Tropospheric Ozone in the United Kingdom Chemistry and Aerosols (UKCA) model

Paul Griffiths

Cambridge University and NCAS Climate

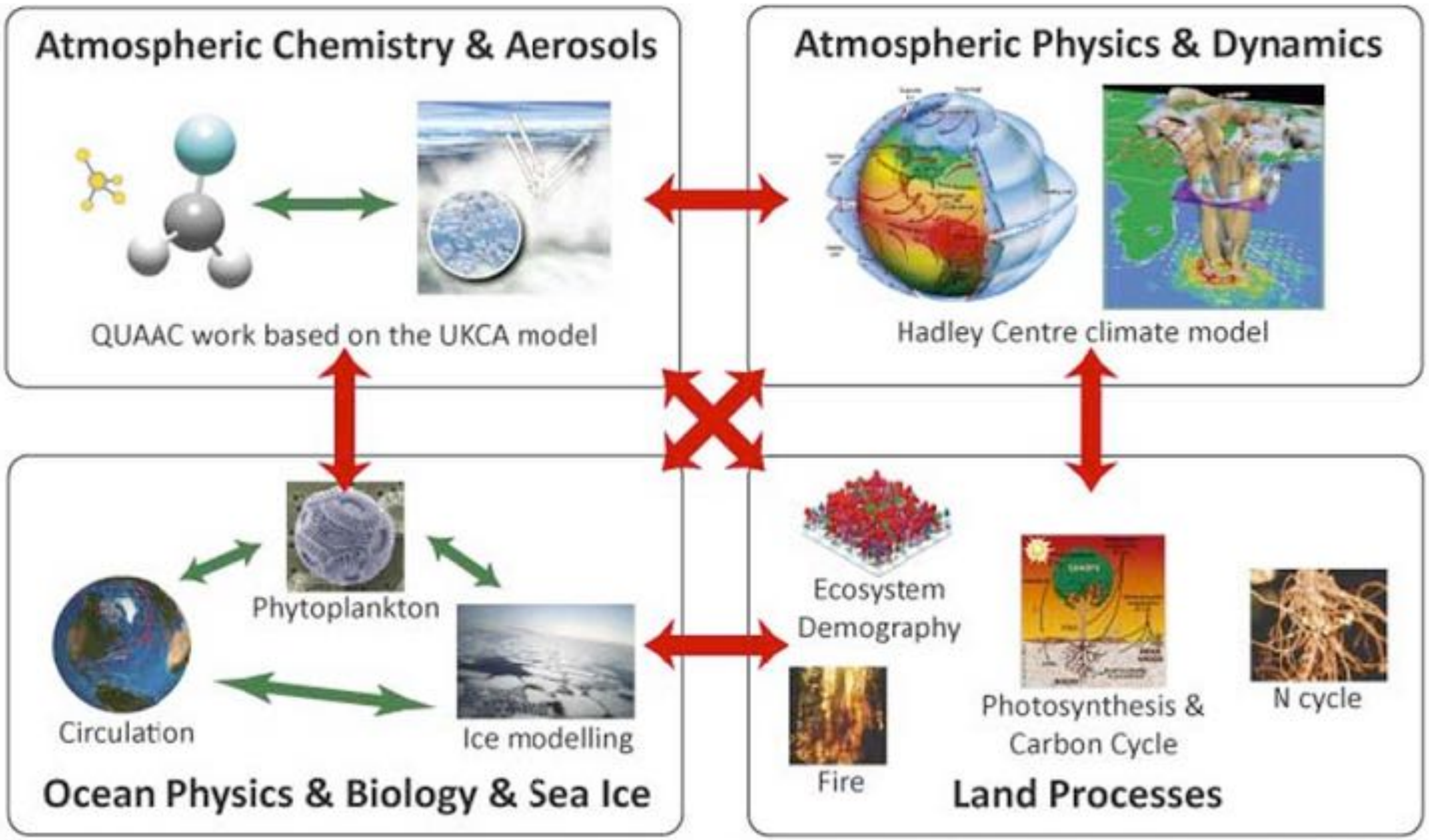
Visiting Scientist, NARIT, Thailand

Talk outline

- **Ozone in the troposphere**
  - Is formed from Volatile Organic Compounds (VOC) and nitrogen oxide emissions
  - Is a non-linear system
  - Large levels of NOx cause a decrease in ozone production
- **The UKCA model and what it says about ozone in the present day**
  - Where are **regions** of **ozone production** and **destruction**?
  - How **accurate** are UKCA predictions of **ozone**?
- **Using UKCA to examine how ozone may change in future**
  - **Anthropogenic emissions** of NOx and VOC change
  - Land is used differently - **deforestation changes biogenic** (natural) **emissions**

UK Chemistry and Aerosols project (UKCA)

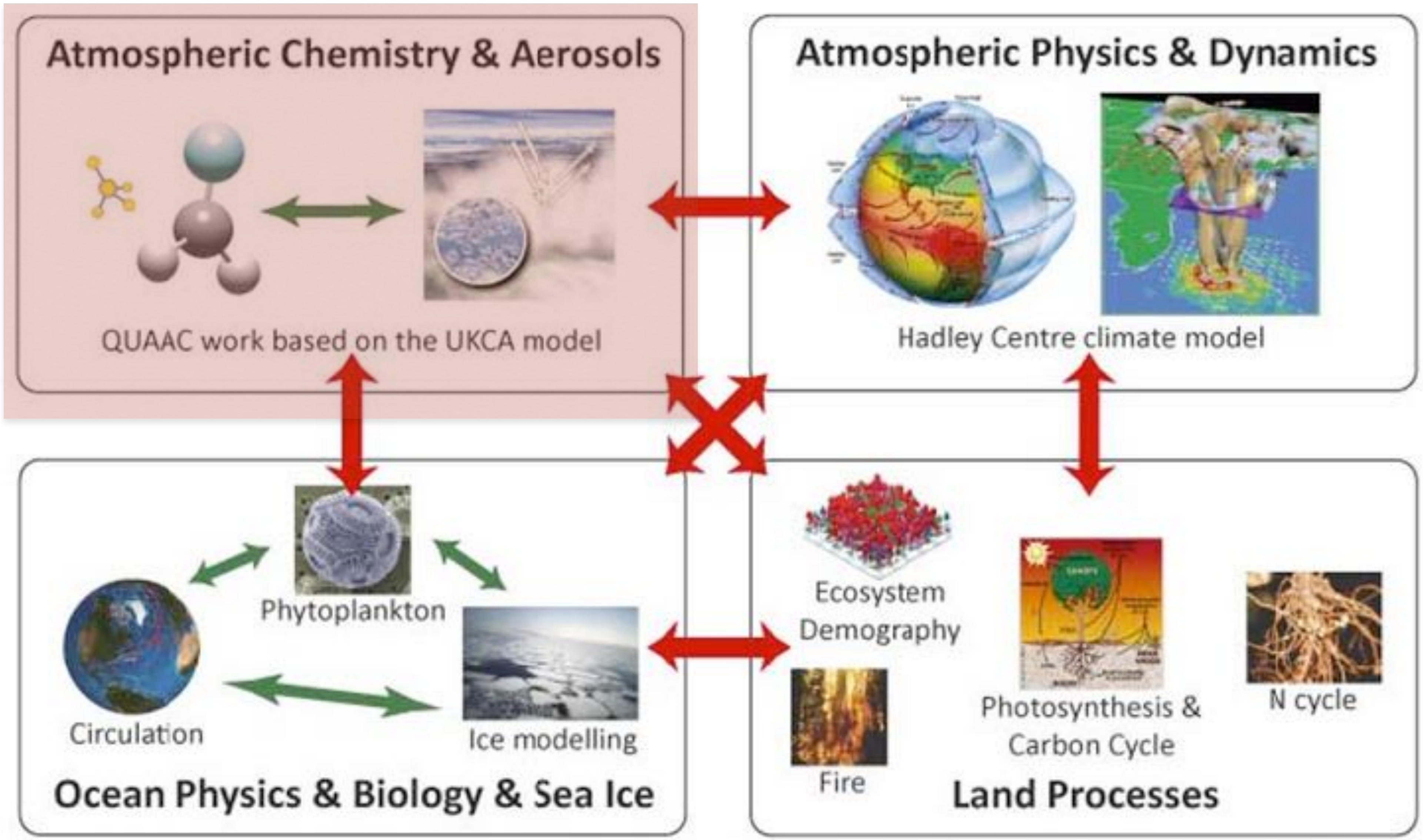
Model components of Earth System



Earth system modelling within QUEST. Based on a diagram by M. Joshi

- UK Met Office Unified Model (UM) is a weather forecast model run in climate mode - basis for HadGEM/HadES models, next generation UK-ESM1
- Online chemistry - feedbacks between atmospheric composition, radiation and transport

