:
 - $\frac{\partial \mathbf{V}}{\partial t}$: Change in velocity over time
 - $\mathbf{V} \cdot \nabla \mathbf{V}$: The speed and direction which the fluid is moving
- FORCE**: All the forces that are acting on the fluid. This is represented by the right side of the equation:
 - ∇P : Internal pressure gradient of the fluid (the change in pressure)
 - $\rho \mathbf{g}$: External forces acting on the fluid (such as gravity)
 - $\mu \nabla^2 \mathbf{V}$: Internal stress forces acting on the fluid (taking into consideration viscous effects)

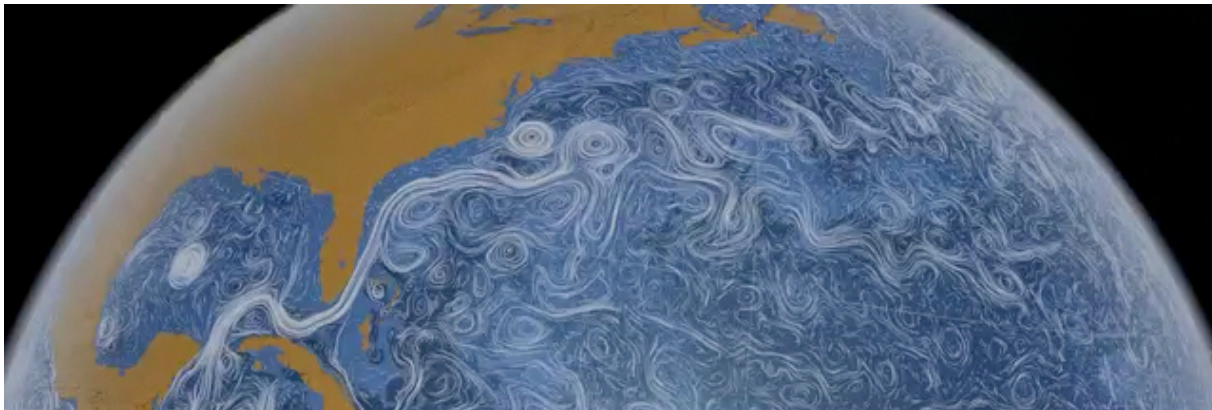
UNRESTRICTED FLOW ON ROTATING BODY

- ▶ Flow unrestrained (no geography)
- ▶ Rotation introduced pressure differentials
 - ▶ Along axis
 - ▶ Around sun
- ▶ Large temperature deviation



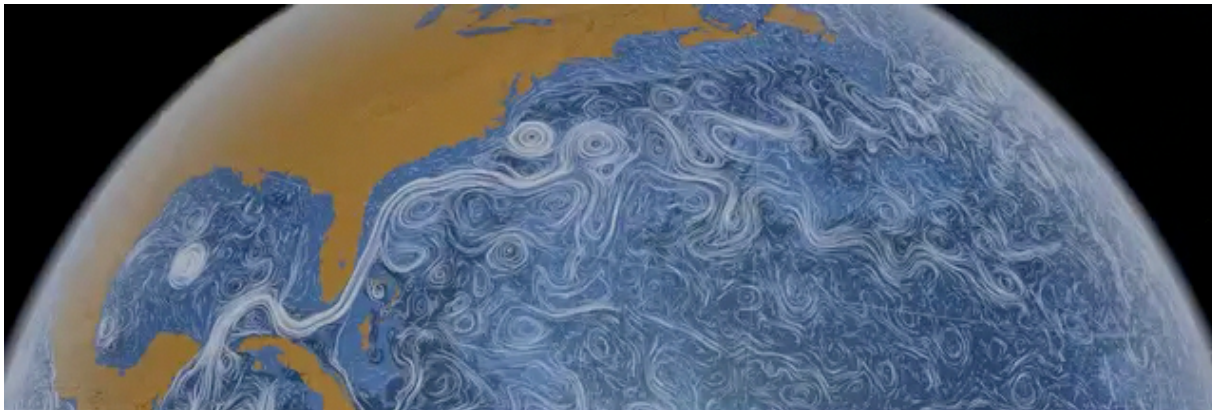
BOUNDARIES & TERRAIN RESTRICT FLOW

- ▶ Boundaries divert flow
- ▶ Density changes
 - ▶ Internal waves / temperature gradient
- ▶ External attraction induces tides



