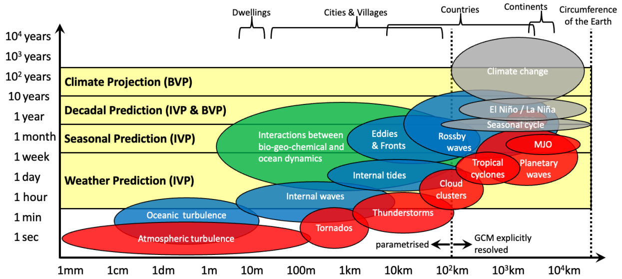
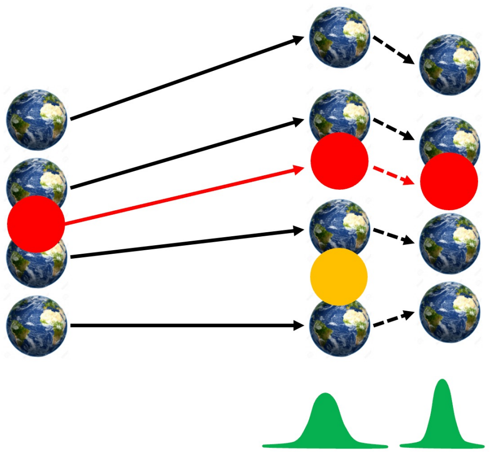
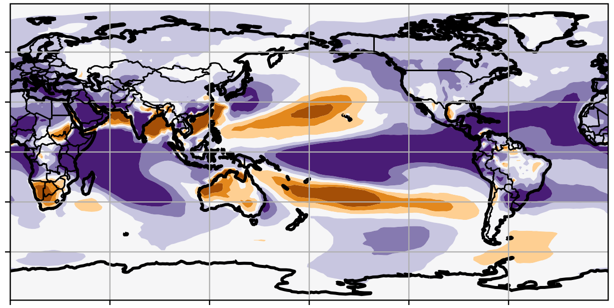
Climate Physics



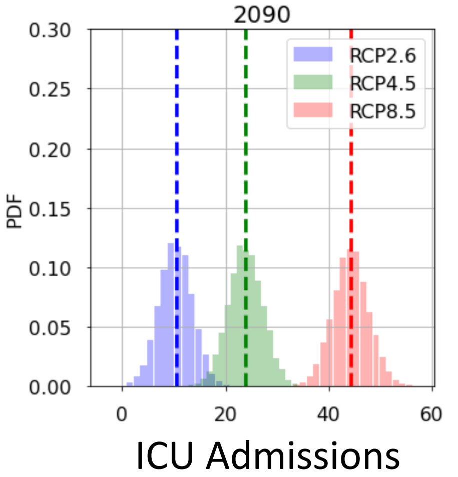
Reanalysis



CMIP Models and Emulators



Risk Assessments



Climate Science Primer:
Physics, Reanalysis, CMIP, Emulators & Risk Assessments

The Climate Sensitive Infectious Disease Network (CSIDNet) for Southeast Asia and the Pacific, 23rd of July 2026, The Tropical Disease Research Center (TDRC) in Kanchanaburi, Thailand

Dr Vassili Kitsios

ENVIRONMENT
www.csiro.au

Acknowledge funding support from SPARKLE

Holistic Climate Risk Assessment:

Evaluate impact on **various economic actors / sectors** (e.g. health) over relevant **time horizons for decision making** (e.g. years to decades)

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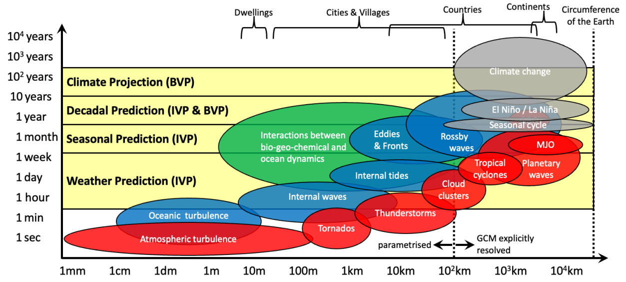
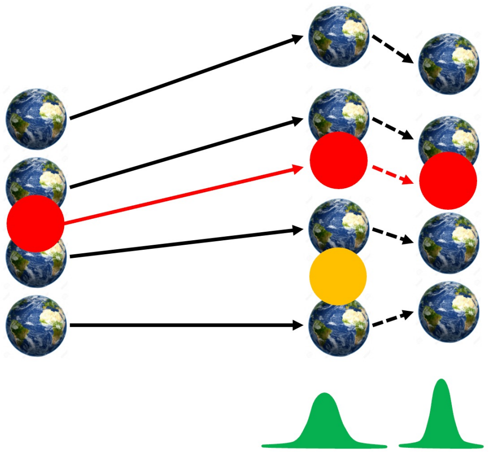
- What is a climate model
- Weather Forecasting vs Climate Projection
- Alignment of time scales for human decision making & physical phenomena



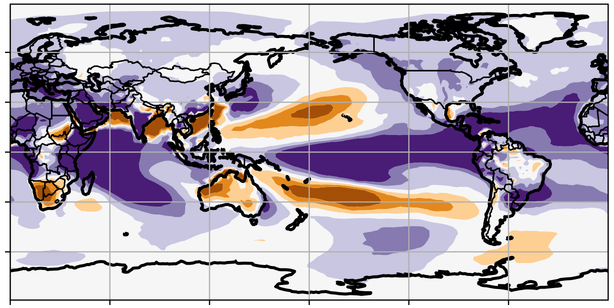
Reanalysis

- Fusing simulations and observations
- Essential for learning historical relationships between climate and health



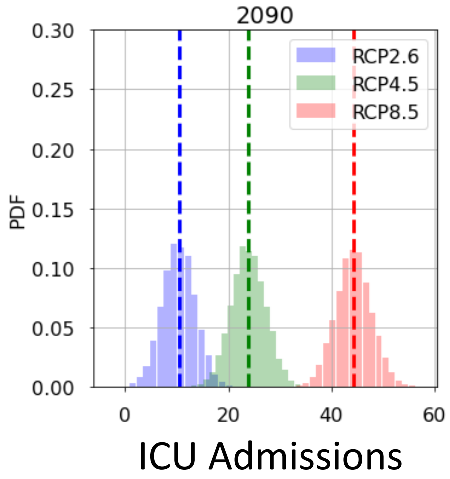
CMIP & Emulators

- Relationship between scenarios, emissions and climate
- Hierarchy of cheap emulators learnt from reanalysis & CMIP



Risk Assessments

- Intensive Care Unit Admissions
- Agricultural production
- Food-security-induced conflict



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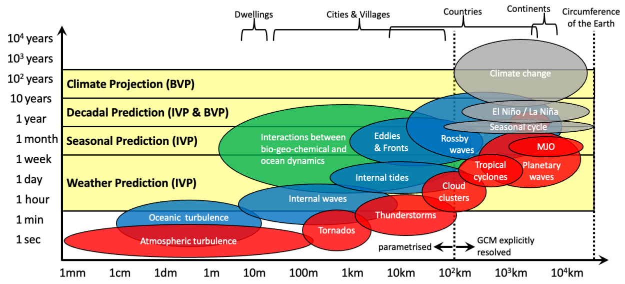

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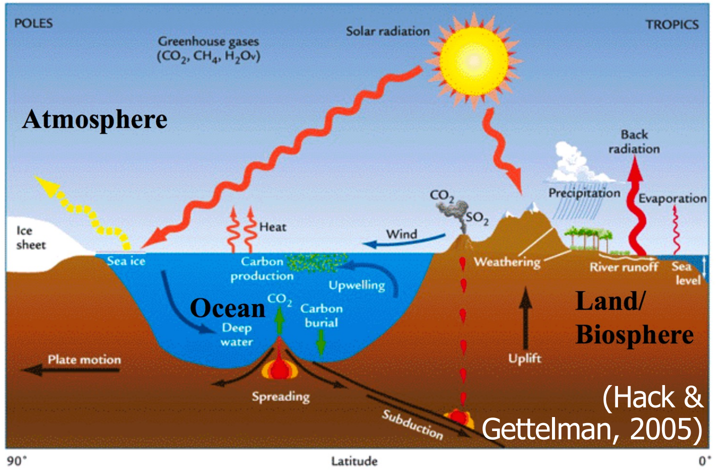
What is a climate model?

- Earth system is complex and multi-disciplinary

Conceptual model

- **Solar radiation**, absorption, reflection and scattering
- Natural and man-made **carbon emissions**
- Dynamics, Chemistry and Biology of the **Atmosphere, Ocean, Land, Sea-Ice**



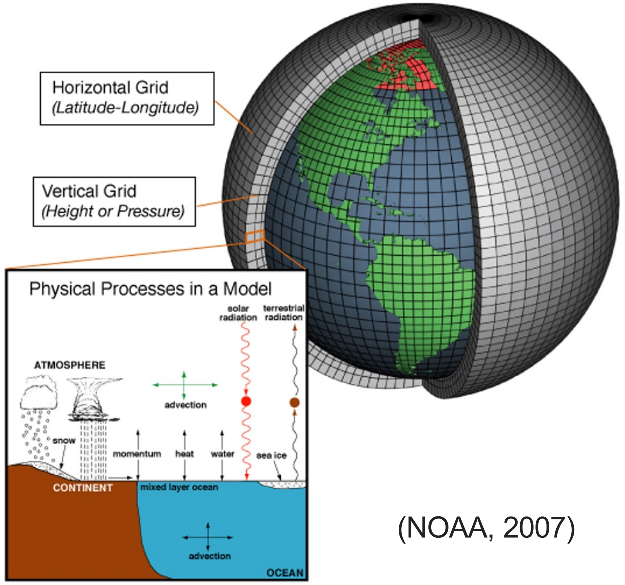
(Hack & Gettelman, 2005)

Mathematical model

- Partial differential equations in each realm for conservation of:
  - **Mass**
  - **Momentum** – Newtons 2nd law (F=ma)
  - **Energy** – 1st law of thermodynamics
  - **Scalars** – e.g. chemical species, salinity, humidity.
- All realms are coupled and interact at their interfaces.

Numerical model

- General Circulation Model

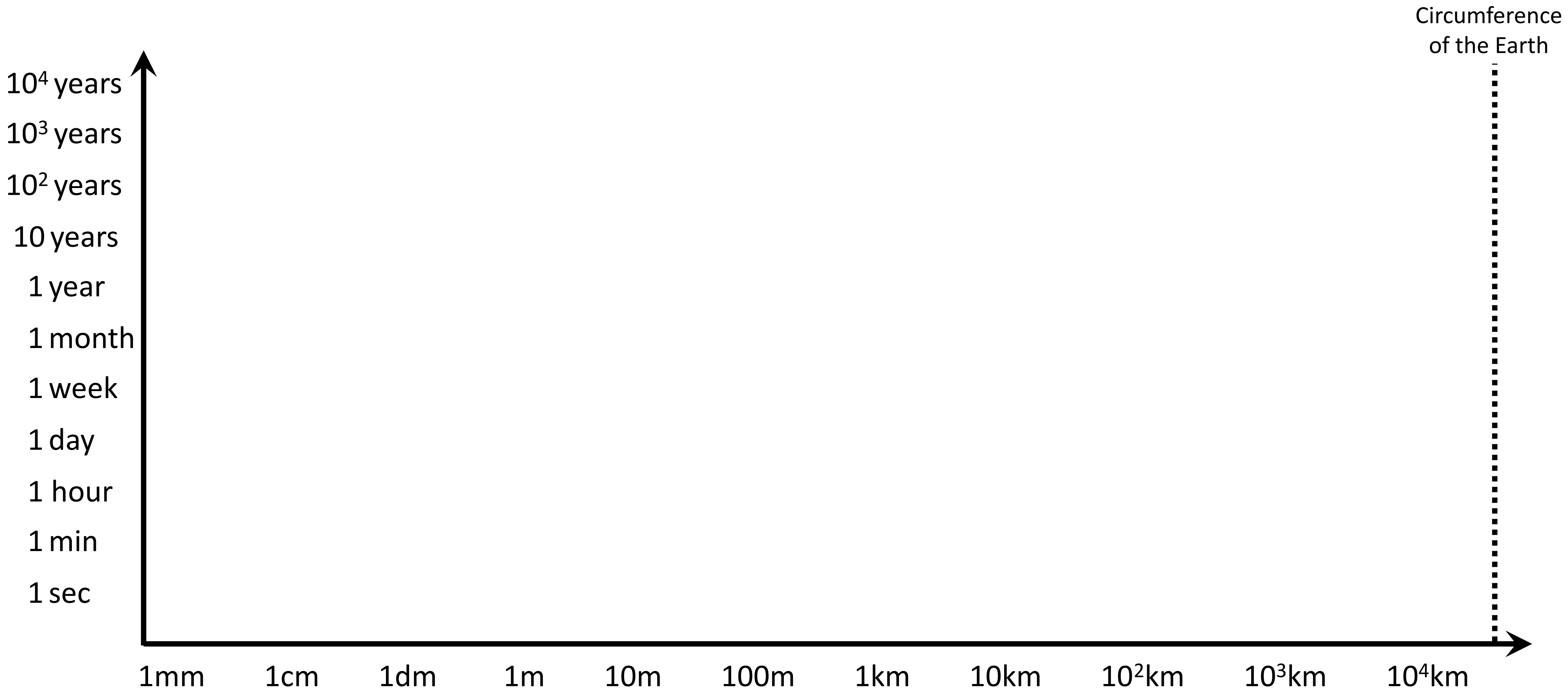


(NOAA, 2007)