Model components of Earth System



Earth system modelling within QUEST. Based on a diagram by M. Joshi

- UK Met Office Unified Model (UM) is a weather forecast model run in climate mode - basis for HadGEM/HadES models, next generation UK-ESM1
- Online chemistry - feedbacks between atmospheric composition, radiation and transport

Ozone in the troposphere

Ozone in the troposphere

- To a chemist, **the atmosphere is an oxidizing environment**
- **Pollution** released into the atmosphere **is slowly degraded by oxidation**
- Viewed a certain way, **the atmosphere is a low temperature combustion system.**
- **Volatile organic compounds are transformed into CO_2**
  - $VOC + O_2 \rightarrow CO_2 + H_2O$
  - **Ozone is can be produced or destroyed during this process**
  - **Ozone affects other pollutants, e.g. NO_2**
- **Ozone**
  - A key component of UK Air Quality
  - Implications for health

Ozone from a chemist's perspective - about in situ production/loss

$$
\begin{aligned}
O_3 + h\nu(\lambda < 310\mathrm{nm}) &\rightarrow O_2 + O^1D \\
O^1D + H_2O &\rightarrow 2OH \\
OH + VOC &\rightarrow RO_2 + H_2O \\
RO_2 + NO &\rightarrow NO_2 + RO \\
NO_2 + h\nu + O_2 &\rightarrow\rightarrow O_3 + NO
\end{aligned}
$$

- Local or regional emissions of **volatile organic compounds** (VOC)
- VOC can have industrial or natural sources.
- React with oxidant OH to make **peroxy radicals**, RO2
- Peroxy radicals, **RO2** react with local or regional emissions of **NO** to make **NO2**
- NO2 is **photolysed** rapidly to **make ozone**
- **More ozone is produced than is consumed = ozone production**
- **Ozone production requires sunlight, VOC and NO**

Ozone from a chemist's perspective - about in situ production/loss

Primary pollutants, local emissions

$$
\begin{aligned}
O_3 + h\nu(\lambda < 310\mathrm{nm}) &\rightarrow O_2 + O^1D \\
O^1D + H_2O &\rightarrow 2OH \\
OH + \boxed{VOC} &\rightarrow RO_2 + H_2O \\
RO_2 + \boxed{NO} &\rightarrow NO_2 + RO \\
NO_2 + h\nu + O_2 &\rightarrow\rightarrow O_3 + NO
\end{aligned}
$$

- Local or regional emissions of **volatile organic compounds** (VOC)
- VOC can have industrial or natural sources.
- React with oxidant OH to make **peroxy radicals**, RO2
- Peroxy radicals, **RO2** react with local or regional emissions of **NO** to make **NO2**
- NO2 is **photolysed** rapidly to **make ozone**
- **More ozone is produced than is consumed = ozone production**
- **Ozone production requires sunlight, VOC and NO**

Ozone from a chemist's perspective - cycle of O3 production

$$
\begin{aligned}
\boxed{O_3} + h\nu(\lambda < 310\mathrm{nm}) &\rightarrow O_2 + O^1D \\
O^1D + H_2O &\rightarrow 2OH \\
OH + VOC &\rightarrow RO_2 + H_2O \\
RO_2 + NO &\rightarrow NO_2 + RO \\
NO_2 + h\nu + O_2 &\rightarrow \boxed{O_3} + NO
\end{aligned}
$$

Ozone is regenerated and amplified

- Ozone **initiates** and is the **product** of this chemistry.

- When NO and VOC present in sufficient concentration, **more ozone is produced than is consumed = ozone production**

- **Ozone production requires sunlight, VOC and NO**

- **OH product affects lifetime of CH_4**

Ozone from a chemist's perspective - cycle of O3 production

$$
\begin{aligned}
O_3 + h\nu(\lambda < 310\text{nm}) &\rightarrow O_2 + O^1D \\
O^1D + H_2O &\rightarrow \boxed{2OH} \\
OH + VOC &\rightarrow RO_2 + H_2O \\
RO_2 + NO &\rightarrow NO_2 + RO \\
NO_2 + h\nu + O_2 &\rightarrow\rightarrow O_3 + NO
\end{aligned}
$$

- Ozone **initiates** and is the **product** of this chemistry.
- When NO and VOC present in sufficient concentration, **more ozone is produced than is consumed = ozone production**
- **Ozone production requires sunlight, VOC and NO**
- **OH product affects lifetime of CH_4**

Ozone from a chemist's perspective - cycle of O3 production

$$
\begin{aligned}
O_3 + h\nu(\lambda < 310\mathrm{nm}) &\rightarrow O_2 + O^1D \\
O^1D + H_2O &\rightarrow \boxed{2OH} \\
OH + VOC &\rightarrow RO_2 + H_2O \\
RO_2 + NO &\rightarrow NO_2 + RO \\
NO_2 + h\nu + O_2 &\rightarrow O_3 + NO
\end{aligned}
$$

More info on Friday at 0930 !!

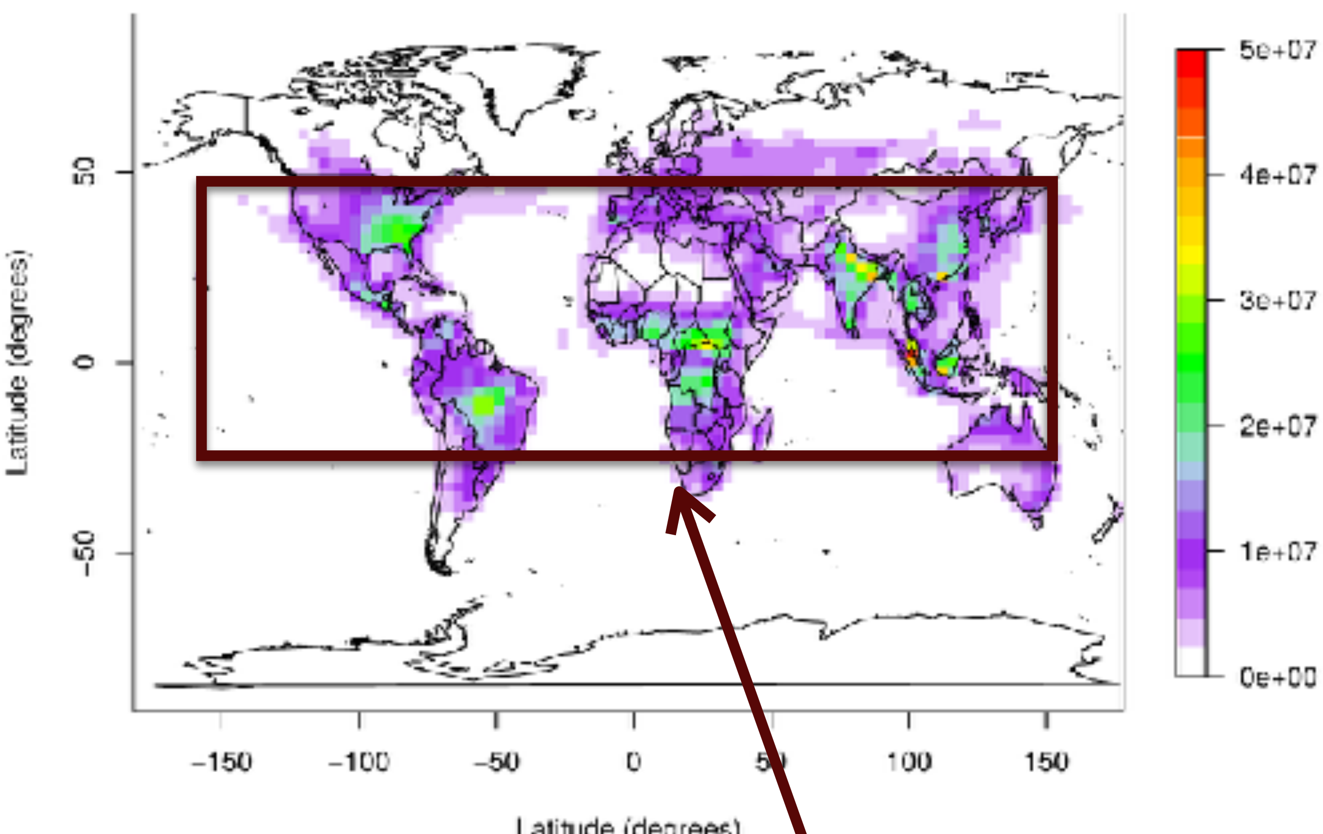
- Ozone **initiates** and is the **product** of this chemistry.
- When NO and VOC present in sufficient concentration, **more ozone is produced than is consumed = ozone production**
- **Ozone production requires sunlight, VOC and NO**
- **OH product affects lifetime of CH_4**

