Predictability of the Evolution of the Earth System and of the Atmosphere:

A Historical Perspective and Future Challenges

Weather, Climate, and Air Quality

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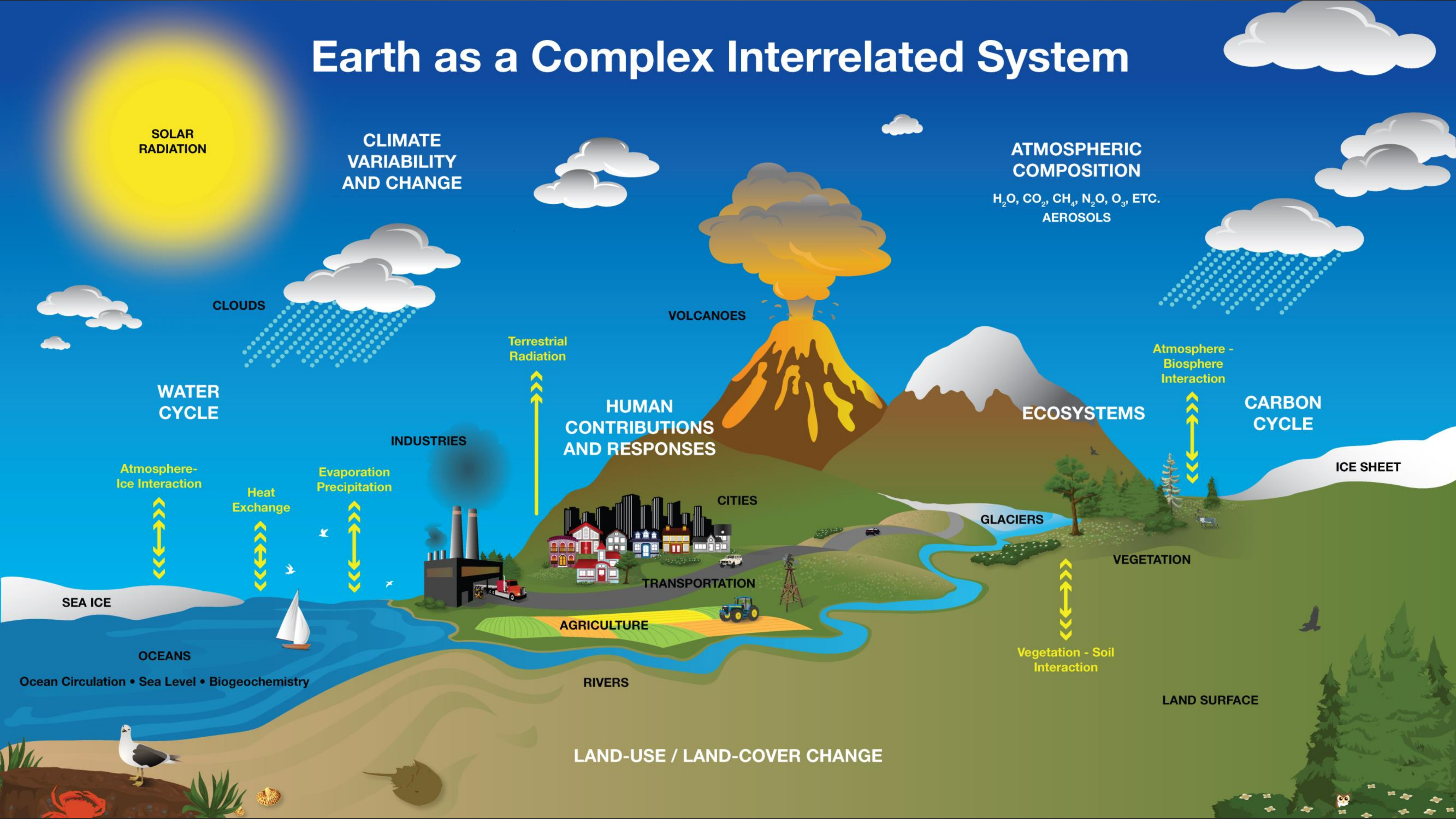
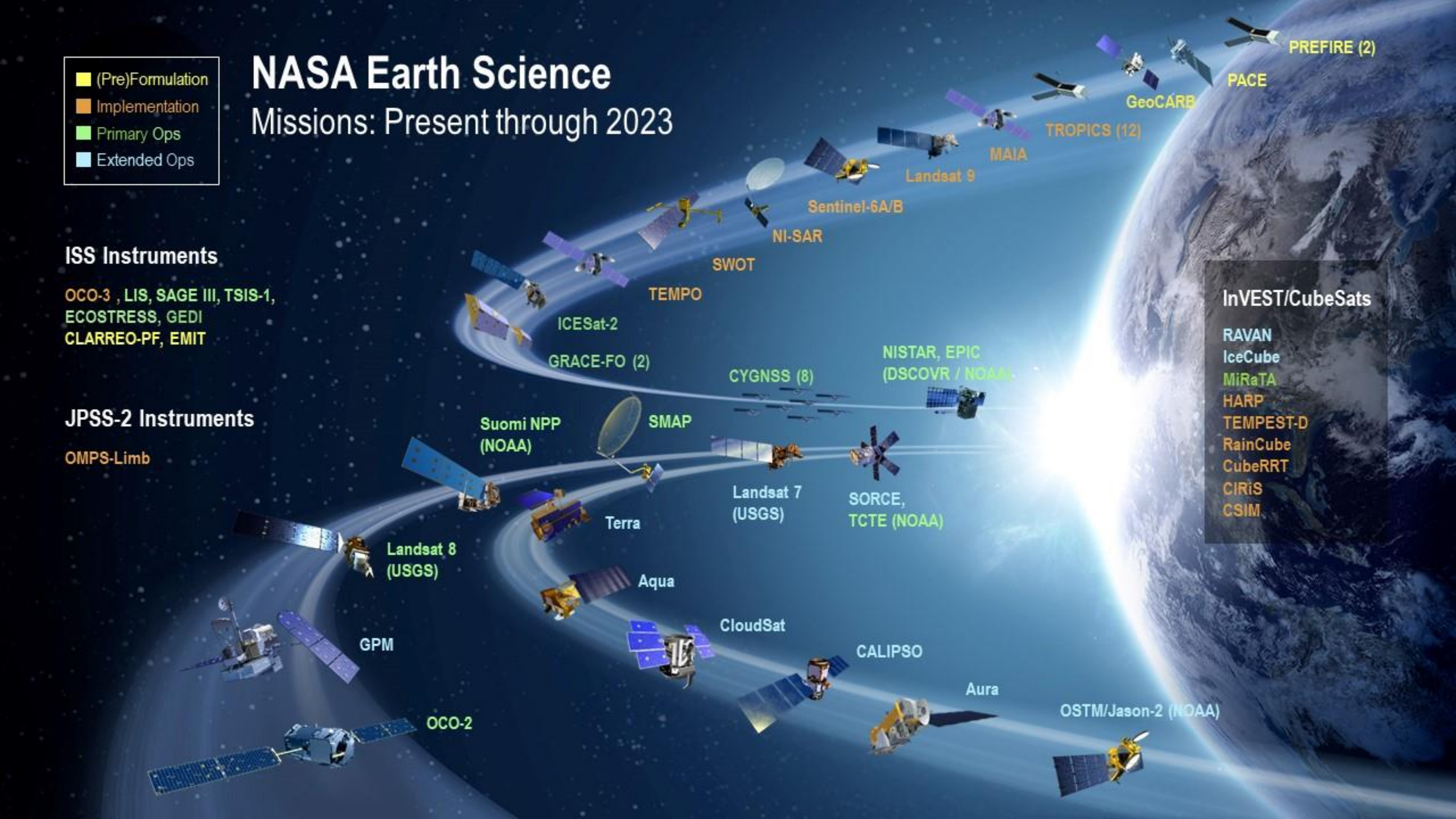
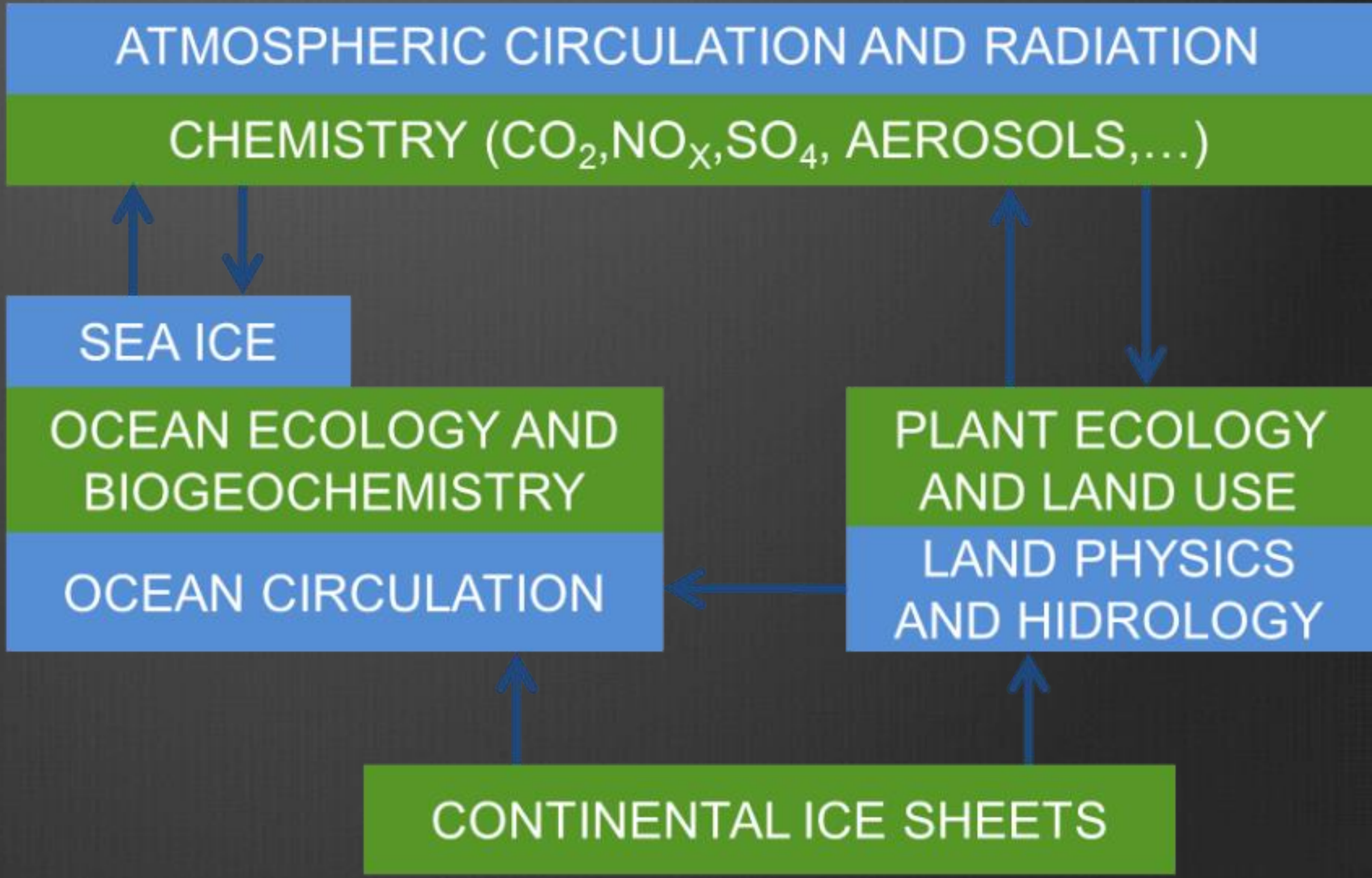
1. Introduction

The Earth should be viewed as a complex system


Earth as a Complex Interrelated System
SOLAR RADIATION
CLIMATE VARIABILITY AND CHANGE
ATMOSPHERIC COMPOSITION
H_2O, CO_2, CH_4, N_2O, O_3, ETC.
AEROSOLS
CLOUDS
VOLCANOES
Terrestrial Radiation
WATER CYCLE
HUMAN CONTRIBUTIONS AND RESPONSES
ECOSYSTEMS
Atmosphere - Biosphere Interaction
CARBON CYCLE
INDUSTRIES
ICE SHEET
Atmosphere-Ice Interaction
Heat Exchange
Evaporation Precipitation
CITIES
GLACIERS
VEGETATION
TRANSPORTATION
SEA ICE
AGRICULTURE
OCEANS
Ocean Circulation • Sea Level • Biogeochemistry
RIVERS
Vegetation - Soil Interaction
LAND SURFACE
LAND-USE / LAND-COVER CHANGE


NASA Earth Science
Missions: Present through 2023
(Pre)Formulation
Implementation
Primary Ops
Extended Ops
ISS Instruments
OCO-3 , LIS, SAGE III, TSIS-1,
ECOSTRESS, GEDI
CLARREO-PF, EMIT
JPSS-2 Instruments
OMPS-Limb
PREFIRE (2)
PACE
GeoCARB
TROPICS (12)
MAIA
Landsat 9
Sentinel-6A/B
NI-SAR
SWOT
TEMPO
ICESat-2
GRACE-FO (2)
CYGNSS (8)
NISTAR, EPIC
(DSCOVR / NOAA)
SMAP
Suomi NPP
(NOAA)
Landsat 7
(USGS)
SORCE,
TCTE (NOAA)
Terra
Landsat 8
(USGS)
Aqua
CloudSat
GPM
CALIPSO
Aura
OCO-2
OSTM/Jason-2 (NOAA)
InVEST/CubeSats
RAVAN
IceCube
MiRaTA
HARP
TEMPEST-D
RainCube
CubeRRT
CIRiS
CSIM


ATMOSPHERIC CIRCULATION AND RADIATION
CHEMISTRY (CO_2,NO_X,SO_4, AEROSOLS,…)
SEA ICE
OCEAN ECOLOGY AND BIOGEOCHEMISTRY
OCEAN CIRCULATION
PLANT ECOLOGY AND LAND USE
LAND PHYSICS AND HIDROLOGY
CONTINENTAL ICE SHEETS

Mathematical Models

- Mathematical models strip the complexity of a system by identifying the essential driving variables and describing the evolution of these variables with equations based on physical laws or empirical knowledge.

- They can be rather general or more specific, they can be guided by *first principles* (physical laws) or by empirical information, they can be analytic or numerical, deterministic or stochastic, continuous or discrete, quantitative or qualitative.

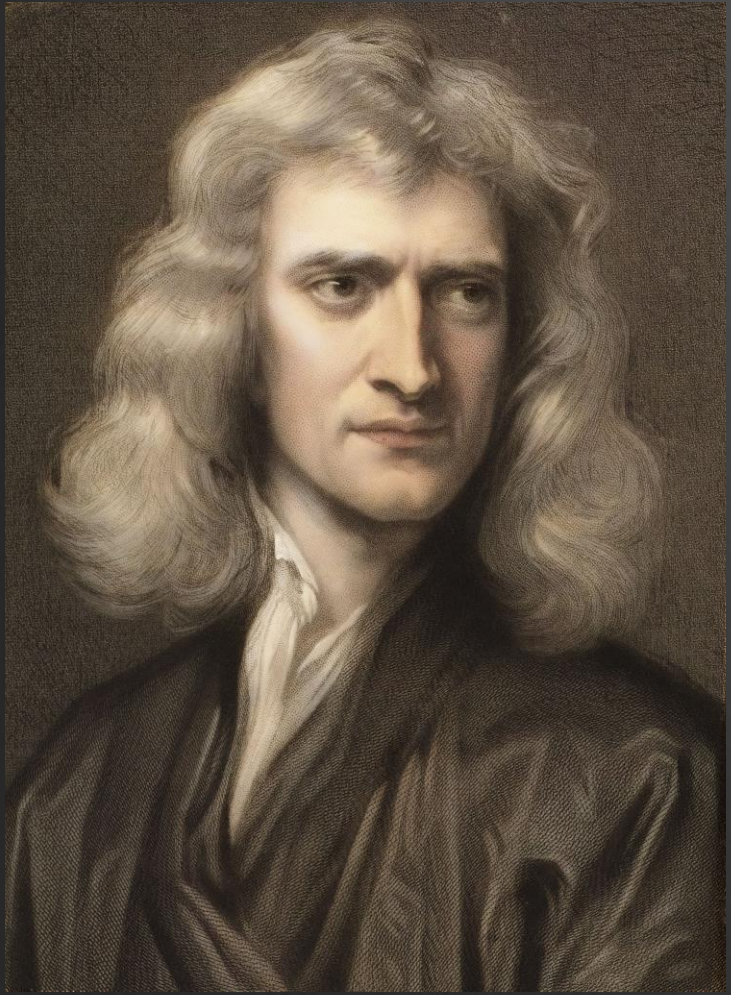
Outline

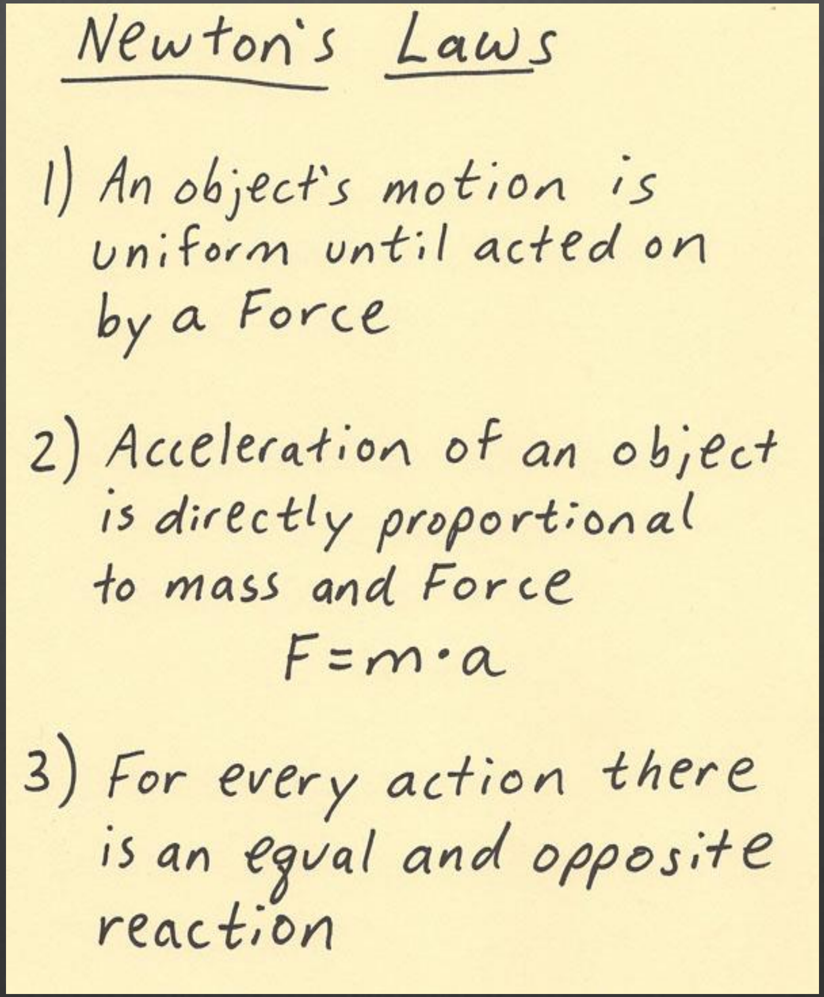
1. Predictability of the Weather
2. Predictability of Climate
3. Predictability of Air Quality
4. Challenges for the Future
5. Conclusions

