Utrecht University

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Waterstaat

TenneT

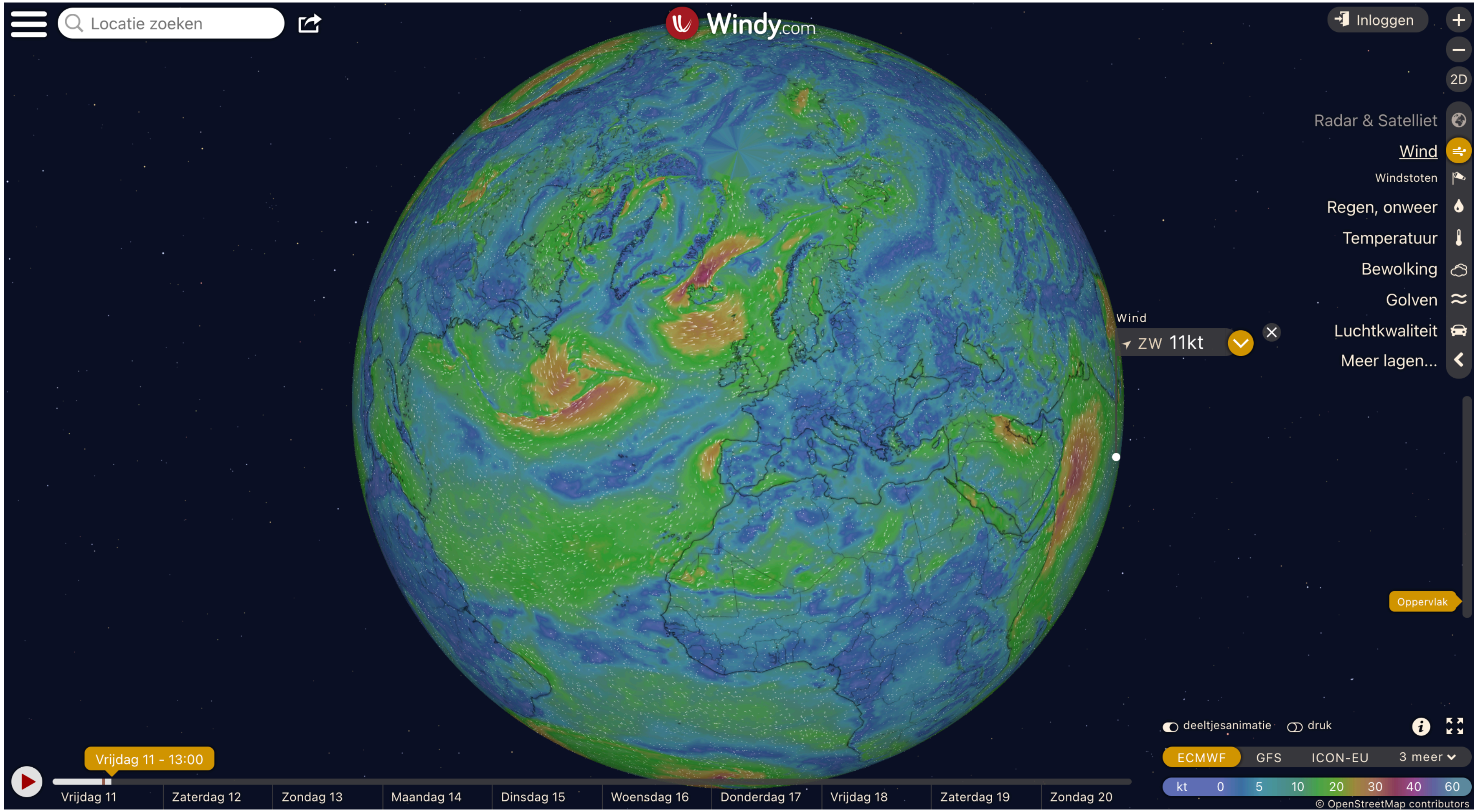
LAURENS STOOP

CLIMATE PHYSICS

www.laurensstoop.nl

l.p.stoop@uu.nl

NUMERICAL PREDICTION BASED ON NAVIER-STOKES EQUATIONS



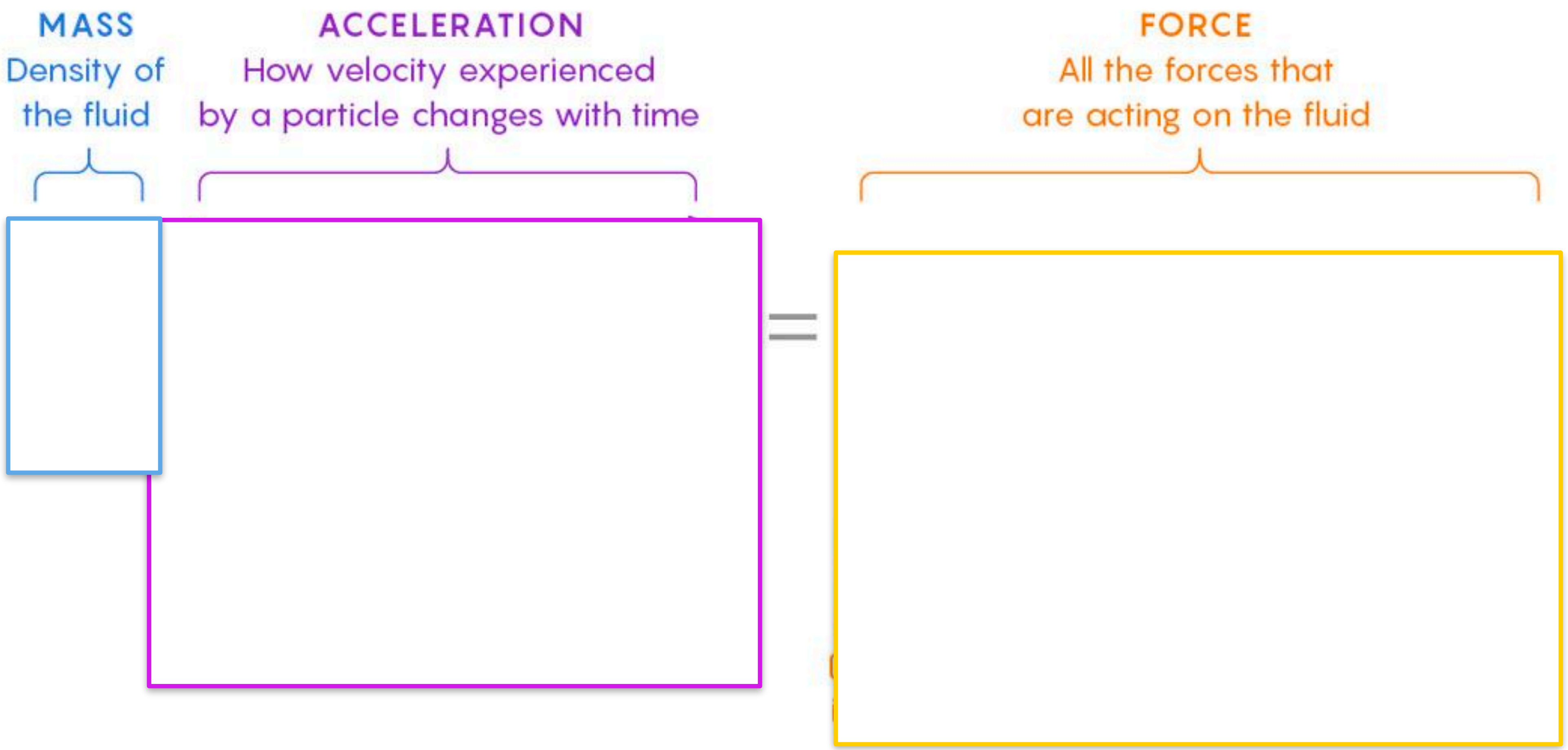
THE NAVIER-STOKES EQUATIONS — ORIGIN

Four equations that determine the properties and behaviour

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

These equations are for a rotating sphere with a compressible fluid

THE NAVIER–STOKES EQUATIONS



THE NAVIER-STOKES EQUATIONS

MASS
Density of the fluid

ACCELERATION
How velocity experienced by a particle changes with time

FORCE
All the forces that are acting on the fluid

ρ =

THE NAVIER-STOKES EQUATIONS

MASS
Density of the fluid

ACCELERATION
How velocity experienced by a particle changes with time

FORCE