Ozone in the troposphere

Ozone production in UKCA: ozone production/loss

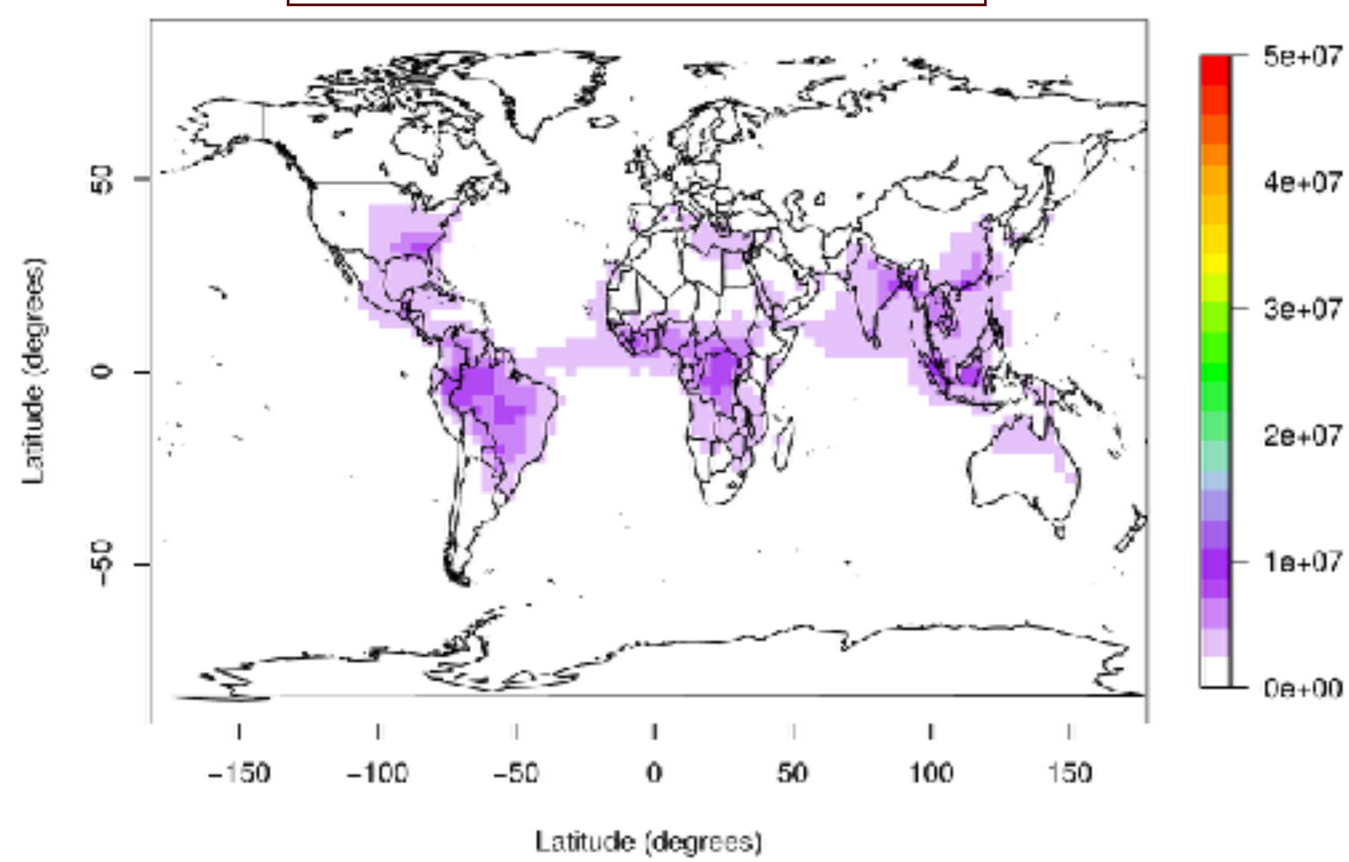
- Ozone is **produced close to the surface** via VOC oxidation
- Some ozone is lost via deposition to the surface (dry deposition)
- Regions with high NOx may not produce as much ozone