1. Predictability of the Weather

An Initial Condition Problem

Newton’s Laws: Force, Mass and Acceleration are related





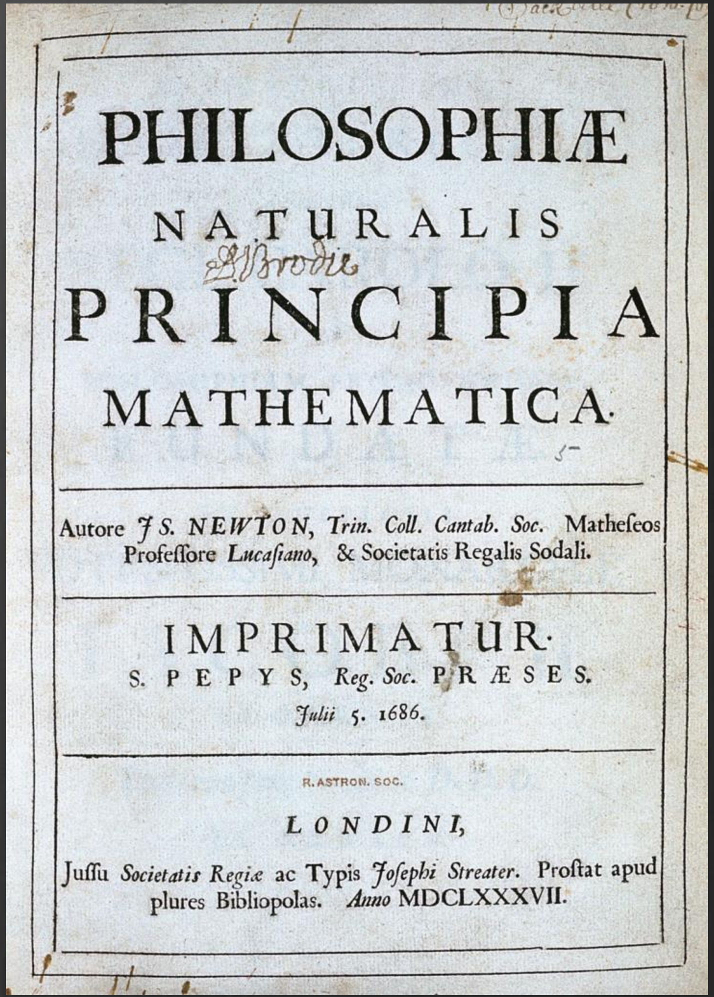
Newton's Laws

1) An object's motion is uniform until acted on by a Force

2) Acceleration of an object is directly proportional to mass and Force

$$F = m \cdot a$$

3) For every action there is an equal and opposite reaction



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

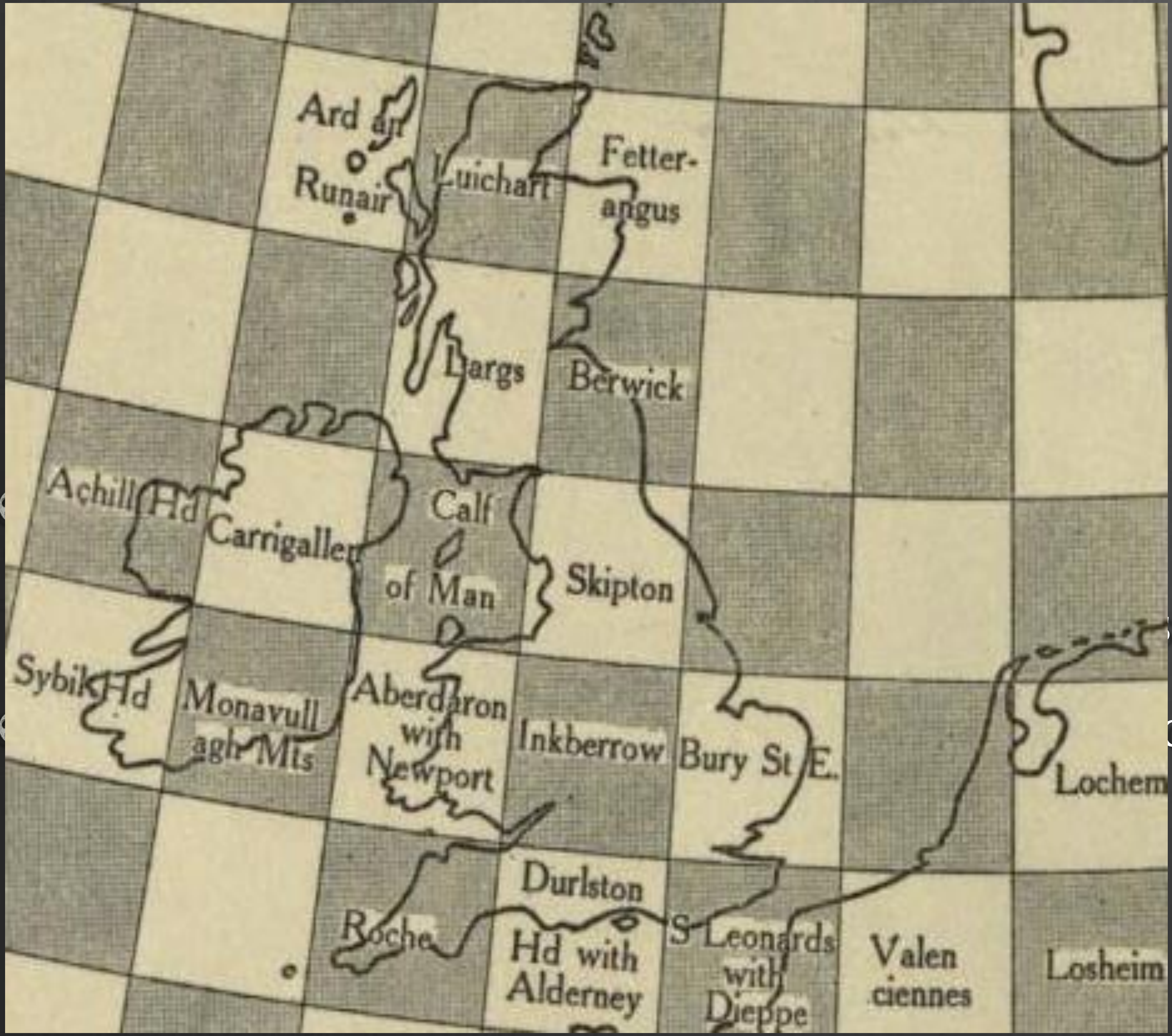
R. ASTRON. SOC.

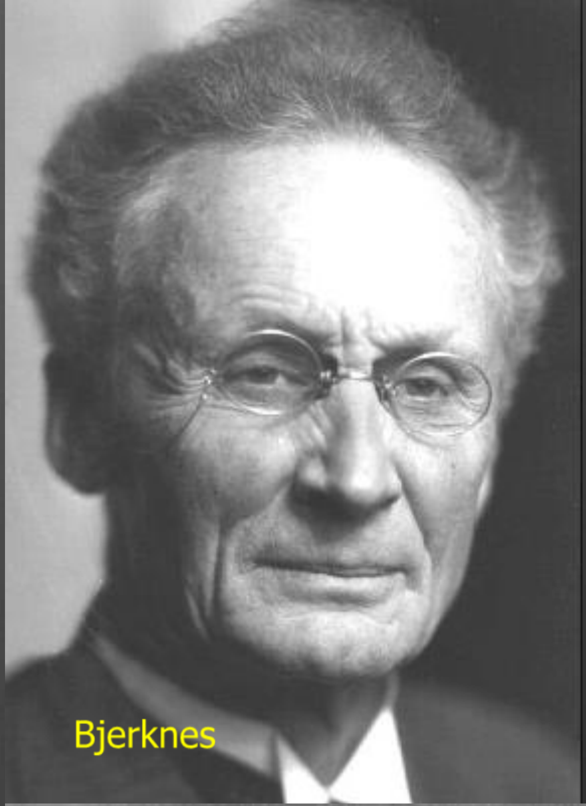
LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

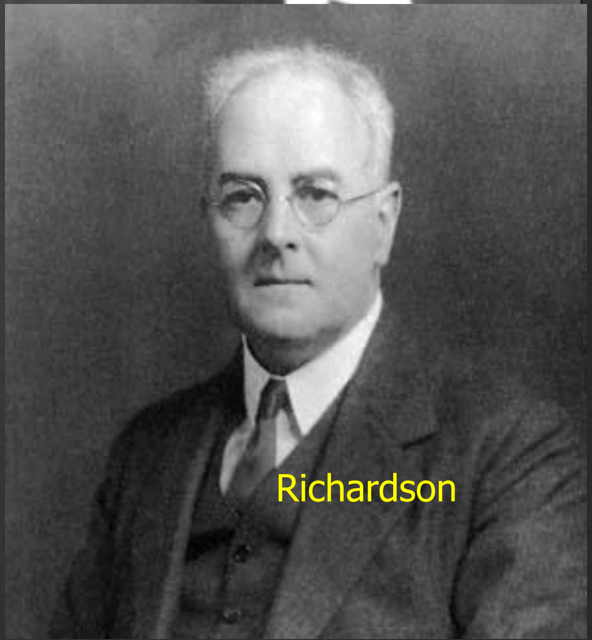
Meteorology as an "Exact Science": V. Bjerknes

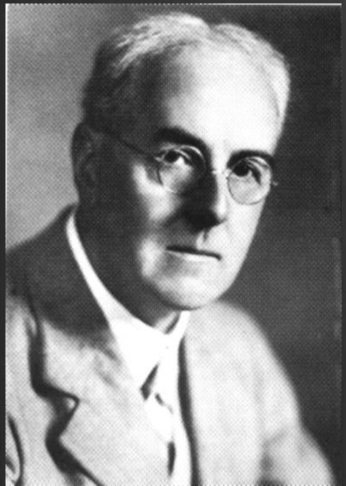
- In 1904, Norwegian meteorologist Vilhelm Bjerknes (1862-1951) argued that weather forecasting should be based on the well-established laws of physics and should therefore be regarded as a deterministic problem:
- "If it is true, as every scientist believes, that subsequent atmospheric states develop from the preceding ones according to physical law, then it is apparent that the necessary and sufficient conditions for the rational solution of forecasting problems are the following:
  - A sufficiently accurate knowledge of the state of the atmosphere at the initial time;
  - A sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another."

100 years ago….





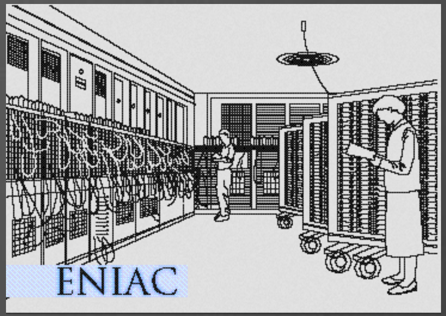




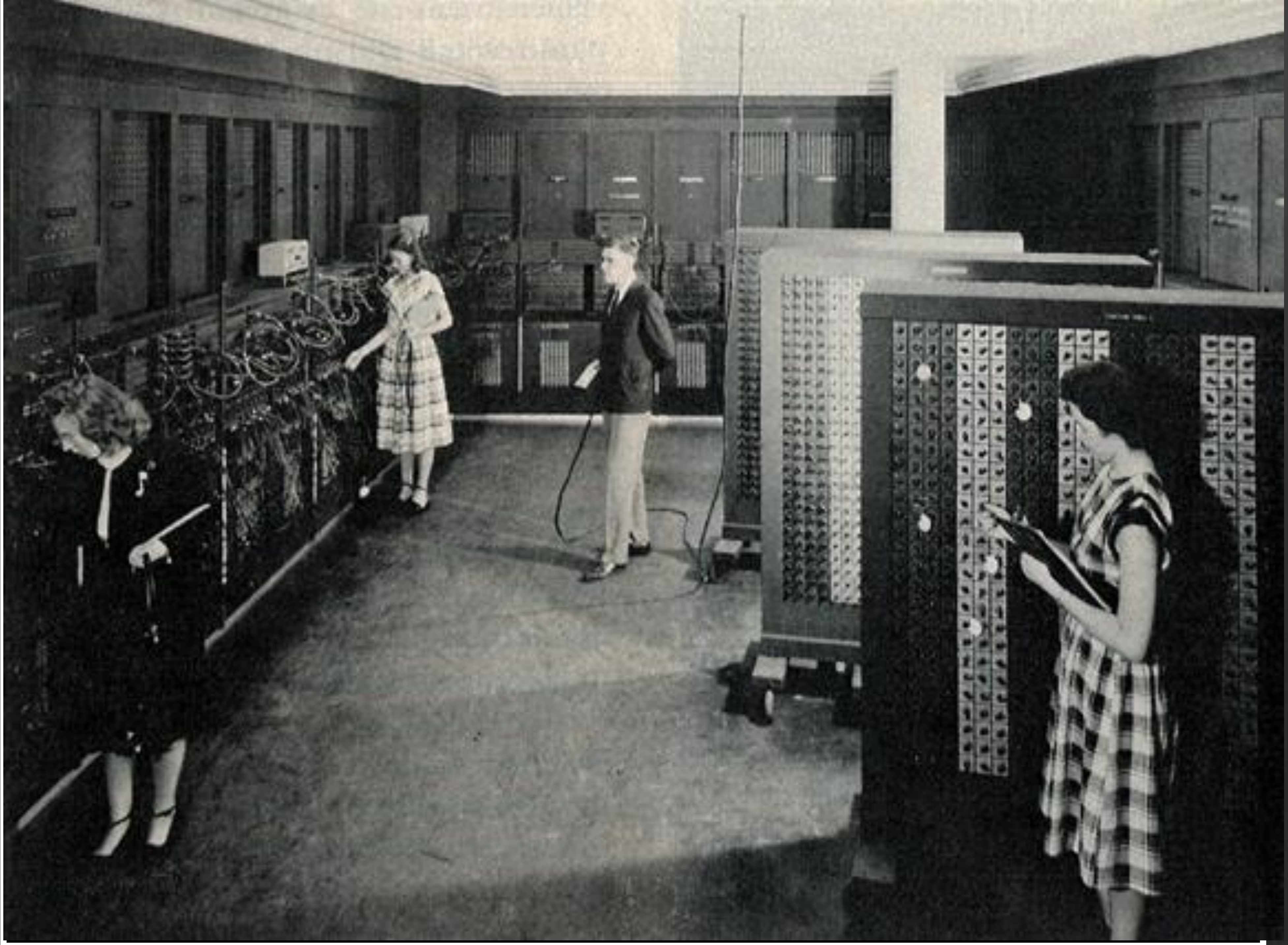
Before the Computer Age

In 1922, Lewis Fry Richardson suggests to assemble 64000 persons in a "numerical factory" to perform in parallel the tremendous number numerical operations required to solve the equations of meteorology. He had proposed the concept of parallel computing before the computer age.

The First Electronic Computers



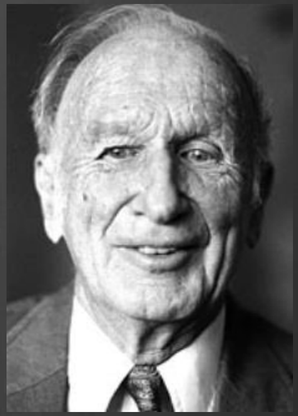
- The development of the **Electronic Numerical Integrator and Computer (ENIAC)** at the University of Pennsylvania's Moore School of Electrical Engineering provided the opportunity for atmospheric scientists to redo the calculations of Richardson.
- The first **computer model of the atmosphere** was developed in the early 1950's by mathematician John von Neumann and meteorologist Jule Charney.
- The model was based on the **quasi-geostrophic approximation of the hydrostatic equations** (eliminates acoustic and gravity waves, but retains planetary waves). It showed therefore success in reproducing the large-scale features of the atmospheric flow.



Chaos and Weather/Climate Forecasting

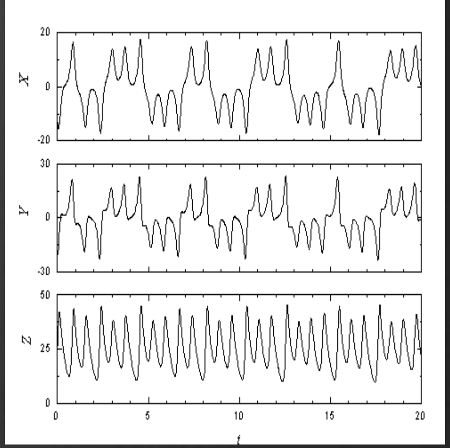
- Henri Poincaré established (ca. 1900) the basic principles of the chaotic behavior for celestial dynamics: strong dependency on initial conditions, complexity of trajectories, 3-body problem (planets/moons), etc.
- The atmosphere is a chaotic system: Predictability is limited because small errors in initial conditions are rapidly growing. Predictability is also limited by model approximations. (discretization, physical. parameters,..)
- Ensemble predictions are performed to address the limits to deterministic forecasts

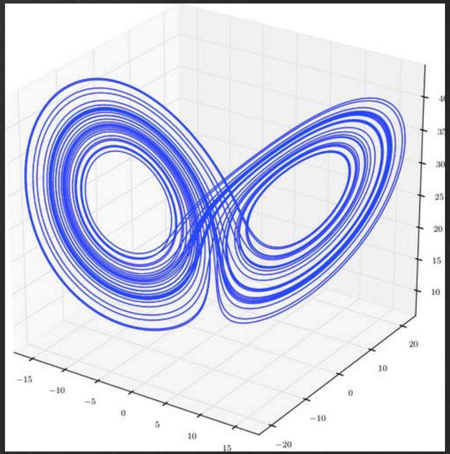
The Lorenz Equations



- In 1963, meteorologist Edward Lorenz (MIT) develops a simplified mathematical model for atmospheric convection.