All the forces that are acting on the fluid

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

Change in velocity over time

The speed and direction which the fluid is moving

THE NAVIER-STOKES EQUATIONS

MASS
Density of the fluid

ACCELERATION
How velocity experienced by a particle changes with time

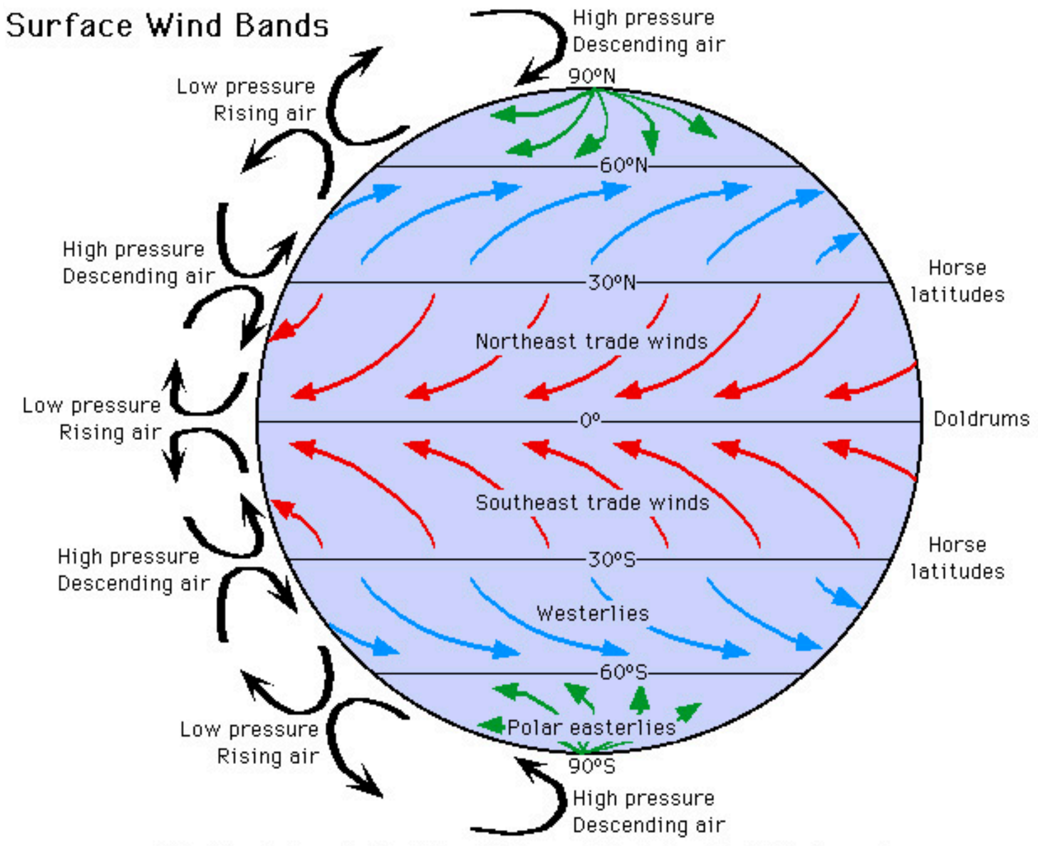
FORCE
All the forces that are acting on the fluid

$$\rho\left(\frac{\partial V}{\partial t} + V\cdot\nabla V\right) = \nabla P + \rho g + \mu\nabla^2 V$$

- $\frac{\partial V}{\partial t}$: Change in velocity over time
- $V\cdot\nabla V$: The speed and direction which the fluid is moving
- ∇P: **Internal pressure gradient** of the fluid (the change in pressure)
- ρg: **External forces** acting on the fluid (such as gravity)
- $\mu\nabla^2 V$: **Internal stress forces** acting on the fluid (taking into consideration viscous effects)