- Resolution ranges from 100km for climate to 10km for weather prediction.
- **Vast space and time scales**
- **Computationally expensive**

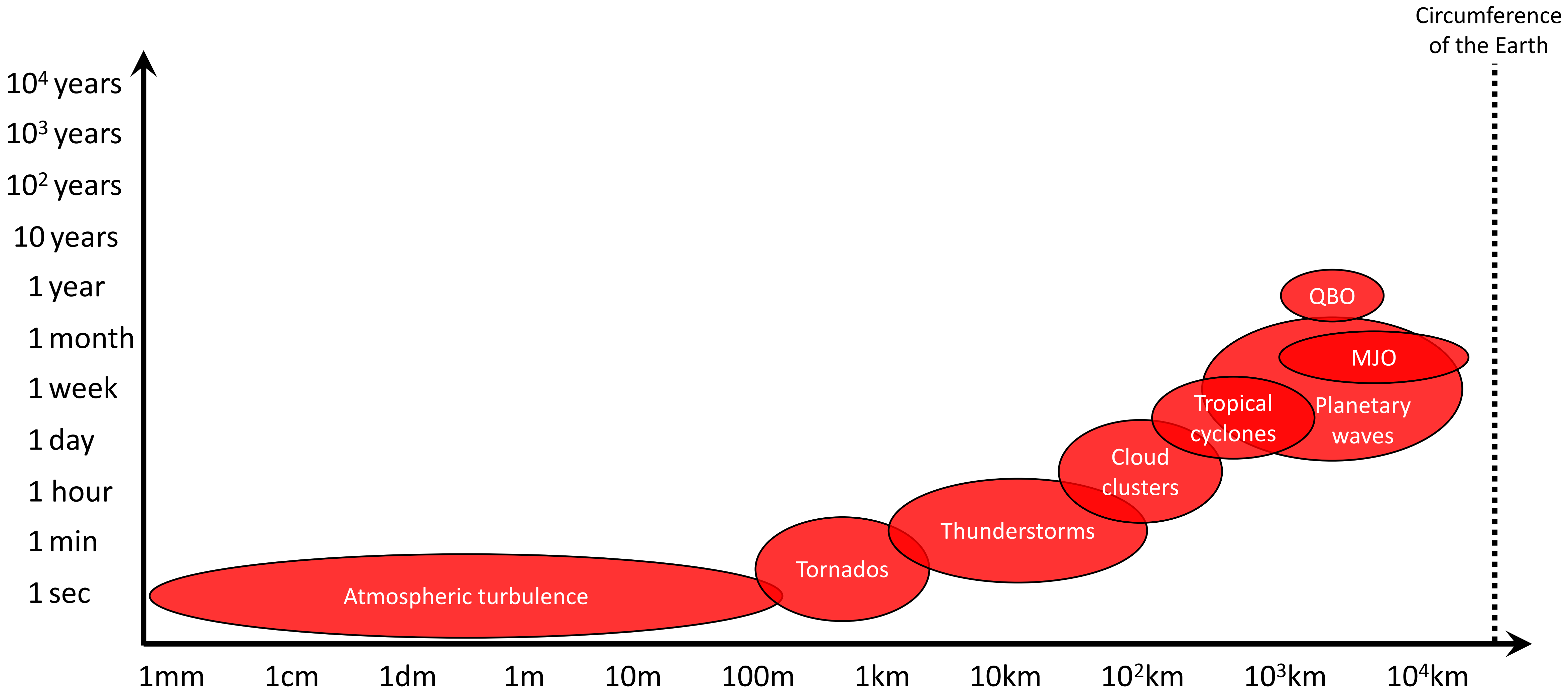
Distinction between Weather and Climate

- Earth system comprises of a spectrum of a wide range time and space scales



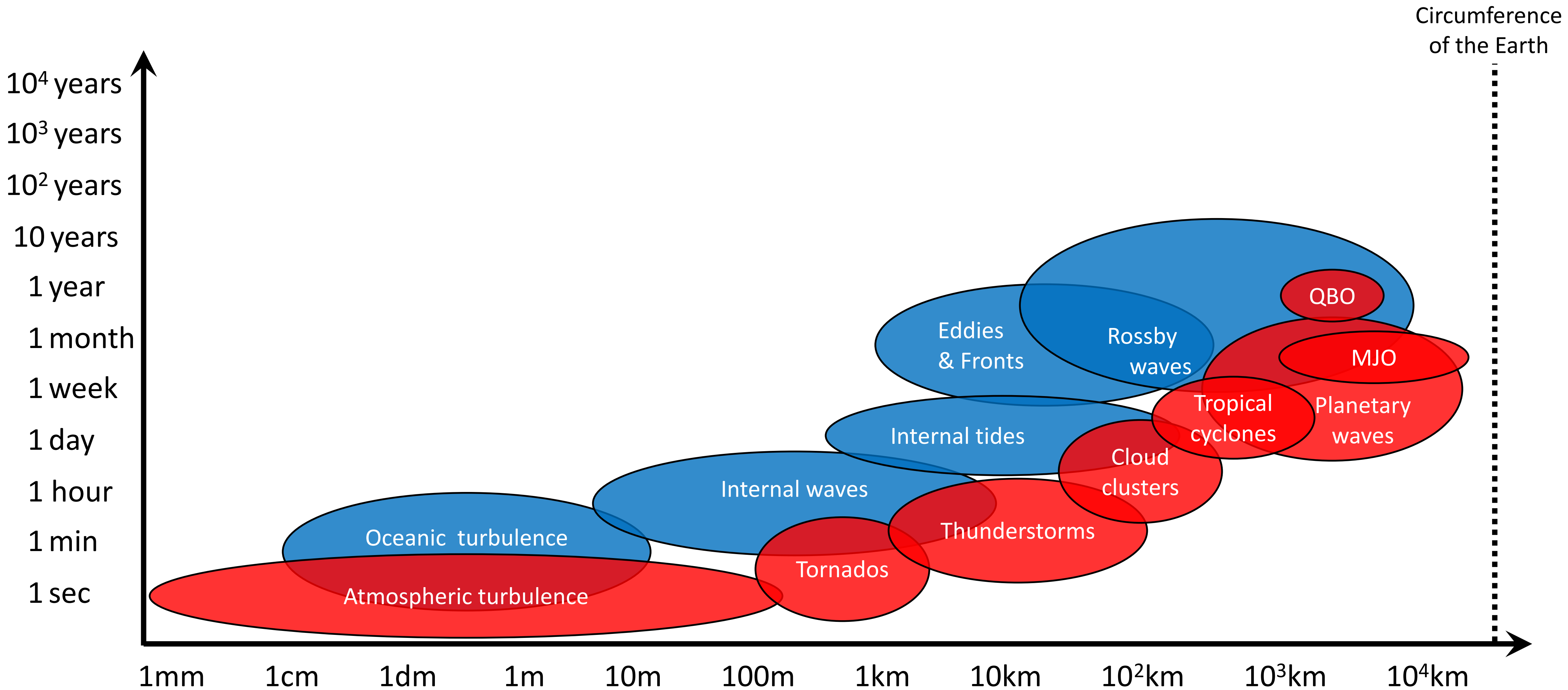
Distinction between Weather and Climate

- In general, in the atmosphere small phenomena have short time scales, large phenomena have longer time scales



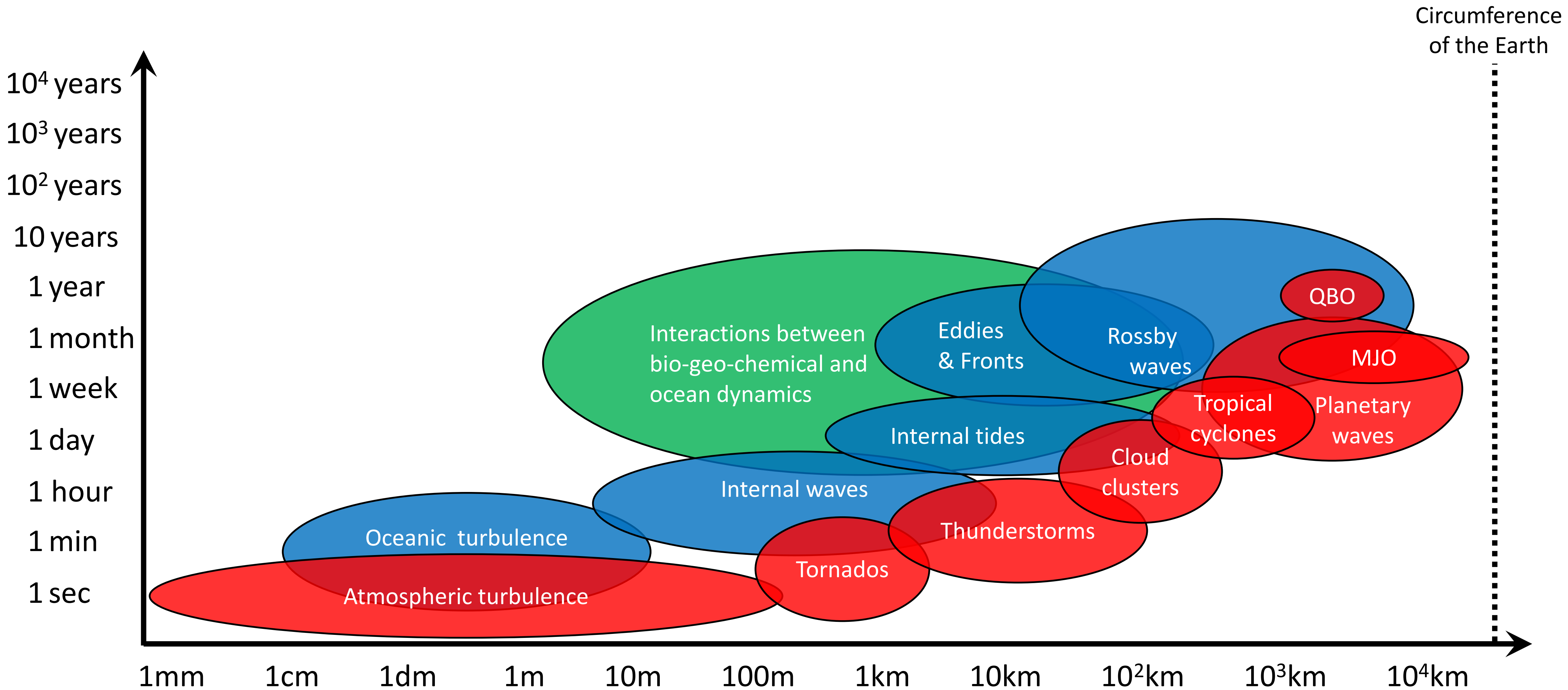
Distinction between Weather and Climate

- Likewise in the ocean, however, ocean phenomena are typically slower for a given sized object.