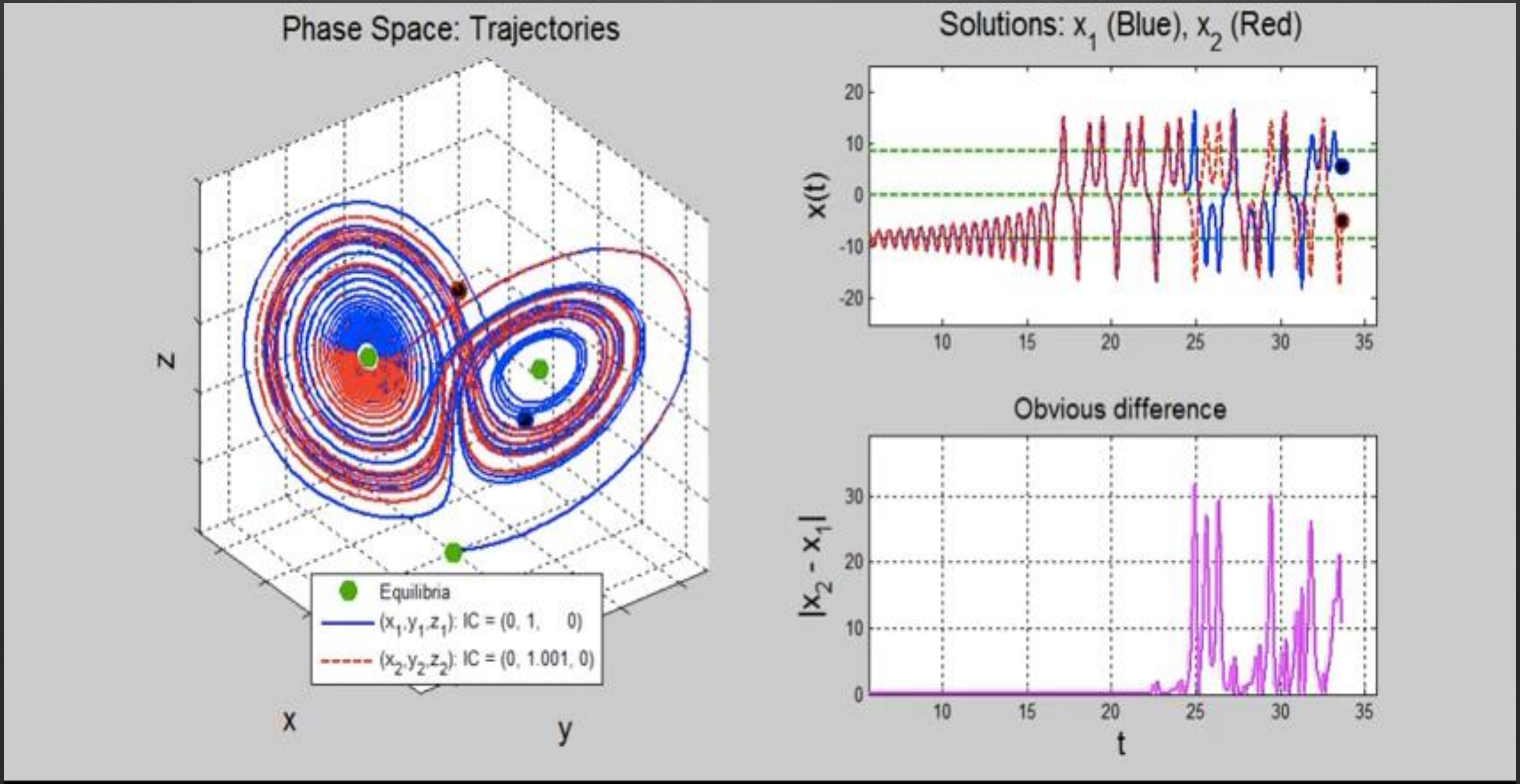
$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sigma(y - x),$$
$$\frac{\mathrm{d}y}{\mathrm{d}t} = x(\rho - z) - y,$$
$$\frac{\mathrm{d}z}{\mathrm{d}t} = xy - \beta z.$$



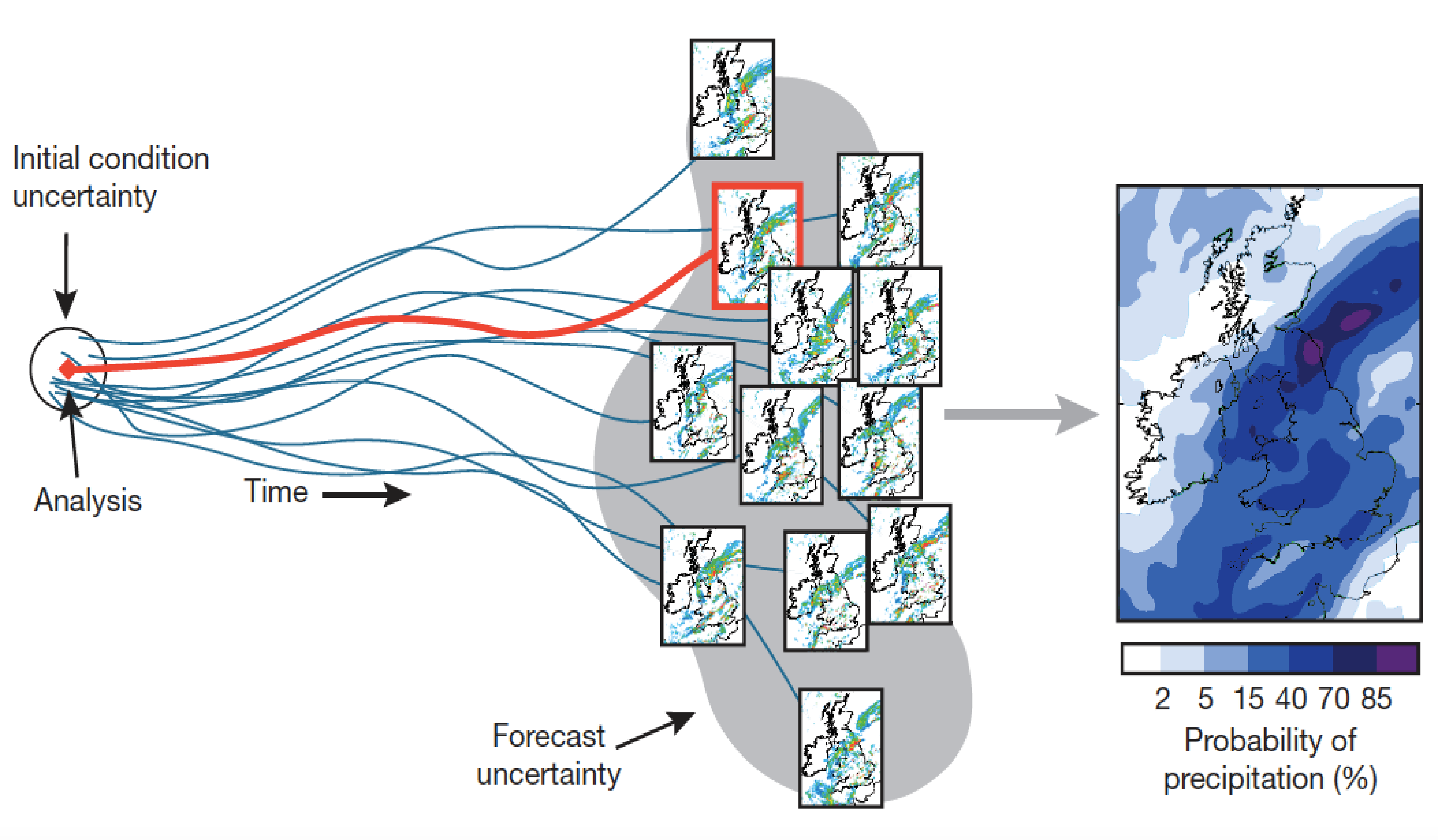


- The Lorenz system is nonlinear, non-periodic, three-dimensional and deterministic.

The Solution of the Lorentz System for Two Slightly Different Initial Conditions



Ensemble Forecast of Precipitation in the United Kingdom



Sources and Limits of Predictability

Sources of Predictability:

- Large scale forcing on smaller-scale weather
- Teleconnections between geographical regions
- Interactions between atmosphere, land surfaces and vegetation, sea-ice and ocean (long time-scales)

Sources of Unpredictability:

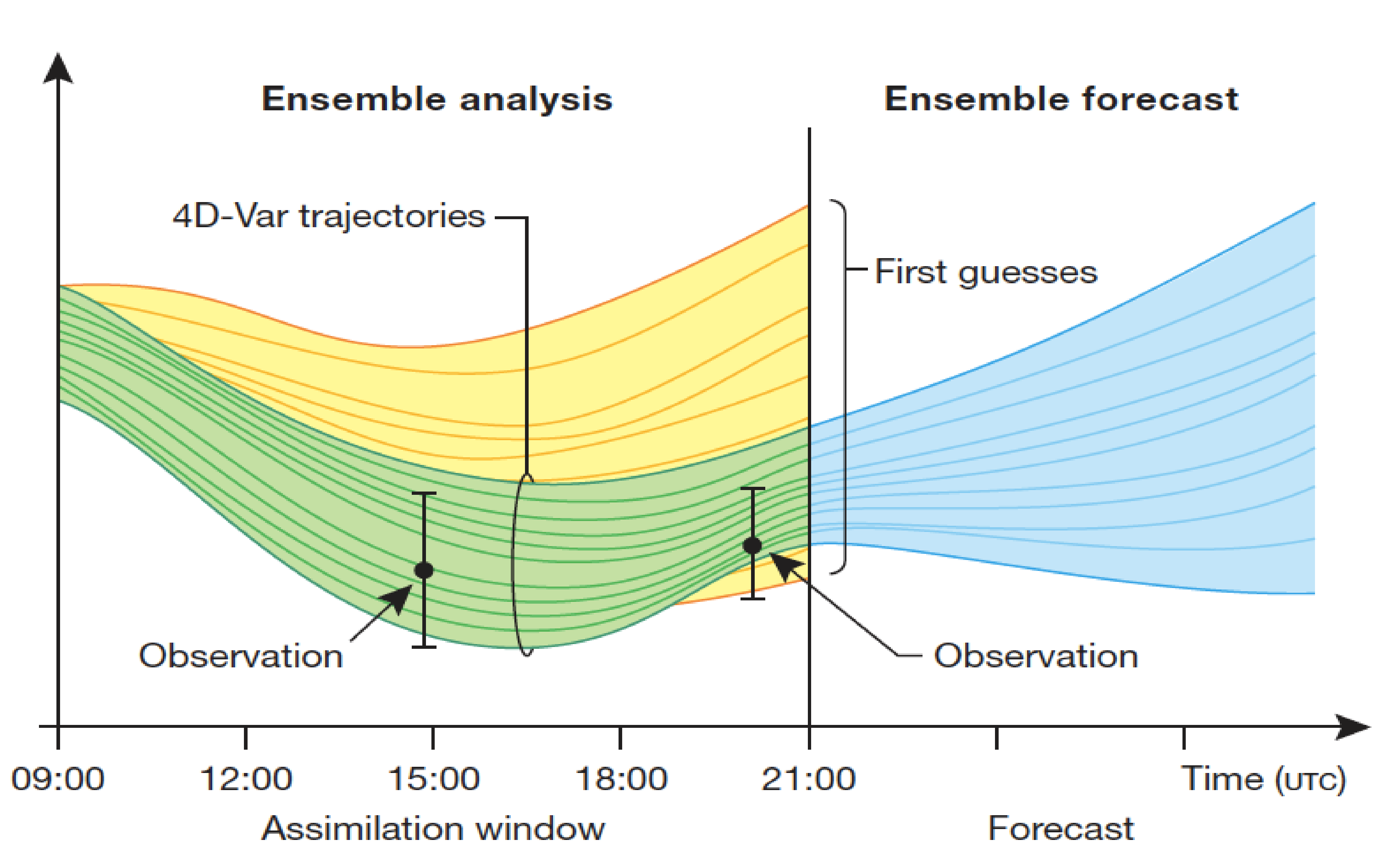
- Instability injecting chaotic noise at small scale
- Upscale propagation of energy from scale-scale interactions
- Errors associated with numerics in the models
- Errors in physical parameterizations
- Insufficient number of observations

Increasing Predictive Skills

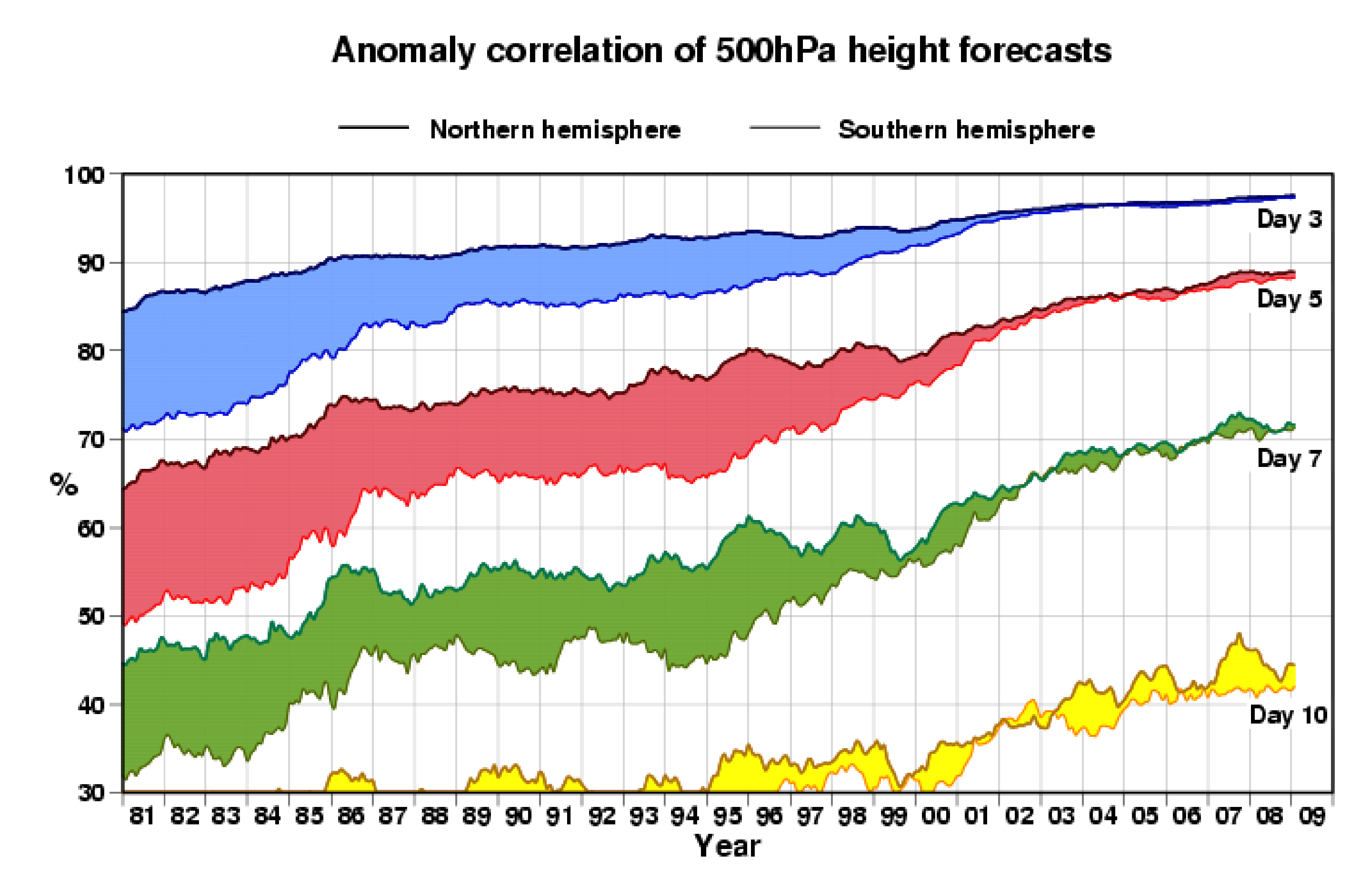
Predictive skill has increased by

- Improving the representation of unresolved processes in models (parameterization of cloud and precipitation physics, formulation of radiative transfer)
- Introducing ensemble methods producing forecast uncertainty estimates, (considering several possible realizations and providing a probabablistic assessment)
- Introducing objective analyses techniques to include information from observations (initial conditions are determined by using observations, prior information from short-term forecasts and uncertainties in observations and models)

Assimilation of Meteorological Observations for Initial Conditions of Ensemble Forecasts



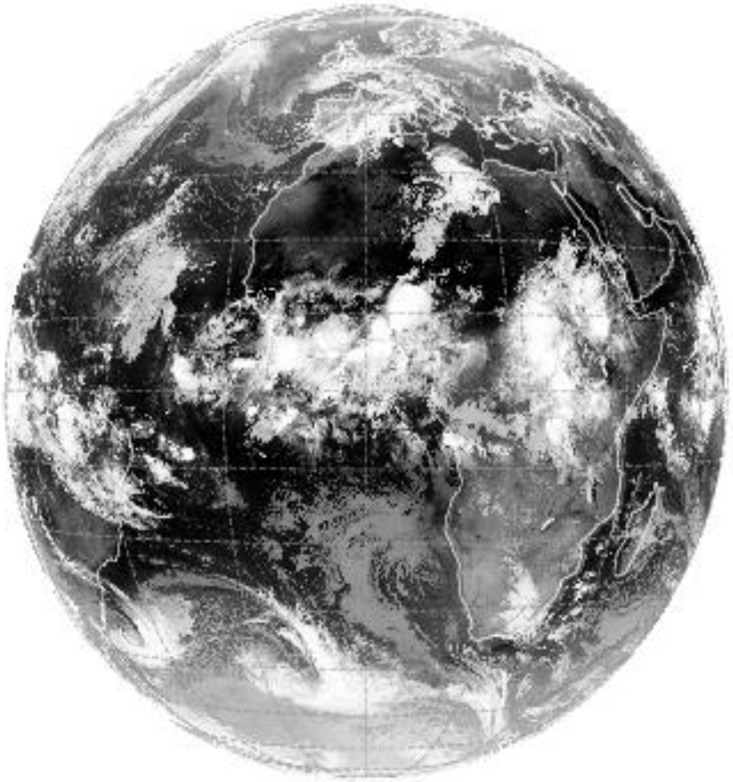
Advances in Weather Forecasts



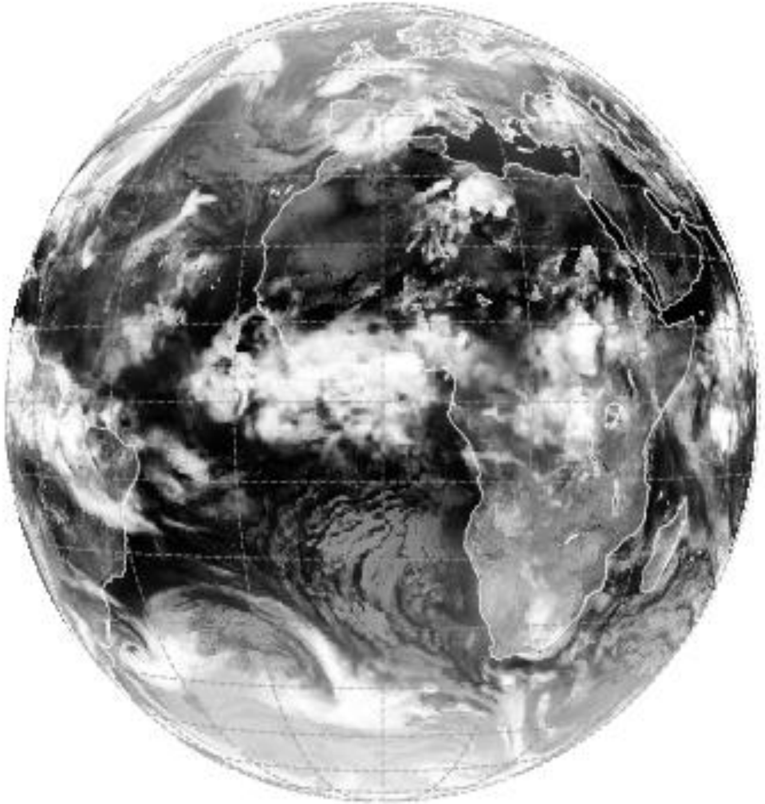
Weather Prediction compared with Satellite Observations

ECMWF predictions and Meteosat observations

Meteosat 9 IR10.8 20080525 0 UTC



ECMWF Fc 20080525 00 UTC+0h:



2. Predictability of Climate

A Boundary Condition Problem

Fourier

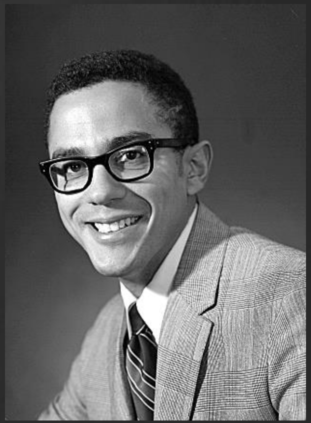
Predicting Climate Change

- Arrhenius quantifies in 1896 the changes in surface temperature (approx. 5 C) to be expected from a doubling in CO_2, based on the concept of ”glass bowl” effect introduced in 1824 by Joseph Fourier.
- Norman Phillips develops the first global atmospheric GCM, and early climate models are being developed by many (Manabe, Mintz and Arakawa, Washington, etc.)