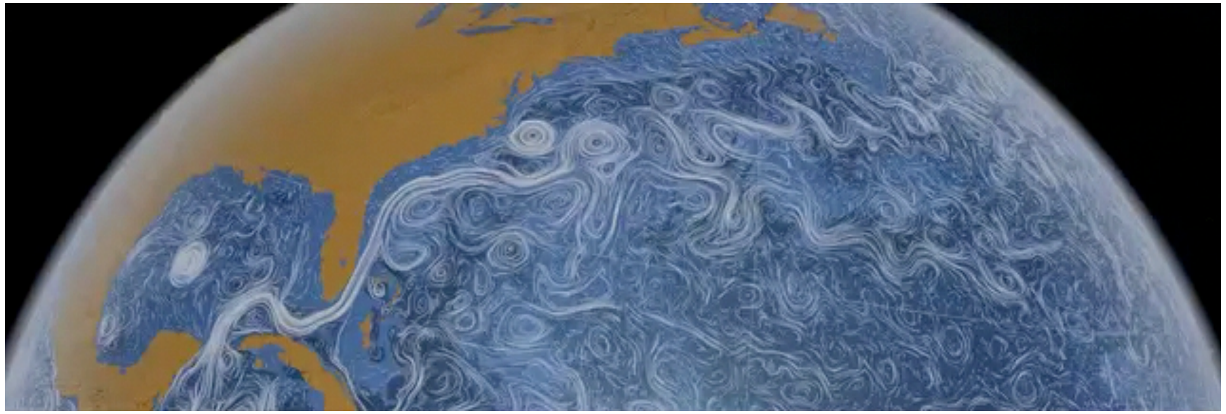
UNRESTRICTED FLOW ON ROTATING BODY

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



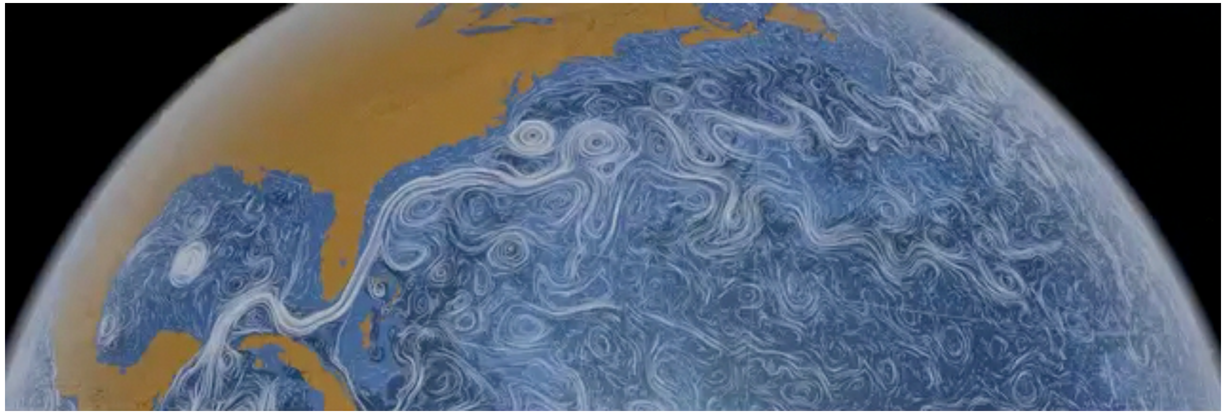
BOUNDARIES & TERRAIN RESTRICT FLOW

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

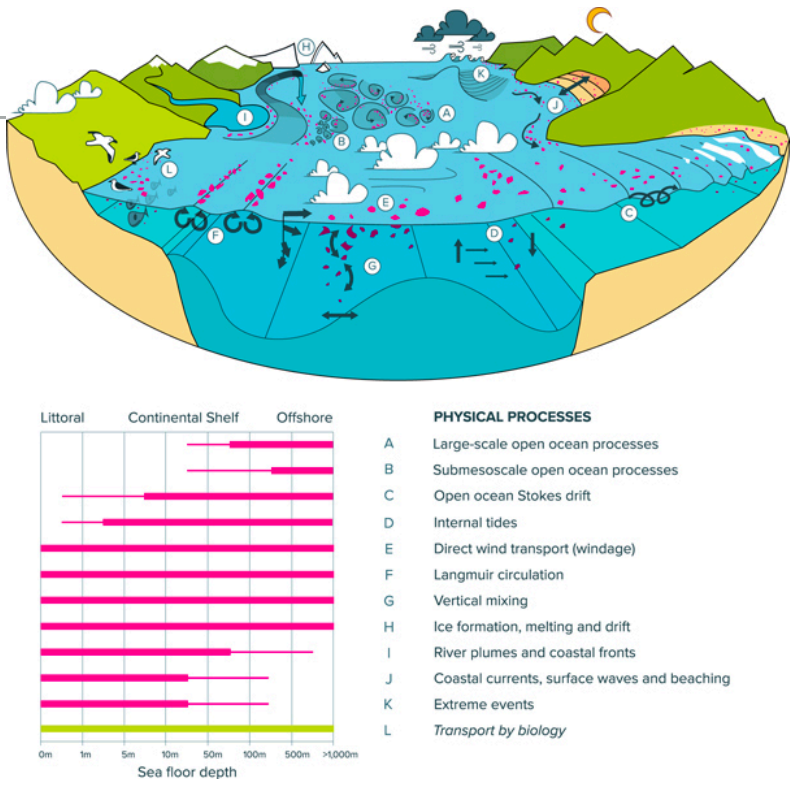


BOUNDARIES & TERRAIN RESTRICT FLOW

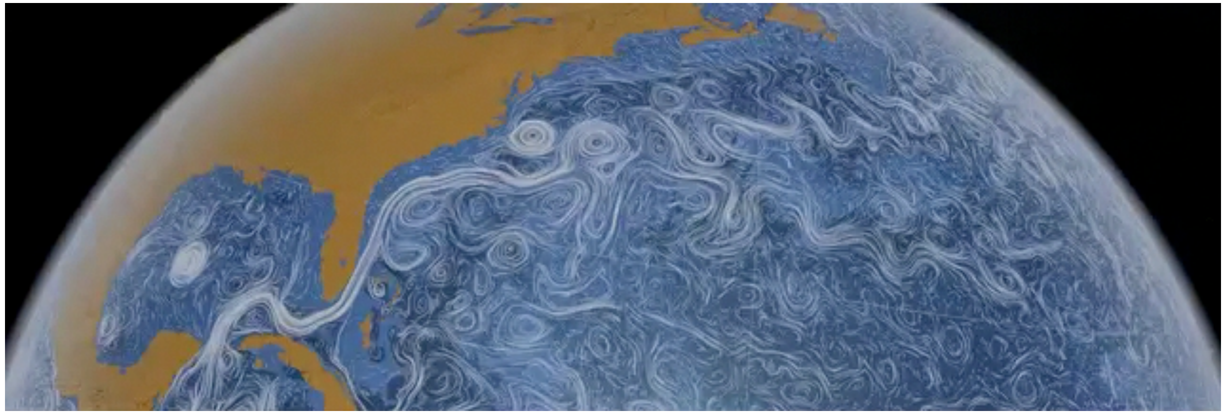
- Boundaries divert flow
- Density changes
    - Internal waves / temperature gradient
- External attraction induces tides



BOUNDARIES & TERRAIN RESTRICT FLOW

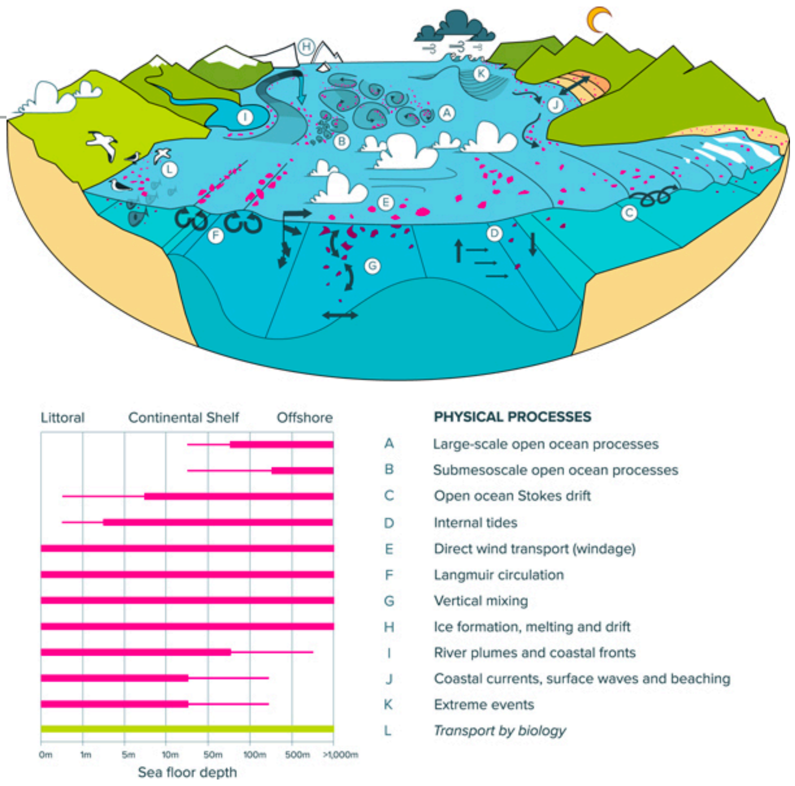


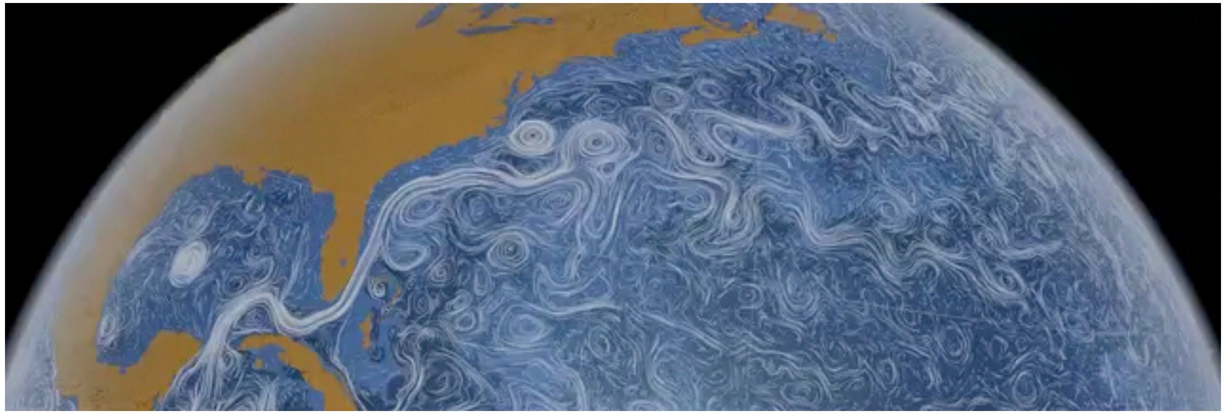
- Boundaries divert flow
- Density changes
    - Internal waves / temperature gradient
- External attraction induces tides