Ozone production at surface



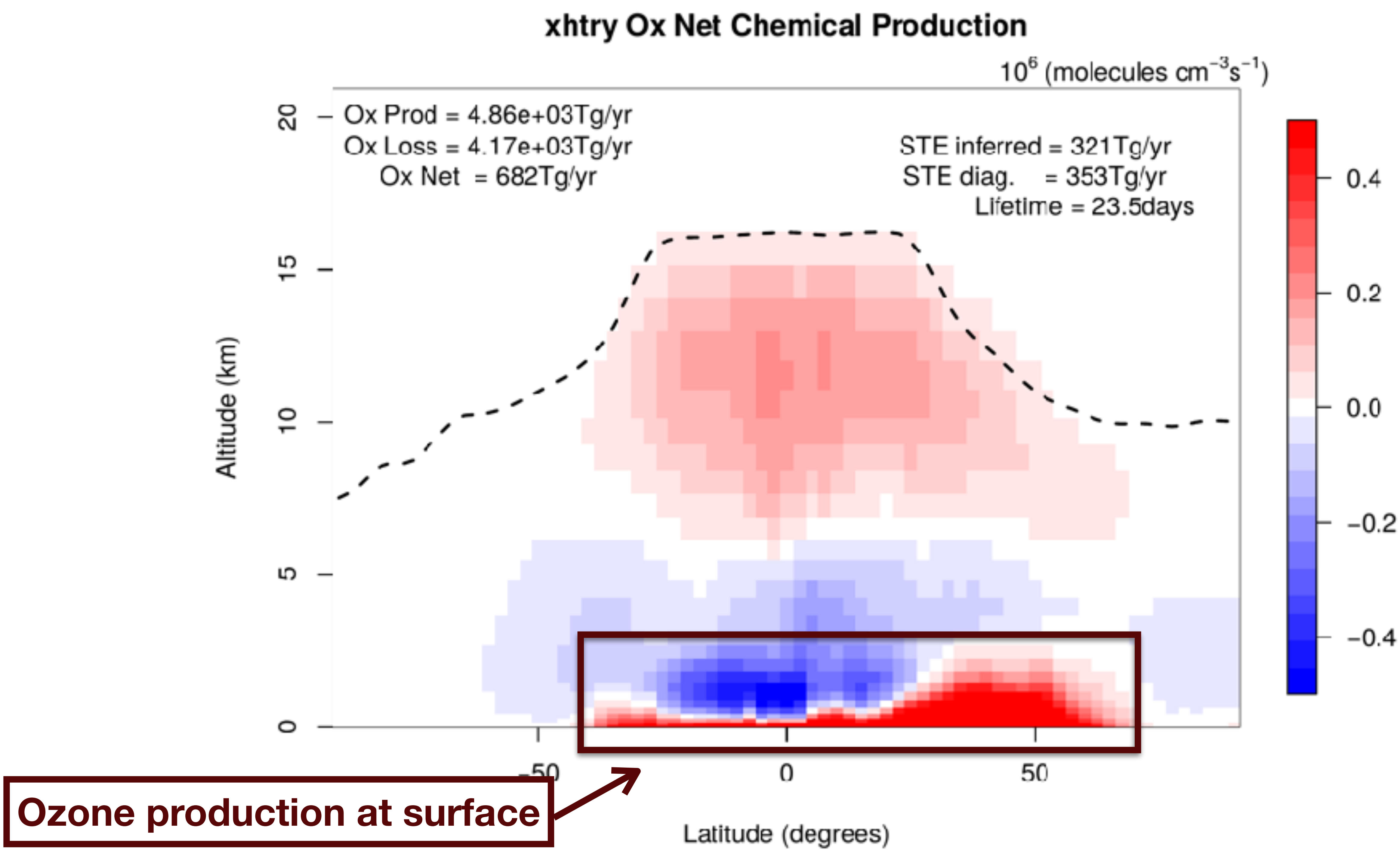
Ozone production in and near to tropics

Ozone loss at surface

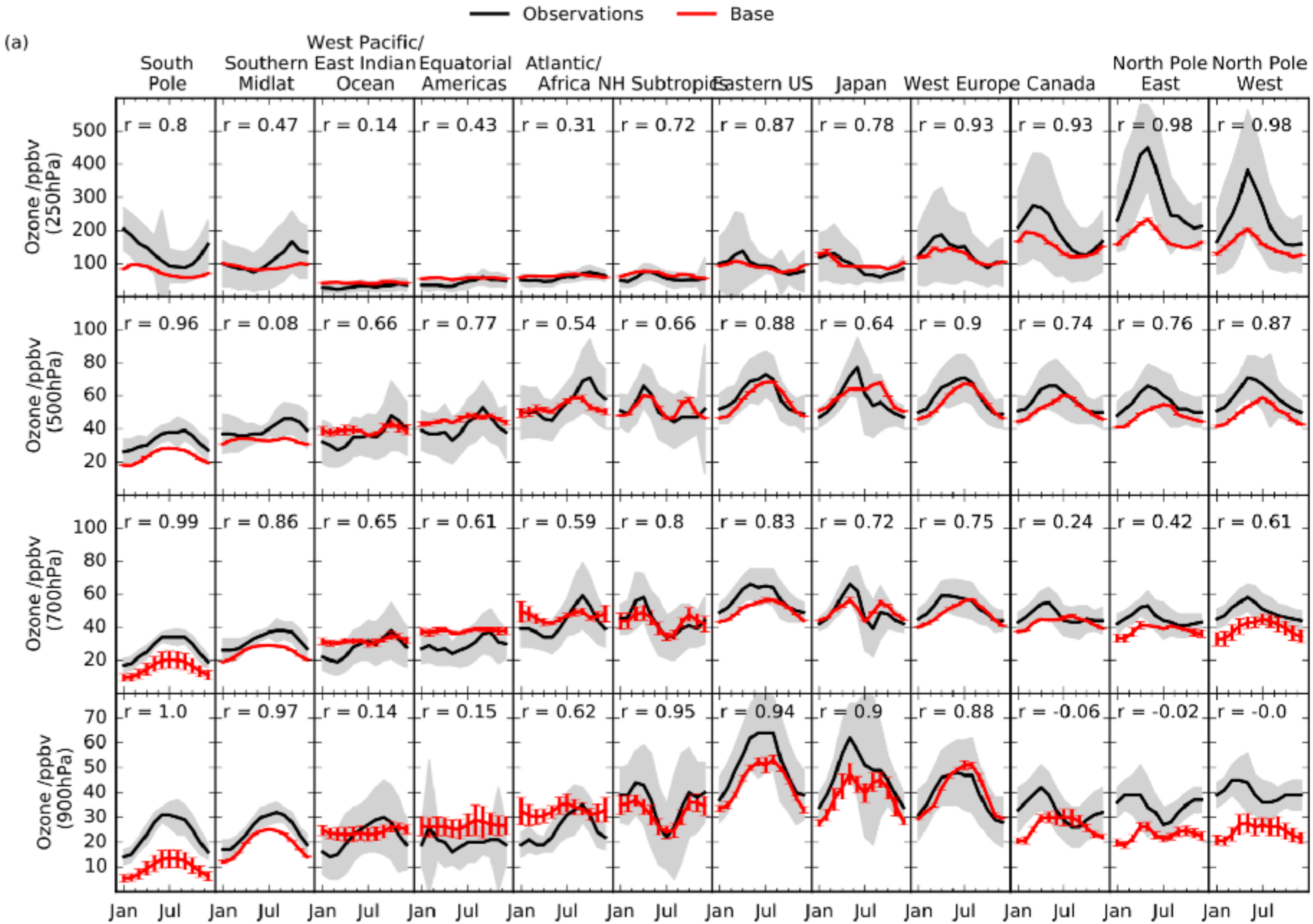


Ozone production in UKCA: ozone production/loss

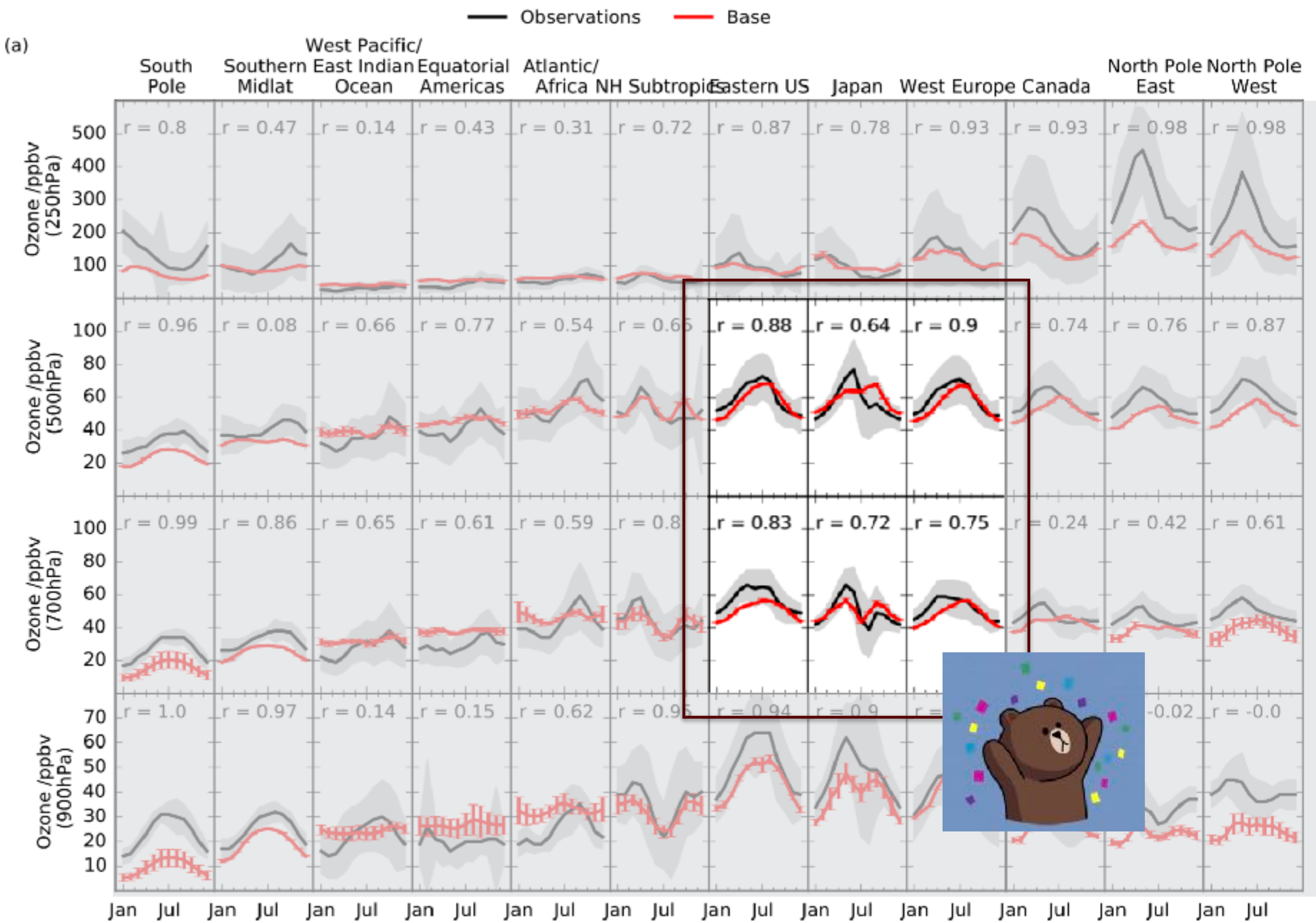
- There is significant **loss in the mid troposphere** (via HO2 + O3)
- Most global tropospheric ozone is produced in the NH and lost in the tropics