Arrhenius

Manabe

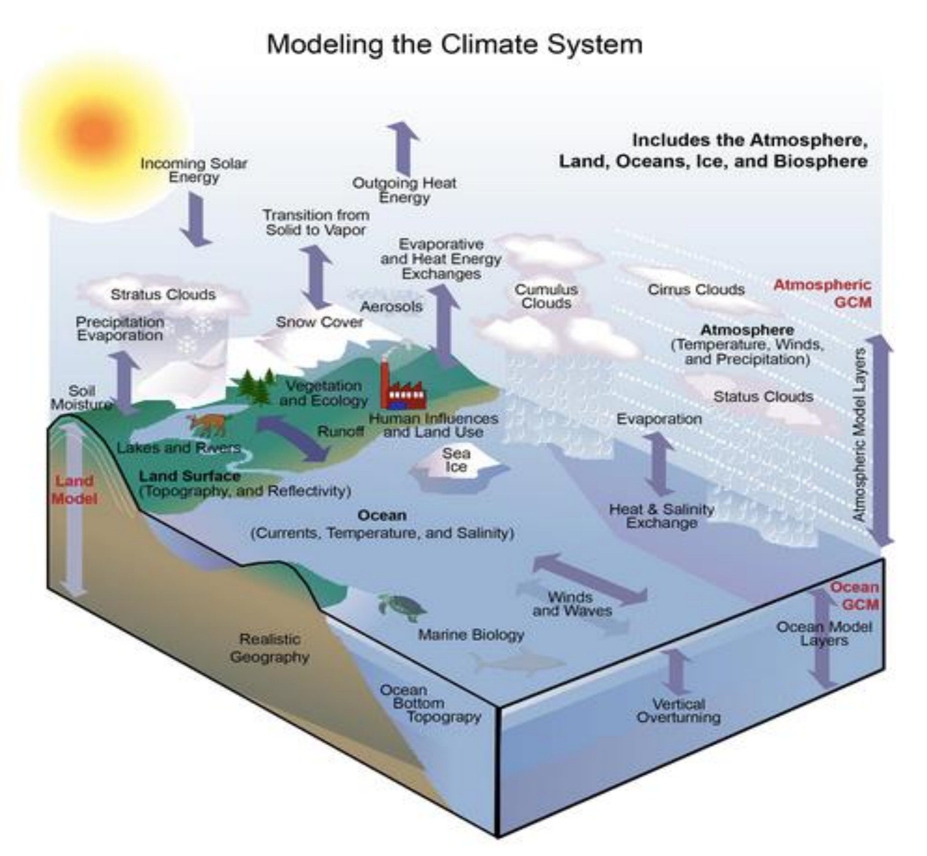
Arakawa

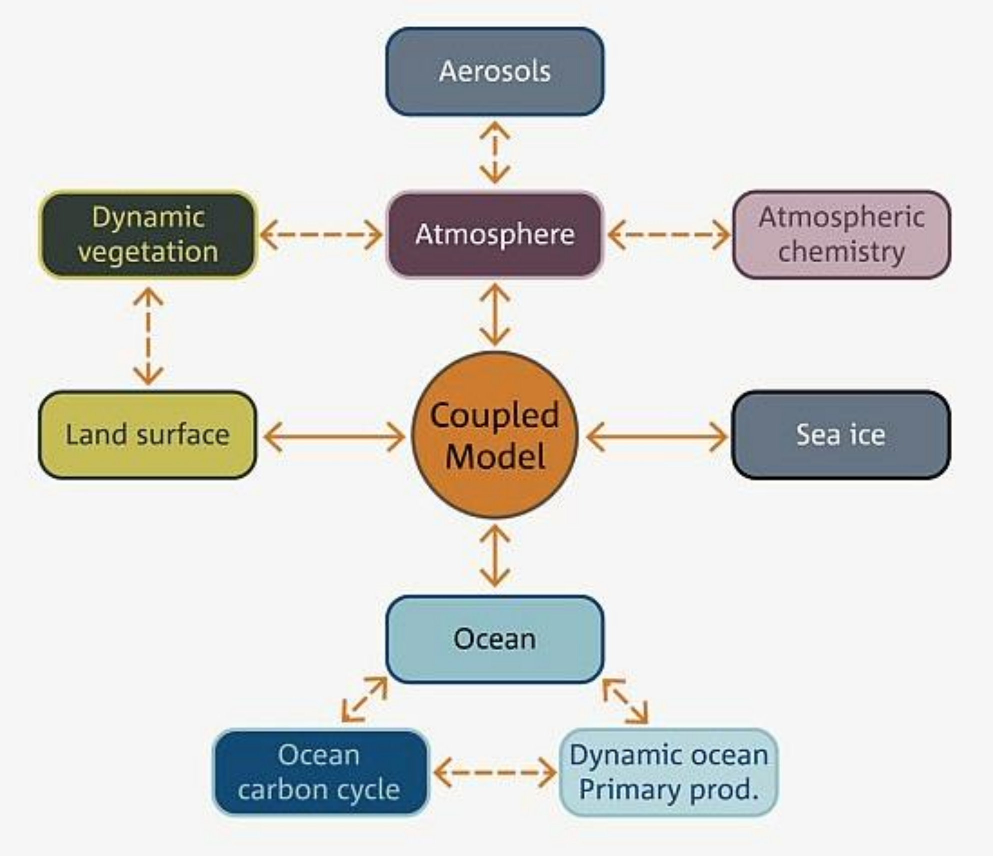


Washington

Long-Term Climate Projections
(Decades to Centuries)

Conceptual Description of a Climate Model

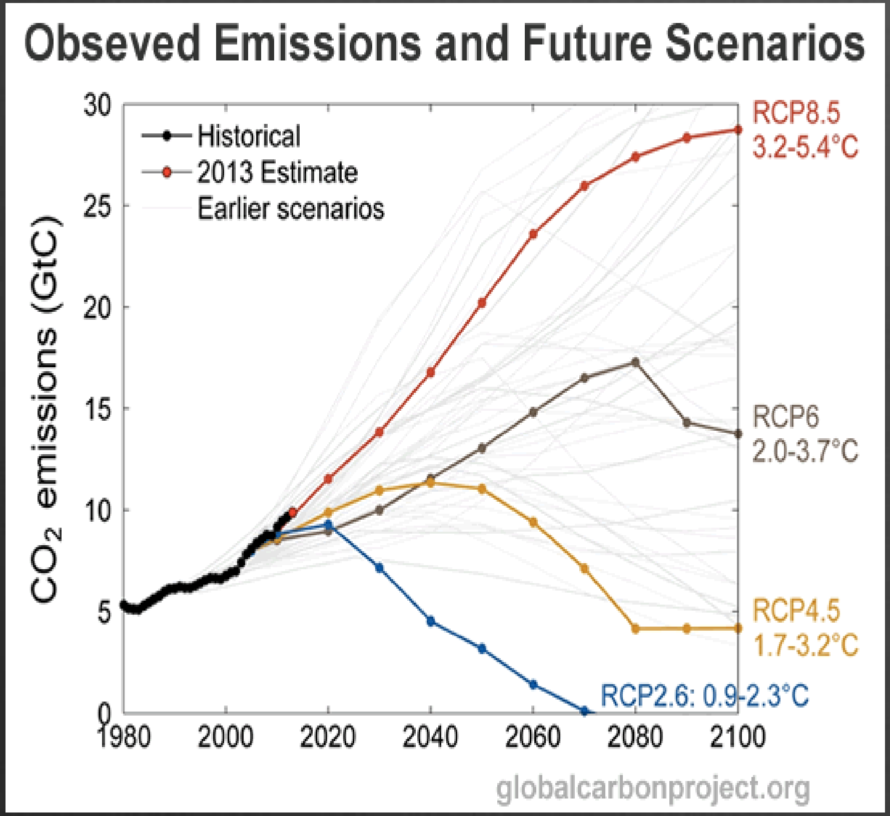


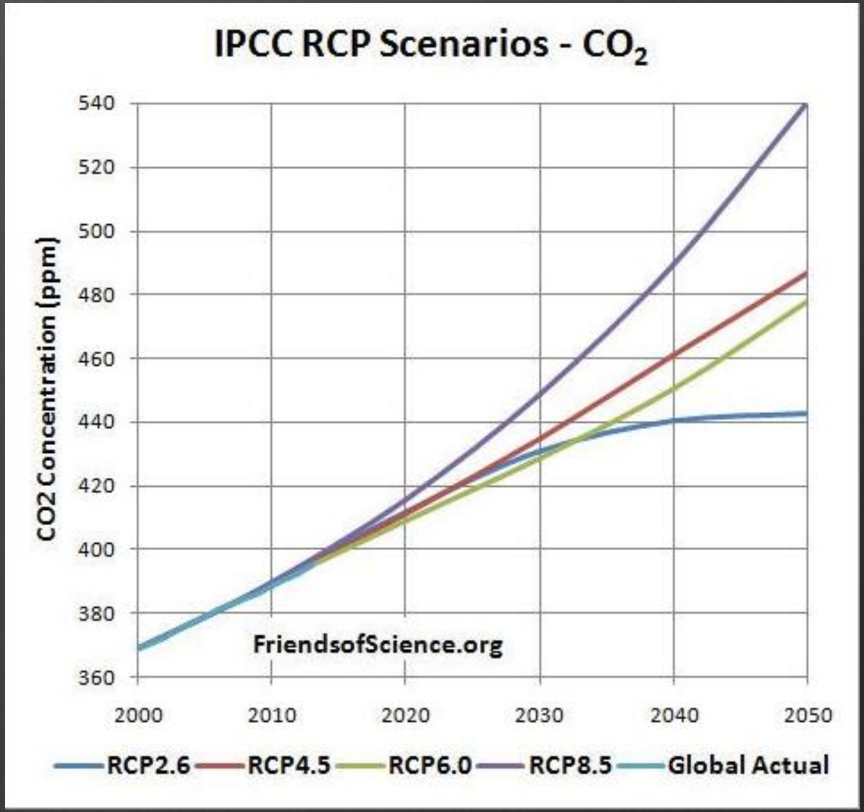


Predictability of Climate

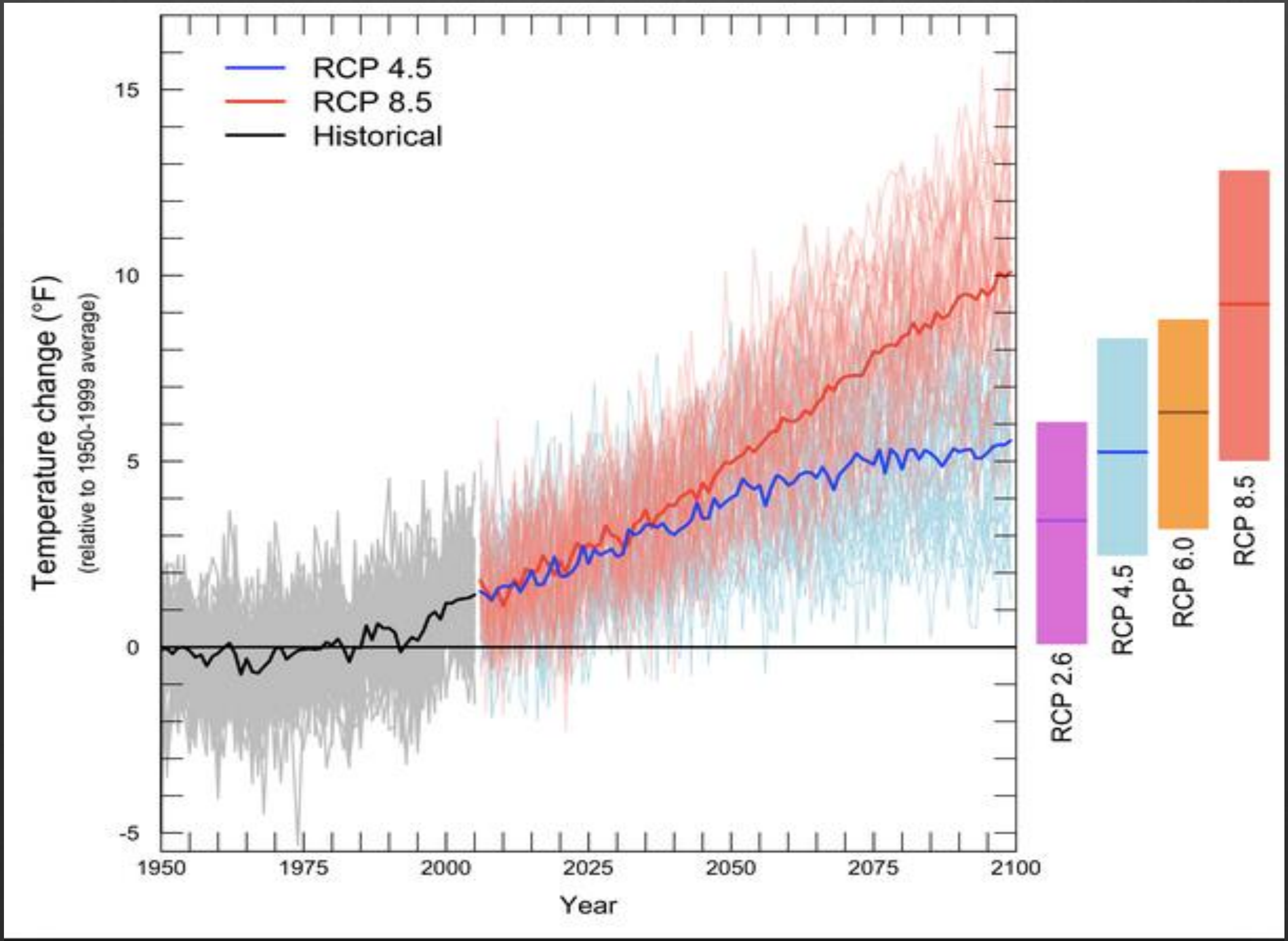
- If weather is not predictable beyond 2 weeks, can we predict future climate?
- No, we cannot **predict** the future state of the atmosphere on decadal to century timescales, but we can perform an ensemble of simulations (many realizations) and derive the change in the probability distribution of climate states.
- Thus, we can **project** the evolution of statistical moments such as the mean and variance of climate variables such as the temperature for different scenarios of greenhouse gas emissions.

RCP Scenarios used by IPCC

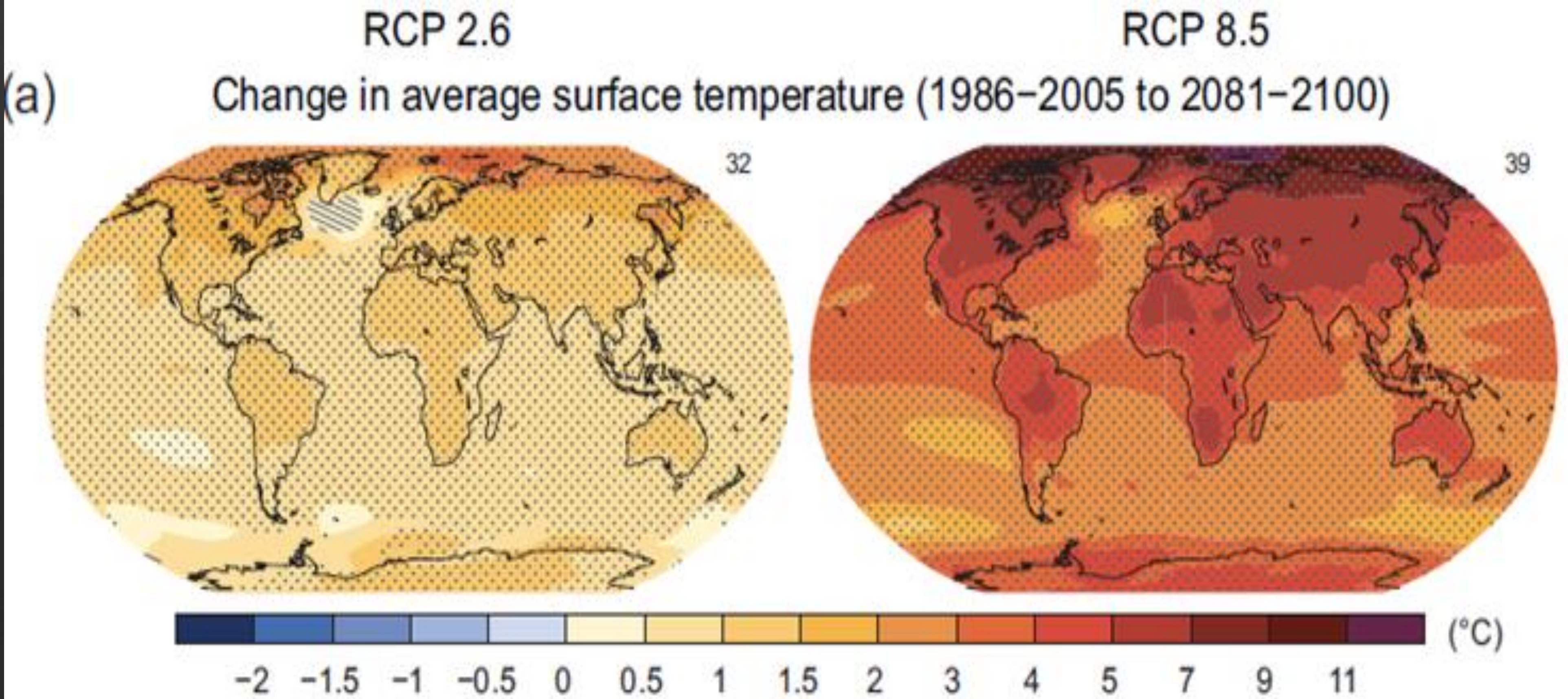




Ensemble of Model Projections for Different Emission Scenarios



Climate Projections for the 21st Century
2 scenarios of CO_2 emissions
(RCP 2.6 and 8.5)