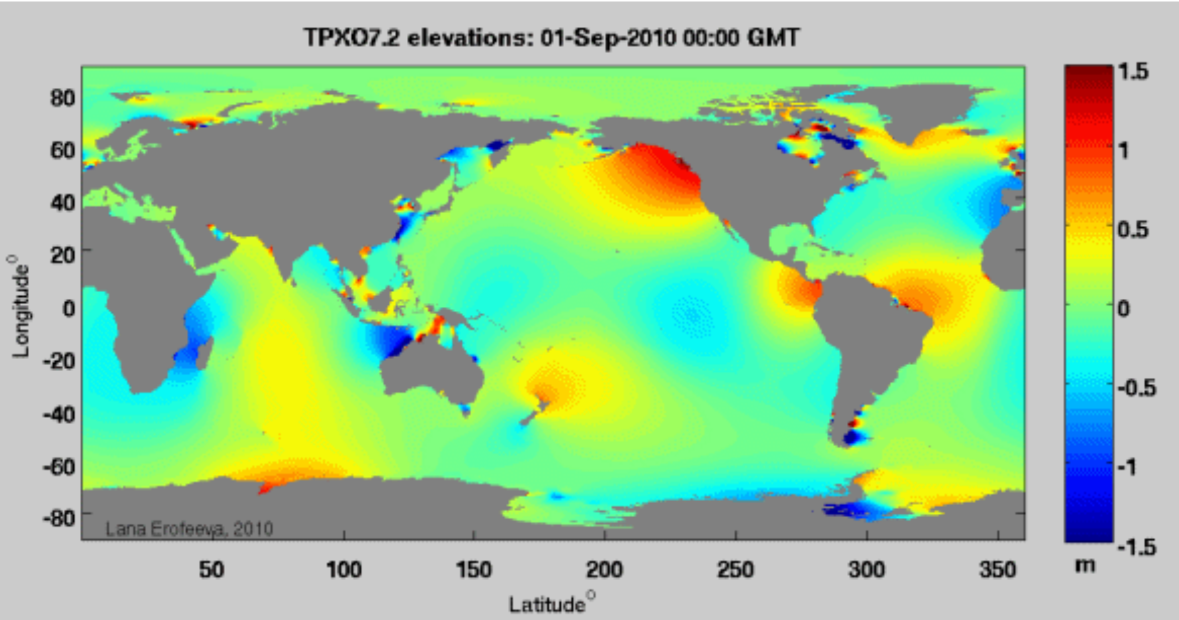


BOUNDARIES & TERRAIN RESTRICT FLOW

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

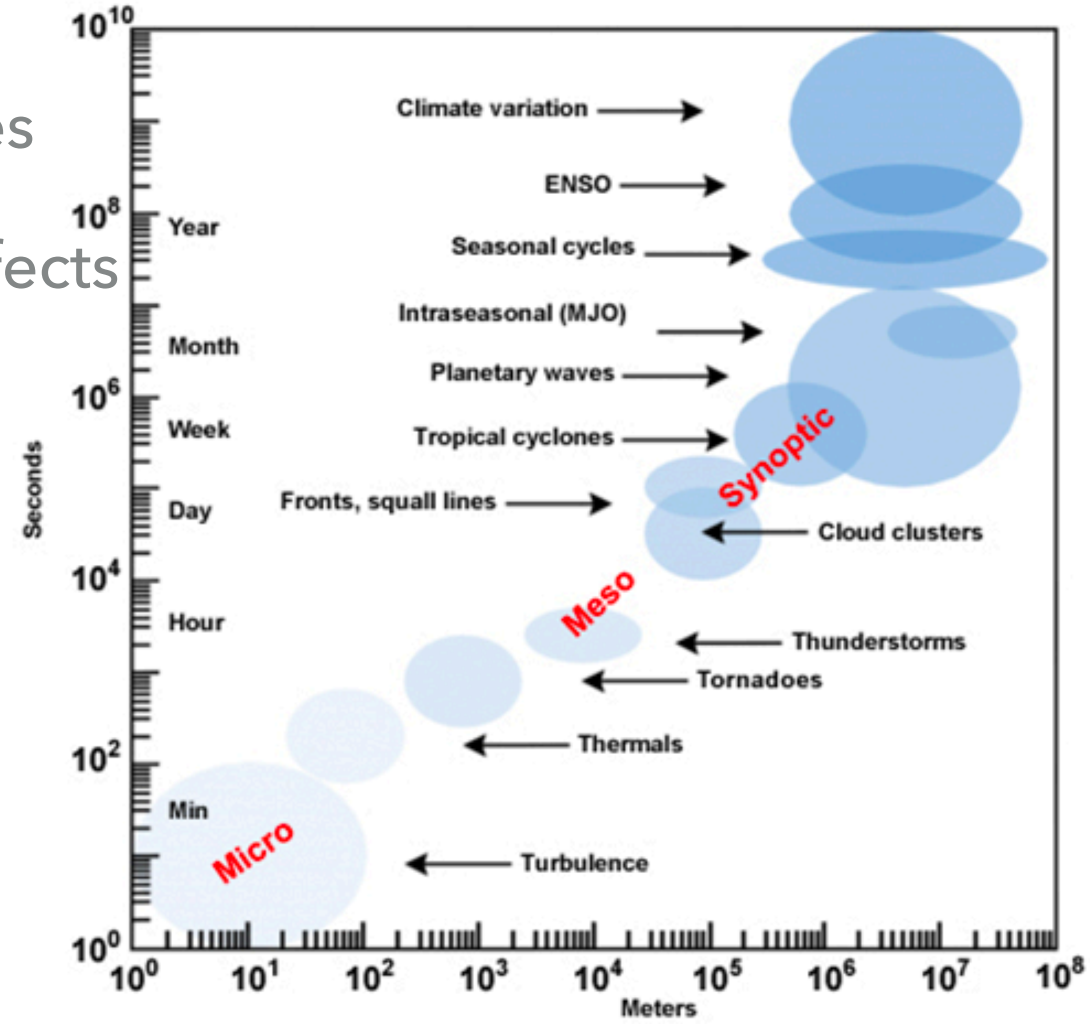




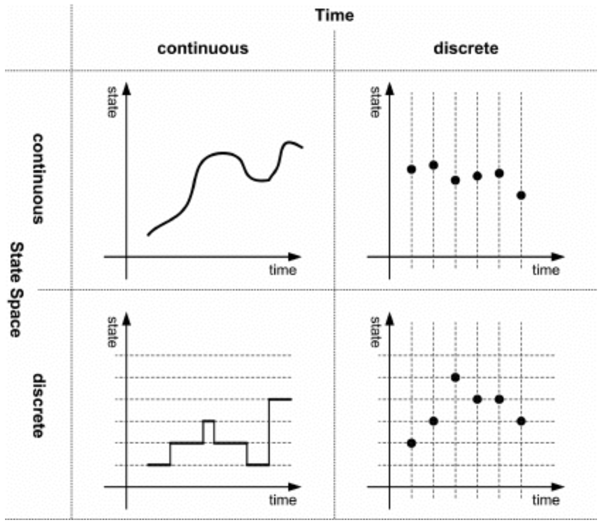


SCALES OF VARIATION

- 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!



