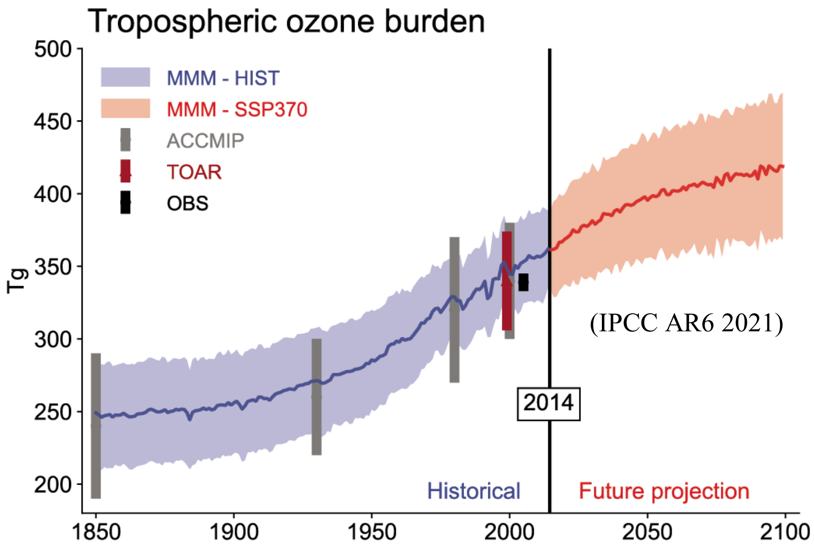
Modeling Ozone-Induced Damage to Vegetation: A New Parameterization Scheme for Land Surface Models

Fang Li

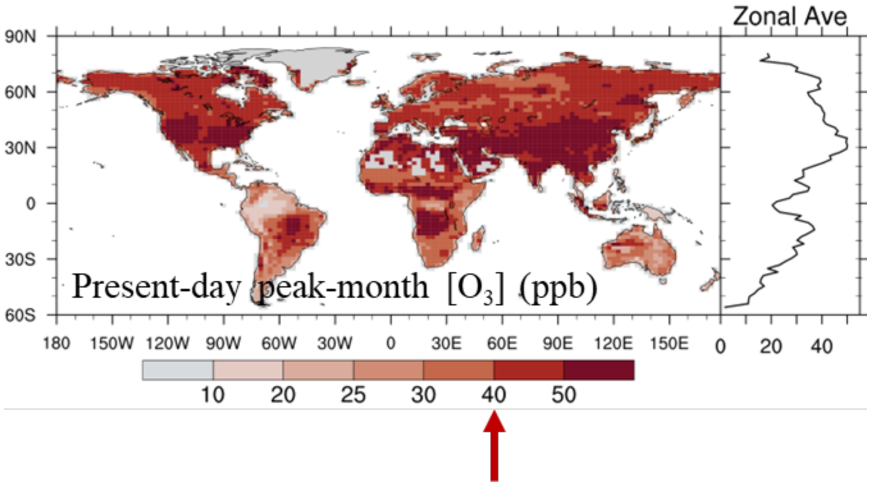
Zhimin Zhou Samuel Levis Stephen Sitch Danica Lombardozzi
Felicity Hayes Zhaozhong Feng Peter B. Reich

Surface ozone (O_3) : the primary air pollutant threatening global vegetation



(IPCC AR6 2021)

Plant sensitivity: ~ 40 ppb



O_3: most observed pollutant affecting plants & mechanisms well understood

O_3

Photosynthetic rate ↓

- decrease Rubisco enzyme content and activity
- decrease chlorophyll content
- alter chloroplast structure
- impair electron transport chain
- decrease mesophyll and stomatal conductance

Stomatal conductance↓

- ABA-triggered Ca^{2+} entry in guard cells
- inhibit K^+ channels
- disrupt signal transduction pathways
- increase internal leaf CO_2
- damage stomatal apparatus

→

- carbon, water, energy cycles
- ecosystem composition and structure
- plant and crop growth
- crop yield, timber, forage
- surface climate
- atmospheric composition

Earlier parameterization schemes

Integrate the photosynthetic and stomatal responses to O_3 in global process-based models

- **Sitch 2007 (S07):** JULES and YiBs (from TRIFFID)