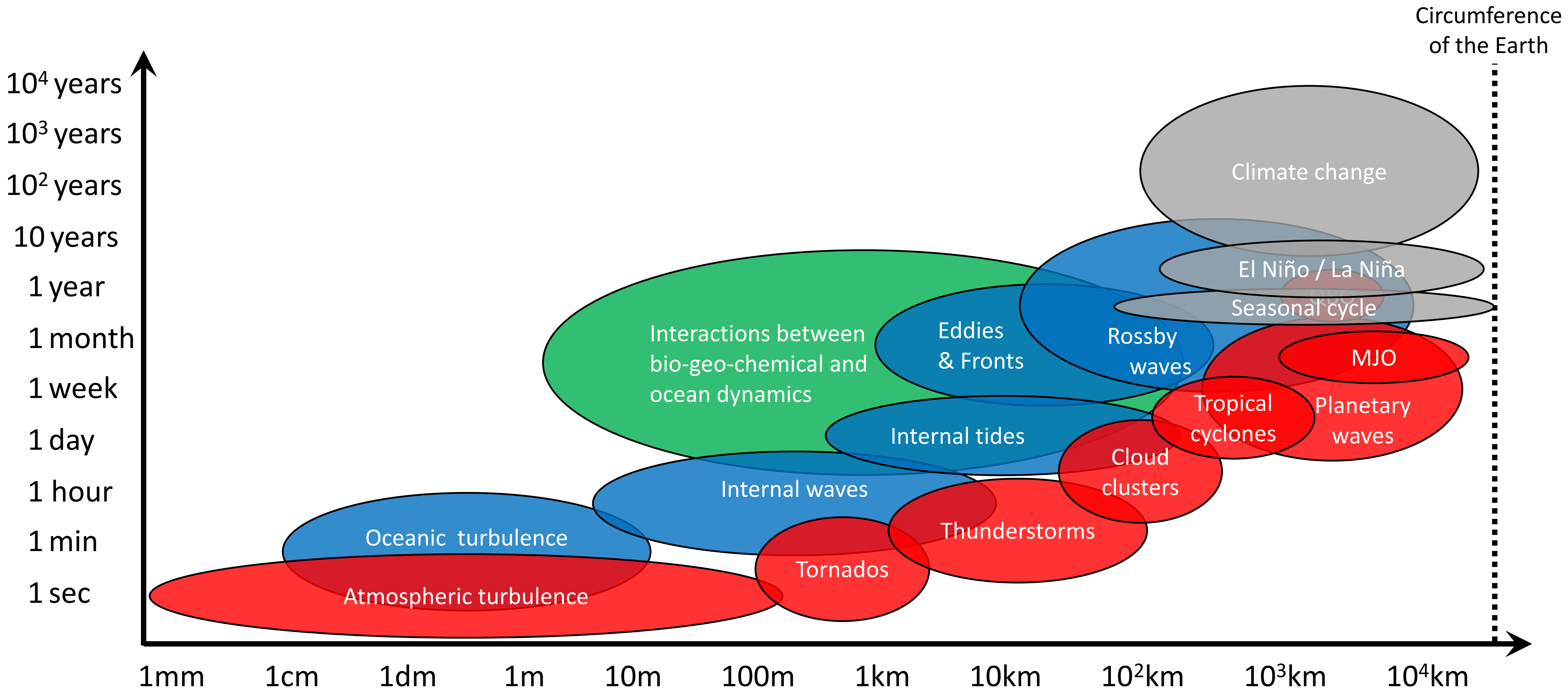
Distinction between Weather and Climate

- Ocean transports biology, and biology can alter ocean fluid properties (e.g. opacity)



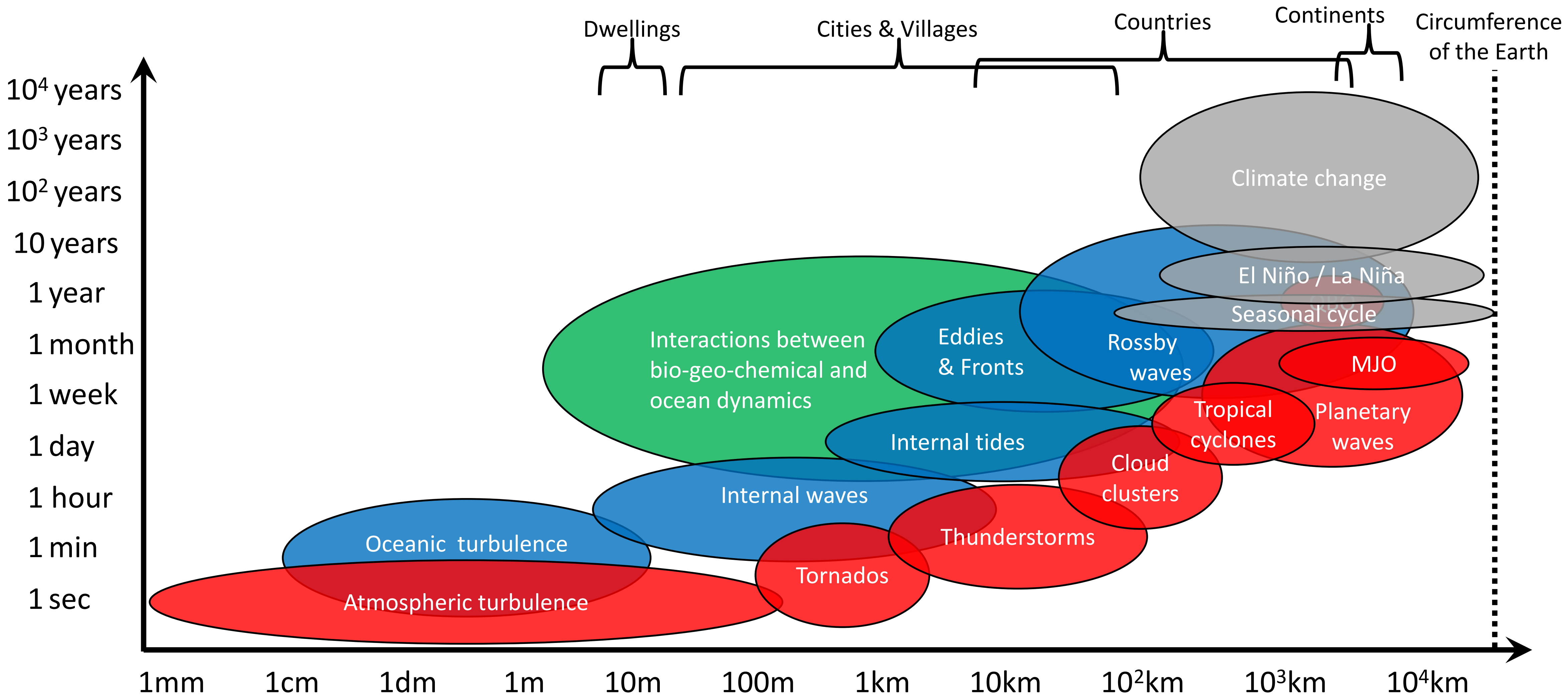
Distinction between Weather and Climate

- Persistent large-scale features pertaining to climate change, La Niña, El Niño and the seasonal cycle influence all realms



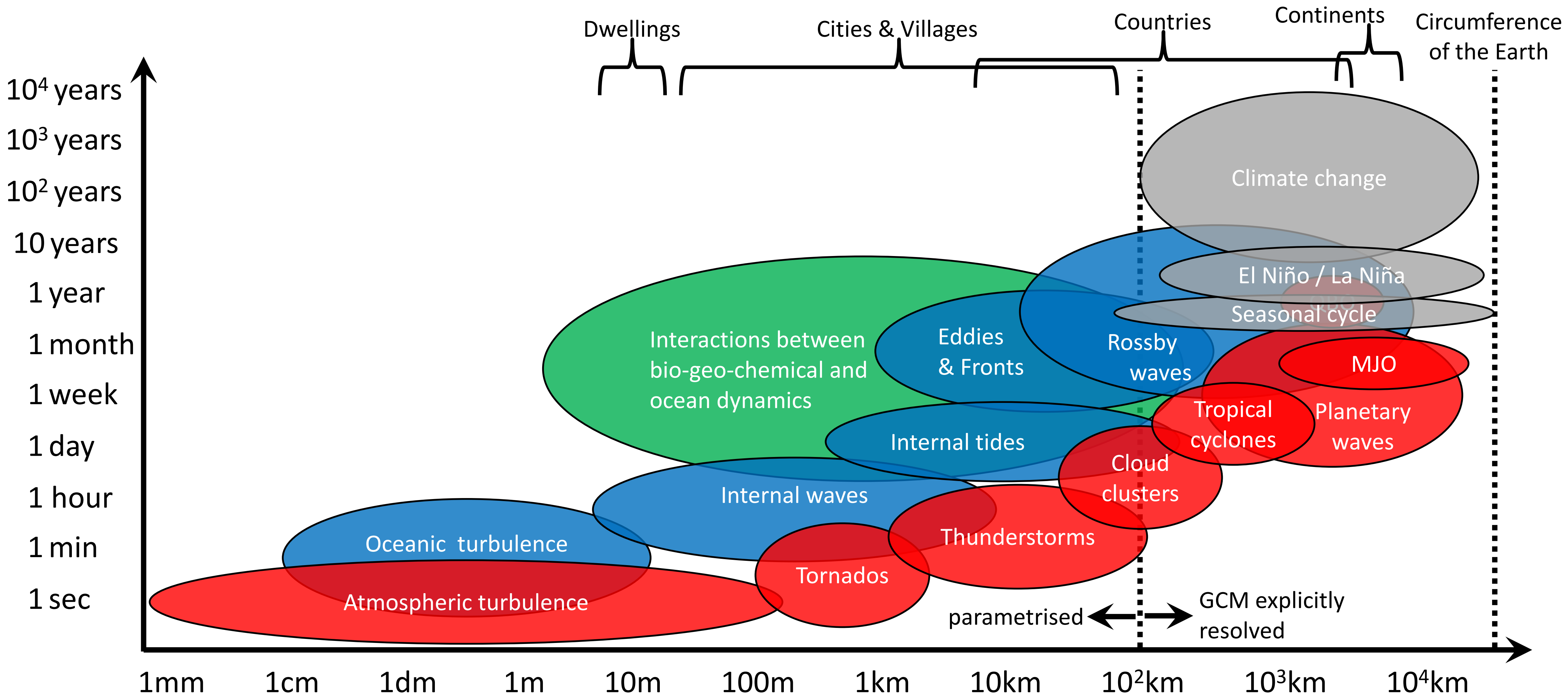
Distinction between Weather and Climate

- For context, overlaid with scales of places in which we live



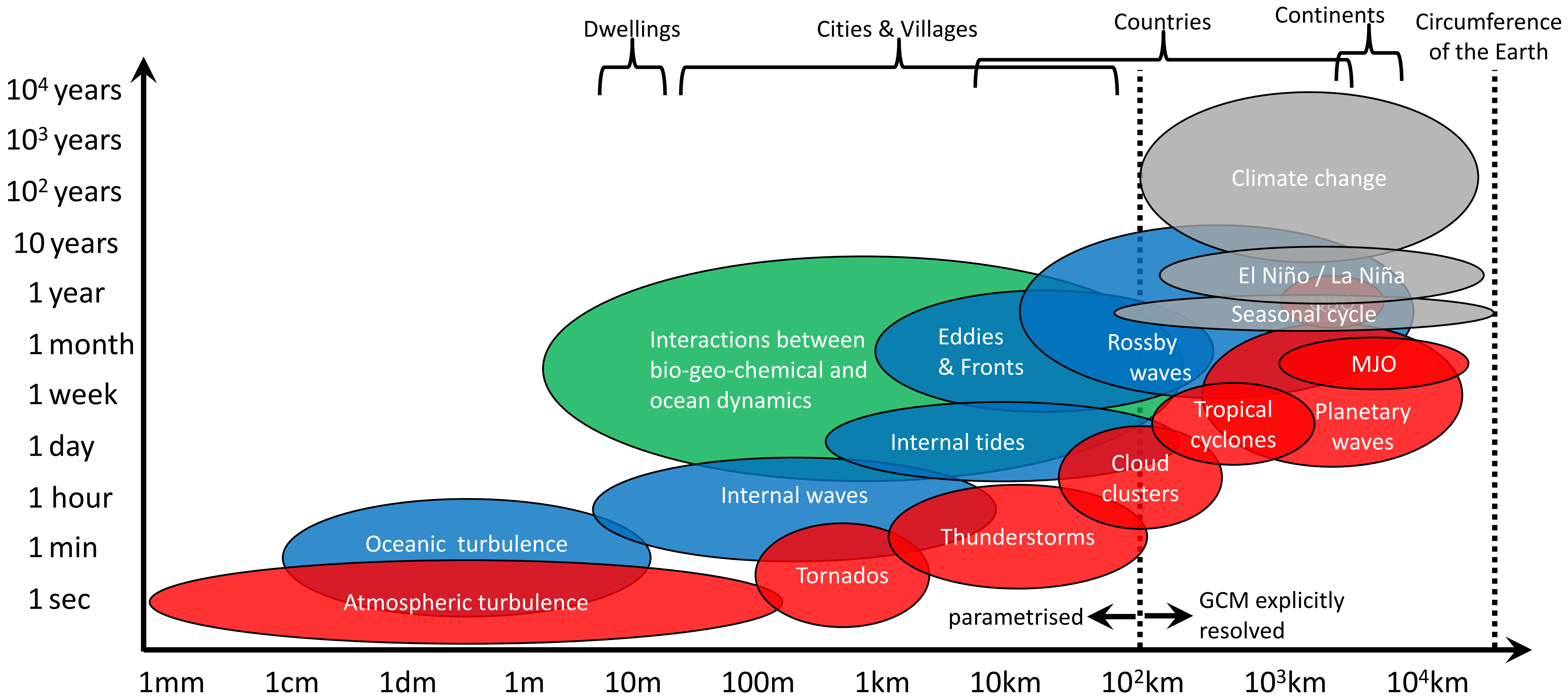
Distinction between Weather and Climate

- Grids typically explicitly resolves scales >100km, and unresolved processes need to be parameterised. One source of **model bias**.