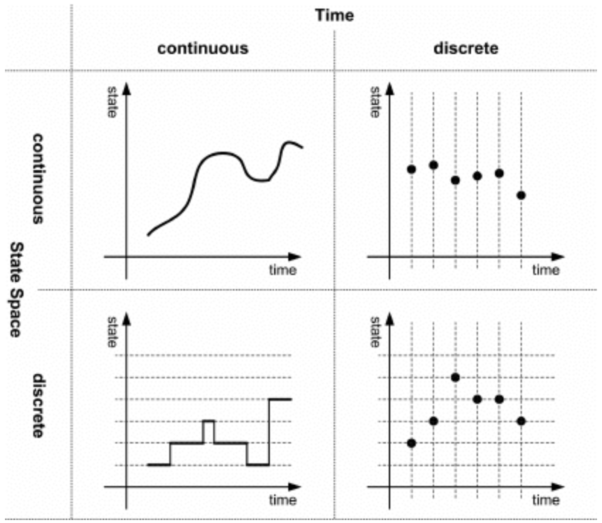
FROM CONTINUES TO DISCRETE

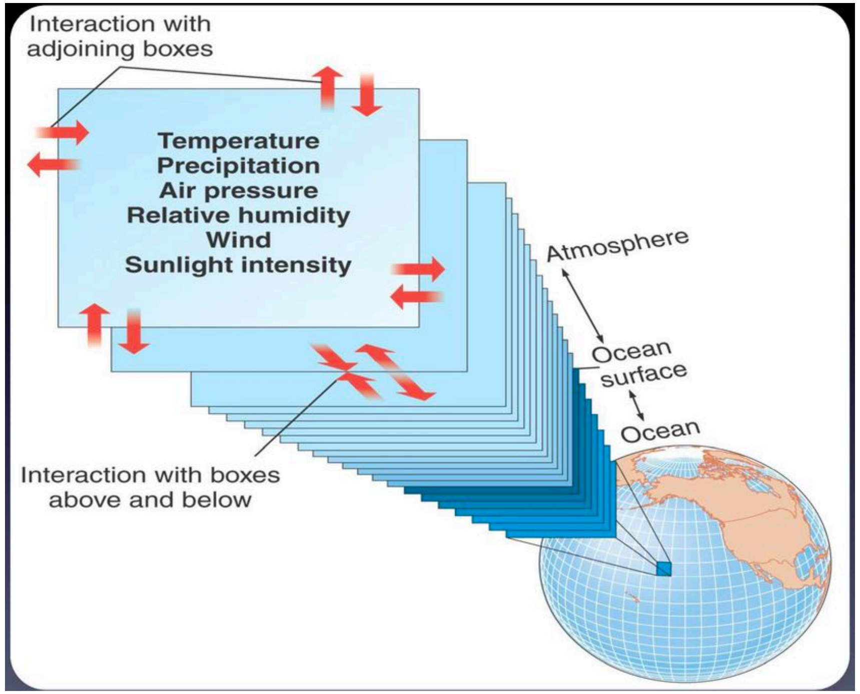


- No exact solution exist (chaos)
- Limitation of General Circulation Models
- Requires parameterisation
  - Empirical formulation of sub-grid process
  - Different insight
  - Variation between models

FROM CONTINUES TO DISCRETE

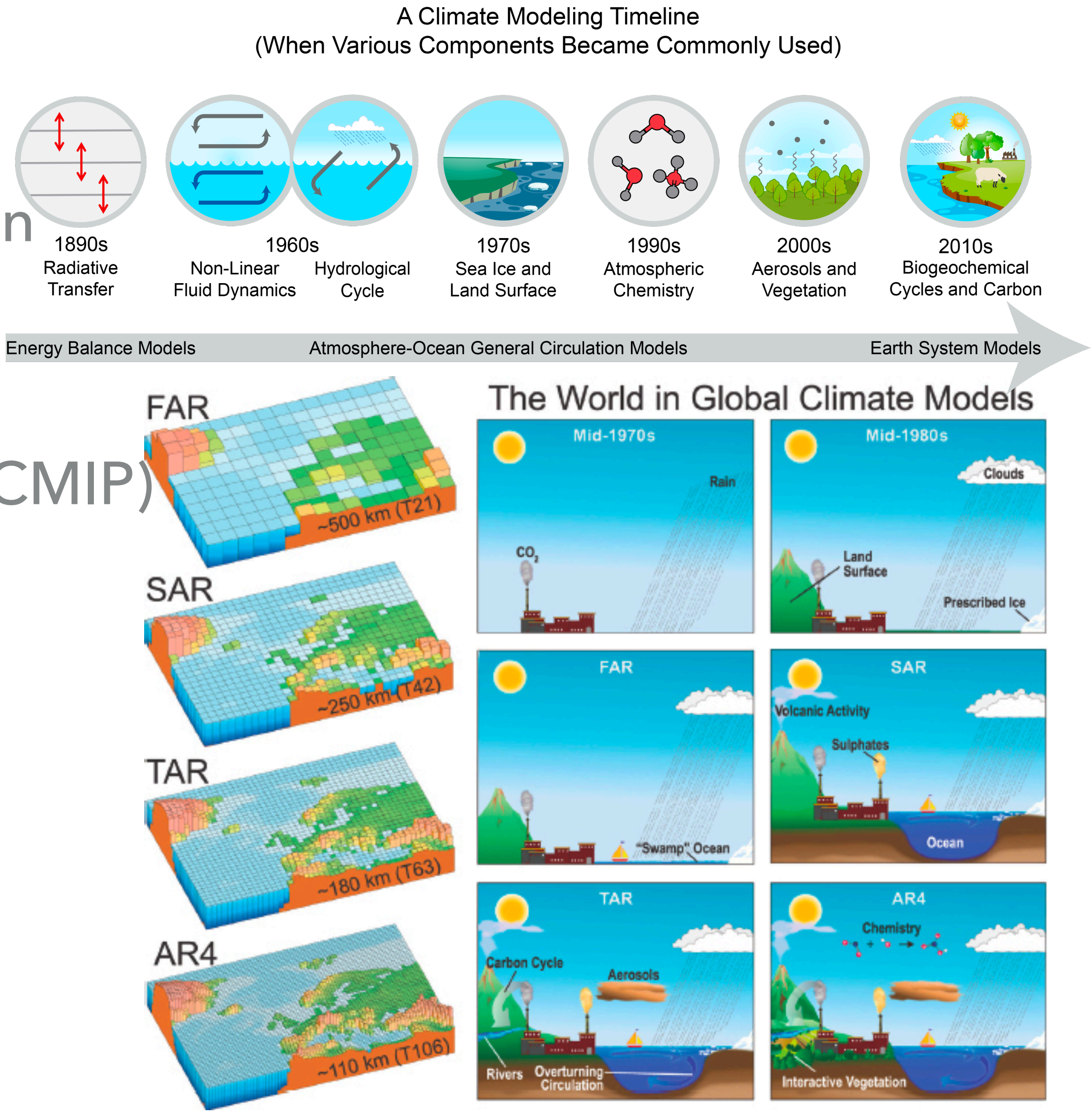
- No exact solution exist (chaos)
- Limitation of General Circulation Models
- Requires parameterisation
    - Empirical formulation of sub-grid process
    - Different insight
    - Variation between models