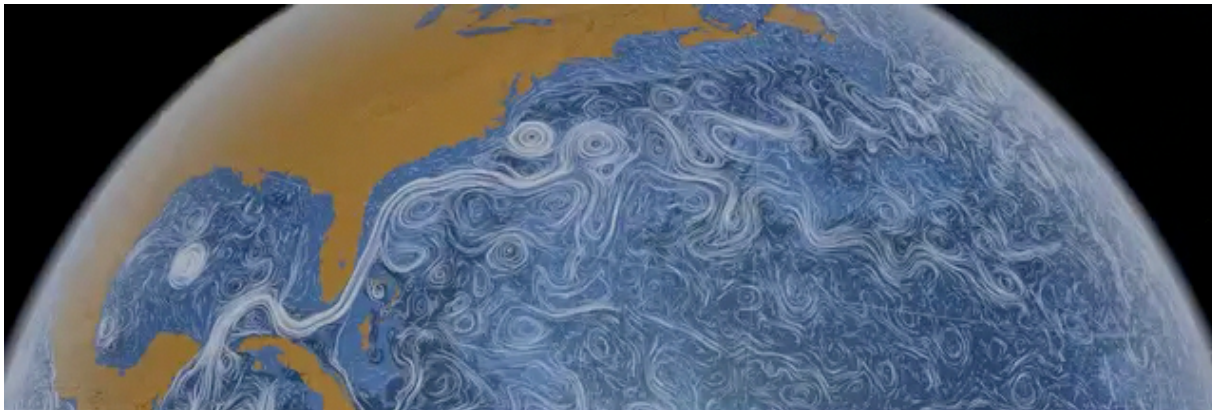
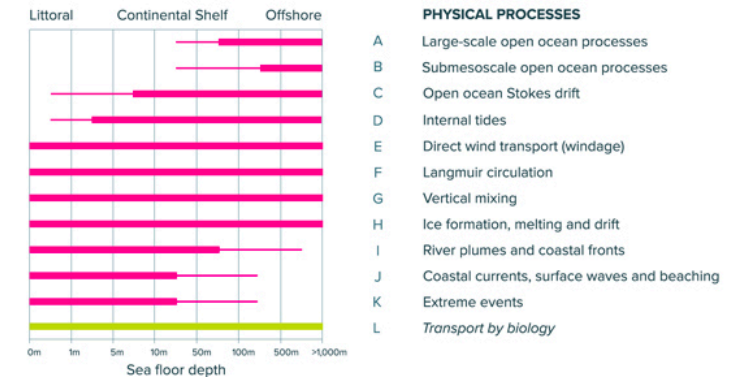
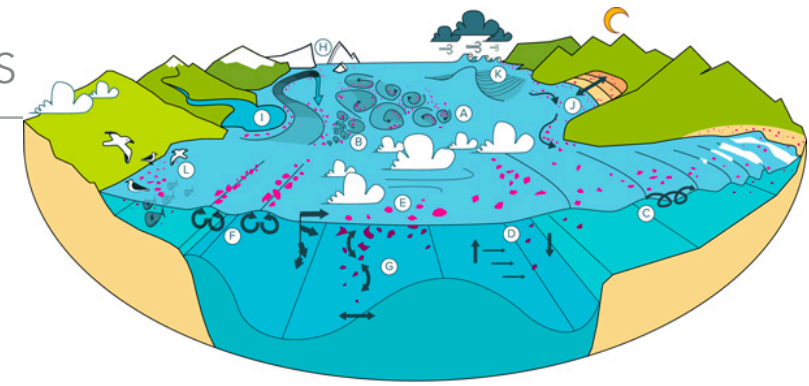
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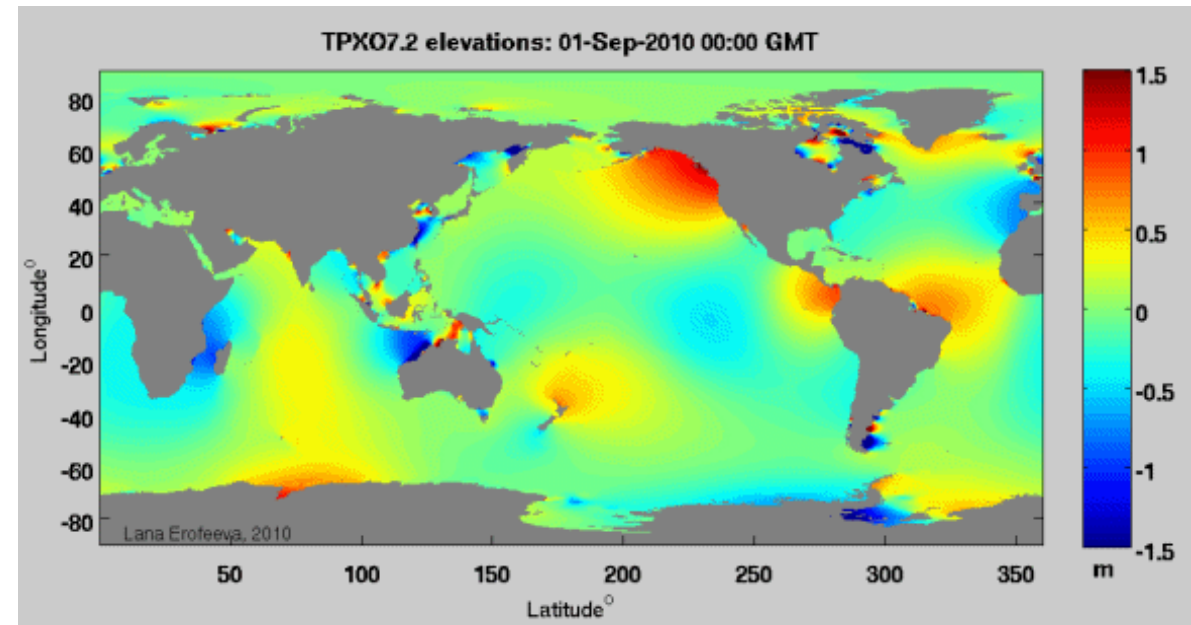
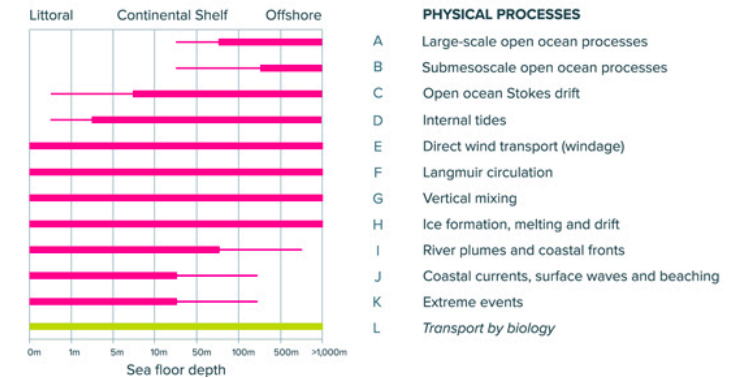