Photosynthetic response thresholds: Linear function of O_3 flux;
parameters derived by fitting observed relationship between POD_Y(cumulative O_3 uptake over a flux threshold Y) and **biomass/yield response**

Cons:

Provides only response thresholds (not optimal)

Assumes model is perfect (not true)

Assumes $F_{O3\_An} = F_{O3\_gs}$ (not true)

Parameters are model-dependent, and for crops, NT, BT (grass uses crop's & shrub uses BT's)

➢ **Lombardozzi 2015 (L15):** CLM5

Responses of An and gs : Different functions of POD0.8, parameters derived based on photosynthetic and stomatal responses

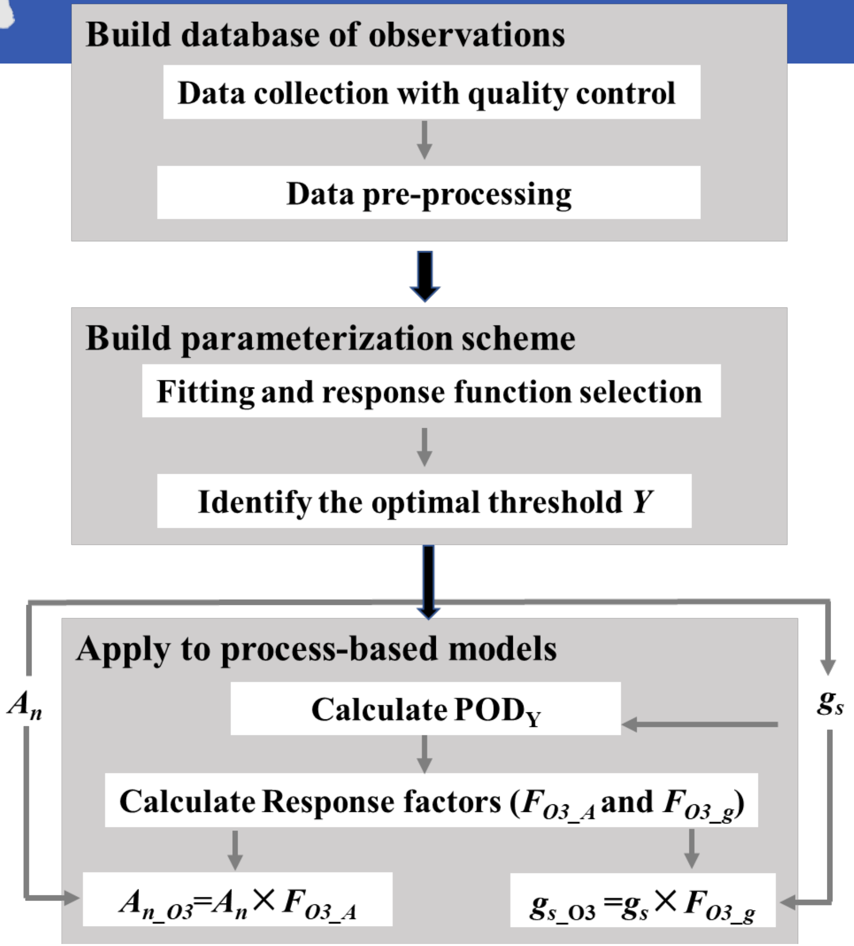
$$F_{O3\_An}=\begin{cases}0.8752 \\ 0.8390 \\ \text{use Crop's} \\ -0.0009POD_{0.8}+0.8021\end{cases} \qquad F_{O3\_gs}=\begin{cases}0.9125 & \text{Broadleaf tree \& shrub} \\ 0.0048POD_{0.8}+0.7823 & \text{Needleleaf tree \& shrub} \\ \text{use Crop's} & \text{Grass} \\ 0.7511 & \text{Crop}\end{cases}$$

Pros:

Address most limitations of S07

Cons:

- Constant responses used except for crop A_n and temperate evergreen tree g_s due to no significant linear fitting Eqs. found
- Grass uses crop’s and shrub uses tree’s parameters due to no obs.