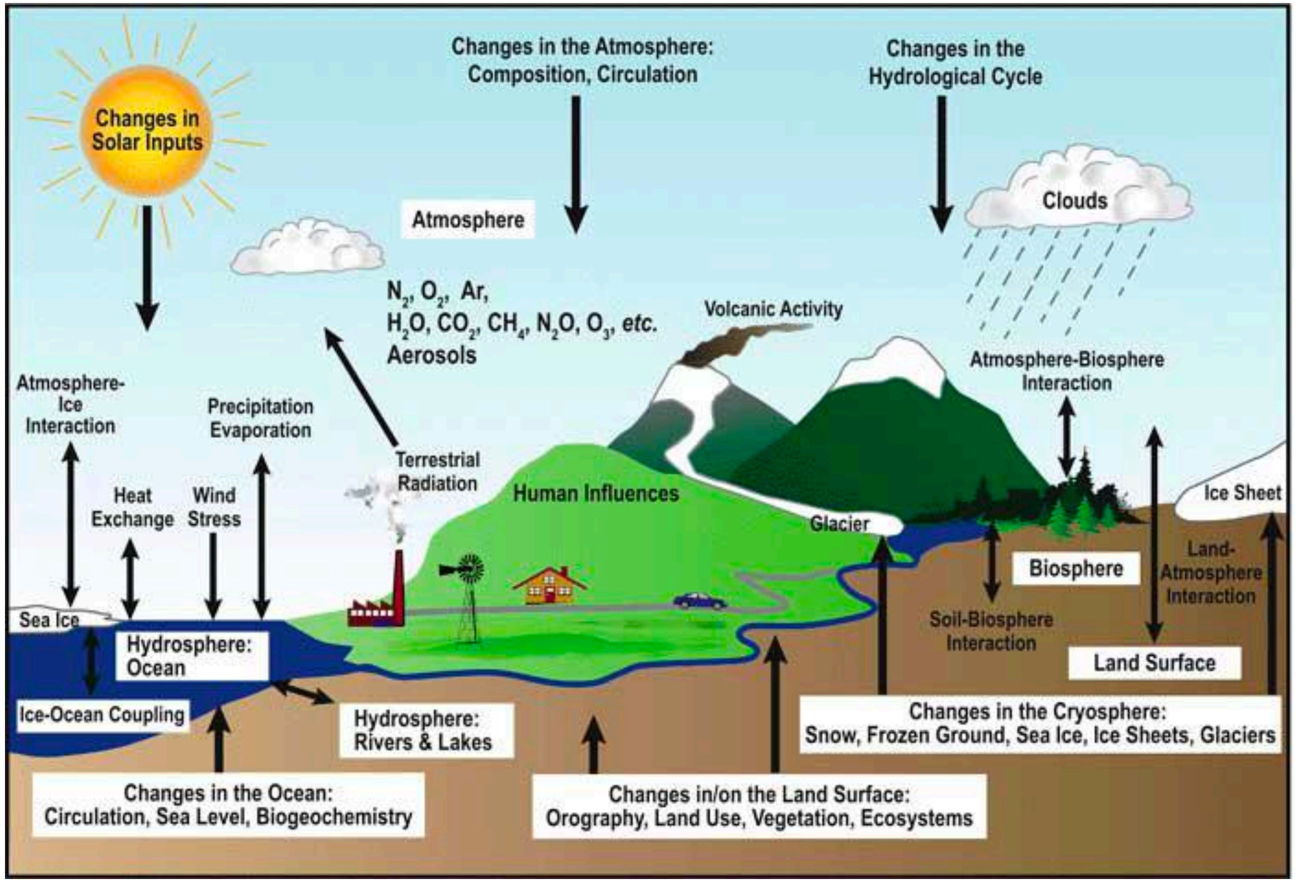
ADVANCEMENTS IN RECENT DECADES

- From Energy budget to General Circulation
- Coupled Model Intercomparison Project (CMIP)
    - Climate model generation
    - Variation is wanted!