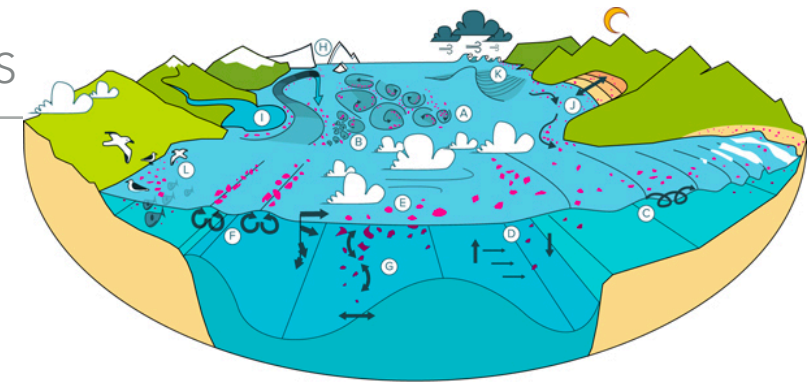
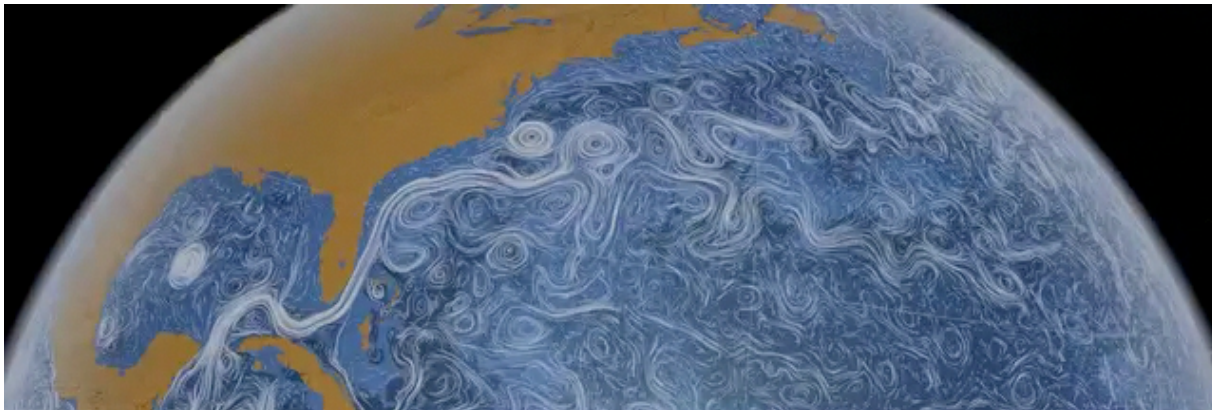
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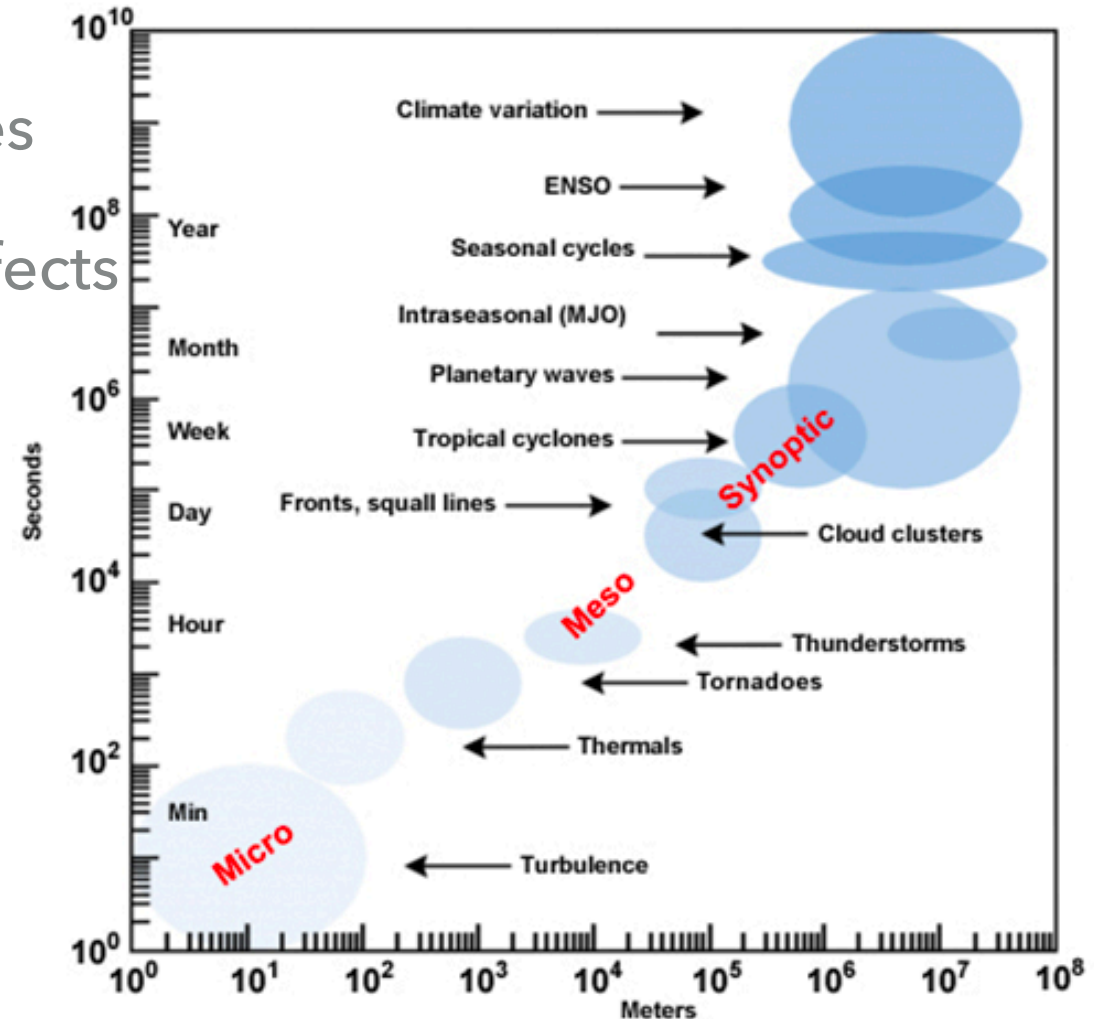
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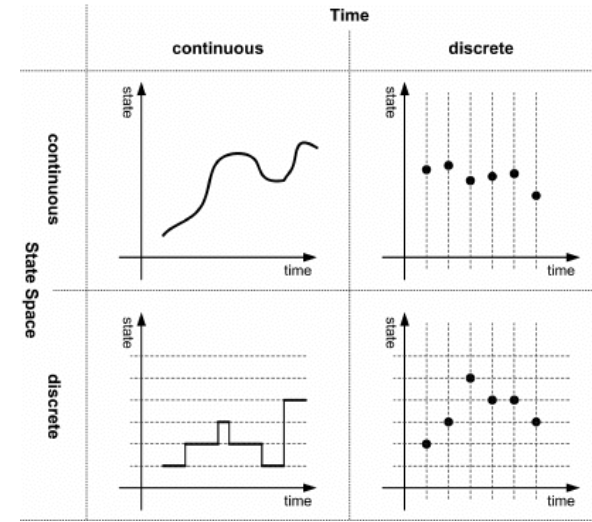
SCALES OF VARIATION