New scheme

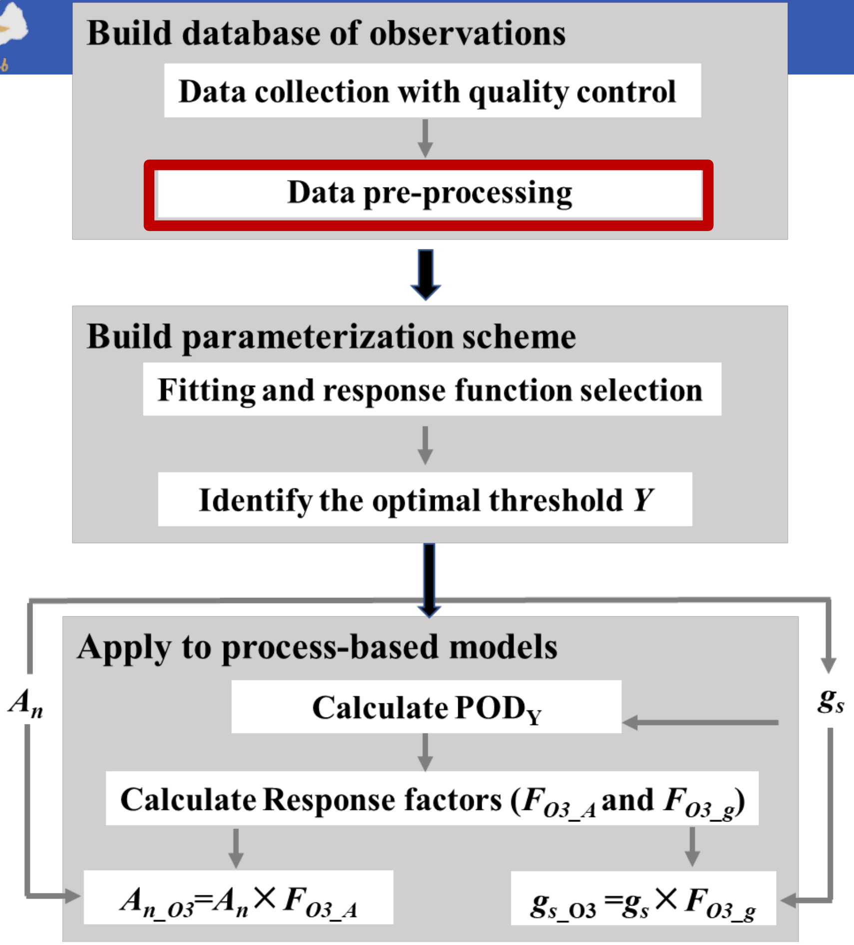
Li et al. (GMD, minor revisions)

Data collection with quality control

3496 (A_n) and **3890** (**gs**) observational data points after strict data quality control from **159** peer-reviewed articles and **238** plant species