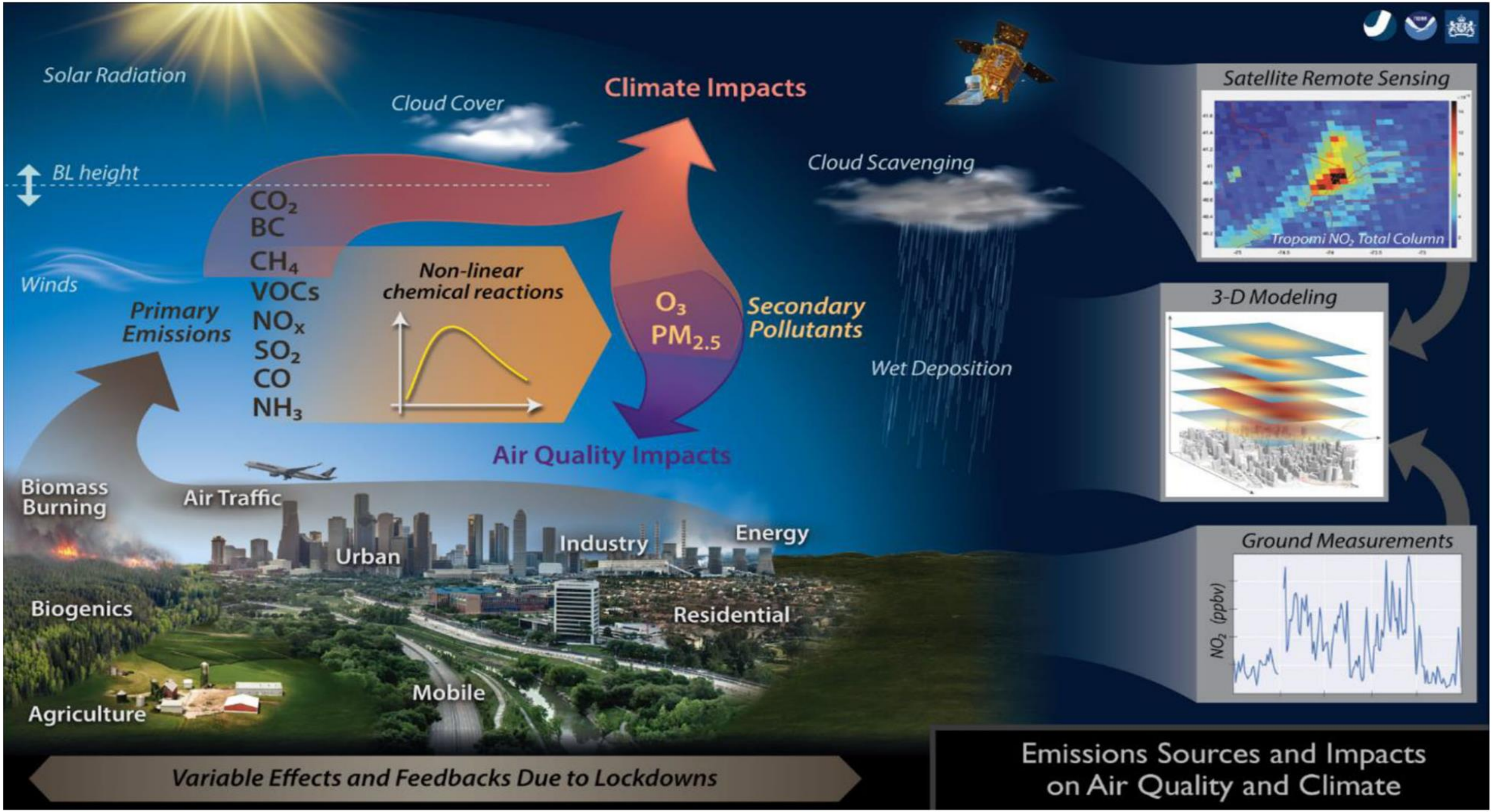


3. Predictability of Air Quality

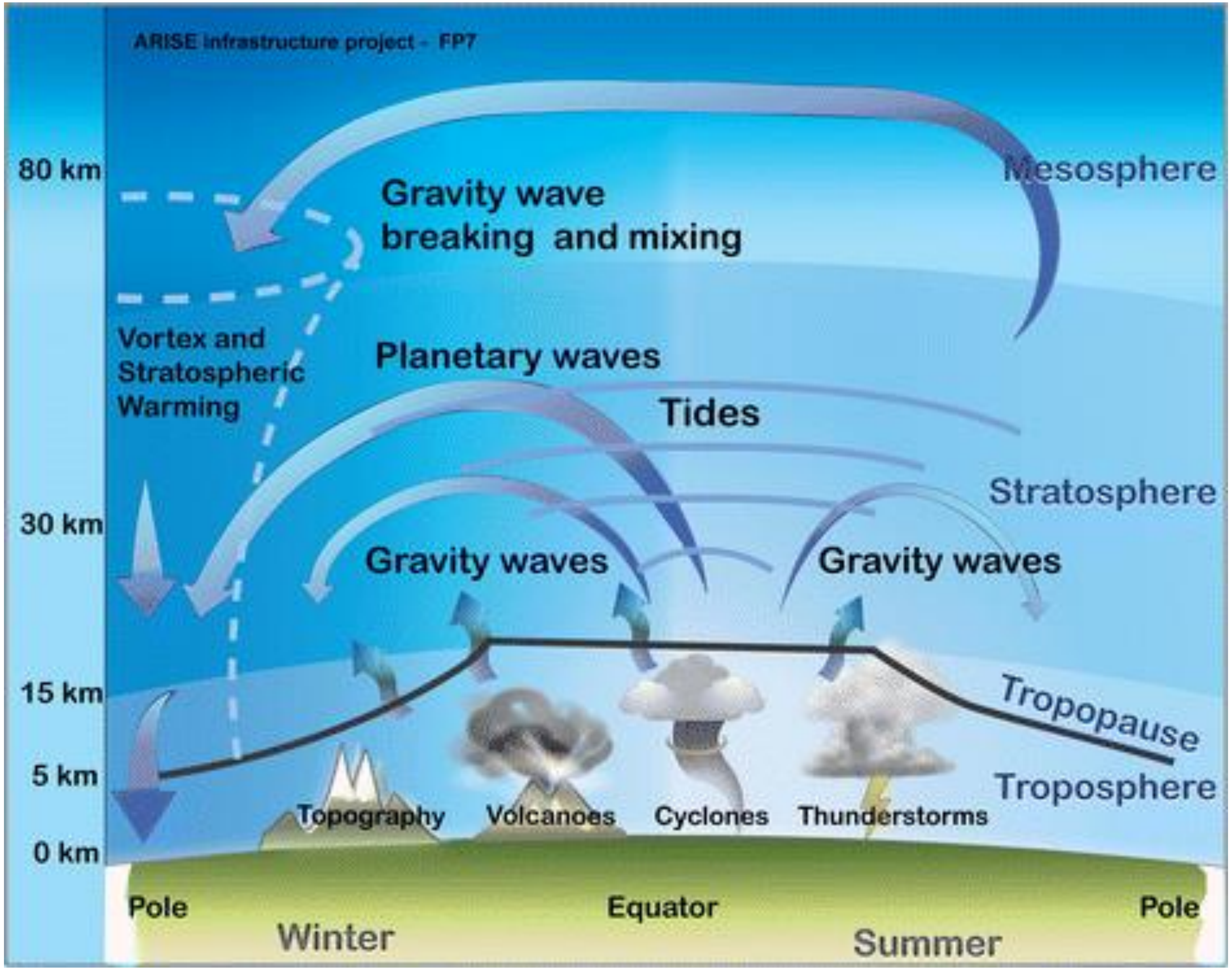
New York Times, 8 November 2017:

"A toxic cloud has descended on India's capital, delaying flights and trains, causing coughs, headaches and even … closing 4,000 schools for nearly a week."

Courtyard of the Jama Masjid mosque in Delhi
Sajjad Hussain/Agence France-Presse



Solar Radiation
Cloud Cover
Climate Impacts
BL height
CO2
BC
CH4
VOCs
NOx
SO2
CO
NH3
Winds
Primary Emissions
Non-linear chemical reactions
O3
PM2.5
Secondary Pollutants
Air Quality Impacts
Cloud Scavenging
Wet Deposition
Satellite Remote Sensing
Tropomi NO2 Total Column
3-D Modeling
Ground Measurements
NO2 (ppbv)
Biomass Burning
Air Traffic
Urban
Industry
Energy
Biogenics
Residential
Mobile
Agriculture
Variable Effects and Feedbacks Due to Lockdowns
Emissions Sources and Impacts on Air Quality and Climate

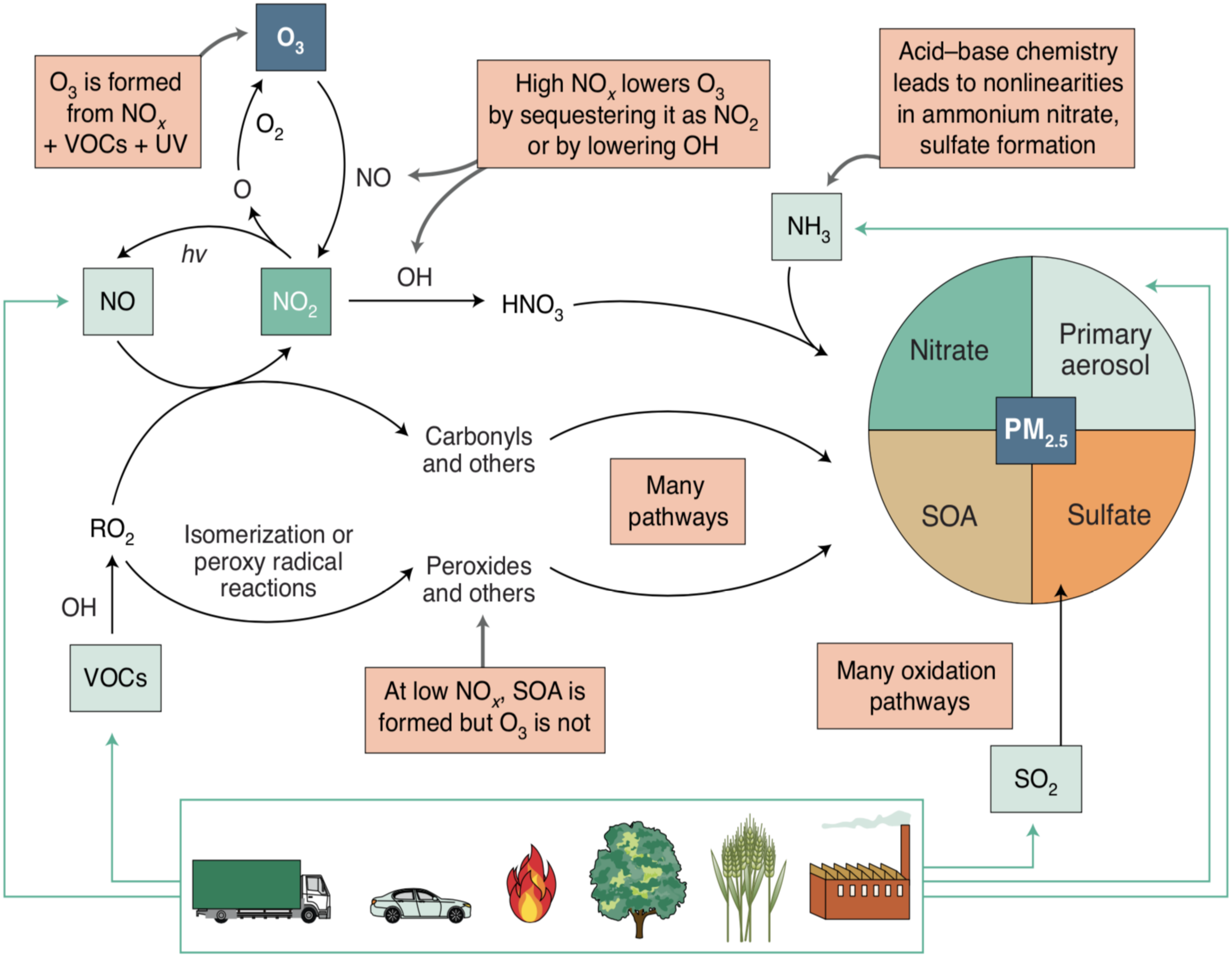


The complexity of the atmospheric dynamics: multi-scale problem

Investigation by the ARISE Project supported by the European Union

Simplified overview of the atmospheric chemistry of ozone and PM2.5.

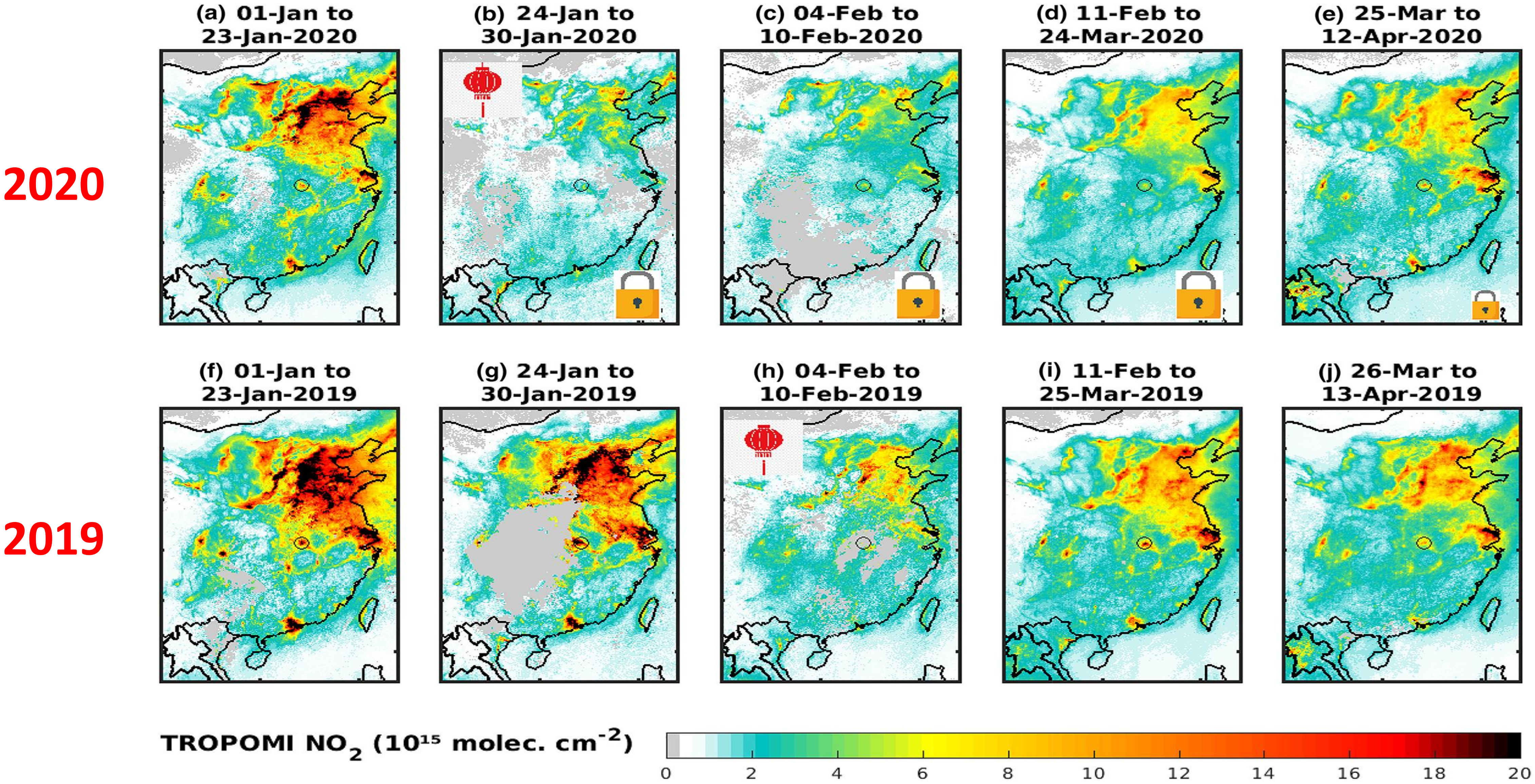
Kroll et al., Nature Chemistry September 2020



2020: A Gigantic and Unplanned Experiment

- We will now follow a gigantic worldwide experiment by which emissions of primary pollutants and greenhouse were severely reduced during several months.
  - First in China during the January-February lockdown
  - Second in the rest of the world during the March-April lockdown (first wave)
- We will analyze the adjustments of chemistry and specifically the changes in secondary species like ozone.
- This world-wide chemistry experiment mimics attempts to clean up the atmosphere from its pollutants. It should help us develop science-based policies towards better air quality.

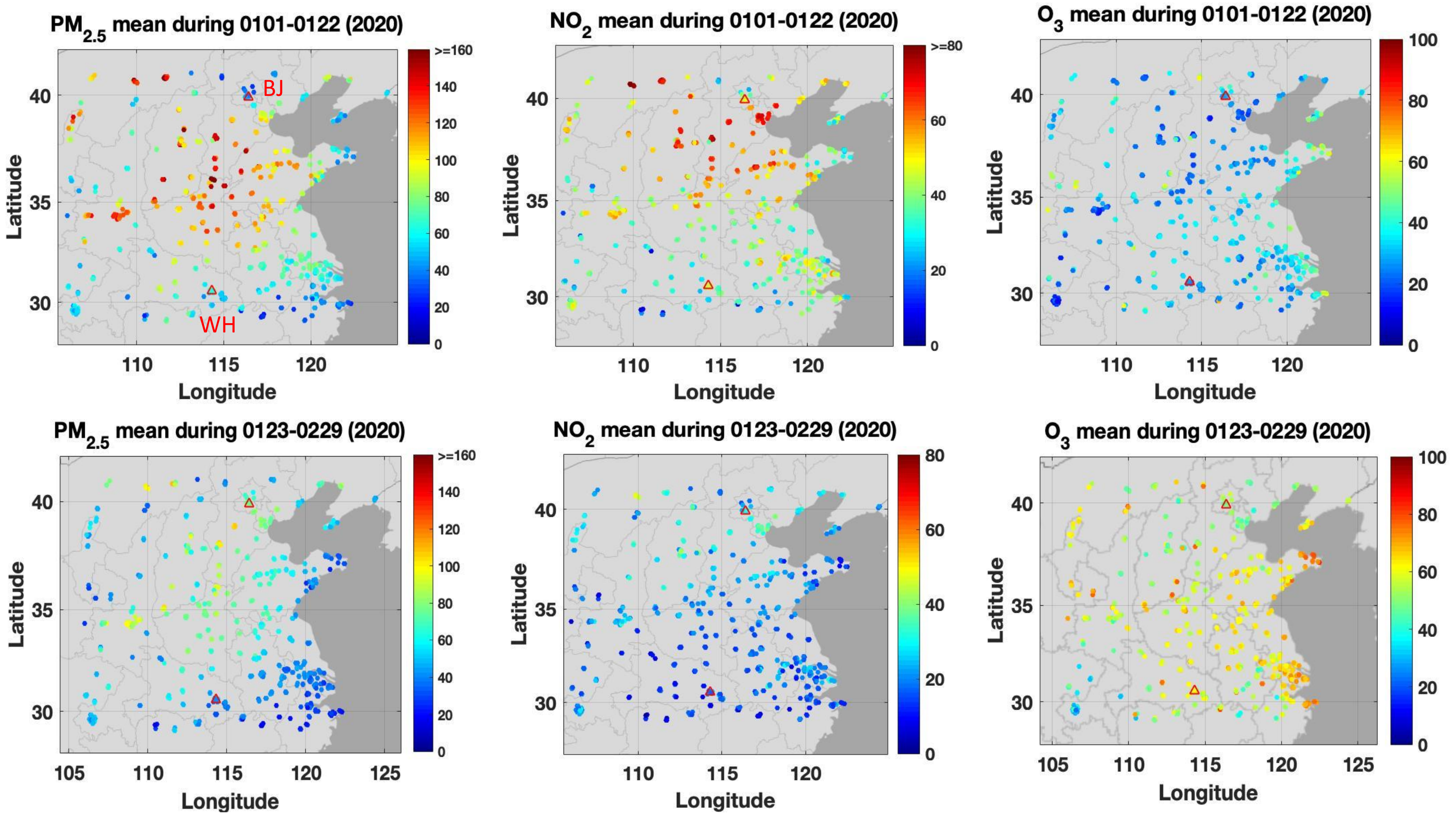
Impact of Coronavirus Outbreak on NO2 Pollution Assessed Using TROPOMI and OMI Observations



Geophysical Research Letters, Volume: 47, Issue: 11, First published: 08 May 2020, DOI: (10.1029/2020GL087978)