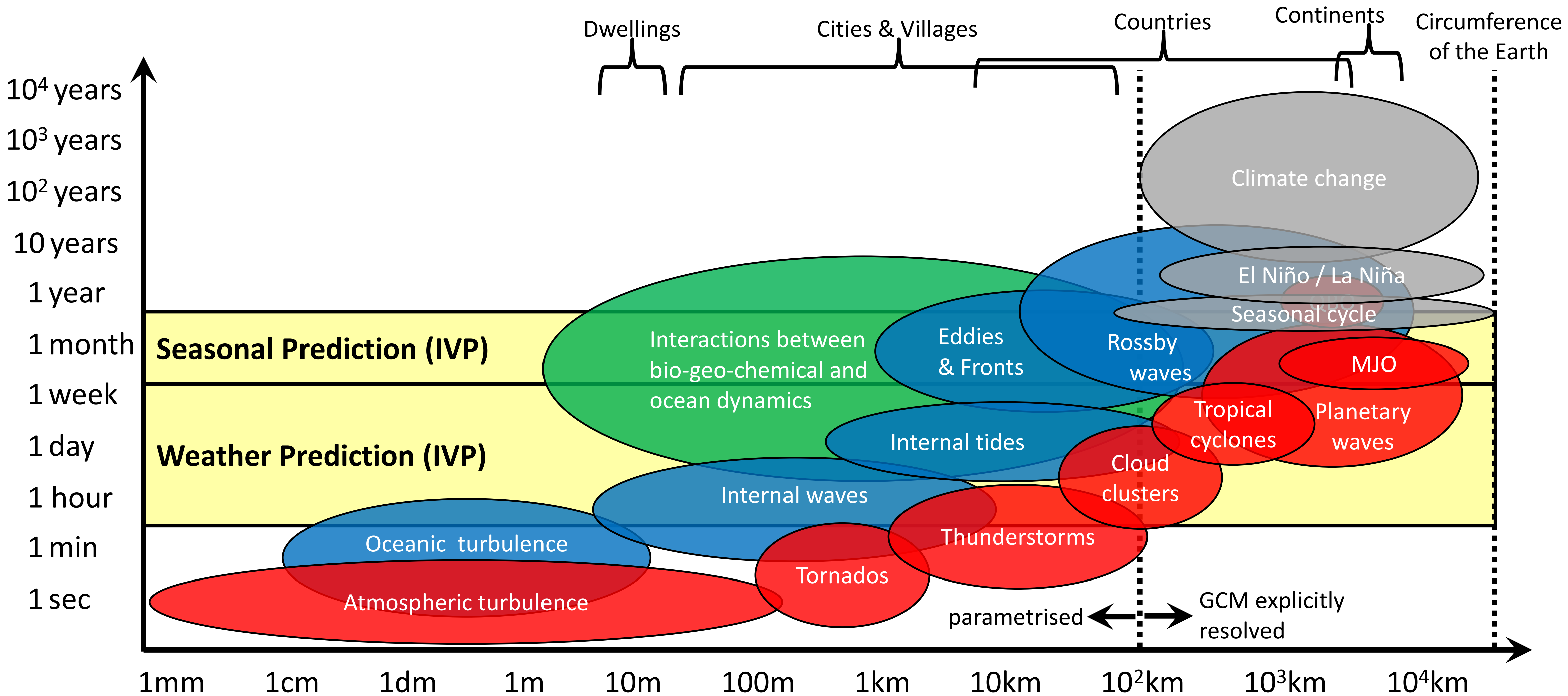
Distinction between Weather and Climate

- Forecast systems are tailored for the time horizon of interest



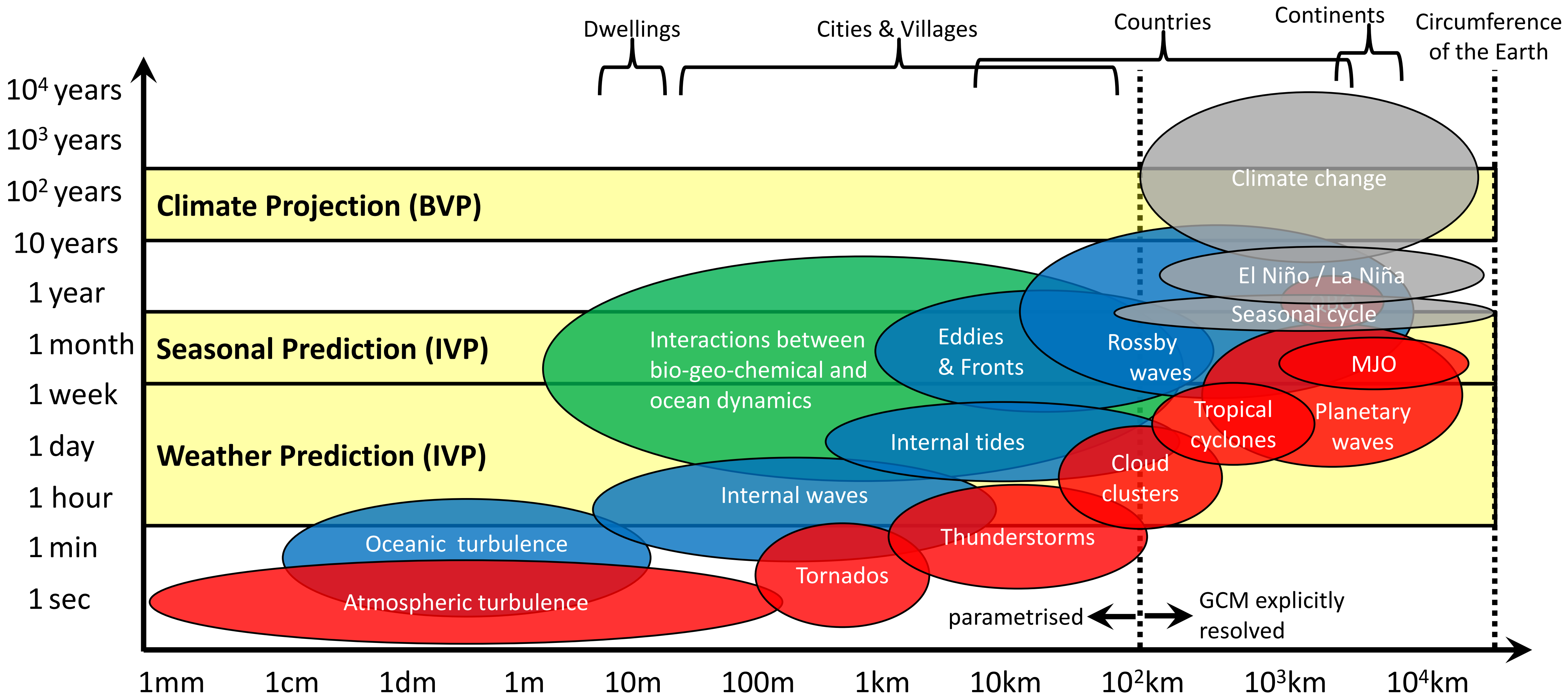
Weather Prediction: Initial Value Problem (IVP)

- Skill comes from the initial conditions i.e. knowing today well
- Scenarios are irrelevant at this timescale



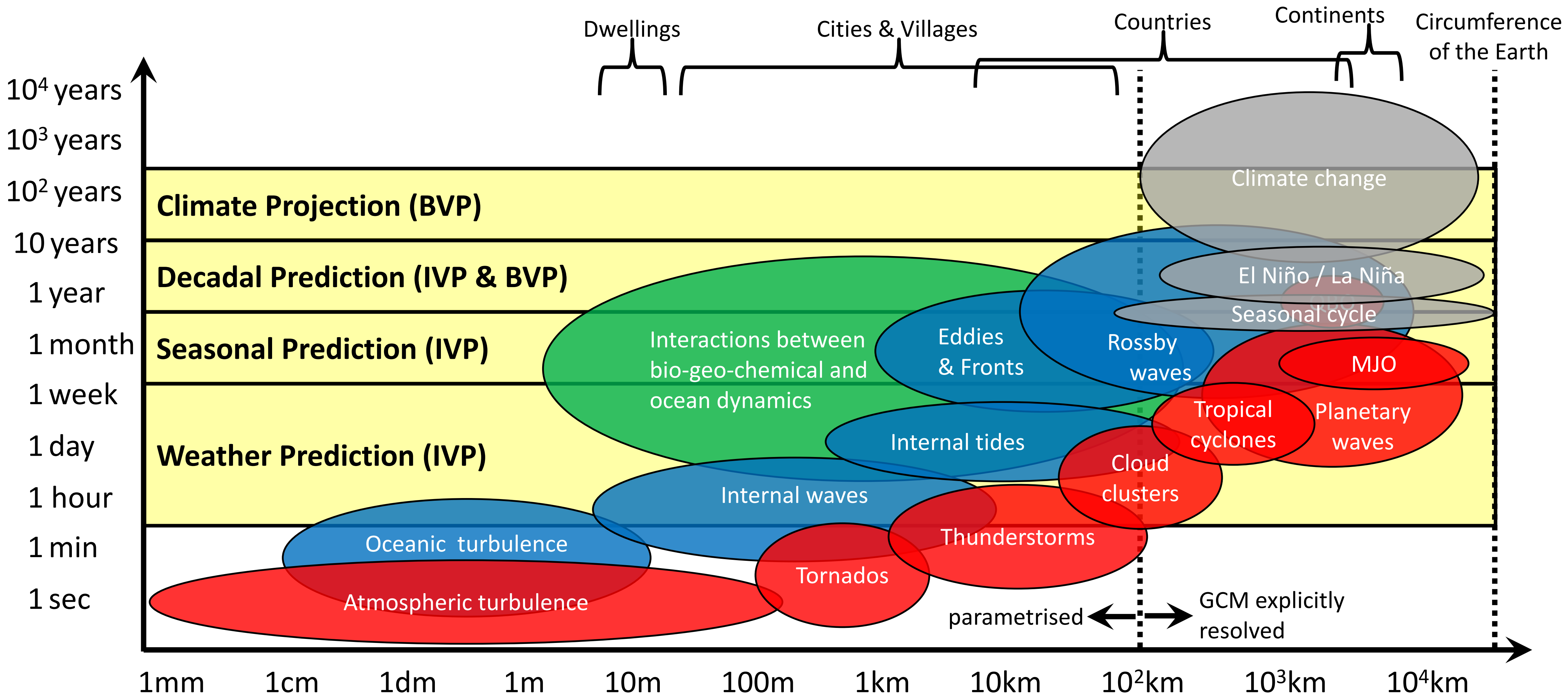
Climate Projection: Boundary Value Problem (BVP)

- Scenario assumptions defining prescribed carbon emissions key.
- Initial conditions irrelevant. This is the role of **CMIP**.