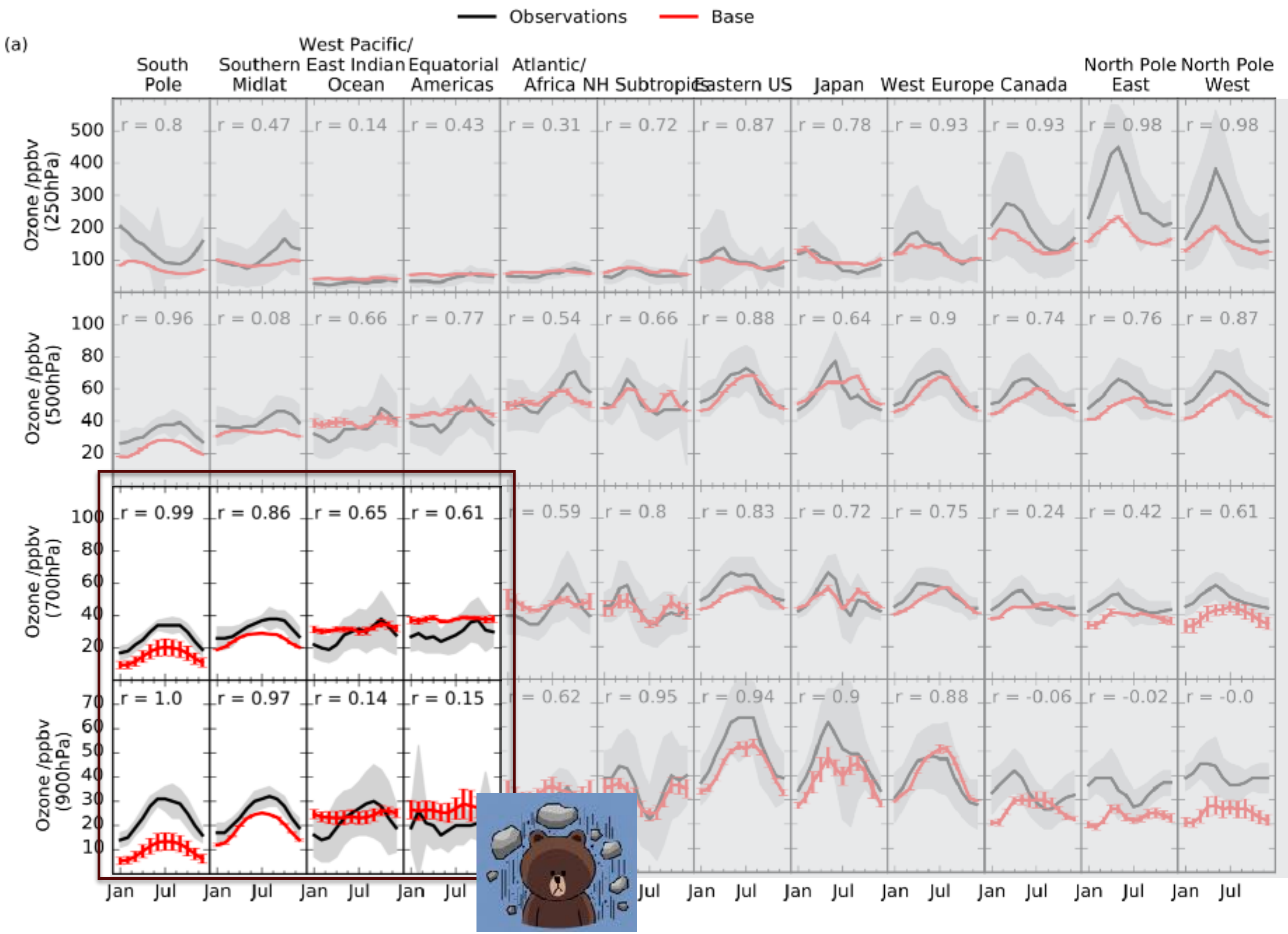
UKCA vs Simone Tilmes' ozonesonde data comparison



UKCA vs Simone Tilmes' ozonesonde data comparison



UKCA vs Simone Tilmes' ozonesonde data comparison



Ozone in future climate:

Vegetation, emissions and chemistry at work

How does atmospheric chemistry change in future climate?

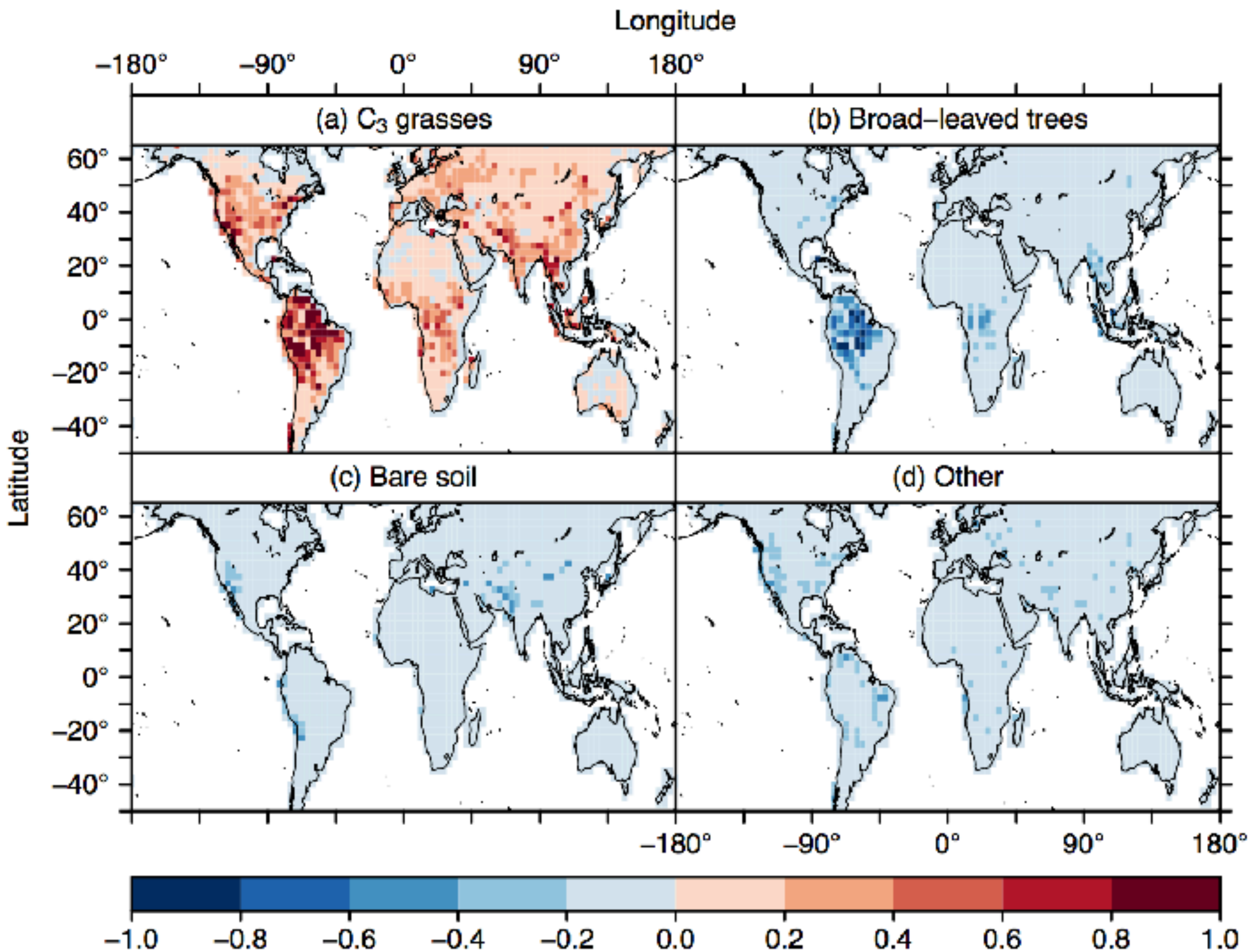
- Ozone levels in future climate is a wicked problem [***‘too important to ignore, too difficult to solve’***]
  - **Anthropogenic emissions** of VOC and NOx will **change**
  - The amount of **water vapour** increases so OH increases
  - What happens to the **atmospheric dynamics** and **transport** of ozone?
  - Biomass burning / lightning (future study)
  - The **temperature** increases - most reactions go faster, **plant emissions increase e.g. isoprene, C5H8 (emitted by trees)**
  - **Land use / land cover** is changing

Isoprene emissions in future climate

- 500 Tg C isoprene emitted annually
- Broad-leafed trees major emitters, crops emit less
- Reacts quickly in the atmosphere in the presence of NOx to produce ozone.
- As temperature increases, isoprene emission is enhanced
- As CO_2 increases, isoprene emission is inhibited