$PM_{2.5}$, NO_2 and O_3 in 2020 before and after the lockdown in China

$PM_{2.5}$ **NO_2** **ozone**



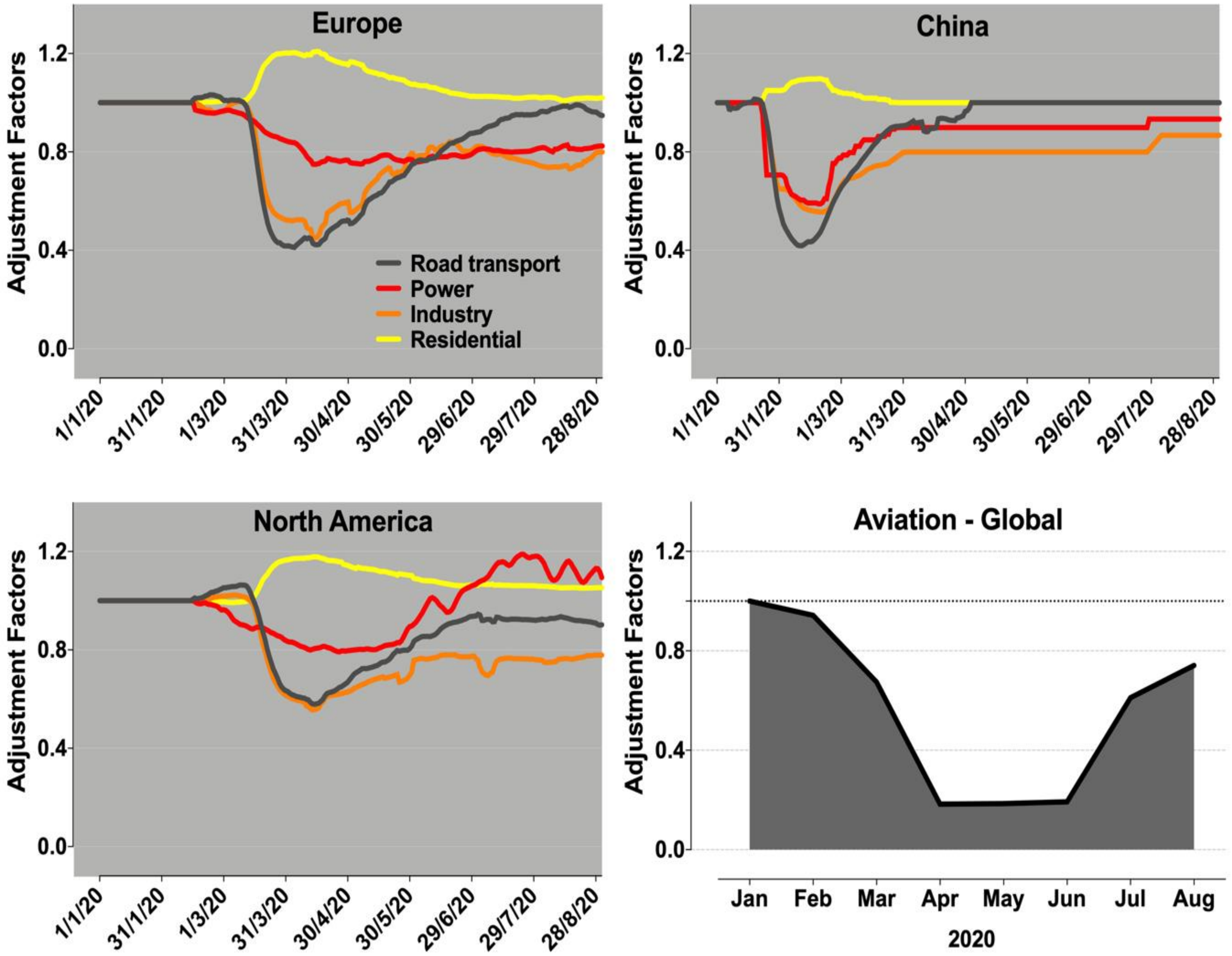
Before

1-22 January 2020

After

23 January to 29 February 2020

Shi and Brasseur, GRL, 2020

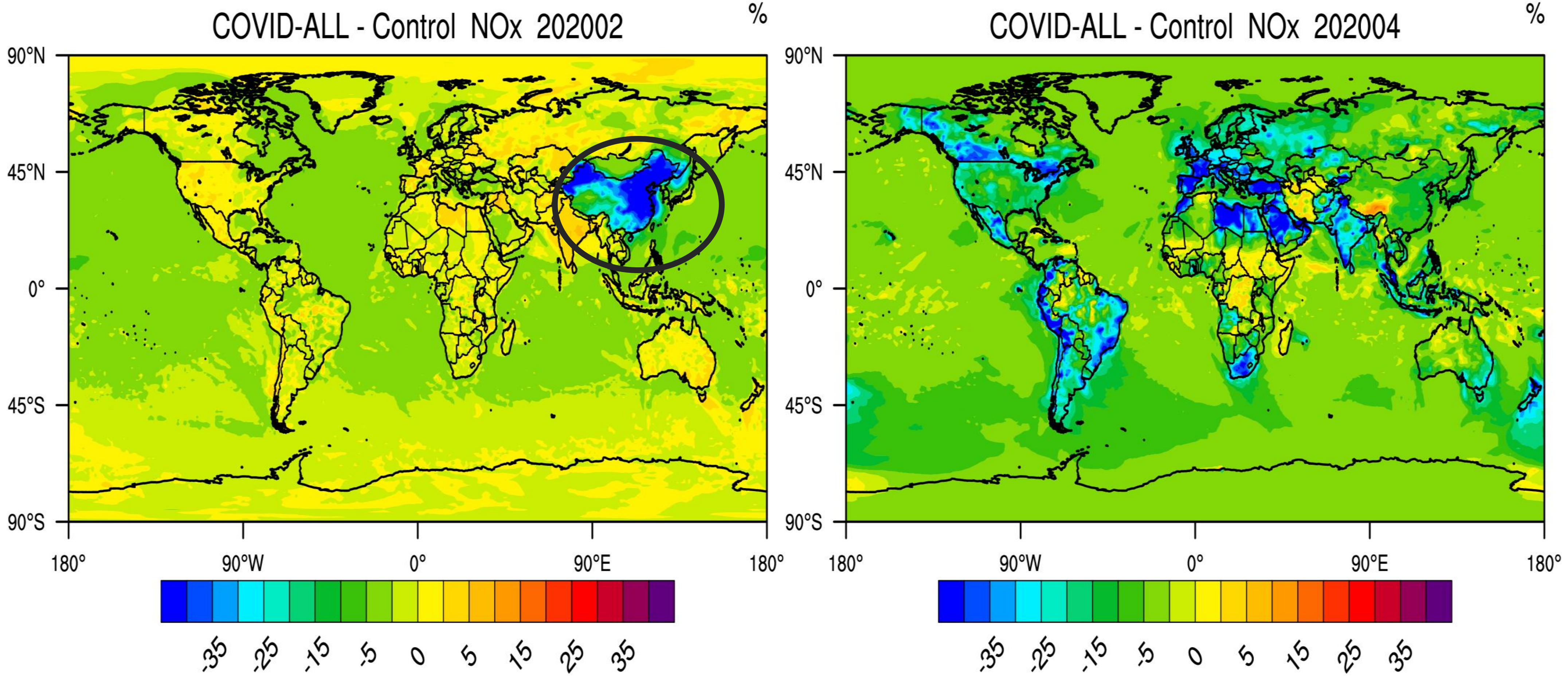


Change in Sector's Activities during COVID-19

Changes in Surface concentrations

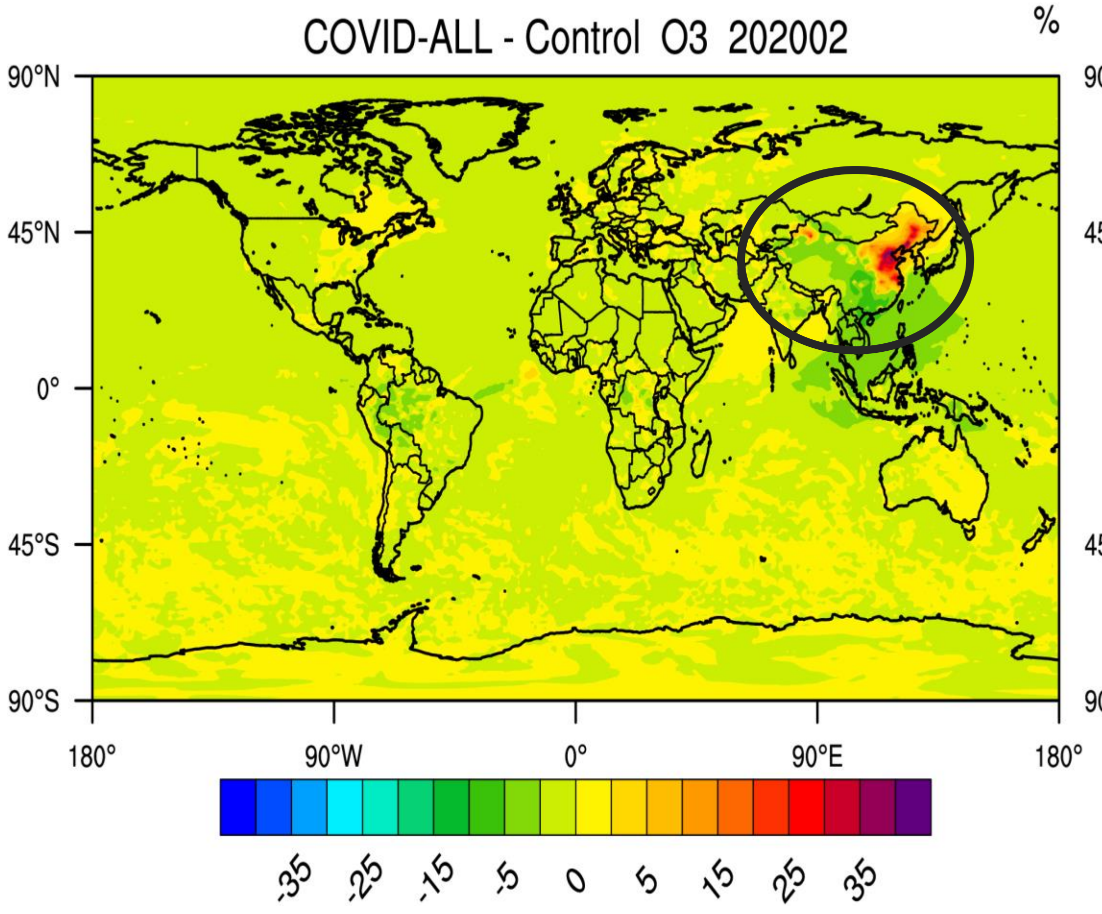
Percentage reduction in surface NOx relative to a case with "standard emissions"

February 2020 April 2020

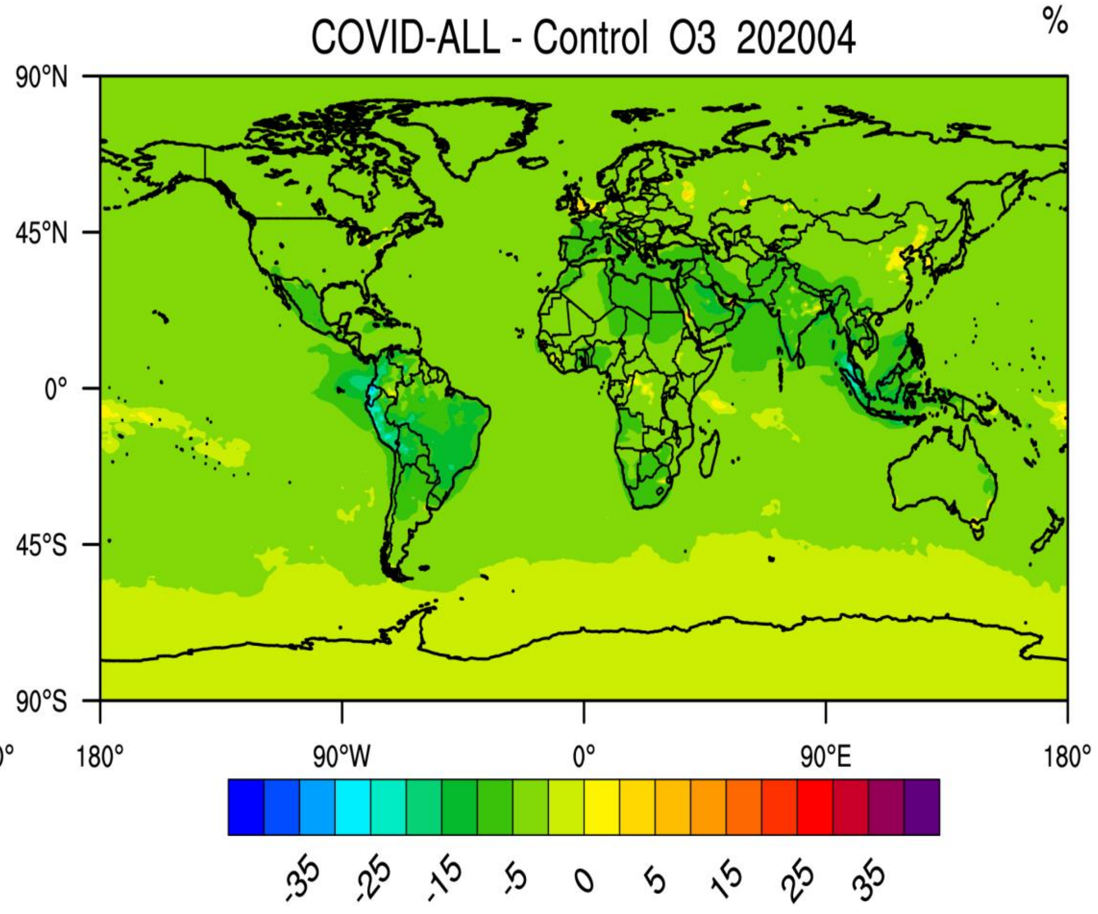


Percentage change in surface ozone relative to a case with “standard emissions”