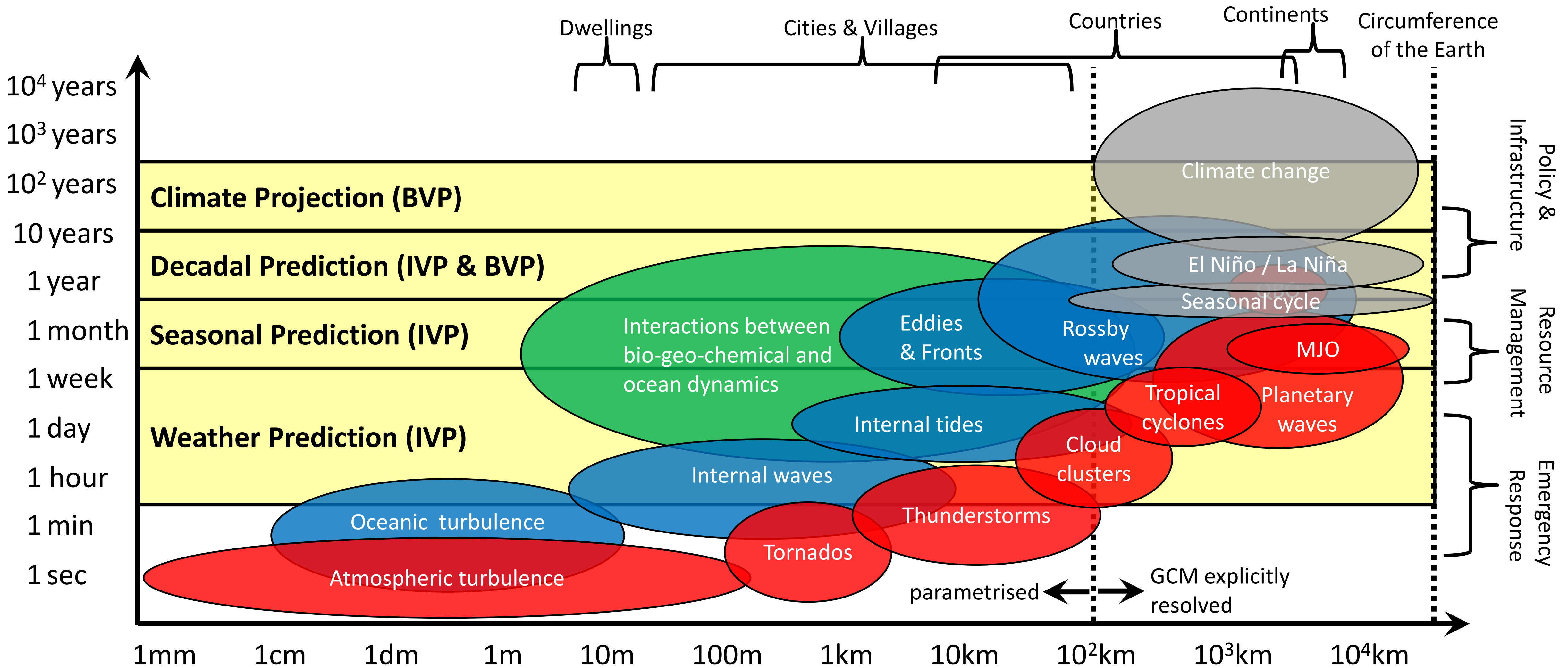
Decadal Prediction: IVP & BVP

- Initial conditions of slow phenomena important (e.g. La Niña / El Niño)
- Boundary conditions sensitives can emerge towards end of decade



Human impacts aligning with physical phenomena

- Human actors each have unique timescales for decision making
- Impacts can be **IVP** or **BVP (i.e. scenarios)** depending on timescale



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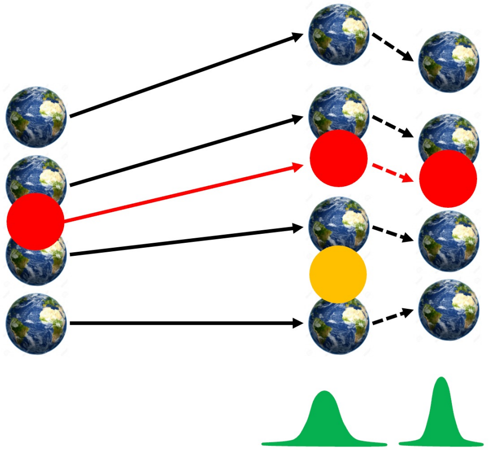

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What is a reanalysis? (i.e. climate digital twin)

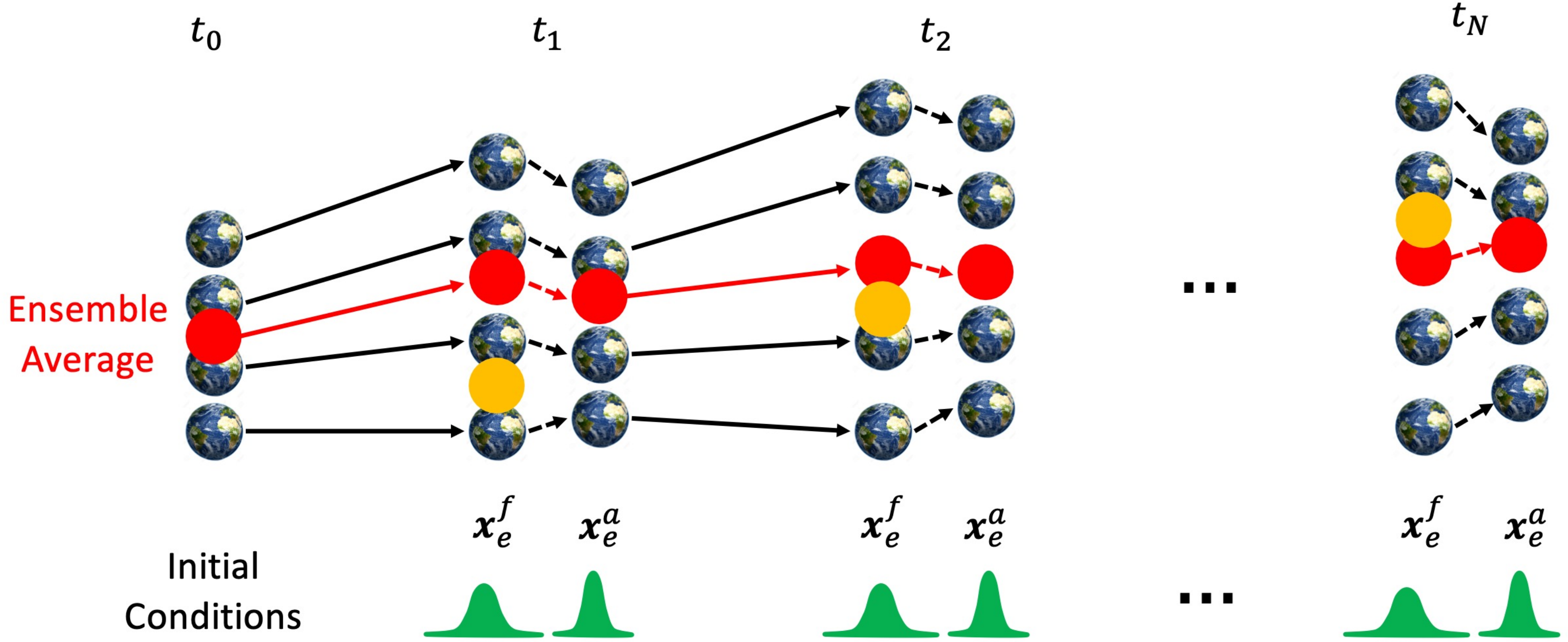
- Weather forecasts and climate projections provide estimates of the potential ***future state***, whereas reanalysis provides lesser biased estimates of the actual ***historical state*** via data assimilation.

- ***Data assimilation*** corrects imperfect numerical simulations by exploiting real-world observations. There are numerous such algorithms for doing so.

- Reanalysis is ***essential for learning the relationships*** between the historical weather / climate and historical human impacts (e.g. health, agriculture, conflict etc.)

Illustration of Data Assimilation Process

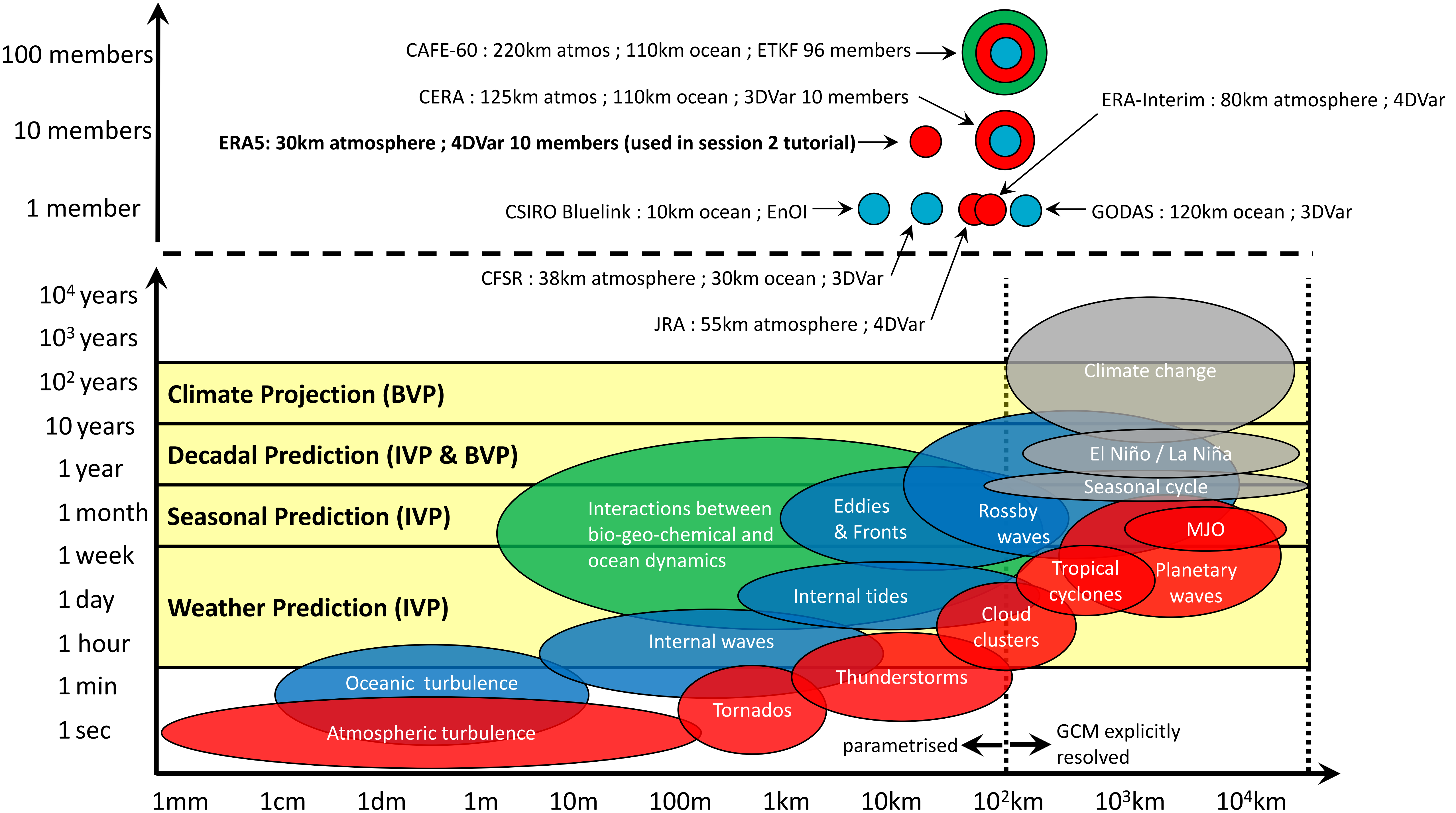
- In our reanalysis (CAFE60), an **Ensemble Kalman Filter** modifies 96 climate model instances based on monthly measurements from 1960-2021



Network of **10^7** multi-variate observations from satellites and in-situ

- Atmosphere (~100km, 24 levels); Ocean (~50km, 50 levels); land; sea-ice; bio-geo-chemistry; **10^8** states simulated over **10^4** CPUs.