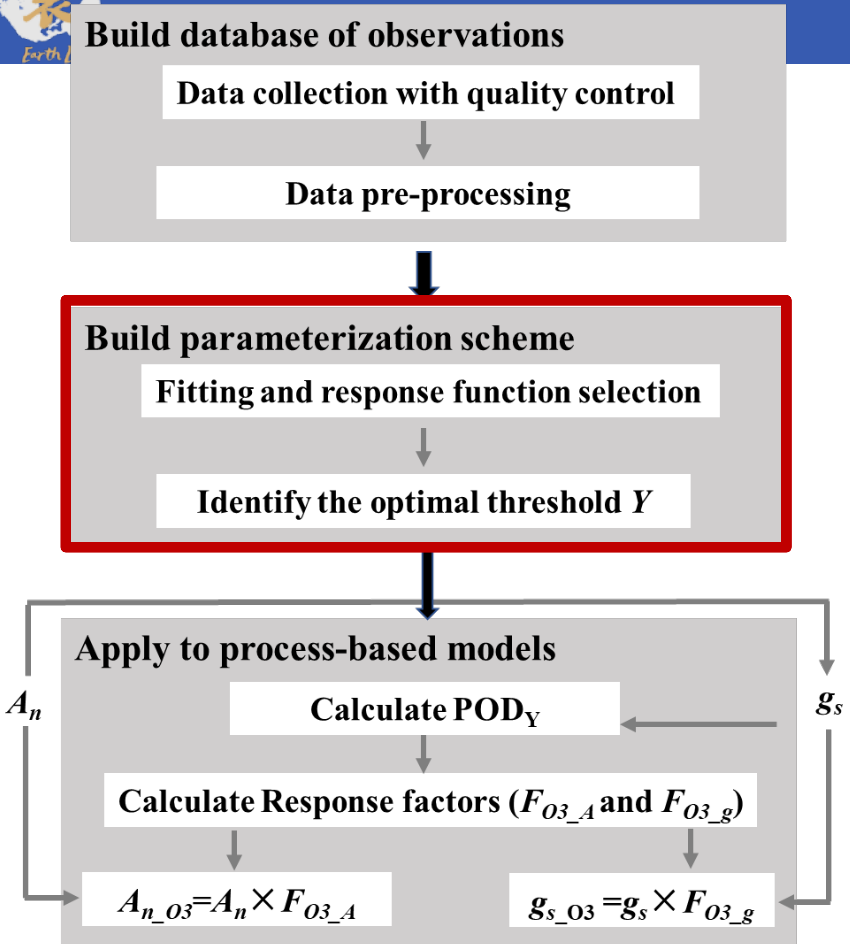
Category	Categorical level				
Plant type	BT (81, 87, 3902)	NT (21, 13, 669)	Crop (52, 117, 2293)	Grass (9, 18, 266)	Shrub (4, 4, 25
Plant age (year)	<1 (63, 135, 2733)	1 to 5 (57, 54, 2735)	>5 (12, 8, 200)	N/A (40, 65, 1718)	
Control Air	Charcoal filtered (86, 145, 4399)	Ambient (48, 71, 1927)	Non-Filtered (6, 7, 198)	N/A (23, 39, 862)	
Exposure system	Growth chamber (41, 57, 1738)	Free-Air enrichment (28, 33, 1583)	Open top chamber (75, 139, 3240)	Greenhouse (17, 30, 756)	Branch chamber (2, 2, 69
Rooting environment	Pot (116, 183, 5178)	Ground (26, 36, 1083)	N/A (19, 33, 1125)		
Response variable	Photosynthesis (140, 211, 3496)	Stomatal conductance (158, 236, 3890)			

New: to **2022**
L15: to **2011**
S07: to **2004**



Data pre-processing

- **Calculate POD_Y** if not reported
- **Calculate relative A_n and g_s** to that without O_3 stress for **comparability** of the O_3 effect across different exp., species, control air types, and dates within a given vegetation category
- Remove data with fitting intercepts outside 0.9 and 1.1 as CLRTAP
- Remove data points at POD_Y=0



Optimal function: least RSS

Linear: $y = ax + b$

and non-linear:

ln: $y = a\ln(x) + b$

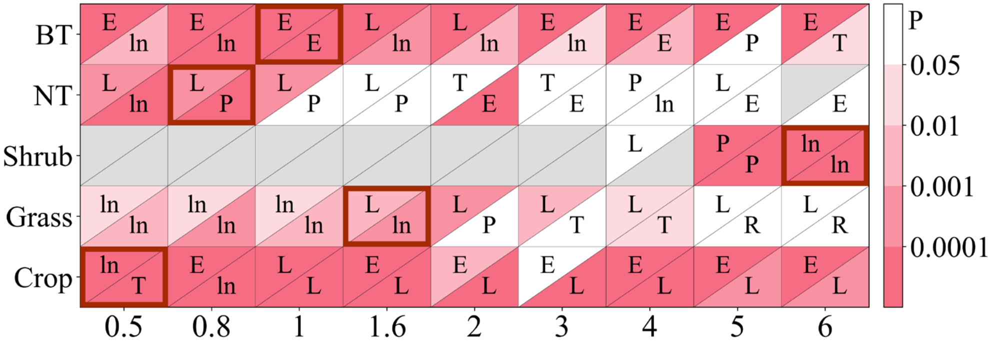
Exponential: $y = be^{ax}$

Power: $y = bx^{a}$

hyperbolic Tangent: $y = a\tanh(x) + b$

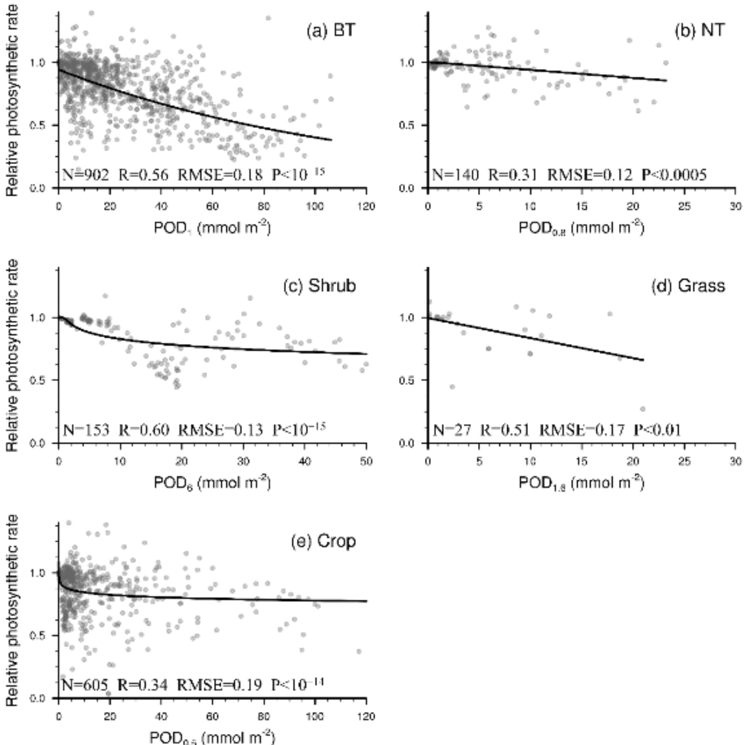
Reciprocal: $y = \frac{a}{x} + b$

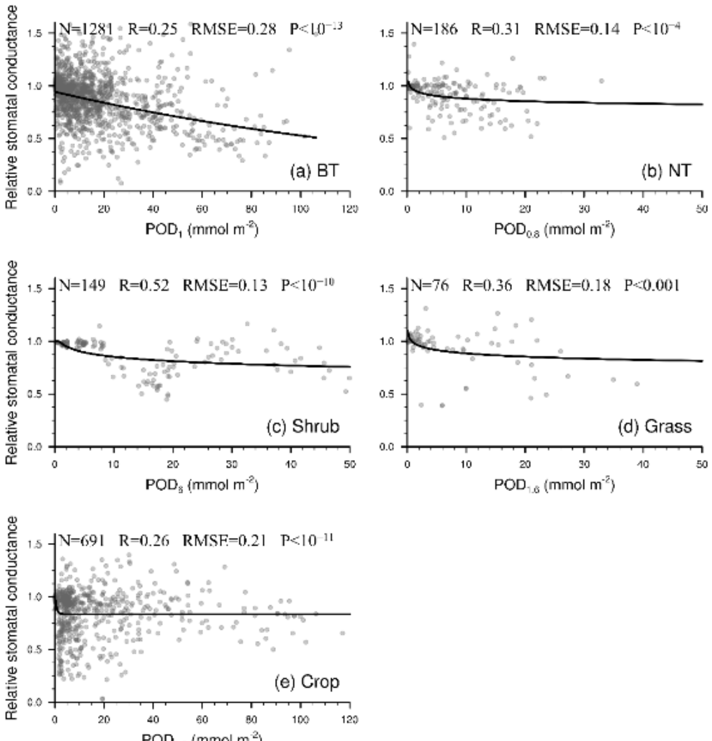
Optimal Y: lowest P-value

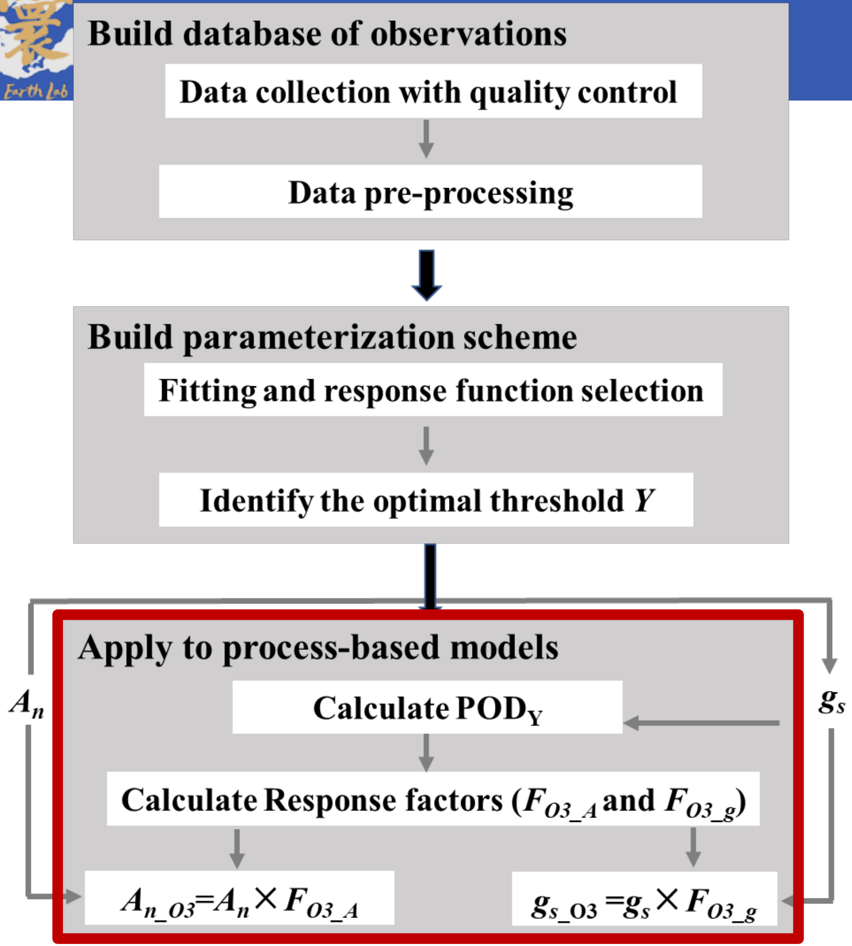


$$
F_{O3\_A} = \begin{cases} 0.943e^{-0.0085POD_1} \\ 1.014 - 0.010POD_{0.5} \\ 1.142POD_5^{-0.140} \\ 0.997 - 0.016POD_{1.6} \\ 0.909 - 0.028\ln\left(POD_{0.5}\right) \end{cases}
$$

$$
F_{O3\_g} = \begin{cases} 0.943e^{-0.0058POD_1} & \text{BT} \\ 0.975 - 0.037\ln(POD_{0.5}) & \text{NT} \\ 1.075POD_5^{-0.104} & \text{Shrub} \\ 0.989 - 0.045\ln(POD_{1.6}) & \text{Grass} \\ 1.005 - 0.169\tanh\left(POD_{0.5}\right) & \text{Crop} \end{cases}
$$







Cumulative O_3 uptake during growing season

$$POD_{Y,t} = POD_{Y,t-1}(1 - D_t) + U_{Y,t} \times 10^{-6}$$

Decay fraction due to leaf senescence and emergence:

$$D_t = \begin{cases} \dfrac{\Delta t}{l_{leaf} \times 3600 * 24 * 365} & \text{evergreen} \\ \max(0,\ 1 - \dfrac{LAI_{t-1}}{LAI_t}) & \text{else} \end{cases}$$

O_3 uptake at timestep t :

$$U_{Y,t} = \begin{cases} \Delta t \times \max(F_{O3,t} - Y, 0) & \text{daytime} \\ 0 & \text{else} \end{cases}$$

O_3 flux at timestep t

$$F_{O3,t} = \frac{[O_3]_t}{r_{b,t} + r_{am,t} + r_{s,t} k_{O3}}$$

Advantages of the new scheme

1. Larger dataset

Veg. type	New	L15	S07
BT	2183	266	45
NT	326	100	51
Shrub	302	0	0
Grass	103	16	0
Crop	1296	270	80
Total	**4210**	**652**	**176**

- Better representation
- Shrub & grass (√)
- Model-independent
- Need not assume model perfect