- ▶ Equations govern behaviour across all scales
- ▶ Kolmogorov scales determine important effects
- ▶ Butterfly effect
 - ▶ A butterfly in Japan can cause an tornado in the US
- ▶ Non-linear dynamics cause chaos!



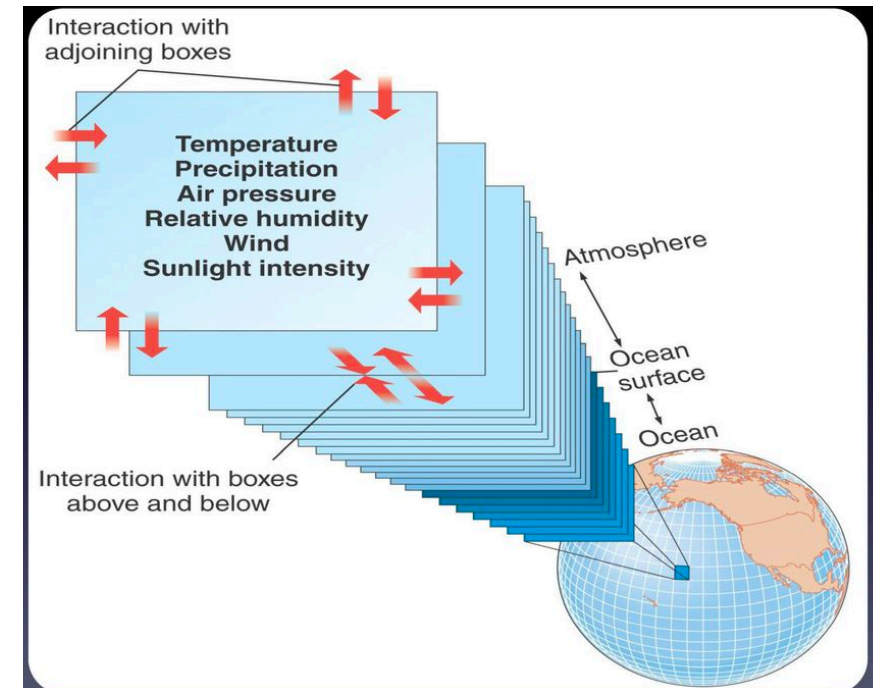
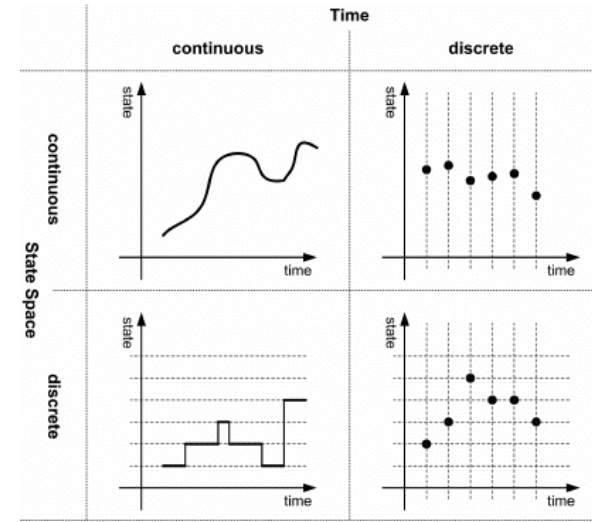
FROM CONTINUES TO DISCRETE

- ▶ No exact solution exist (chaos)
- ▶ Limitation of General Circulation Models
- ▶ Requires parameterisation
 - ▶ Empirical formulation of sub-grid process
 - ▶ Different insight
 - ▶ Variation between models



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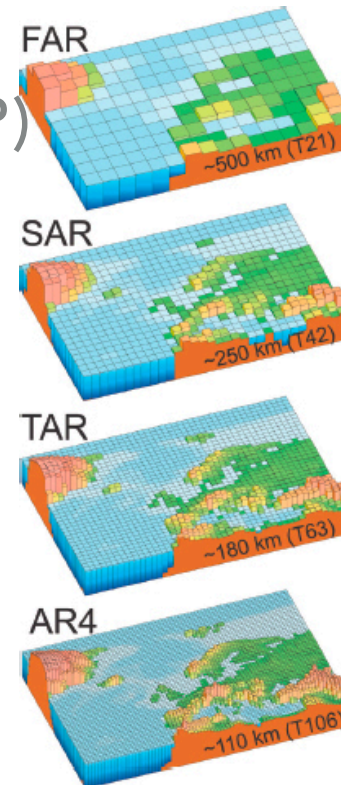
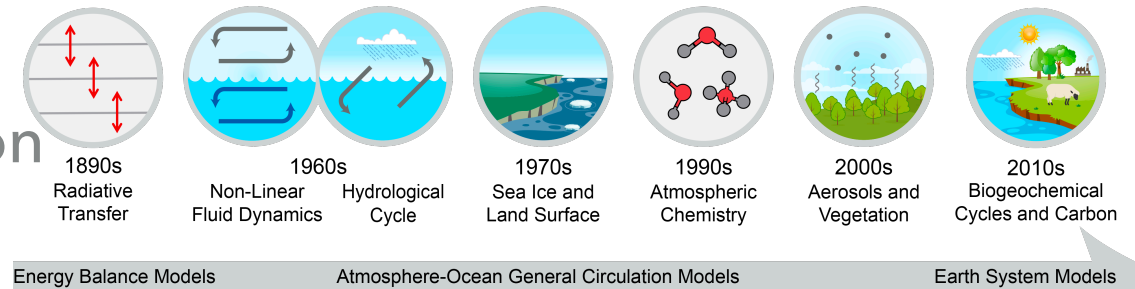
ADVANCEMENTS IN RECENT DECADES