O'Kane, T.J. et al., 2021, ***Journal of Climate***, Vol. 34 (13), pp 5153-5169. https://doi.org/10.1175/JCLI-D-20-0974.1 . Dataset https://registry.opendata.aws/csiro-cafe60/



100 members
10 members
1 member
CAFE-60 : 220km atmos ; 110km ocean ; ETKF 96 members
CERA : 125km atmos ; 110km ocean ; 3DVar 10 members
ERA5: 30km atmosphere ; 4DVar 10 members (used in session 2 tutorial)
ERA-Interim : 80km atmosphere ; 4DVar
CSIRO Bluelink : 10km ocean ; EnOI
GODAS : 120km ocean ; 3DVar
CFSR : 38km atmosphere ; 30km ocean ; 3DVar
JRA : 55km atmosphere ; 4DVar
10^4 years
10^3 years
10^2 years
10 years
1 year
1 month
1 week
1 day
1 hour
1 min
1 sec
Climate Projection (BVP)
Decadal Prediction (IVP & BVP)
Seasonal Prediction (IVP)
Weather Prediction (IVP)
Climate change
El Niño / La Niña
Seasonal cycle
Interactions between bio-geo-chemical and ocean dynamics
Eddies & Fronts
Rossby waves
MJO
Tropical cyclones
Planetary waves
Internal tides
Cloud clusters
Internal waves
Thunderstorms
Oceanic turbulence
Tornados
Atmospheric turbulence
parametrised
GCM explicitly resolved
1mm
1cm
1dm
1m
10m
100m
1km
10km
10^2km
10^3km
10^4km

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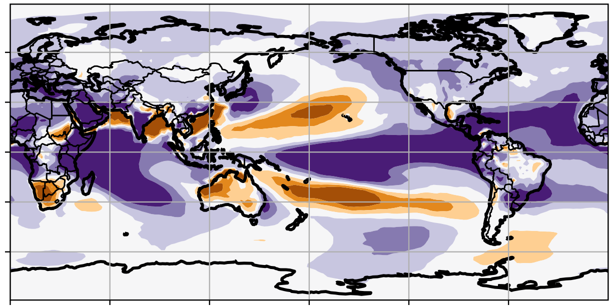

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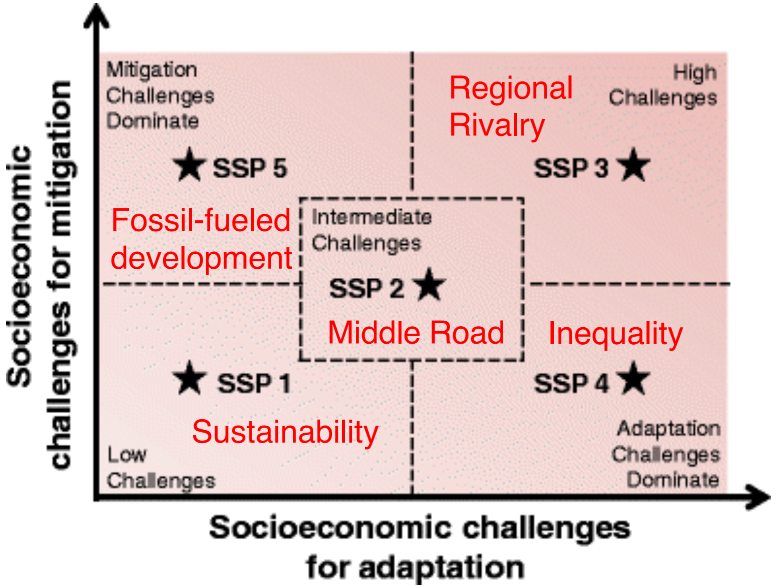
What is CMIP, storylines and scenarios?

- The **C**oupled **M**odel **I**nter-comparison **P**roject is an international effort in which many institutions simulate agreed upon experiments to understand past climate (including attributing human influence) & estimate potential future climates under various scenario assumptions.
- For each storyline a multi-disciplinary team (i.e. demographers, economists, engineers, climate scientists) makes assumptions for future scenarios / pathways / trajectories of
  - Population (**P**) growth
  - Affluence (**A**) in terms of per capita energy consumption
  - Energy generation technology (**T**) in terms of carbon intensity of production
- The impact (**I**) in terms of emissions is then given by **I = P A T**

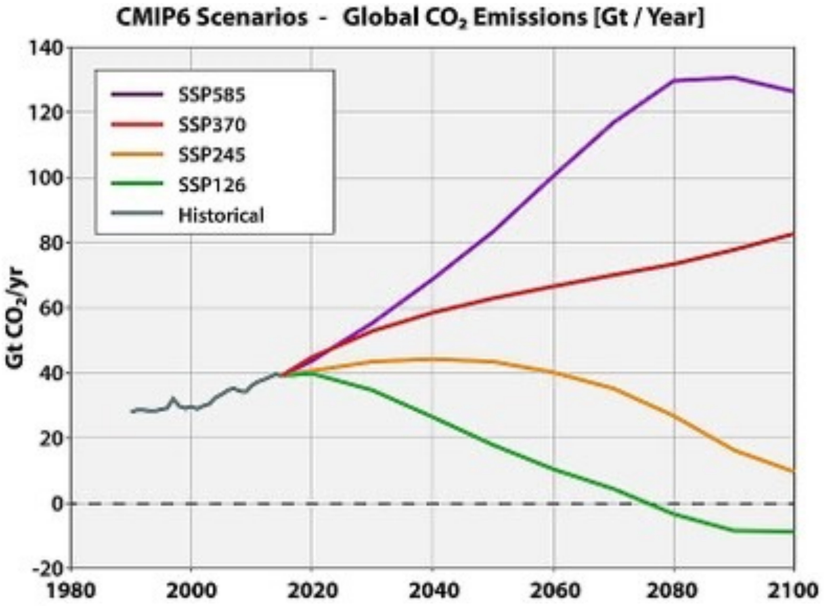
What are the CMIP6 scenarios?

- In **CMIP6**, narratives are developed for levels of challenges in mitigation & adaptation, with representative population (**P**) and GDP / affulence (**A**) assumptions are made.



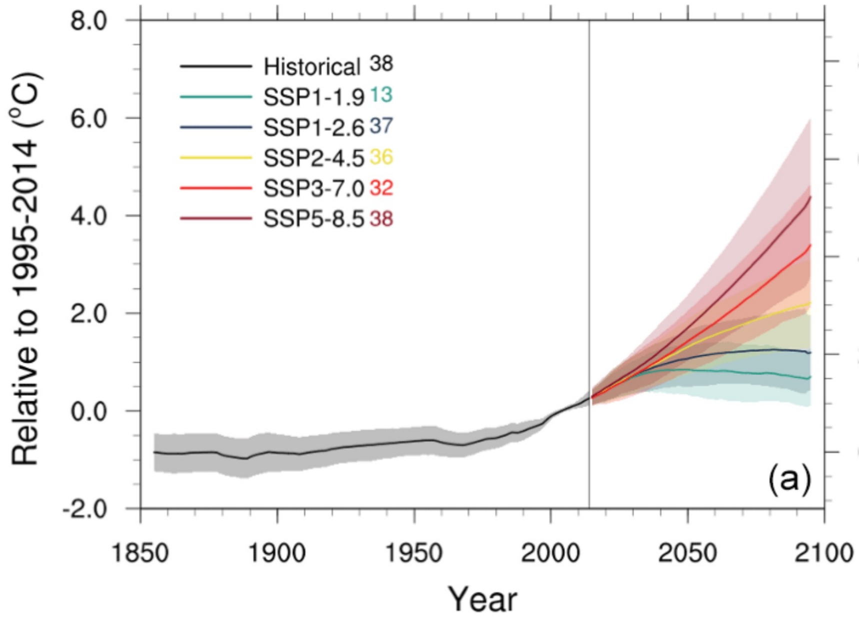
[O'Niell et al. (2014)]

- These were input into economic integrated assessment models (IAM) to achieve target warming levels (via technological assumptions, **T**) producing emissions impacts (**I**).



[www.dkrz.de/en/communication/climate-simulations/cmip6-en/the-ssp-scenarios]

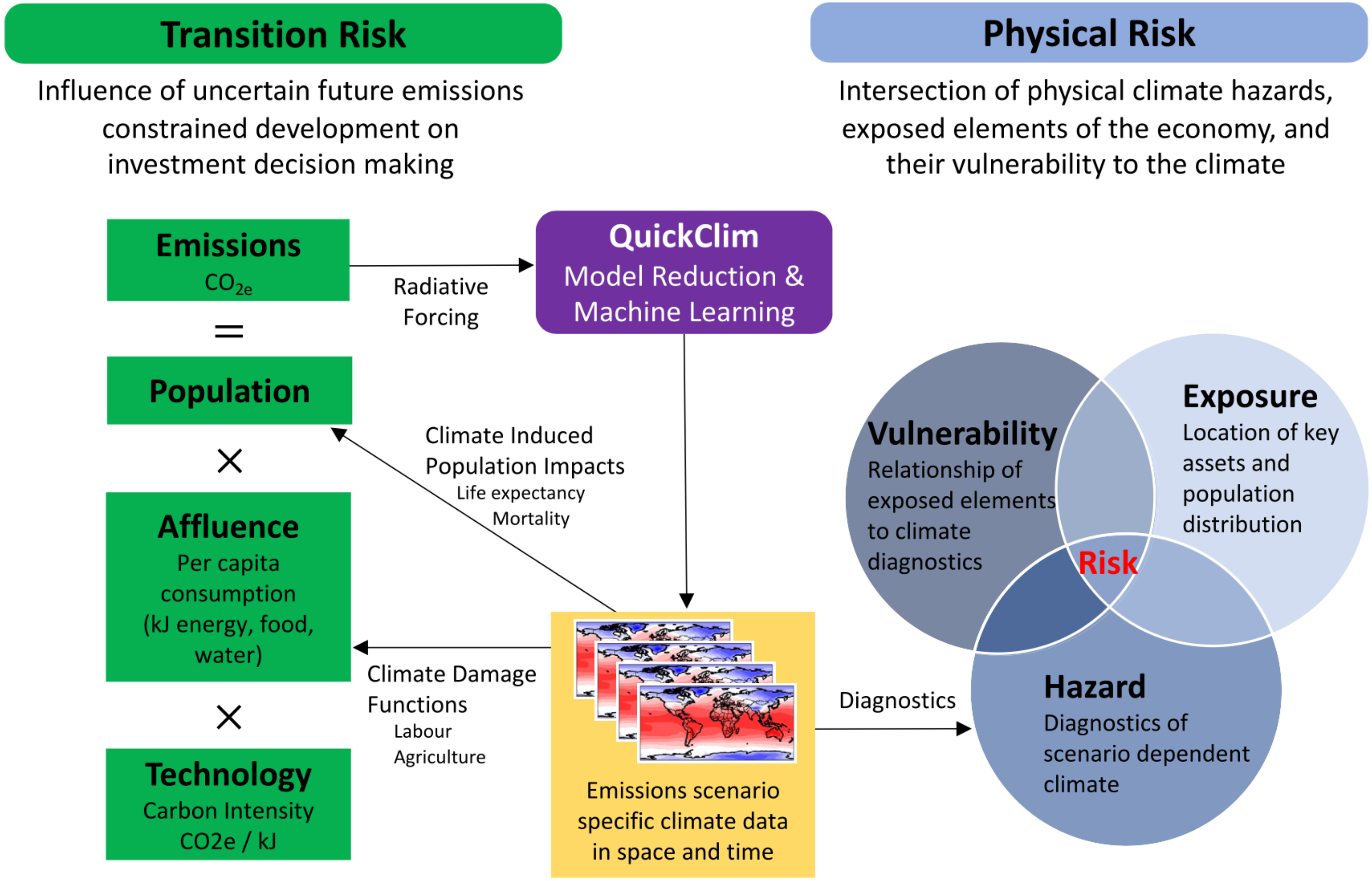
- Emissions pathways simulated by ***CMIP6 models*** produced a ***range*** of global temperatures
- Not all variables do change significantly across scenarios (e.g. rainfall)



[esd.copernicus.org/articles/12/253/2021/#&gid=1&pid=1]

Role of climate emulators

- CMIP models are computationally expensive, hence can only provide data for a small number of the potential future scenarios.
- Climate emulators are learnt from data, and can rapidly estimate 100s of scenarios.