2. Found functions to represent statistically significant responses in obs. for all veg. categories

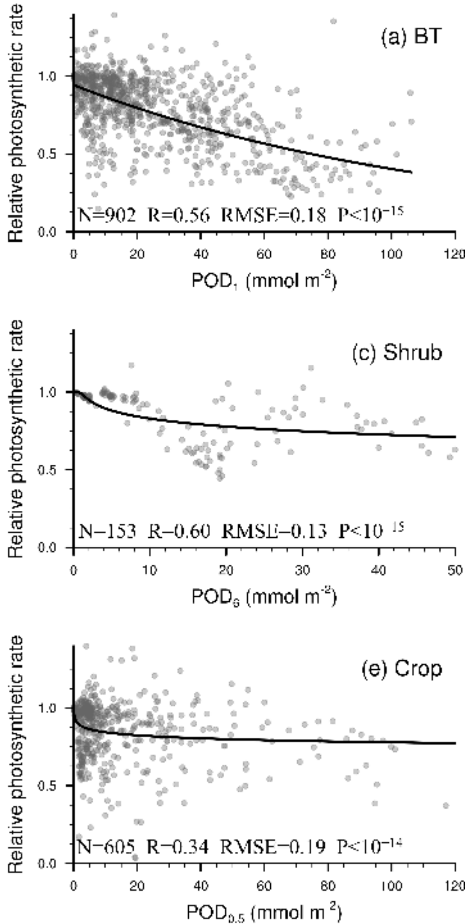
L15 → New

Veg. type	Photosynthetic rate	Stomatal conductance
BT	NS→***	NS→***
NT	NS→***	NS→***
Shrub	NS→***	NS→***
Grass	NS→**	NS→***
Crop	Both ***, New: + 8.1% R^2	NS→***

NS: non-significant, *: $P<0.05$, **: $P<0.01$, ***: $P<0.001$

- No need to apply function from one vegetation category to another
- No need to use constants

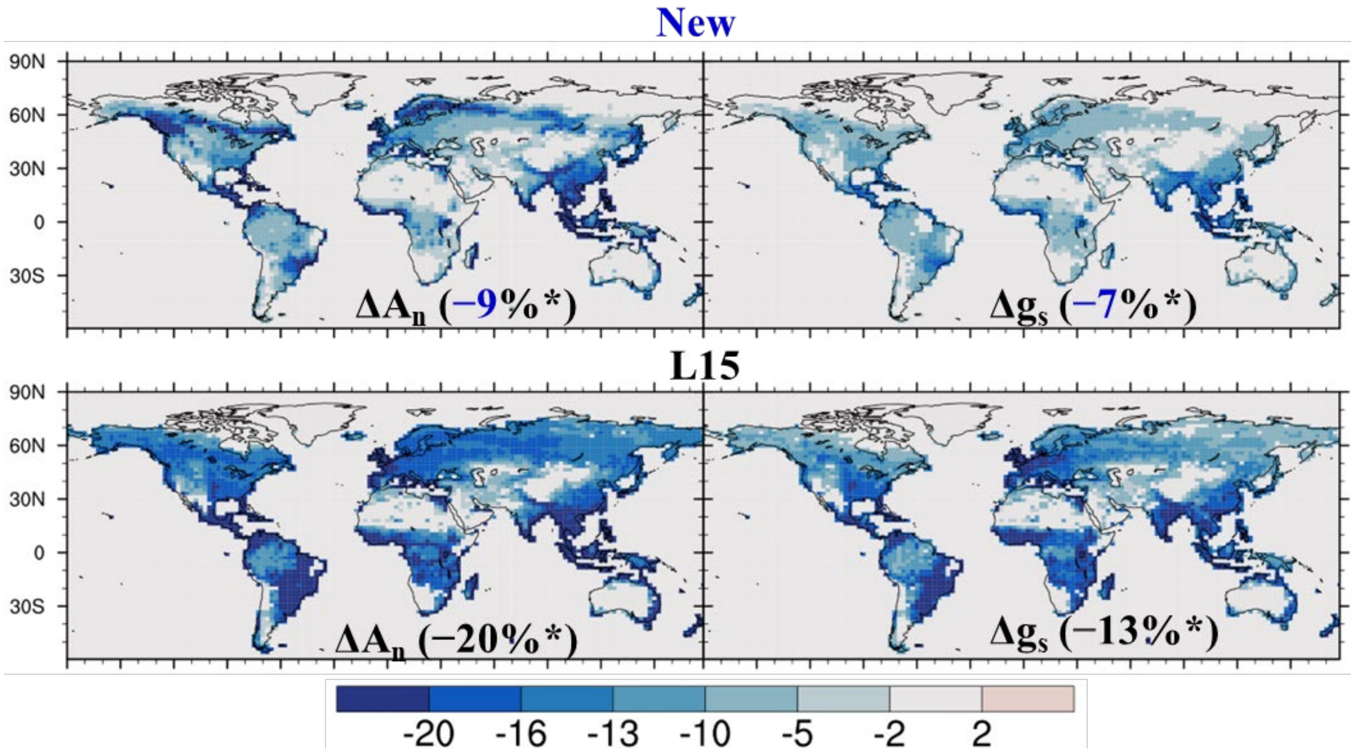
Nonlinear functions we built depict decreasing plant sensitivity with increasing POD_Y