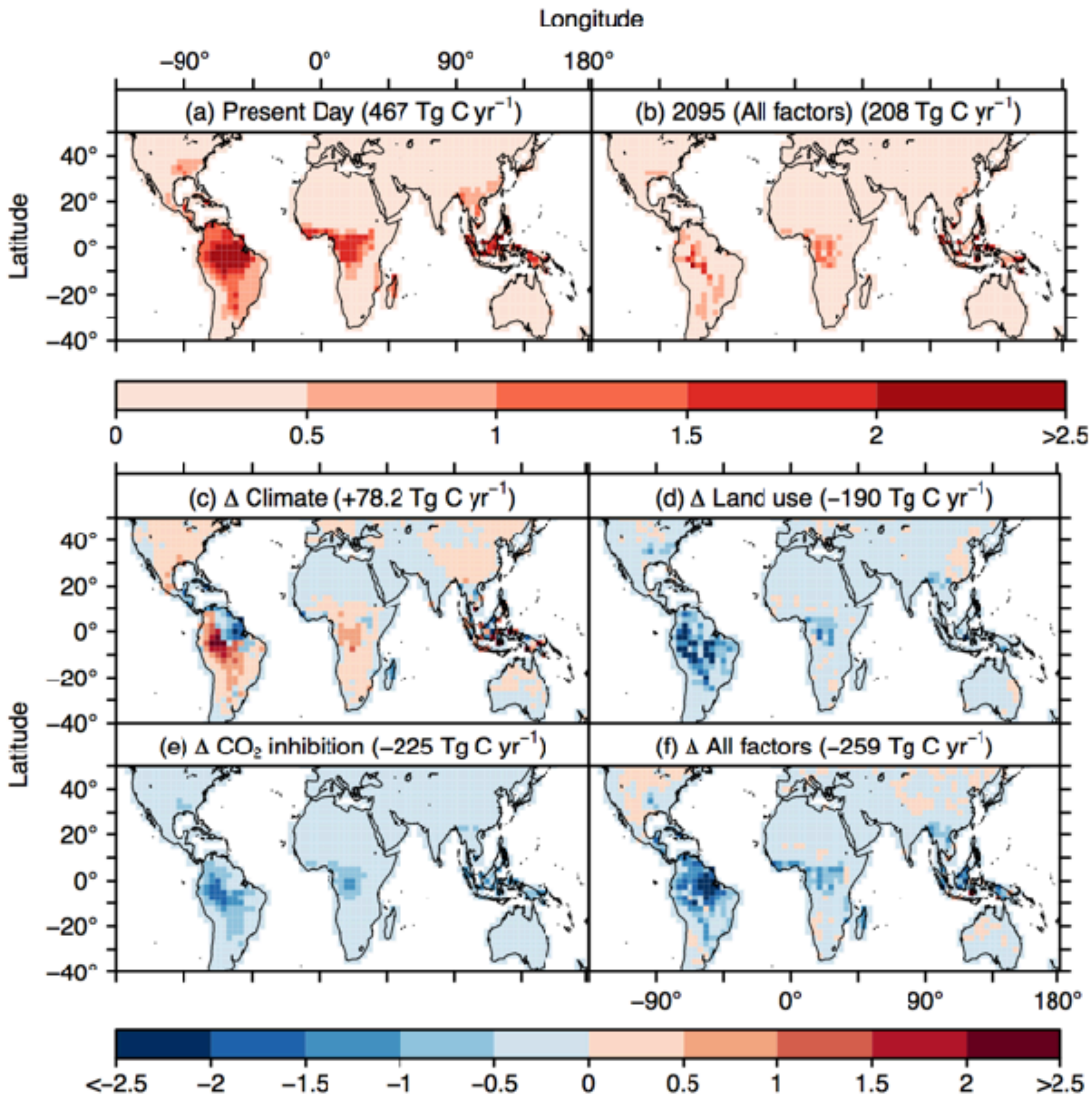
Need to consider temperature, CO_2 and land use to quantify isoprene

Land use changes - from Sheffield Digital Vegetation Model



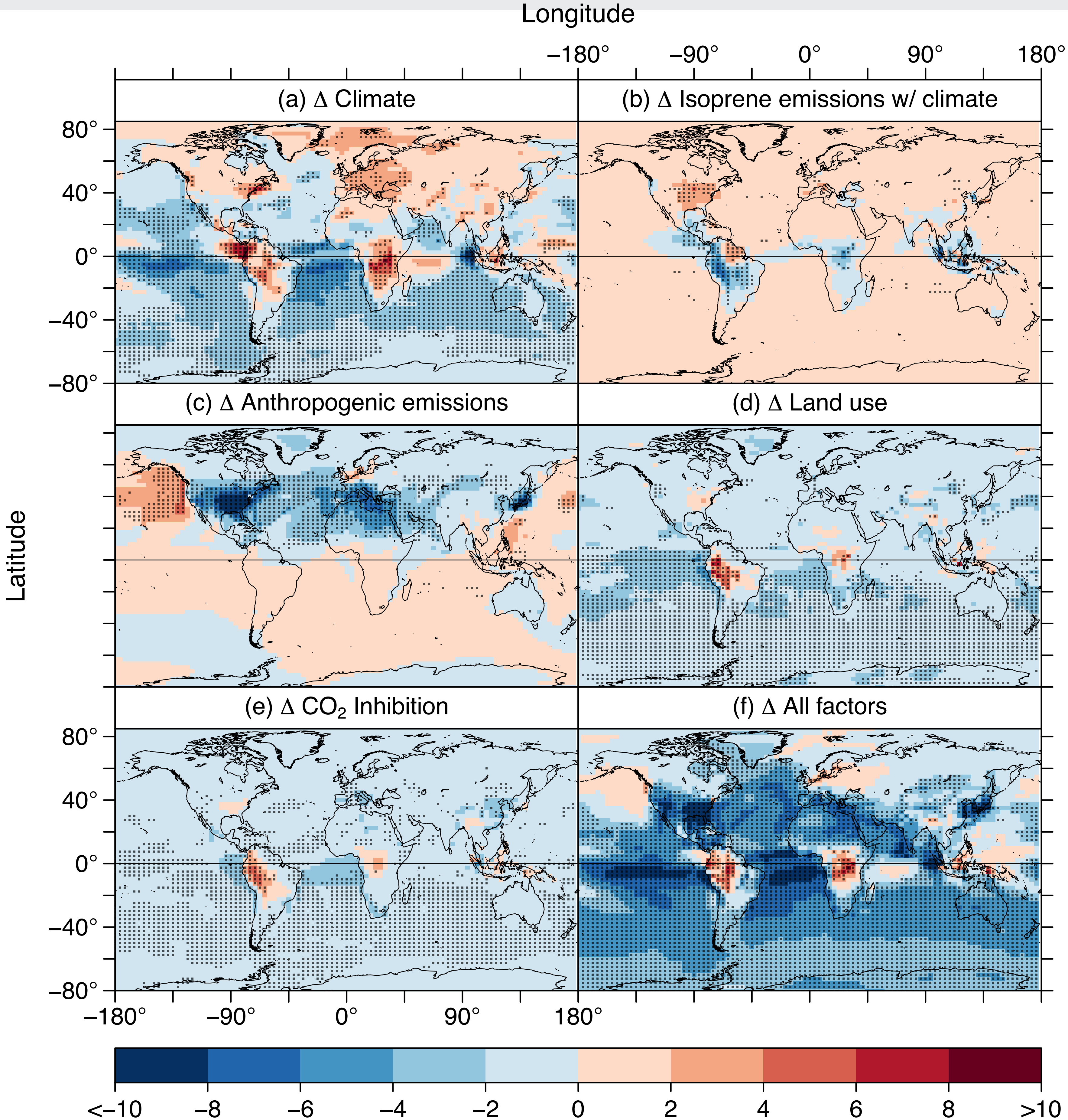
Change in grid cell fraction in the model in year 2095

Isoprene emissions changes - from MEGAN



Change in isoprene emissions in the model year 2095

How does ozone respond in future climate?