Kitsios, V., O'Kane, T.J. & Newth, D., 2023, A machine learning approach to rapidly project climate responses under a multitude of net-zero emission pathways, ***Nature Communications Earth and Environment***, Vol 4, 355.
https://doi.org/10.1038/s43247-023-01011-0

Hierarchy of climate emulators

	QuickClim	3D Ocean	3D Dry Atmosphere	3D Moist Atmosphere
Monthly Mean Data	CMIP Future Scenarios	CAFE60 Reanalysis	CAFE60 Reanalysis	ERA5 Reanalysis & CMIP
Time period	2005 – 2100	2010 – 2020	1980 – 2020	1984 – 2024
Dynamical Scales	Climate Change	Climate Variability	Climate Change & Variability	Climate Change & Variability
Dimension Reduction	Multi-variate Multi-scenario EOF	Separate 3D EOFs of velocity & temperature	Separate 3D EOFs of velocity & temperature	Single 3D multi-variate EOF
Autoregressive Model	FEM-BV-VARX	Galerkin Projection Coefficient Regression	Galerkin Projection Coefficient Regression Stochastic parameterisation	Galerkin Projection Constrained Coefficient Regression Stochastic parameterisation
Reference	Kitsios, V., O'Kane, T.J. & Newth, D., 2023, *Nature Communications Earth and Environment*	Kitsios, V., Cordier, L. & O'Kane, T.J., 2024, *Theoretical and Computational Fluid Dynamics*	Kitsios, V., Cordier, L. & O'Kane, T., 2026, *International Journal of Heat and Fluid Flow*	Kitsios, V., Cordier, L. & O'Kane, T.J., 2024, *AFMC2024*

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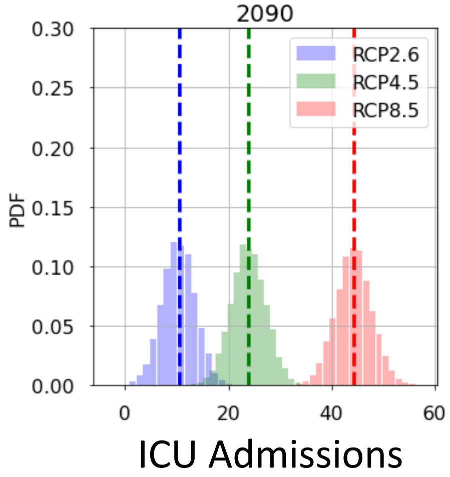
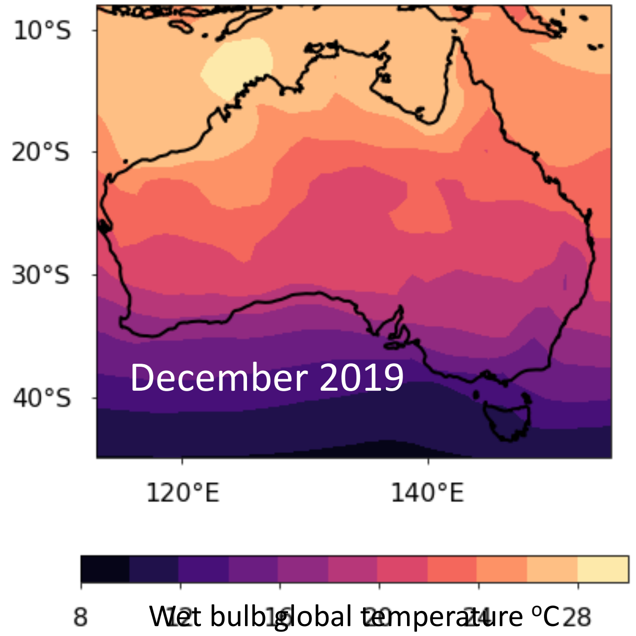


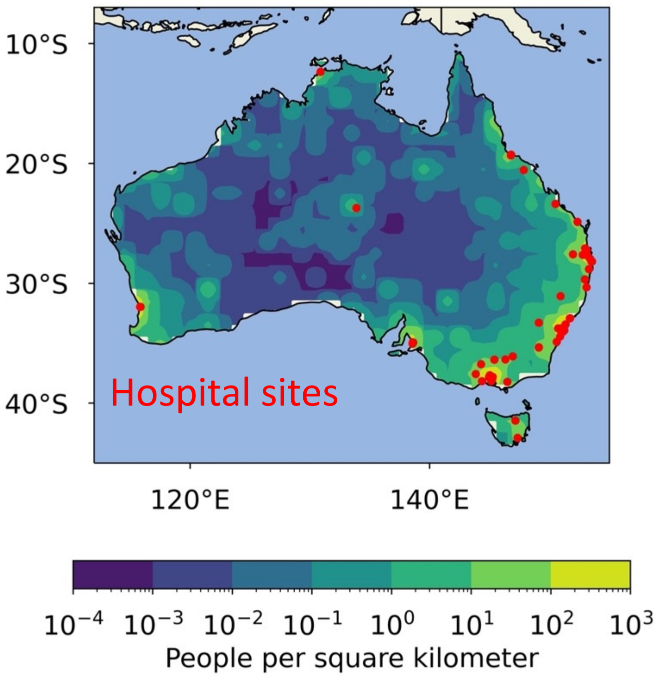
Climate Impacts on Intensive Care Unit Admissions (BVP)

- Australia-wide respiratory ICU per capita admissions related to **wet bulb globe temperature** from reanalysis.
- **Shape files** contain polygons defining national / state / province / district boundaries, to aggregate gridded climate data over these regions

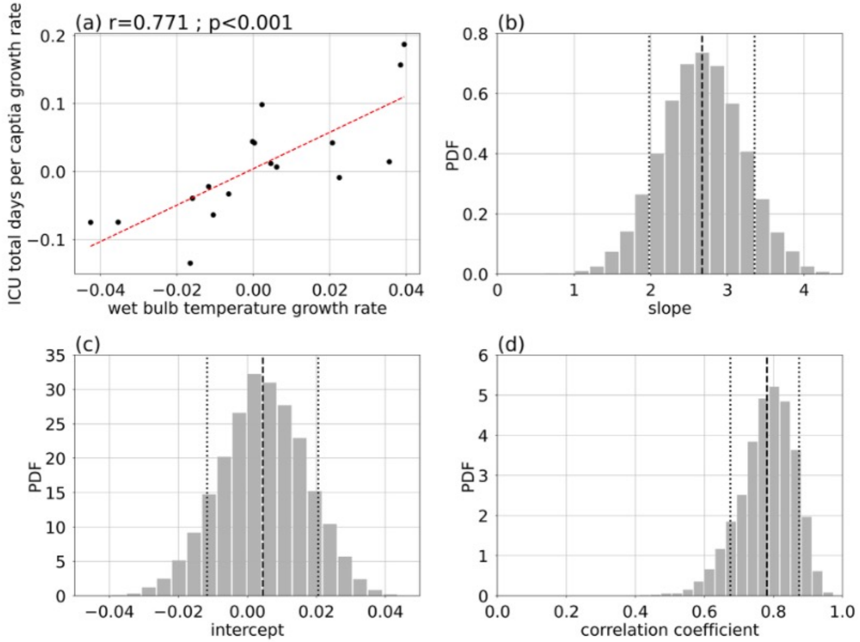
Climate Reanalysis



Population & hospital sites



Climate / ICU Relationships

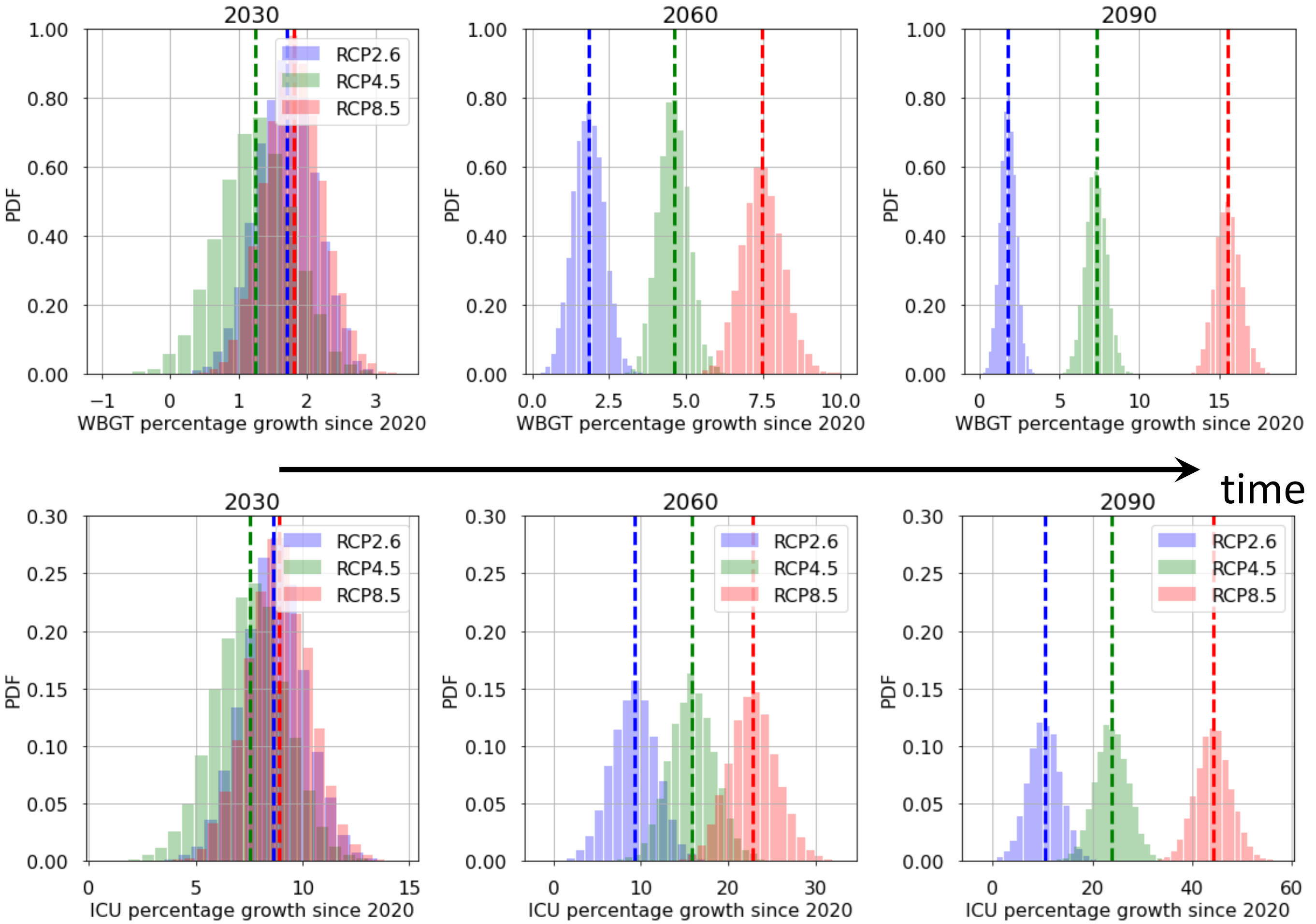


Bootstrapped to produce family of relationships to capture some of the parameter uncertainty

Poon, E.K.W., Kitsios, V., Pilcher, D., Bellomo R. & Raman, J., 2023, Projecting future climate impact on national Australian respiratory-related intensive care unit demand, *Heart Lung and Circulation*, Vol. 32(1), pp 95-104. https://doi.org/10.1016/j.hlc.2022.12.001

Climate Impacts on Intensive Care Unit Admissions (BVP)

- PDFs of **CMIP5** climate model WBGT projections for 3 future scenarios (RCP2.6,4.5,8.5), with climate change becoming more important with time.
- Applying learnt relationship between ICU admissions and WBGT, indicates significantly greater ICU load for an RCP8.5 world.