► From Energy budget to General Circulation

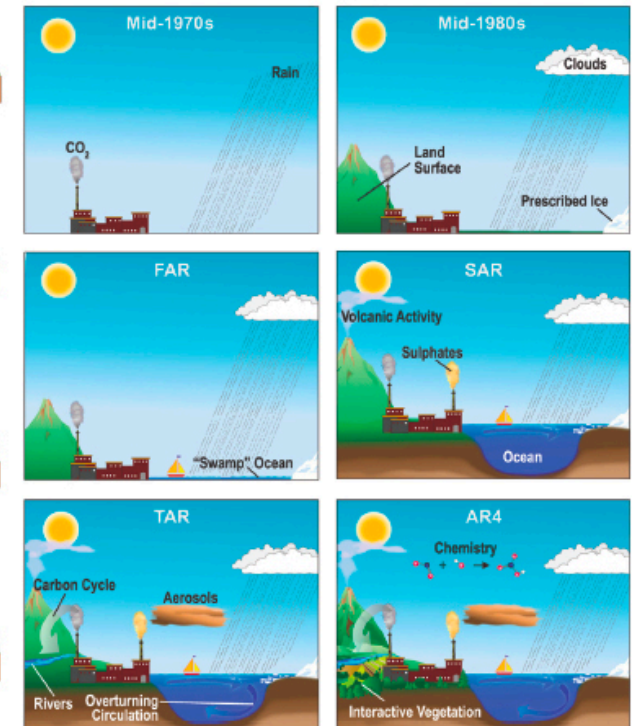
► Coupled Model Intercomparison Project (CMIP)

- Climate model generation
- Variation is wanted!

A Climate Modeling Timeline
(When Various Components Became Commonly Used)