February 2020

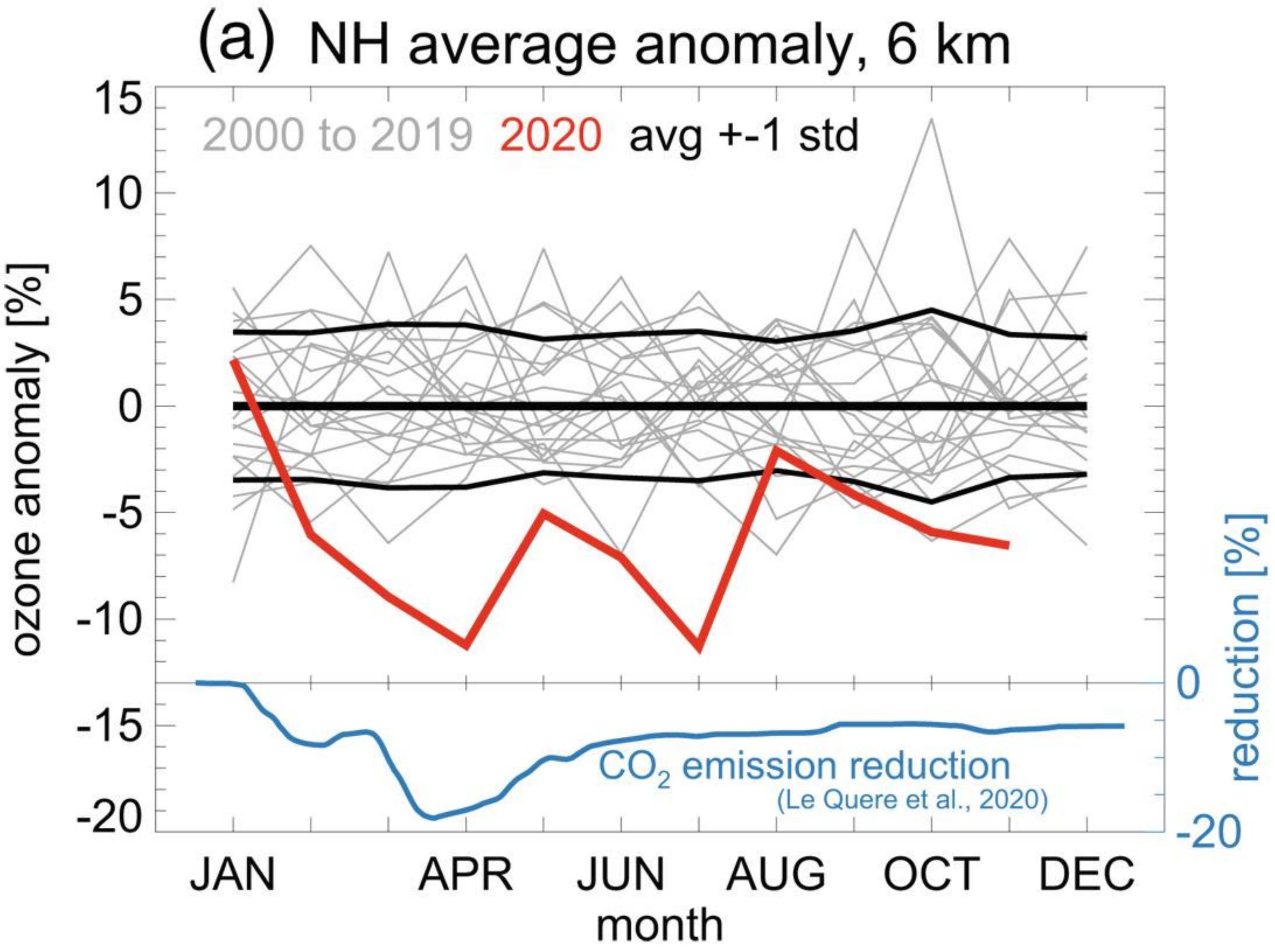


April 2020



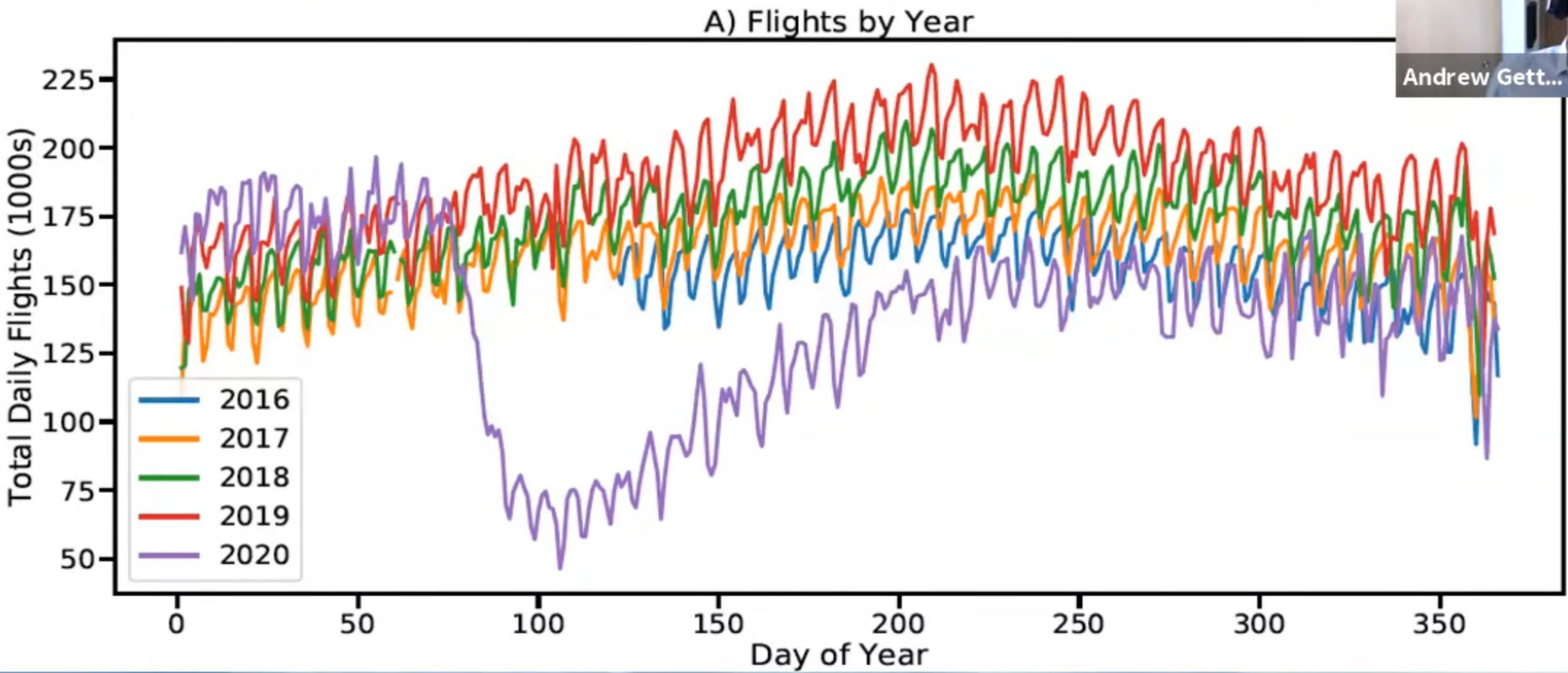
Changes in the Free Troposphere

Steinbrecht et al. report a large ozone reduction during the COVID-19 crisis



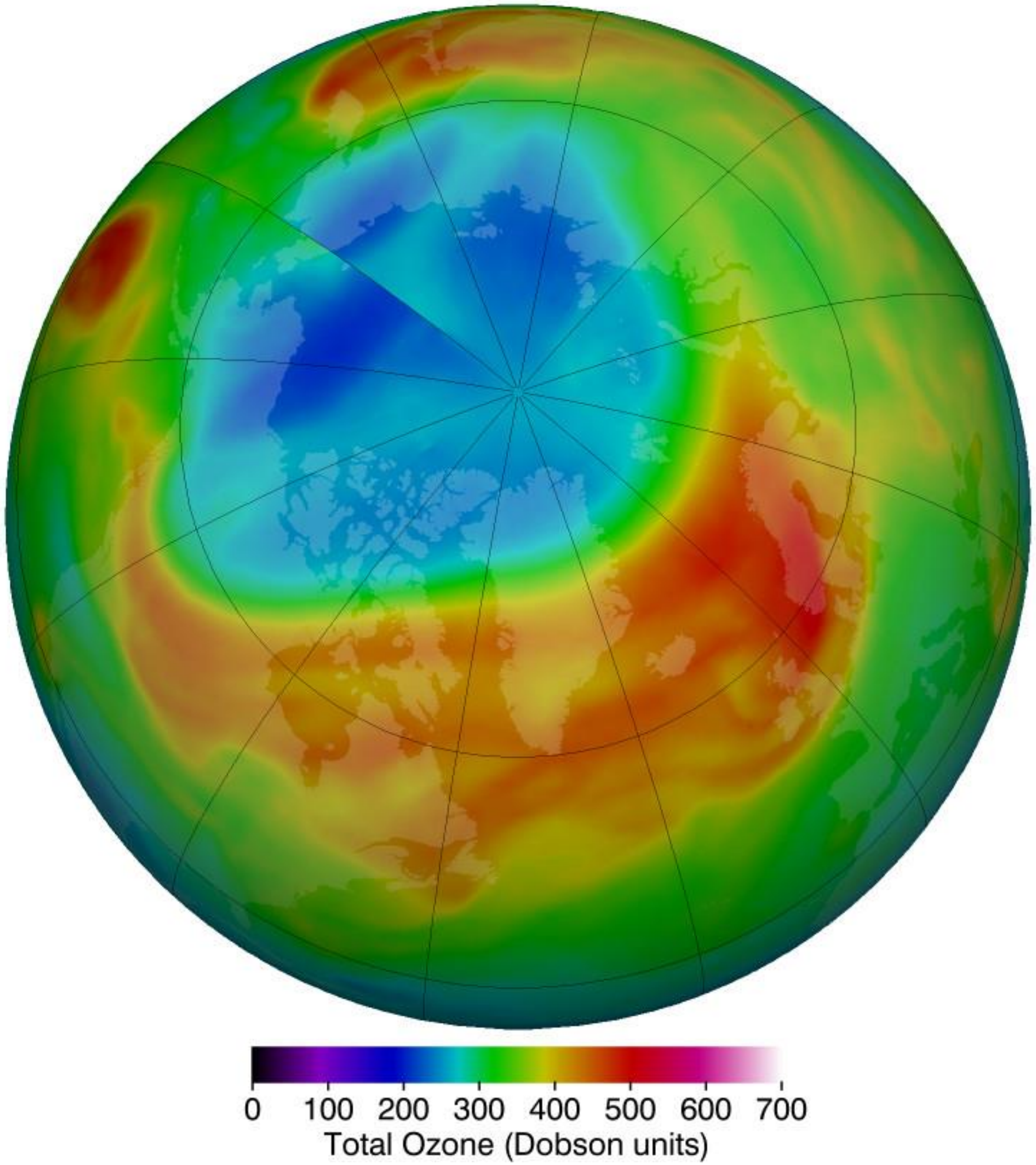
Potential forcing processes during 2020
(Free Troposphere)

1. Reduction in surface emissions due to reduced activities caused by COVOD-19
2. Reduction in aircraft emissions during the pandemic
3. Influence of the exceptionally large reduction in Arctic ozone in the lower stratosphere during March and April 2020 (“Arctic ozone hole”) associated with anomalous meteorology



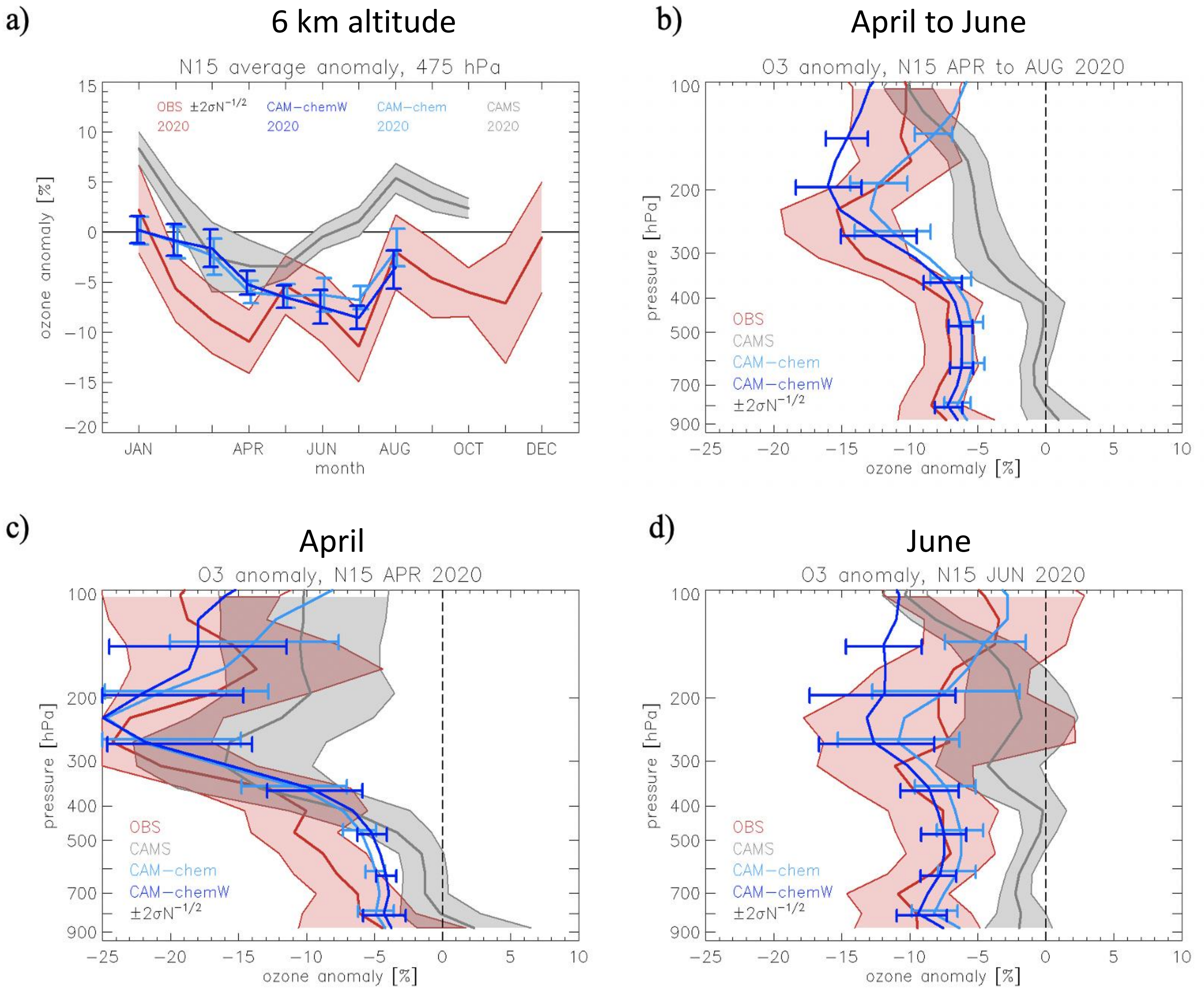
Gettelman et al 2021, ACP (in review)

Exceptional Arctic Ozone Hole in March-April 2020



2020 ozone anomaly north of 15 N

Comparison between observed data and different model simulations

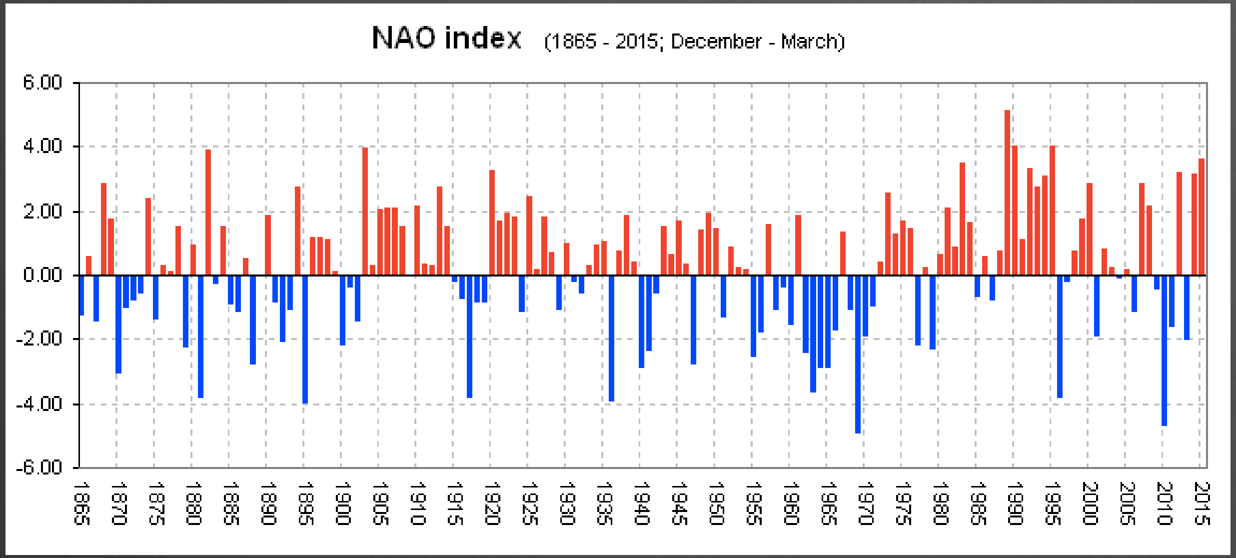


4. Challenges for the Future

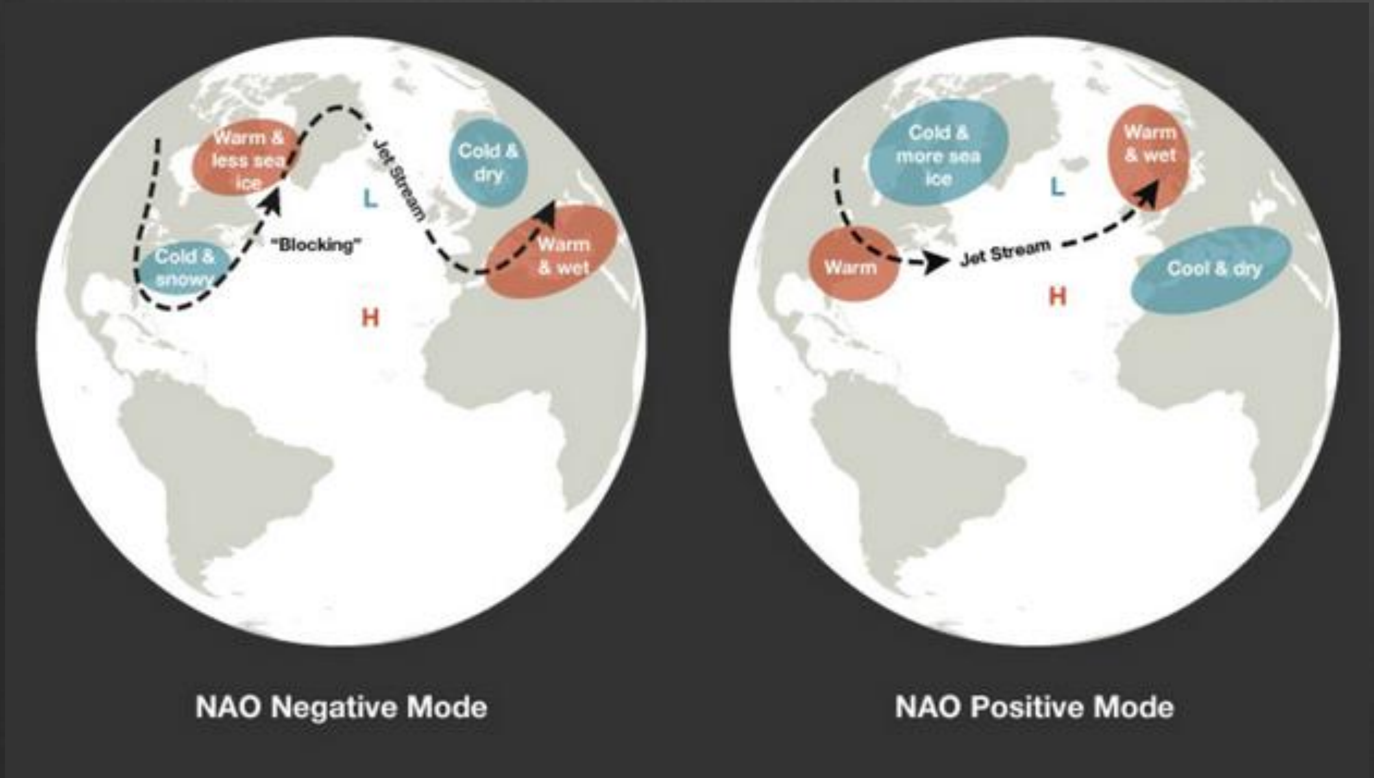
Seasonal to Decadal Climate Predictions

Patterns of Atmospheric Circulation Variability at Decadal Timescale

- El Niño-Southern Oscillation
- Pacific Decadal variability
- North Atlantic Oscillation and Northern Annular Mode
- Southern hemisphere and Southern Annular Mode
- Atlantic Multi-decadal Oscillation



The North Atlantic Oscillation (NAO)



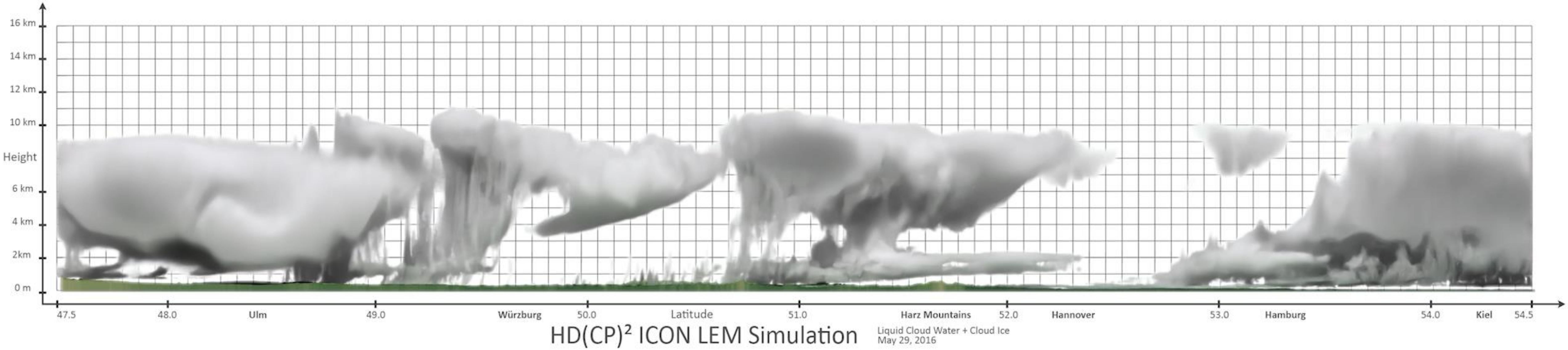
North Atlantic Oscillation (NAO) Index: Difference of normalised MSLP anomalies between Lisbon, Portugal and Stykkisholmur, Iceland

Sources of Predictability for Decadal Climate Variations

- **External Forcing:**
  - Greenhouse gas emissions (global importance)
  - Aerosols (regional importance)
  - Changes in solar irradiance (11-year cycle)
  - Volcanic eruptions ("wild card")
- **Natural Internal Variability**
  - Slowly evolving modes of variability of the ocean
  - Long-term persistence of certain physical and biogeochemical processes
  - Initial state of climate components must be accurately known (less critical for the atmosphere)

For seasonal forecasts: sea surface temperature, sea ice extent, upper ocean heat content, soil moisture, snow cover, state of surface vegetation, state of the stratosphere are important.