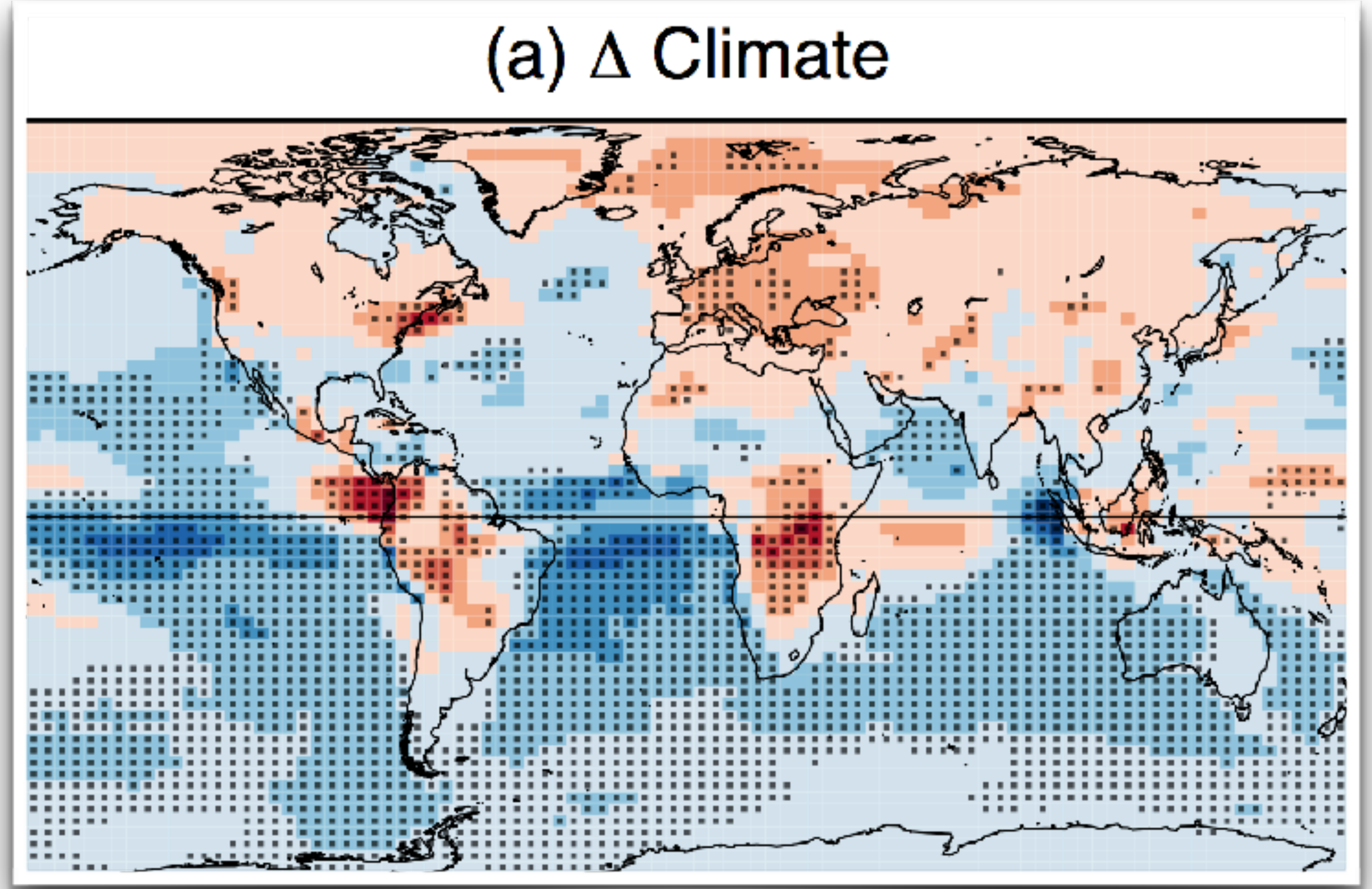


Squire et al., 2015, Atm Chem Phys

- How does ozone respond?
- **Single** perturbations to climate system for each forcer
- Focus on **isoprene (VOC)** from vegetation.
- Then allow perturbations to **interact**
- UM/UKCA N48L60, CheT chemistry,
  - isoprene emissions from MEGAN
  - vegetation distribution from Sheffield Dynamic Vegeation model,
  - other emissions according to IPCC REF B2 scenario

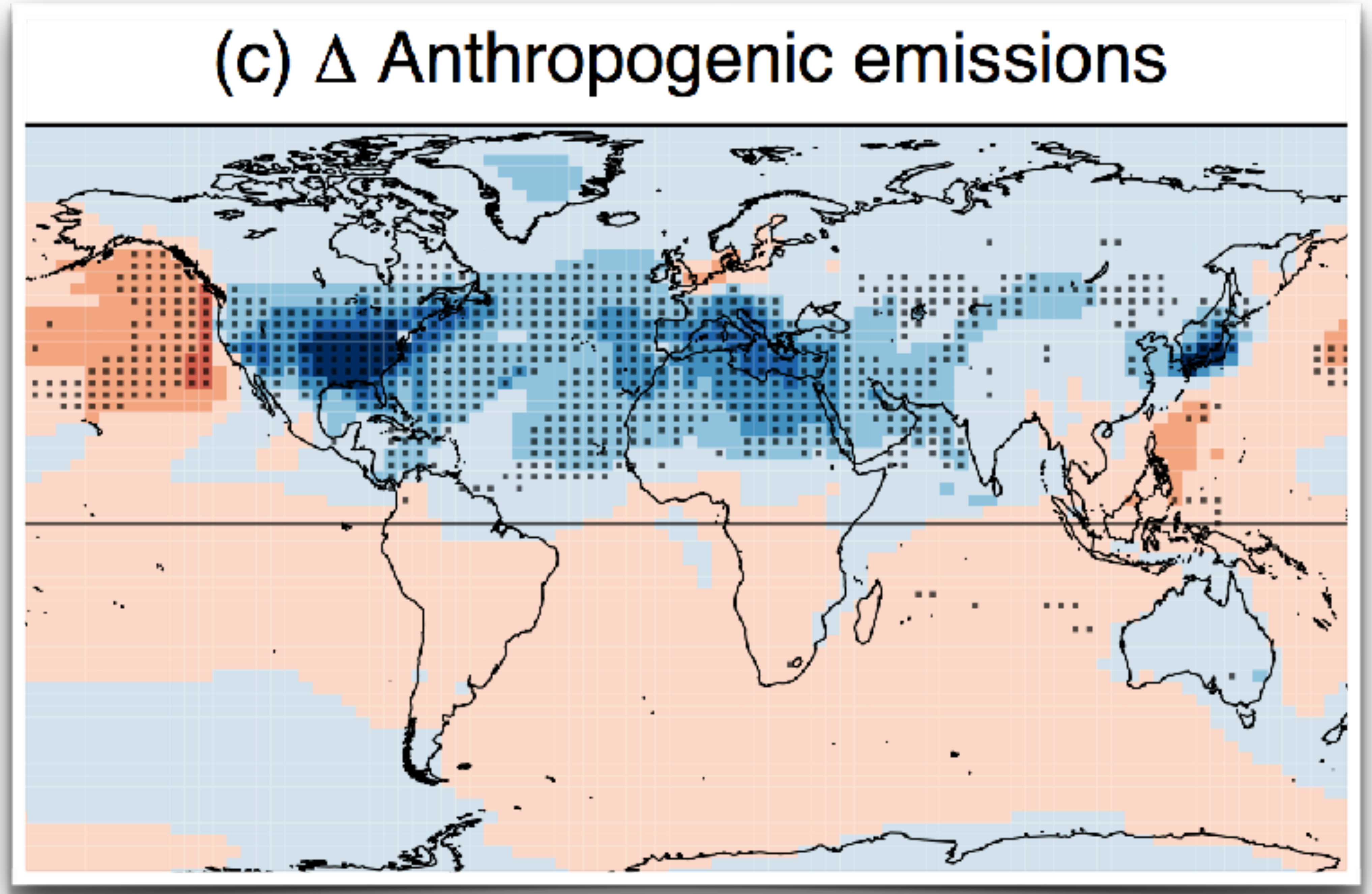
How does ozone respond in future climate?

Squire et al., 2015, Atm Chem Phys



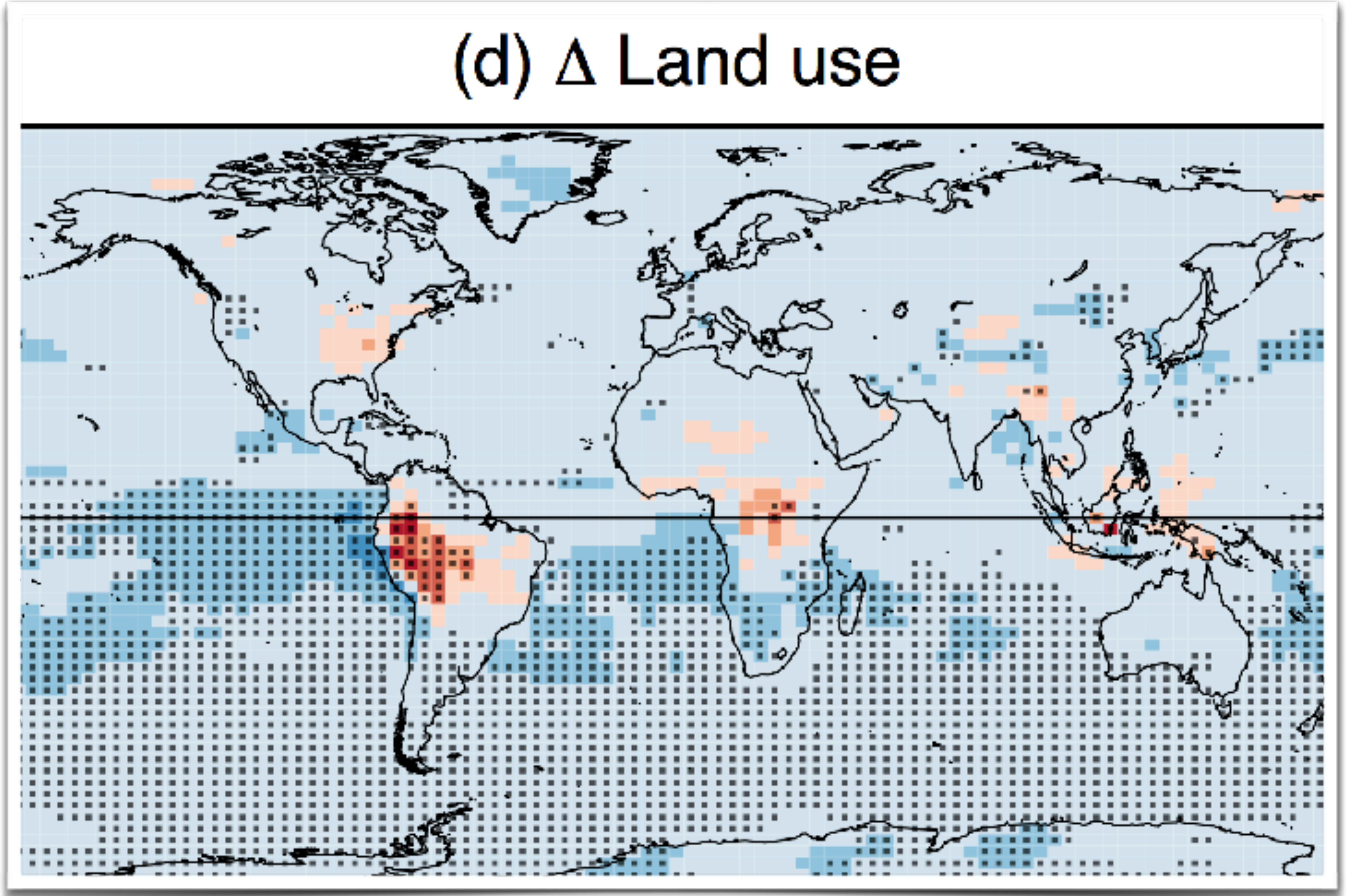
How does ozone respond in future climate?