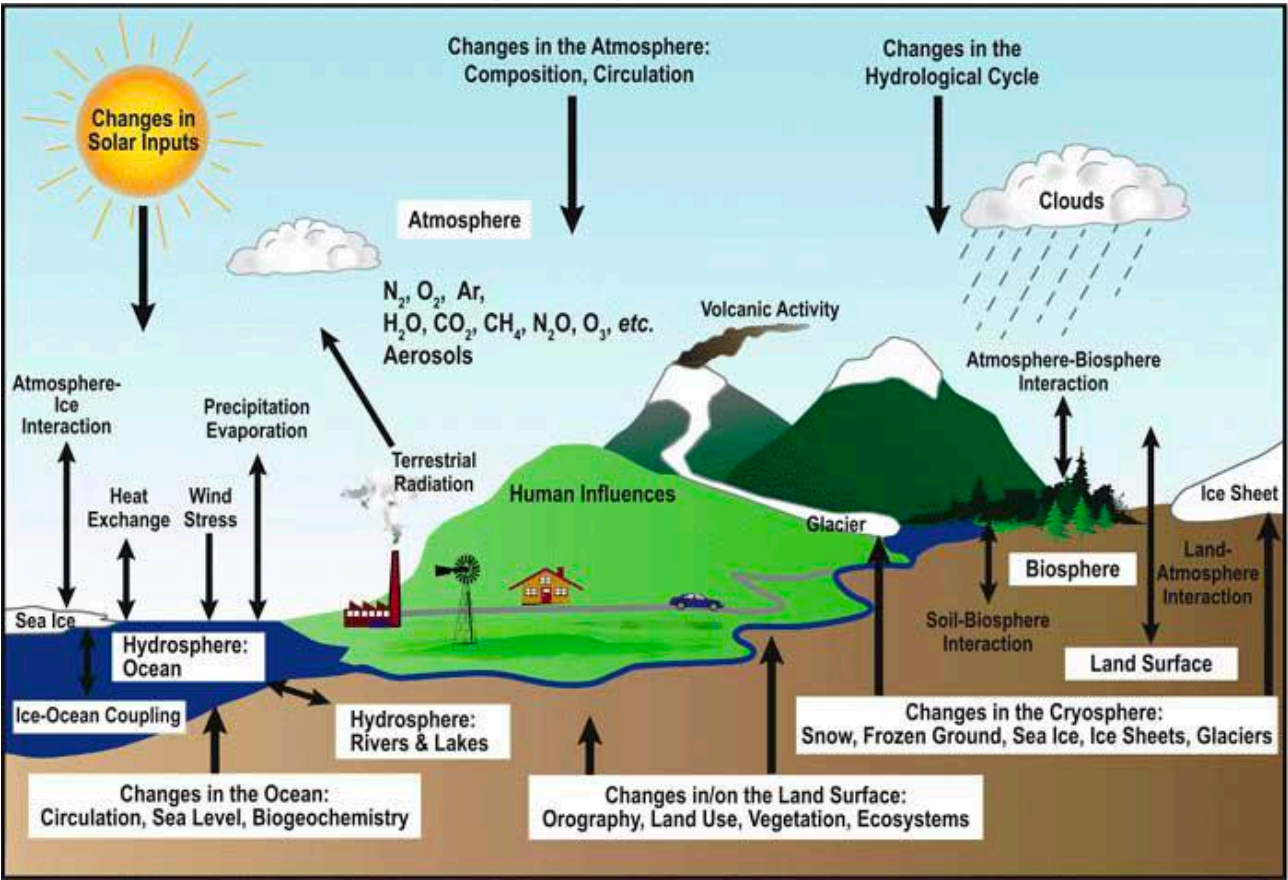


The World in Global Climate Models

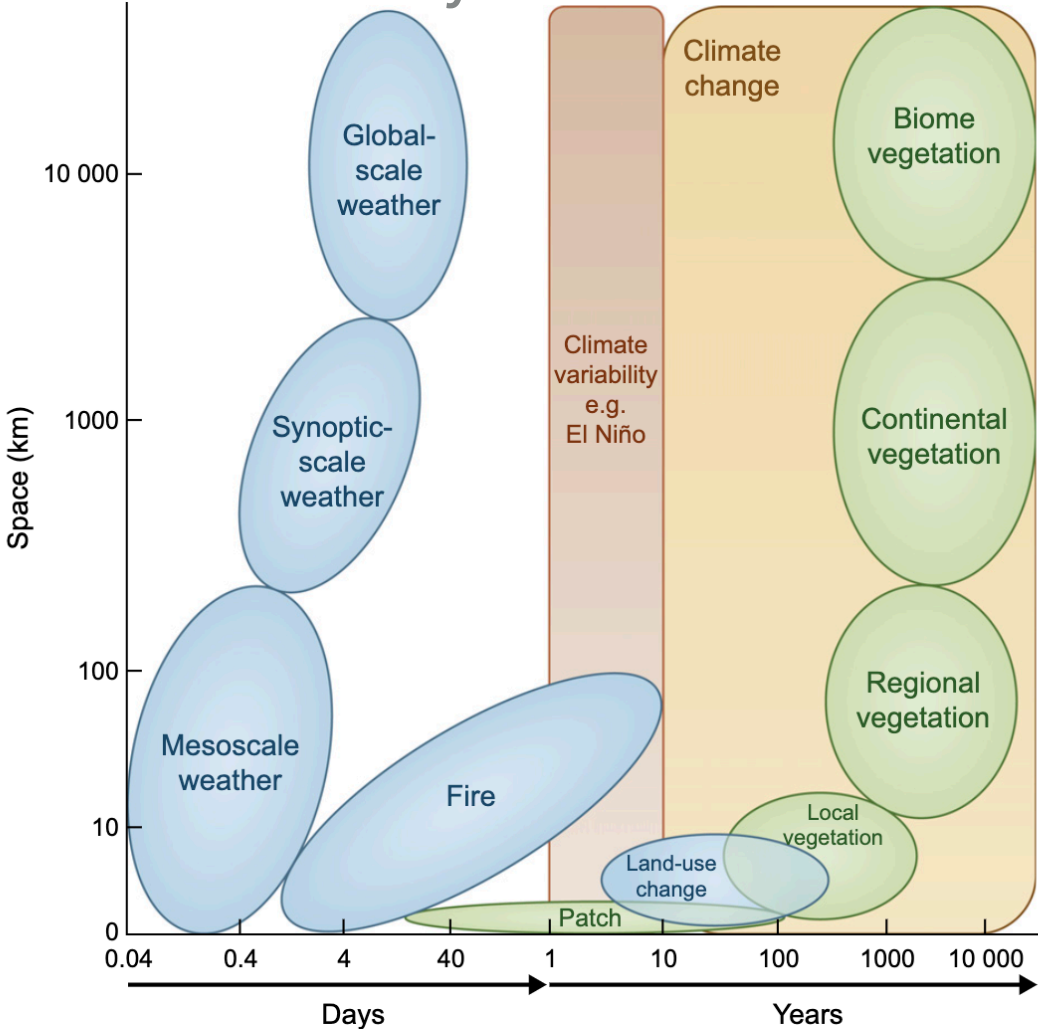


CHANGES AND DRIVERS IN GCMS

Coupling & drivers

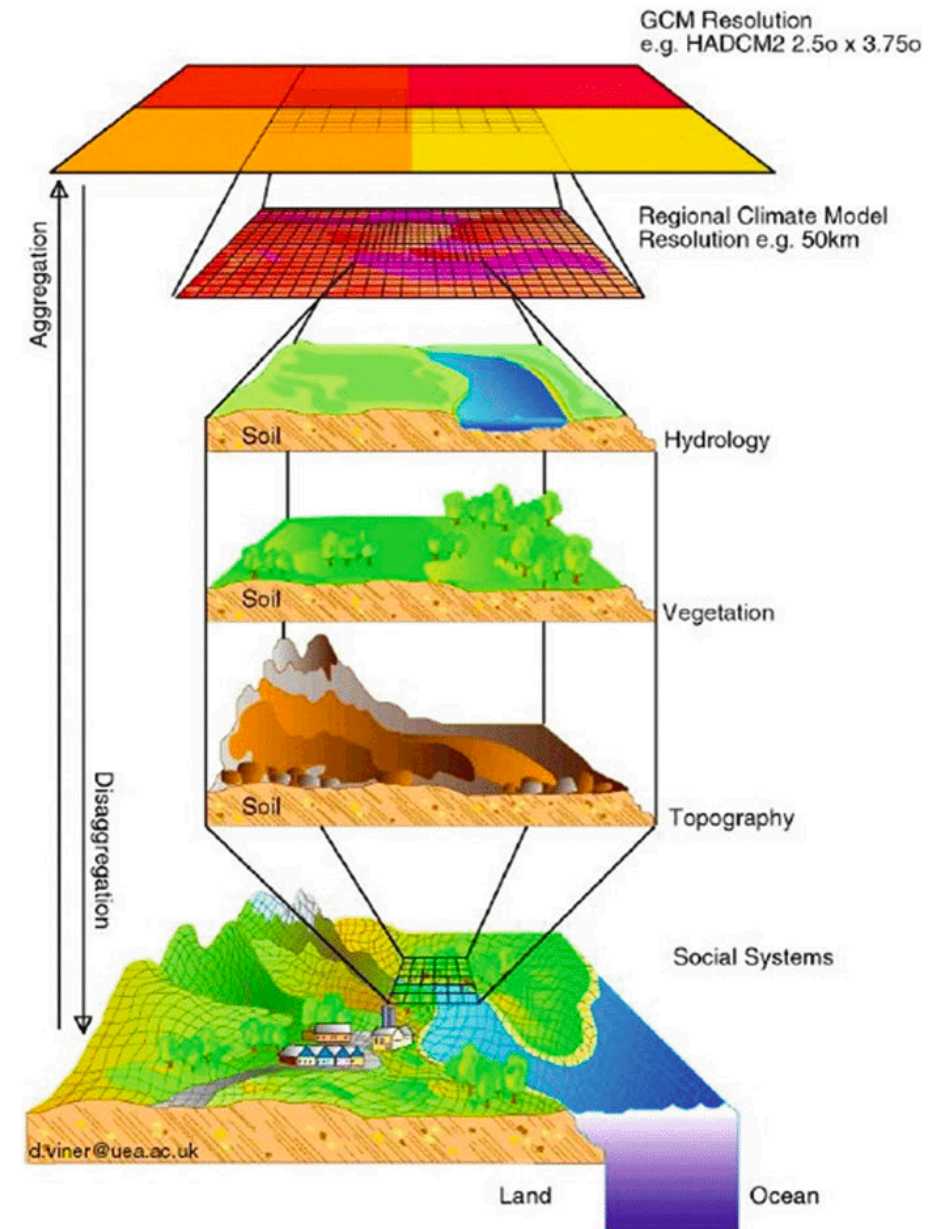