3. Enable models to implicitly capture plant ozone tolerance variability and shift among species within a vegetation category

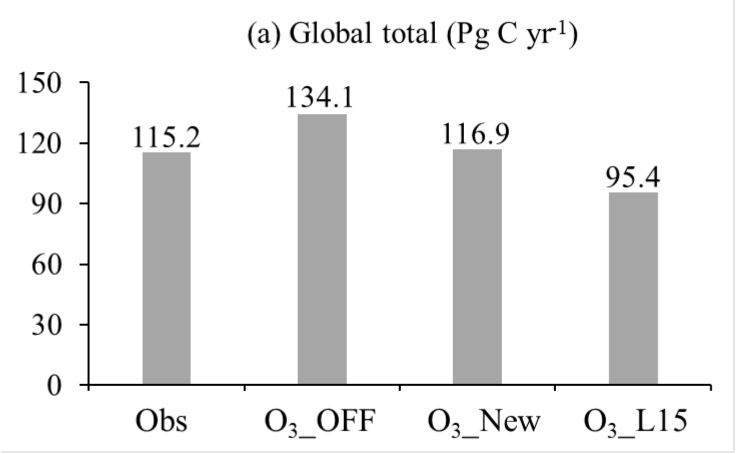
Influence of O_3 plant damage

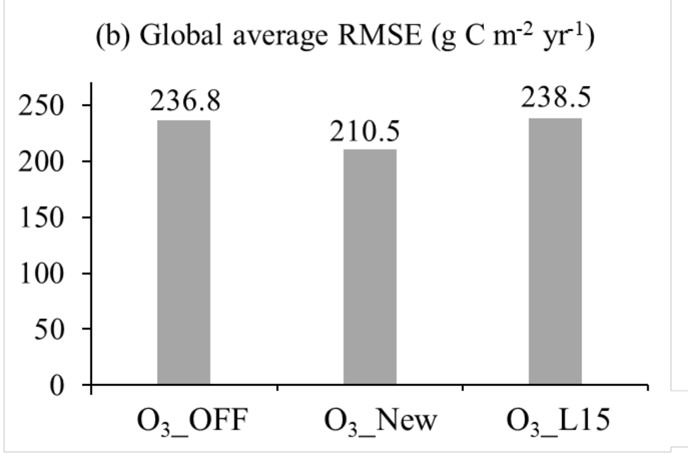
on present-day photosynthetic rate (A_n) and stomatal conductance (g_s)



CLM5SP driven by EAC4 3-hr $[O_3]$ reanalysis

- New scheme decreases RMSE by 11% compared to no O_3 stress and by 12% compared to L15





- O_3 effect on global GPP total:

–13% (New) vs **–29% (L15)** in CLM5.0 I2000SP

– 9% (New) vs **–32% (L15)** in CLM5.2 I2000SP

Further development & Application

Further development:

- Use sample size and standard error of data points
- Explore alternative functions
- Introduce other explanatory variables (e.g., leaf traits)
- PFT-level fitting

Email: lifang@mail.iap.ac.cn

Application:

- Quantify the role of O_3 plant damage in the Earth system
- Prediction & projection
- Quantify the contribution & potential impact of pollution reduction policies on ecosystem services

Li, F., et al., Quantifying the role of ozone-caused damage to vegetation in the Earth system: A new parameterization scheme for photosynthetic and stomatal responses, GMDD, https://doi.org/10.5194/gmd-2024-6, minor rev., 2024.