High-resolution Representation of Atmospheric Physics in Earth System Models

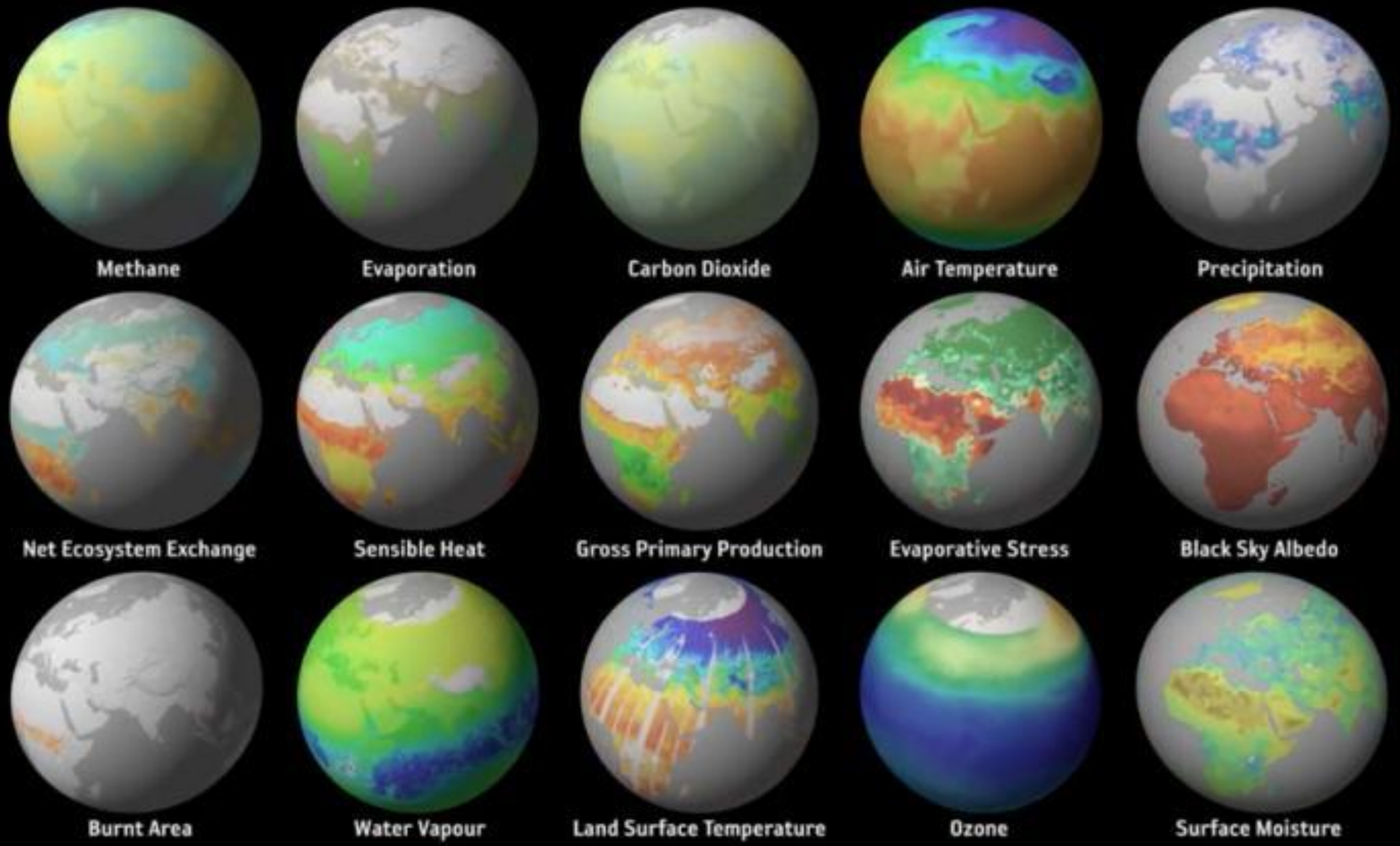

16 km
14 km
12 km
10 km
Height
6 km
4 km
2km
0 m
47.5
48.0
Ulm
49.0
Würzburg
50.0
Latitude
51.0
Harz Mountains
52.0
Hannover
53.0
Hamburg
54.0
Kiel
54.5
HD(CP)² ICON LEM Simulation
Liquid Cloud Water + Cloud Ice
May 29, 2016

X

Implement Artificial Intelligence for Improving Predictions

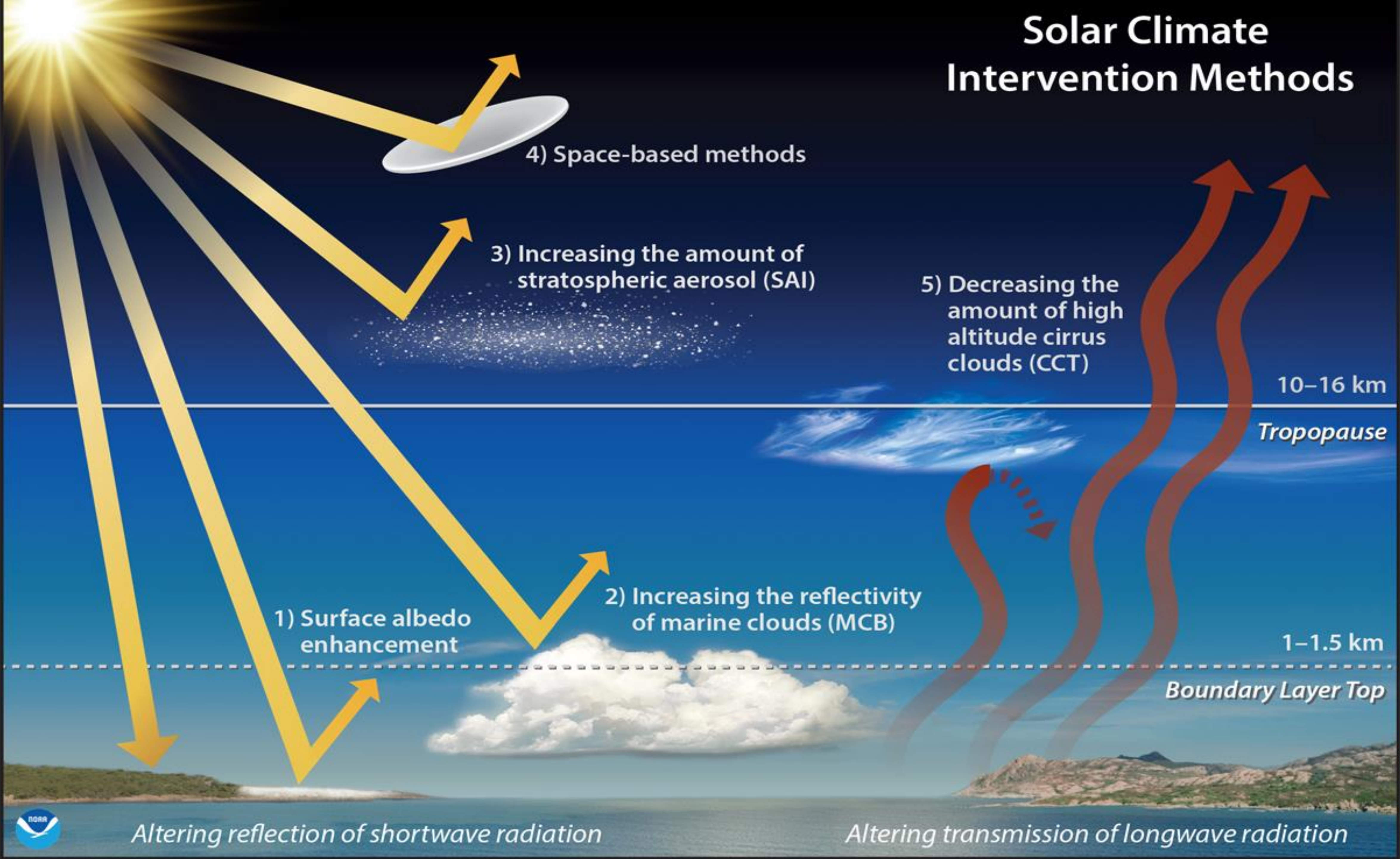
Improve Predictions by Machine Learning

- The field of machine learning enables breakthroughs in the detection and analysis of complex relationships and patterns in large multivariate datasets.
- Machine learning algorithms will allow
  - (1) to enhance Earth observation datasets accounting for spatio-temporal covariations, and
  - (2) to develop machine-learning-based parameterizations and sub-models for clouds and land-surface processes that have hindered progress in climate modeling for decades.


Methane
Evaporation
Carbon Dioxide
Air Temperature
Precipitation
Net Ecosystem Exchange
Sensible Heat
Gross Primary Production
Evaporative Stress
Black Sky Albedo
Burnt Area
Water Vapour
Land Surface Temperature
Ozone
Surface Moisture

Climate Intervention

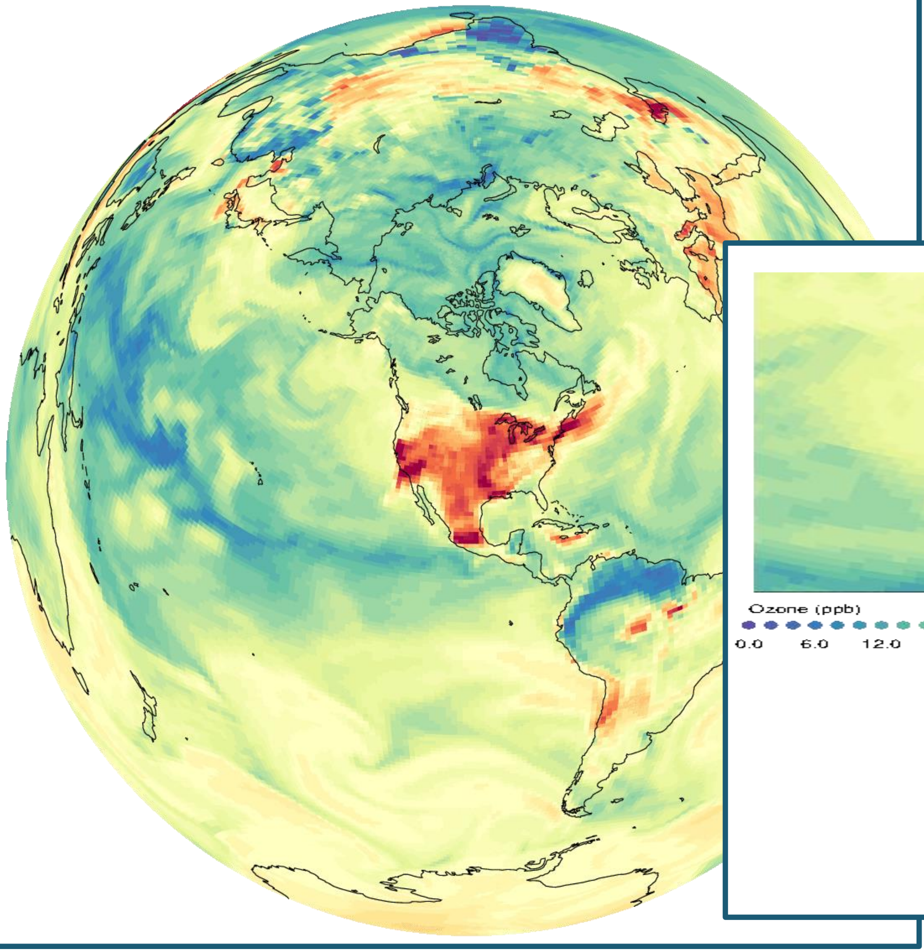
- While efforts to reduce emissions and adapt to climate impacts are the first line of defense, researchers are exploring other options to reduce warming.
- Solar geoengineering strategies are designed to cool Earth either by adding small reflective particles to the upper atmosphere, by increasing reflective cloud cover in the lower atmosphere, or by thinning high-altitude clouds that can absorb heat.
- While such strategies have the potential to reduce global temperatures, they could also introduce an array of unknown or negative consequences.


Solar Climate
Intervention Methods
4) Space-based methods
3) Increasing the amount of
stratospheric aerosol (SAI)
5) Decreasing the
amount of high
altitude cirrus
clouds (CCT)
10–16 km
Tropopause
2) Increasing the reflectivity
of marine clouds (MCB)
1) Surface albedo
enhancement
1–1.5 km
Boundary Layer Top
Altering reflection of shortwave radiation
Altering transmission of longwave radiation

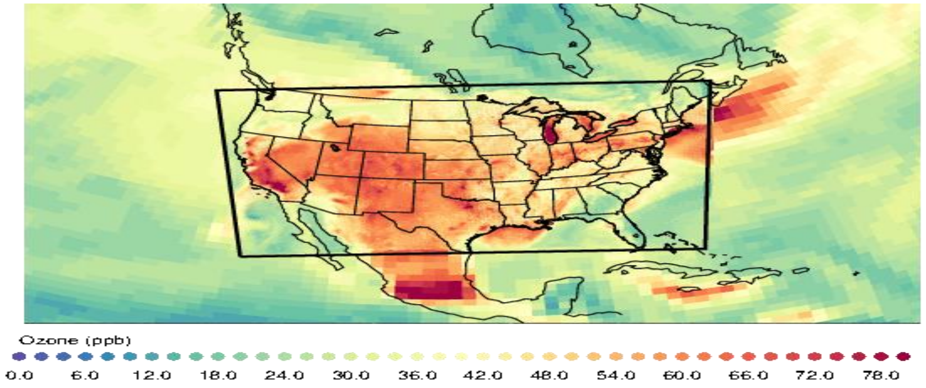
Air Quality Analysis and Forecasts

Current Air Quality Predictions

Global Prediction, ~100km resolution



Regional Prediction, 12km resolution

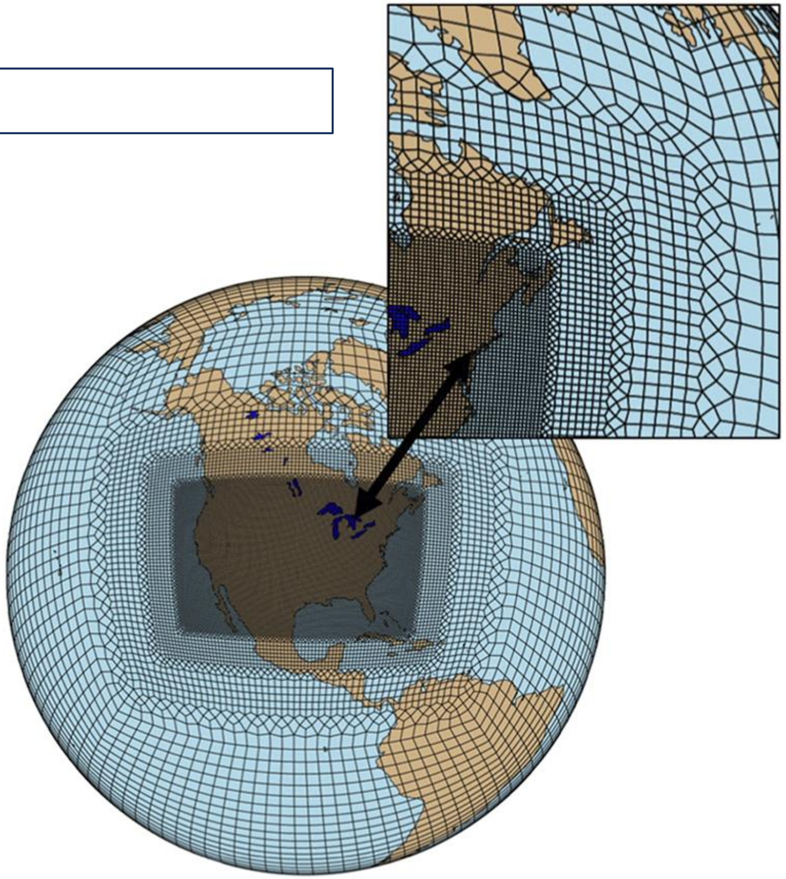


Ozone (ppb)

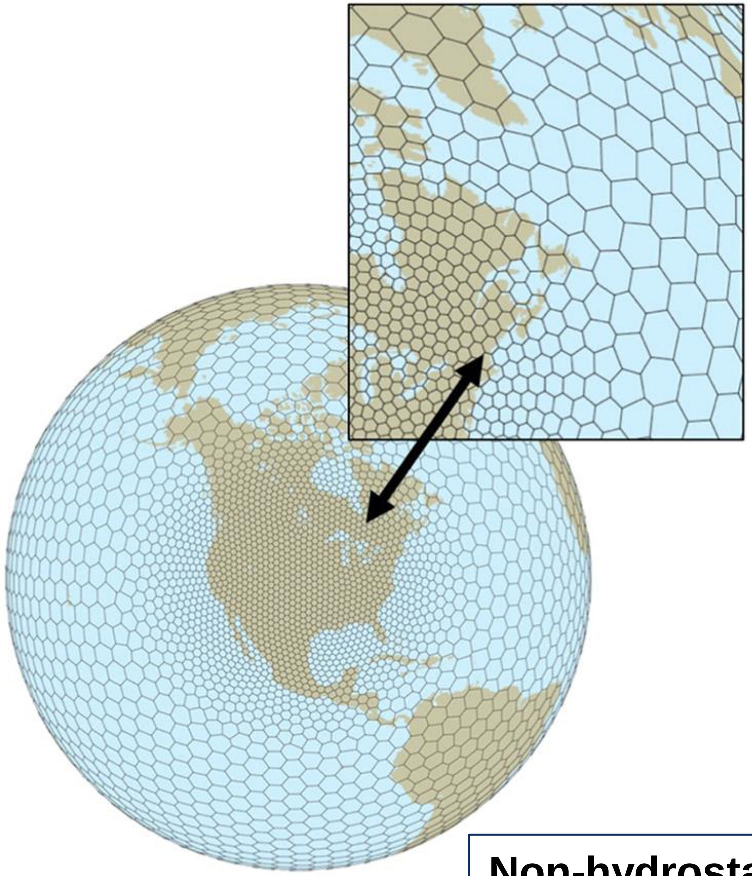
https://www2.acom.ucar.edu/acresp/forecasts-and-near-real-time-nrt-products

MUSICA – Current variable resolution choices

Spectral Element (cubed sphere)



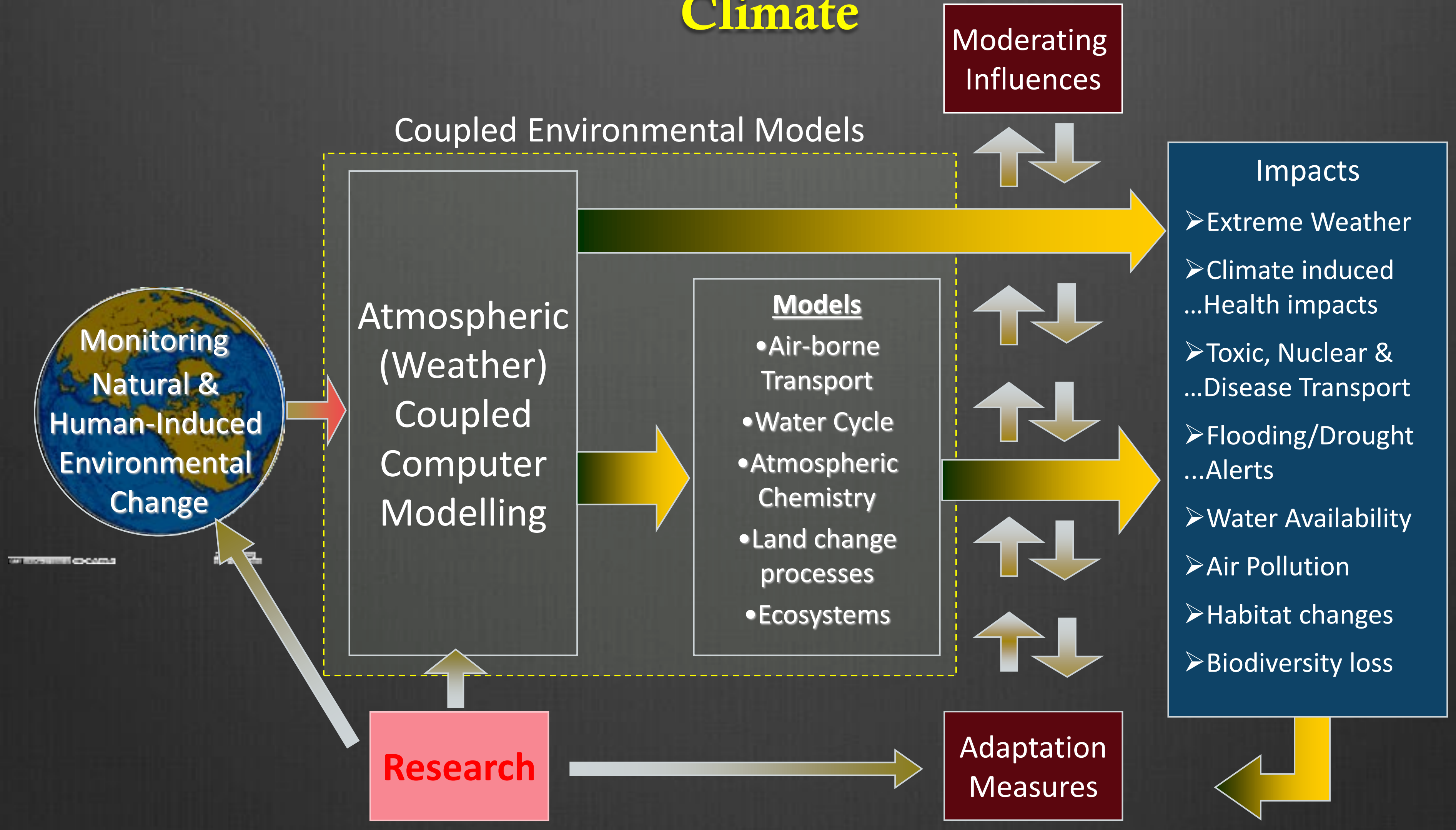
MPAS (hexagonal mesh)



Non-hydrostatic allowing for finer scales

5. Conclusions

Overarching Research Need: Improve Prediction Capabilities via Incorporating/Integrating Composition, Weather and Climate



Across Relevant Temporal and Spatial Scales


Thank You
Enhancing adaptive capacity for society
in the context of changing weather and climate