Squire et al., 2015, Atm Chem Phys



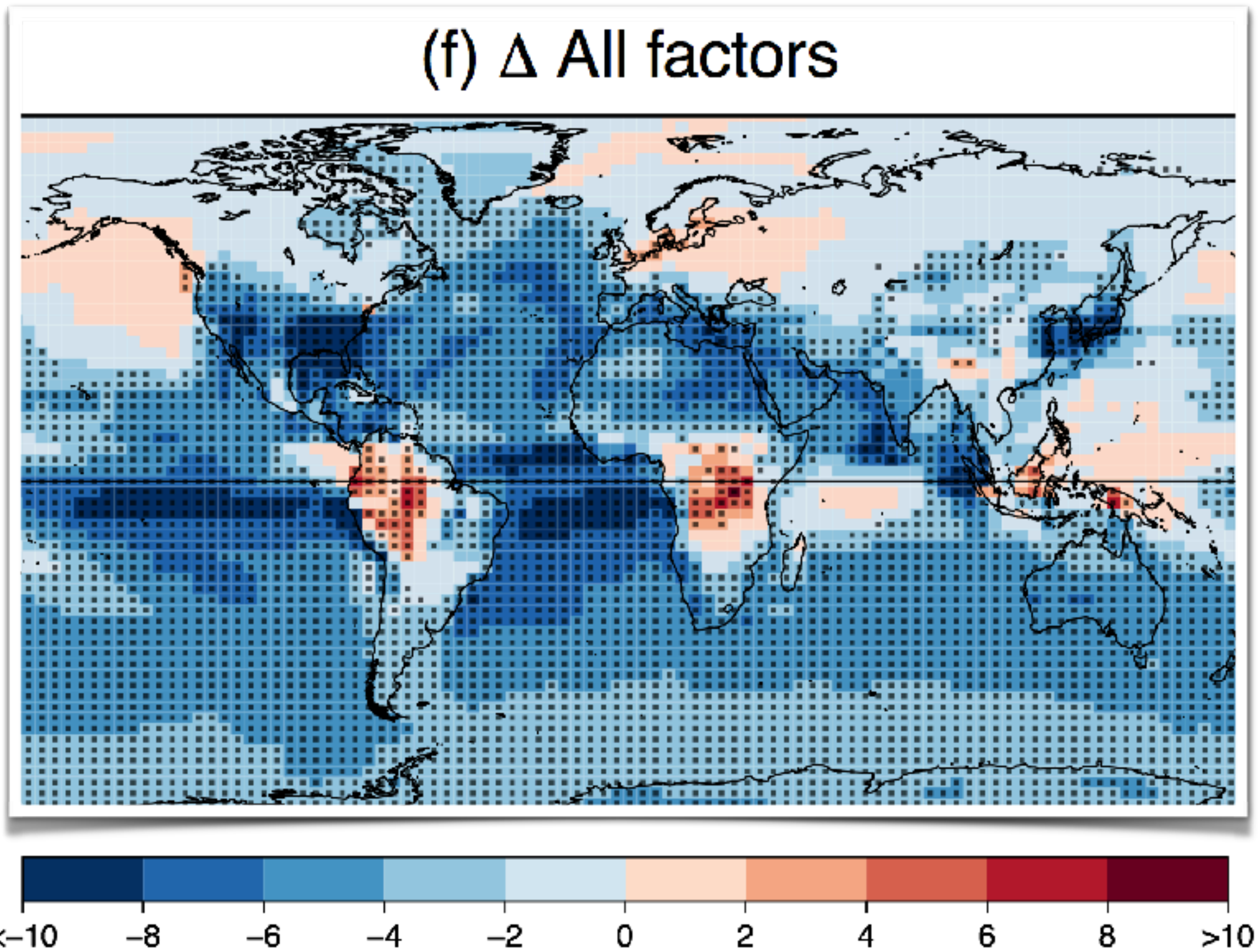
How does ozone respond in future climate?

Squire et al., 2015, Atm Chem Phys



How does ozone respond in future climate?

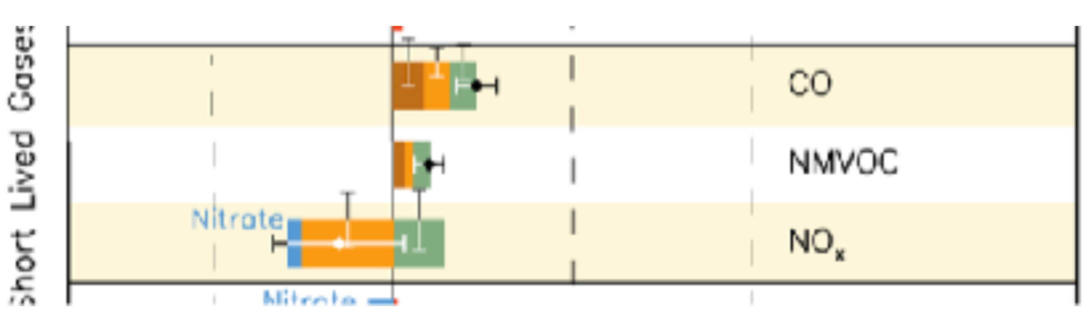
Dots indicate regions of significant change compared to model variability

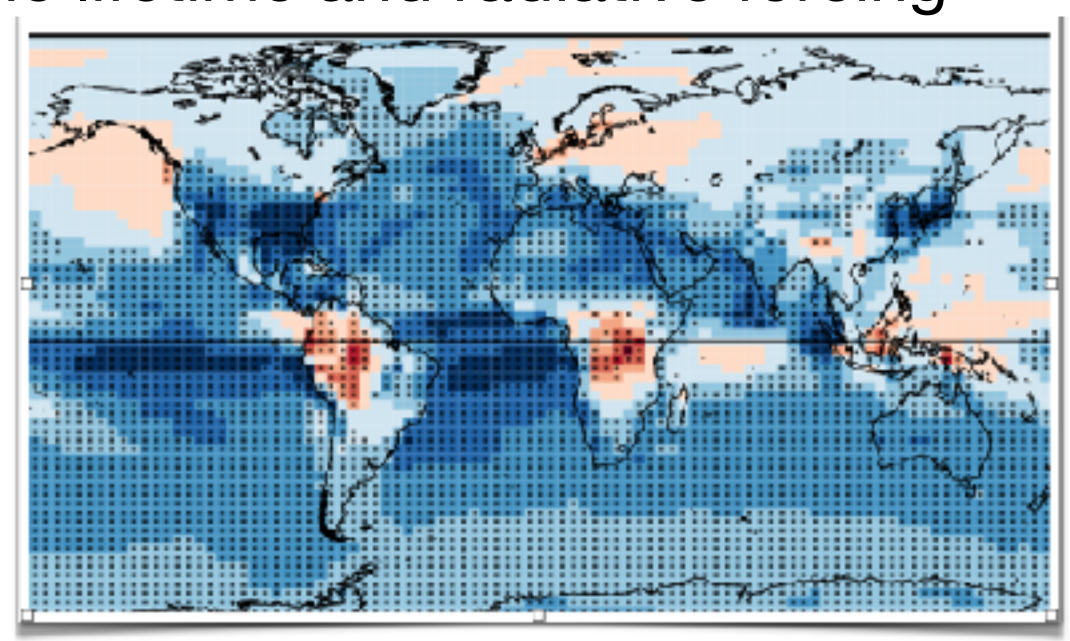


Conclusions

Conclusions

- Ozone in global climate models is challenging
  - While **Emissions, chemistry** have strong effect, **land use change** play a significant role.
  - Strong effects where vegetation cover is changing due to changes to deposition.
- Underpinning emissions estimates and sinks depend crucially on land use and land cover estimates
- Air quality, health, climate connect at local level
  - Long range transport of ozone precursors also important regionally
- Tropospheric ozone burden important to methane lifetime and radiative forcing





National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Thank you!

Questions?

UNIVERSITY OF CAMBRIDGE

NARIT