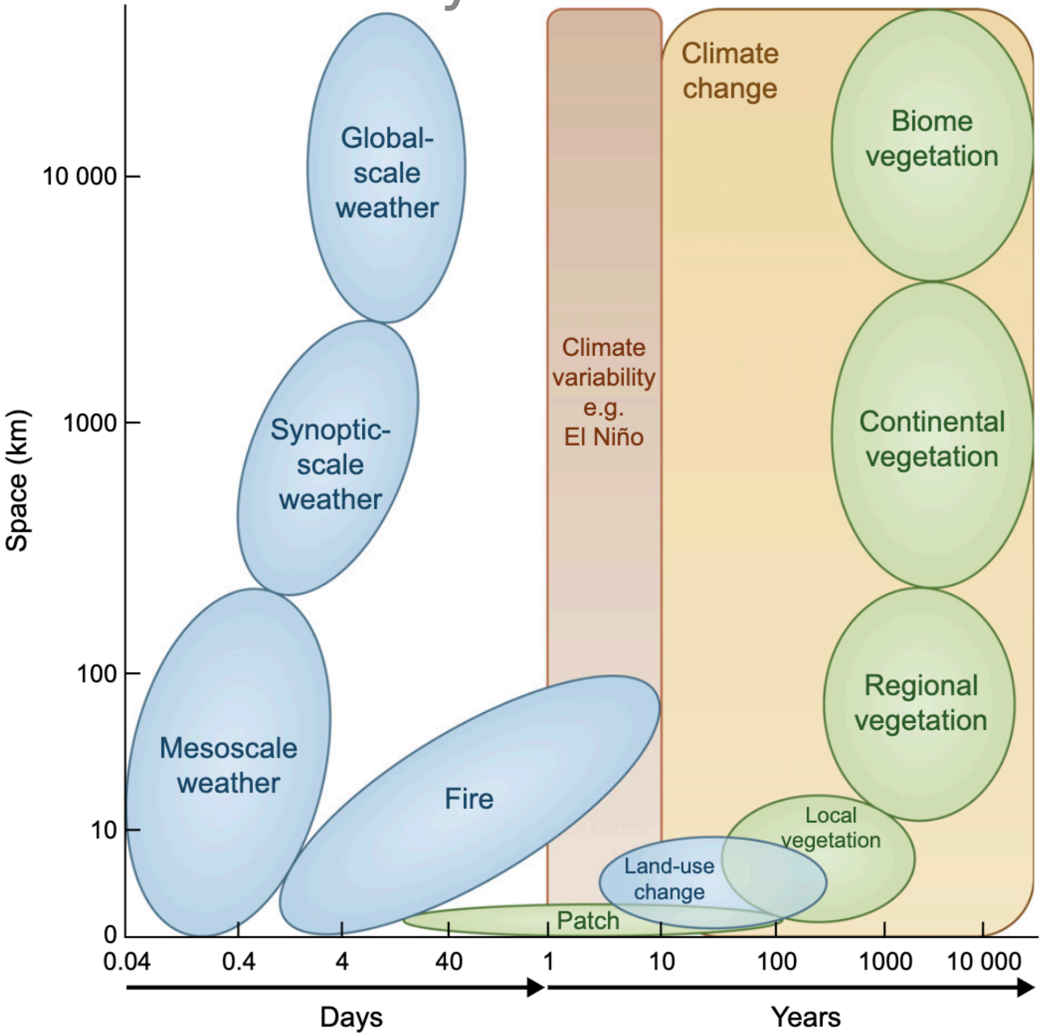


CHANGES AND DRIVERS IN GCMS

Coupling & drivers

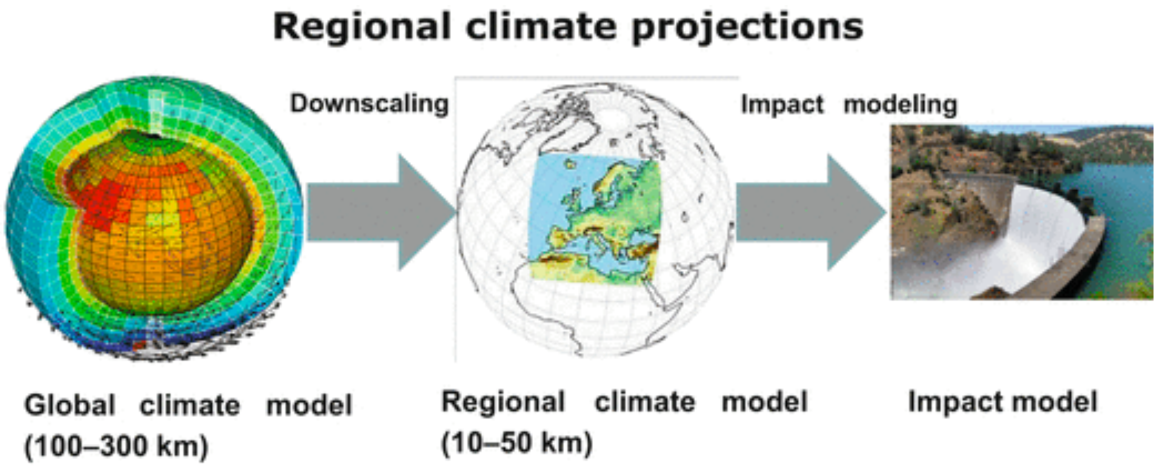


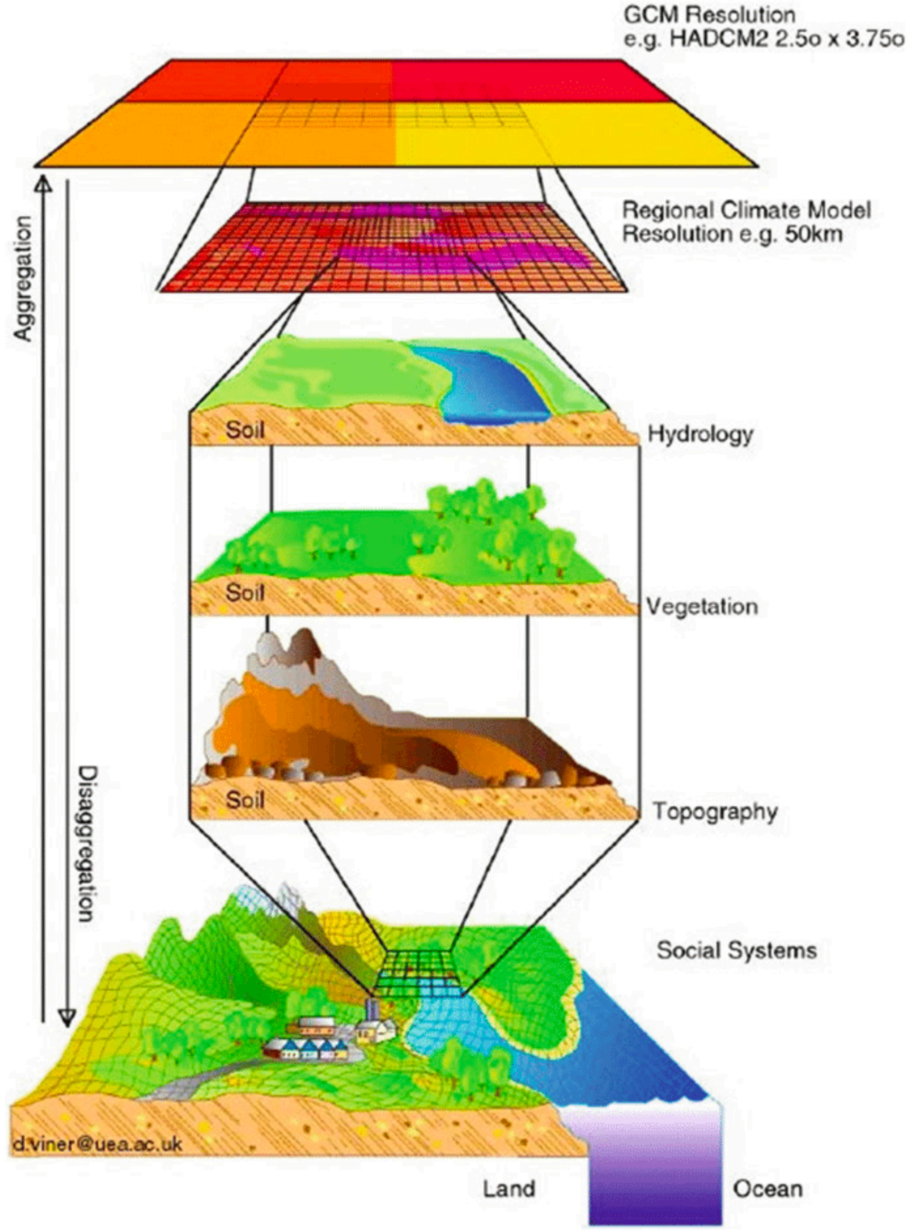
Ecosystem drivers



REGIONAL VS GLOBAL

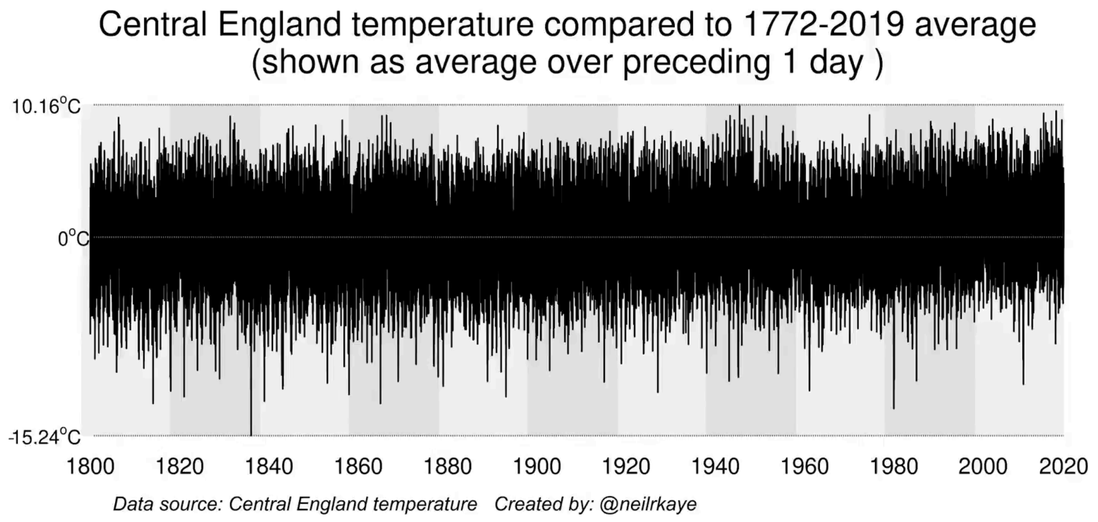
- Regional models are driven by a global model
- Local re-parameterisation of effect
    - Boundaries and transition one-way