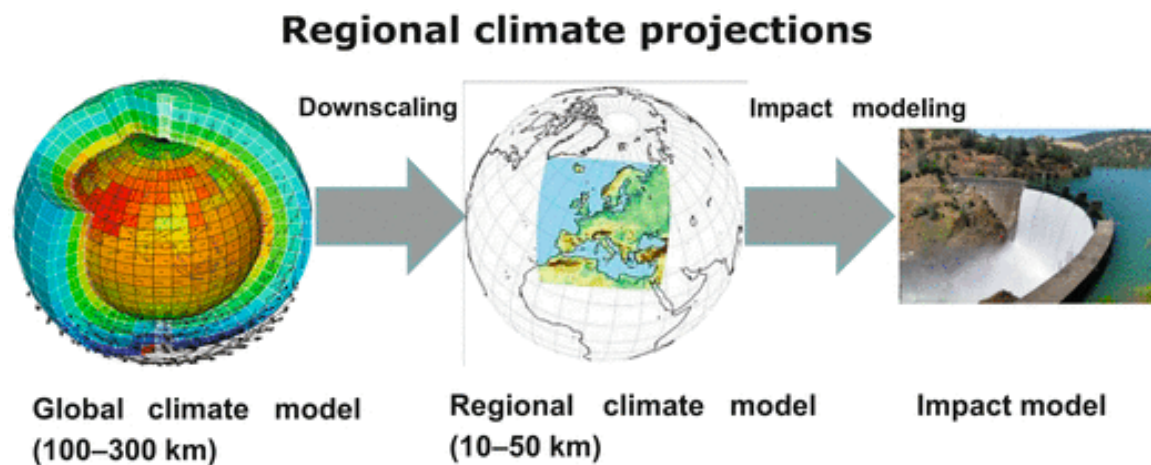


Ecosystem drivers



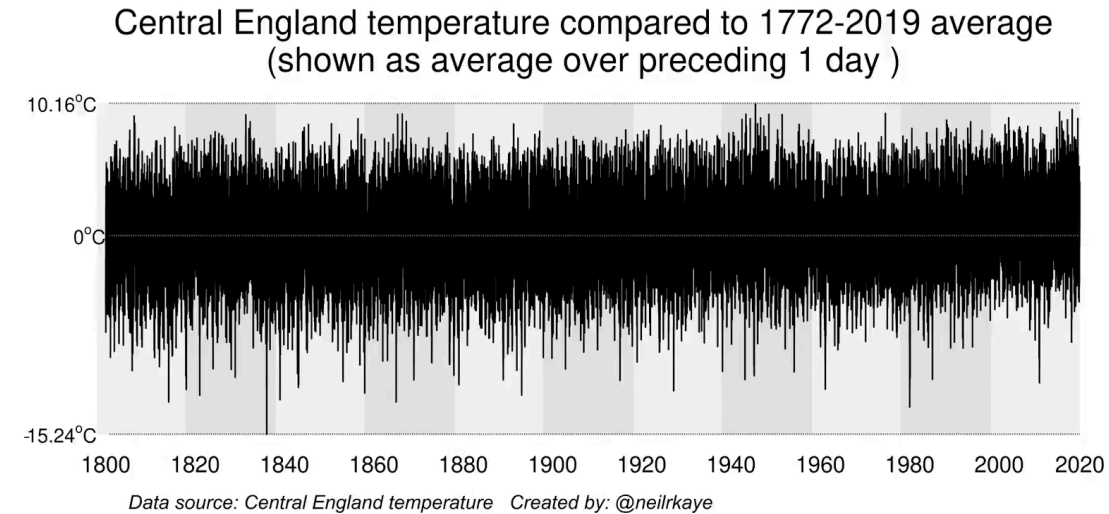
REGIONAL VS GLOBAL

- ▶ Regional models are driven by a global model
- ▶ Local re-parameterisation of effect
 - ▶ Boundaries and transition one-way