- **Tutorial Session 2** – Will use general philosophy to develop models estimating climate impacts on **malaria infection rates** in Thailand

Poon, E.K.W., Kitsios, V., Pilcher, D., Bellomo R. & Raman, J., 2023, Projecting future climate impact on national Australian respiratory-related intensive care unit demand, *Heart Lung and Circulation*, Vol. 32(1), pp 95-104. https://doi.org/10.1016/j.hlc.2022.12.001

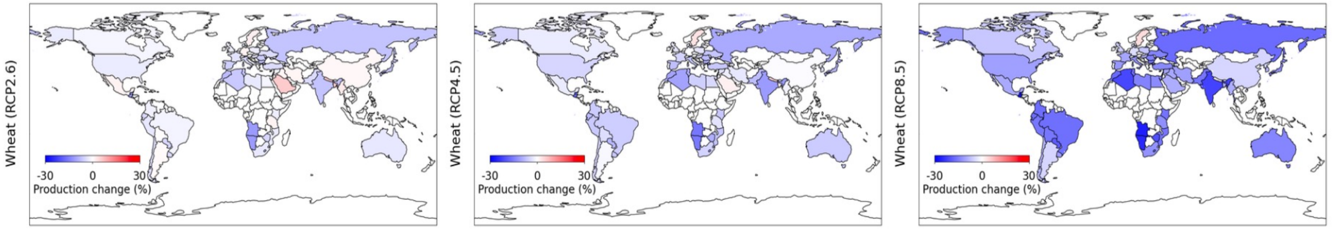
Climate & Technology Impacts on Agriculture (BVP)

- Collaboration with Dr Dan Li of QUT, to estimate change in yield, $\boldsymbol{y_t}$
- Model learnt from climate reanalysis and UNFAO national annual crop yield data.

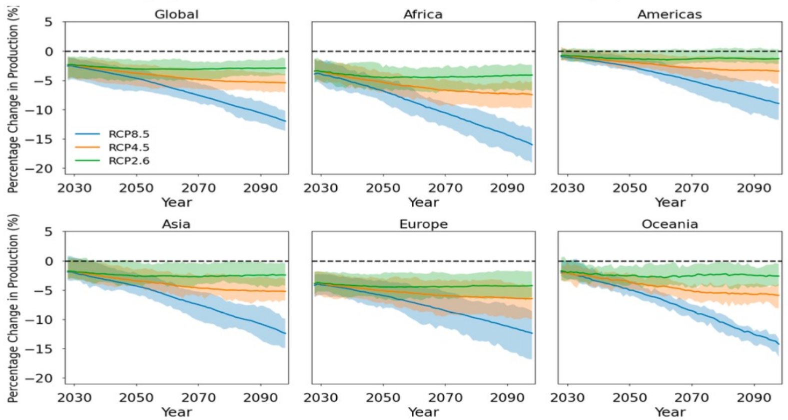
$$\mathbf{y}_t = \alpha_0(t) + \underbrace{\alpha_1 \mathbf{y}_{t-1} + \alpha_2 \mathbf{y}_{t-2}}_{\text{Autoregressive Factors}} + \underbrace{\beta_1 \Delta\mathbf{T}_t + \beta_2 \Delta\mathbf{T}_t^2 + \beta_3 \Delta\mathbf{P}_t + \beta_4 \Delta\mathbf{P}_t^2}_{\text{Exogenous Climate Factors}} + \boldsymbol{\epsilon}_t,$$

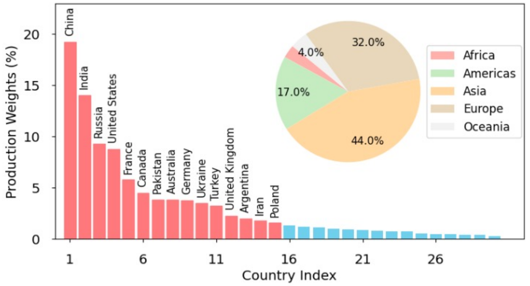
$$\boxed{\alpha_0(t) = \begin{cases} \alpha_0^{\text{const}}(t) = K & \text{(constant value)} \\ \alpha_0^{\text{exp}}(t) = a \cdot e^{-kt} & \text{(exponential decay function)} \\ \alpha_0^{\text{lin}}(t) = \max(C + rt, 0) & \text{(linear decay function)}, \end{cases}}$$

Technology Assumptions



(a) RCP2.6 (b) RCP4.5 (c) RCP8.5



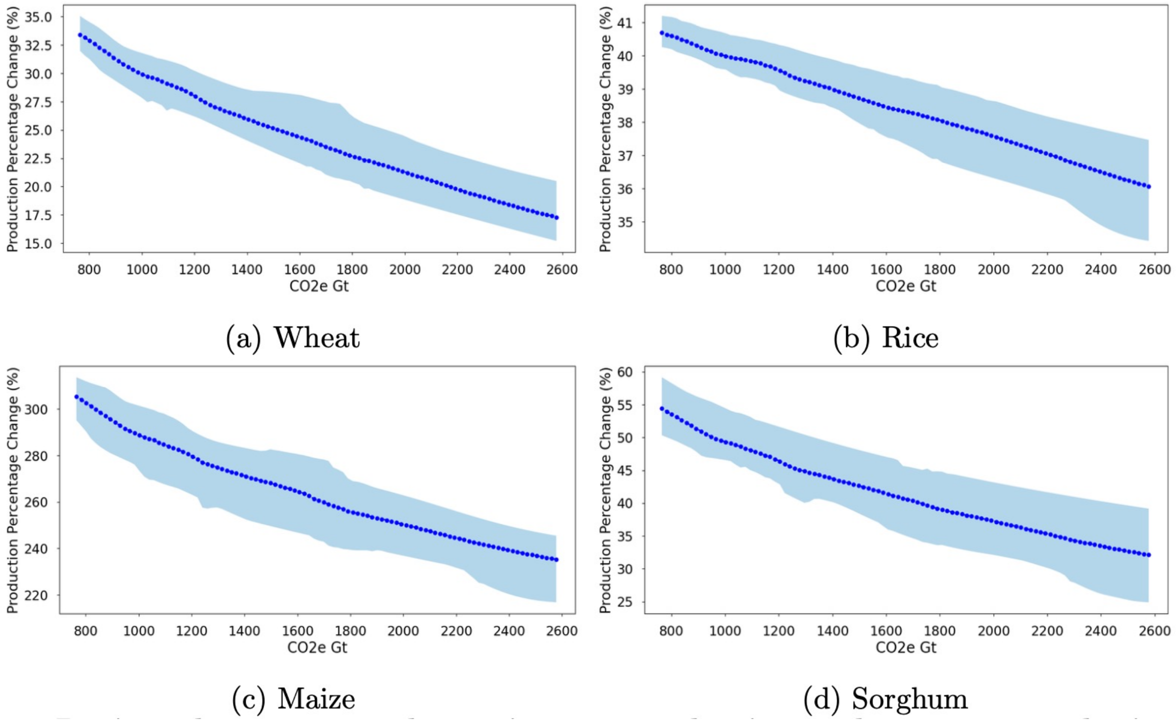


- Evaluate annual national production in response to future climate and aggregate as required.
- Ordinarily, can only assess the standard future climate scenarios.

Li, D., Kitsios, V., O'Kane, T. & Newth, D., Machine learning projection of climate and technology impacts on crops key to food security, Environmental Research Climate, Vol. 4, 025003.

Climate & Technology Impacts on Agriculture (BVP)

- However, our emulator ***QuickClim*** reconstructs the climate response for a multitude of emissions pathways, enabling the quantification of agricultural production across a wide range of scenarios.
- Global production over decade 2090-2100 as a function of end-of-century CO_{2e} concentration for crops key to food security.



(a) Wheat (b) Rice (c) Maize (d) Sorghum

- Shaded blue range illustrates uncertainty in climate model input factors.
- Latest developments adopt particle filtering for **uncertainty quantification of parameters** in agricultural production model.

Li, D., Kitsios, V., O'Kane, T. & Newth, D., Machine learning projection of climate and technology impacts on crops key to food security, Environmental Research Climate, Vol. 4, 025003.

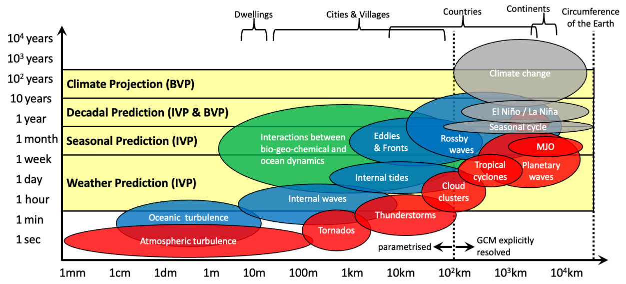
Key take home points

1. **What is a climate model?**
   - Numerical simulation of the physical equations of motion in the atmosphere, ocean, …
2. **What is the distinction between weather and climate?**
   - Weather forecasting predicts specific events up to weeks into the future.
   - Climate projections estimate how statistics change decades into future per scenario.
3. **What is a reanalysis?**
   - Simulations corrected using historical real-world observations.
   - Essential for learning relationships between climate and human impacts (e.g. health).
4. **What is CMIP, and where do climate emulators fit in?**
   - CMIP provides projections from numerous climate models for selected future scenarios.
   - Climate emulators can rapidly estimate data for user-defined scenarios.
5. **Climate risk case studies**
   - Estimate future human impacts by applying relationships learnt from reanalysis, to future projections from CMIP or climate emulators.

Holistic Climate Risk Assessment:
Evaluate impact on **various economic actors / sectors** (e.g. health) over relevant **time horizons for decision making** (e.g. years to decades)

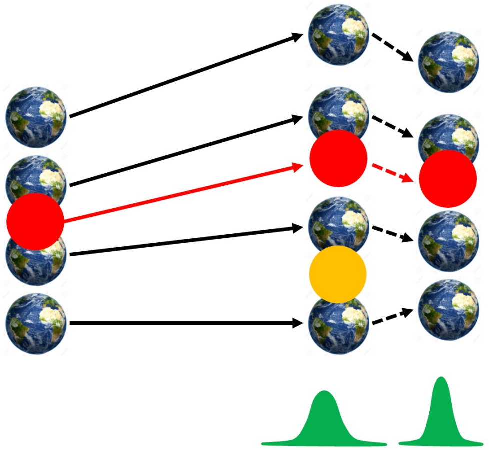
Climate Physics

- What is a climate model
- Weather Forecasting vs Climate Projection
- Alignment of time scales for human decision making & physical phenomena



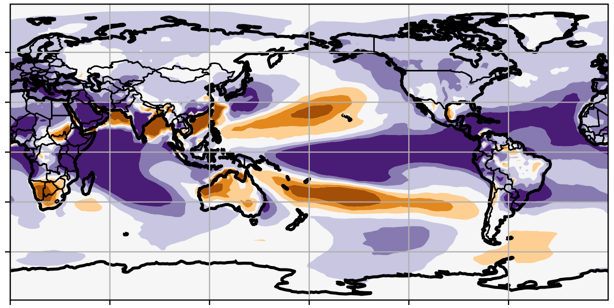
Reanalysis

- Fusing simulations and observations
- Essential for learning historical relationships between climate and health



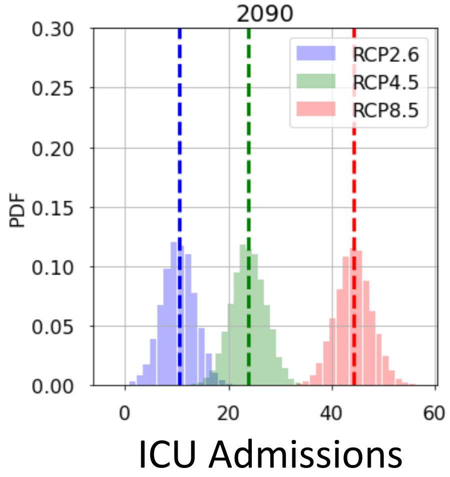
CMIP & Emulators

- Relationship between scenarios, emissions and climate
- Hierarchy of cheap emulators learnt from reanalysis & CMIP



Risk Assessments

- Intensive Care Unit Admissions
- Agricultural production
- Food-security-induced conflict



Thank you

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