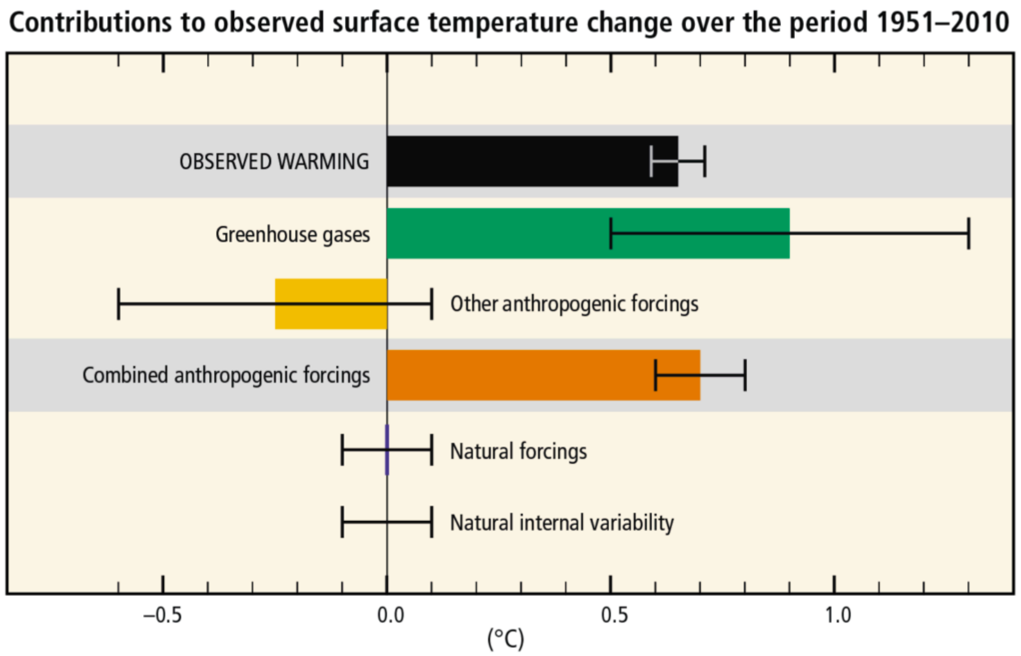




CLIMATE CHANGE OBSERVED

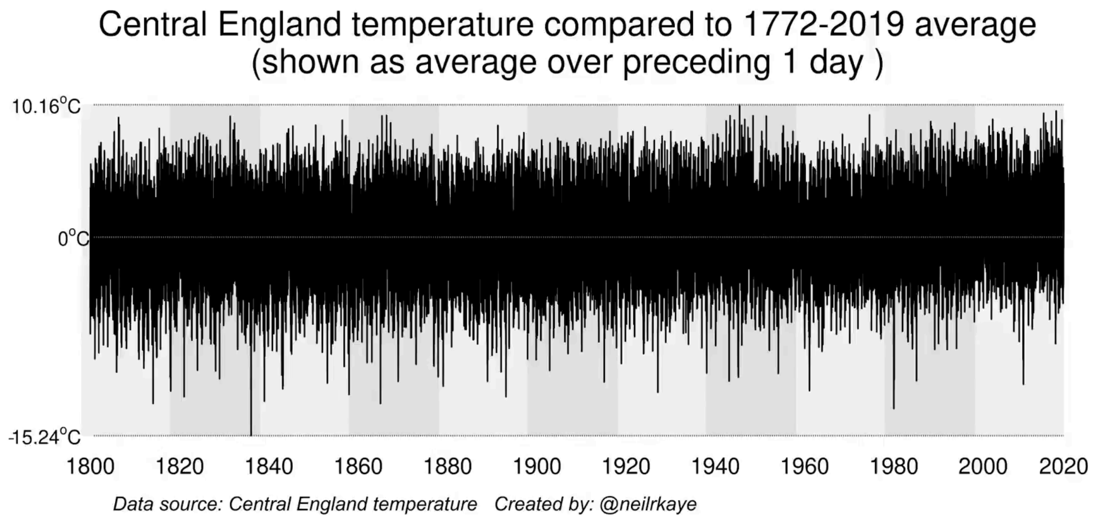
- Weather shows large variability
- Climate is average weather
- Observed climate change depends on
  - Anthropogeninc forcings
  - Natural forcings

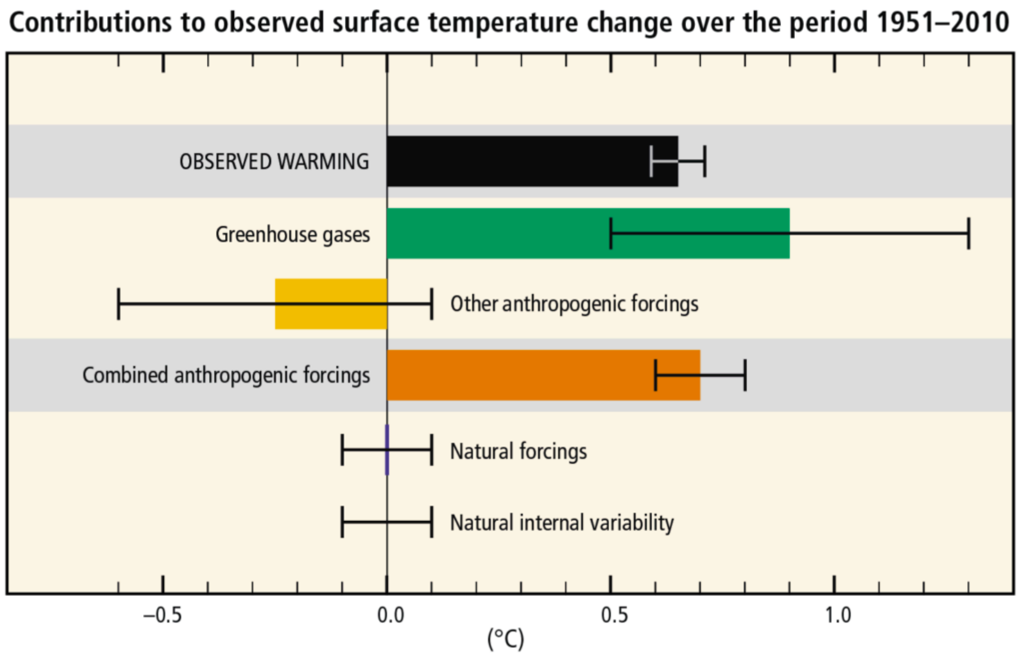




CLIMATE CHANGE OBSERVED

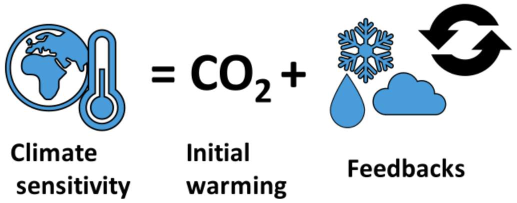
- Weather shows large variability
- Climate is average weather
- Observed climate change depends on
    - Anthropogeninc forcings
    - Natural forcings





CLIMATE SENSITIVITY

- Feedbacks are important



- Climate Sensitivity – not only based on models
  - Equilibrium: stabalization after $2xCO_2$
  - Transient: 20-year mean change at time of $2xCO_2$ with 1% increase CO_2 per year
- Exact value uncertain, but signal very clear!