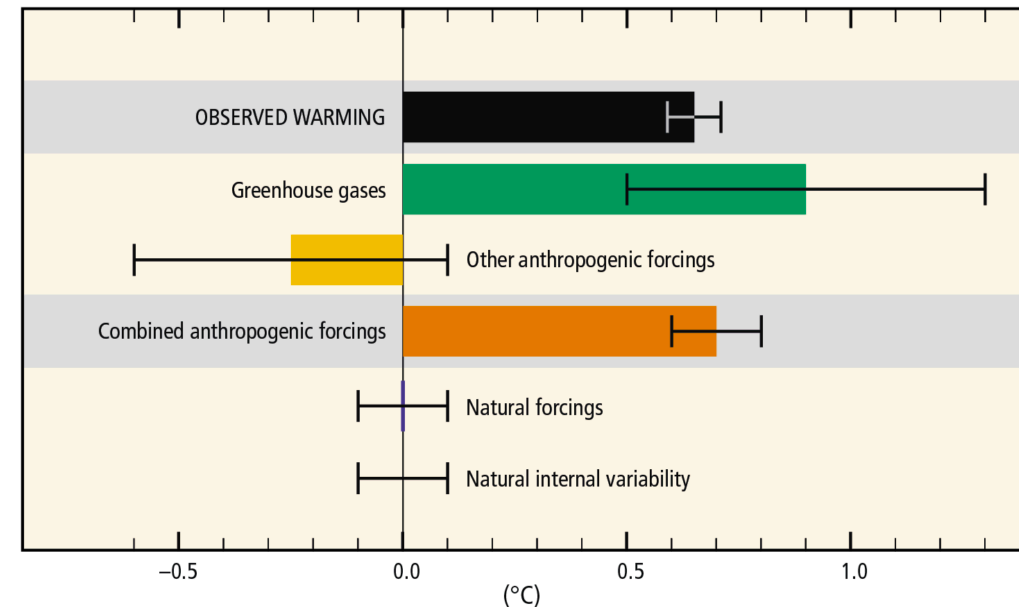


CLIMATE CHANGE OBSERVED

- ▶ Weather shows large variability
- ▶ Climate is average weather
- ▶ Observed climate change depends on
 - ▶ Anthropogenic forcings
 - ▶ Natural forcings

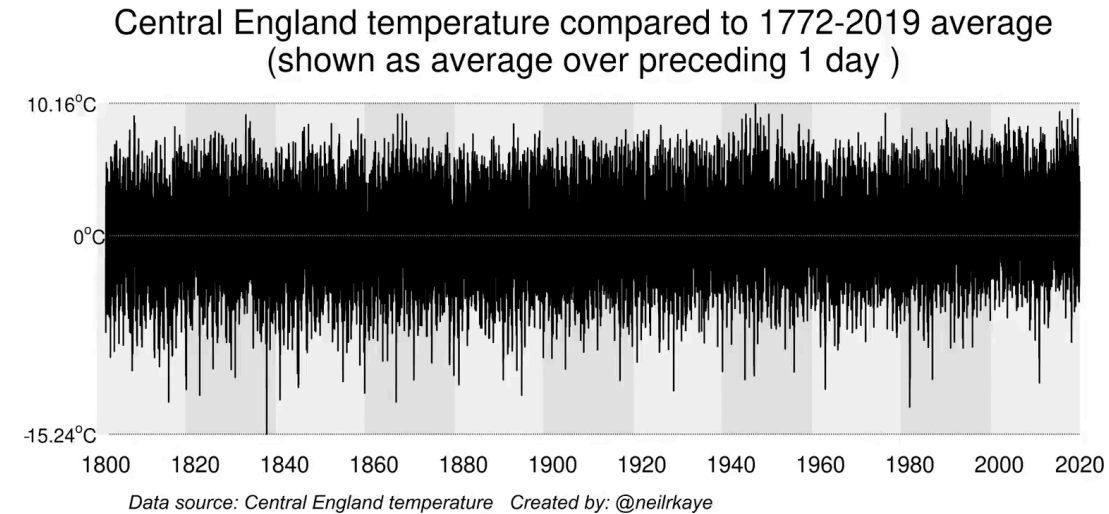


Contributions to observed surface temperature change over the period 1951–2010

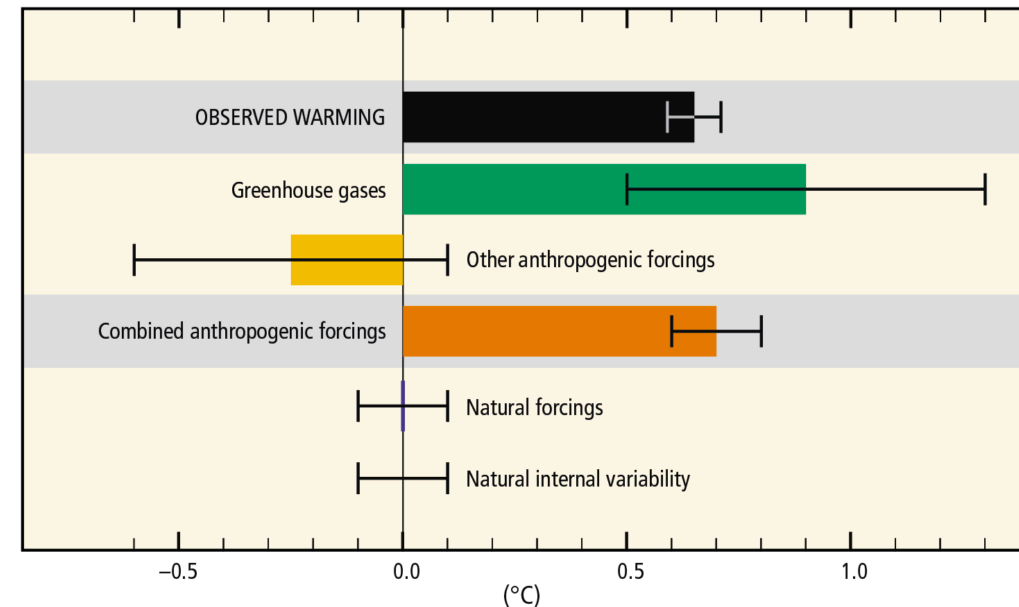


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Contributions to observed surface temperature change over the period 1951–2010



CLIMATE SENSITIVITY

- ▶ Feedbacks are important
- ▶ Climate Sensitivity – not only based on models
 - ▶ Equilibrium: stabilization after $2\times\text{CO}_2$
 - ▶ Transient: 20-year mean change at time of $2\times\text{CO}_2$ with 1% increase CO_2 per year
- ▶ Exact value uncertain, but signal very clear!

