Using atmospheric oxygen in the global carbon budget and monitoring systems

Ingrid Luijkx*, Kim Faassen, Doris Vertegaal, Joram Hooghiem*,
Auke van der Woude, Lucas Hulsman, Lois de Beijl,
Katia Savin, Harro Meijer

Plus discussion session

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university of groningen

Timeline of the talk and discussion session (13:55-15:05)

- Using atmospheric oxygen in the global carbon budget and monitoring systems

- Discussion on merging datasets and creating an O_2 Obspack product

- If time allows: discussion on concerns raised by Andrew Kowalski in a review to Yan et al. (2023) on transport of O_2 in the atmosphere, and the effects of different forms of diffusion for non-trace gases

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CORSO (Copernicus CO2MVS) & PARIS projects

- Currently 2 EU projects are taking O_2 onboard as tracers for CO_2, specifically for estimating fossil fuels, and emission monitoring, based on the methodologies developed by Pickers et al. (2022).

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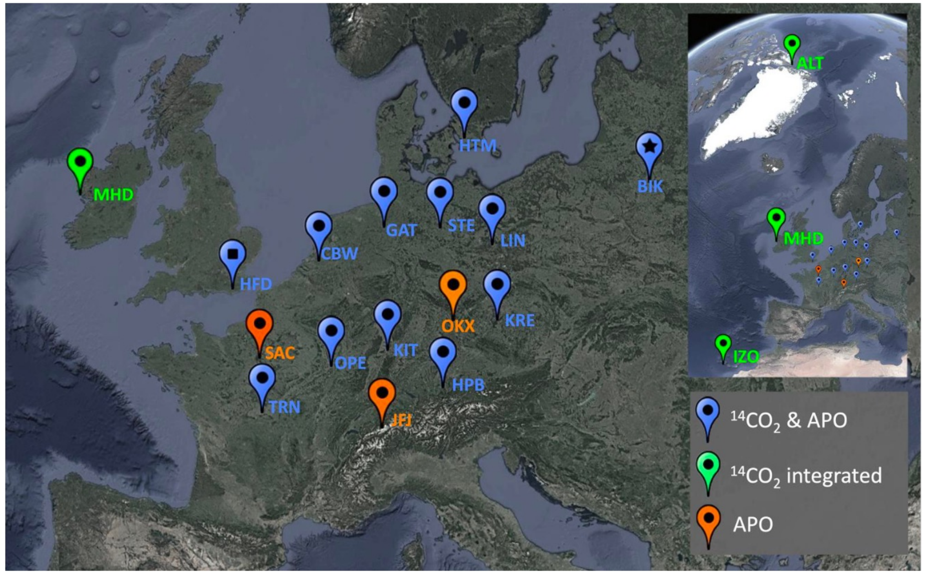
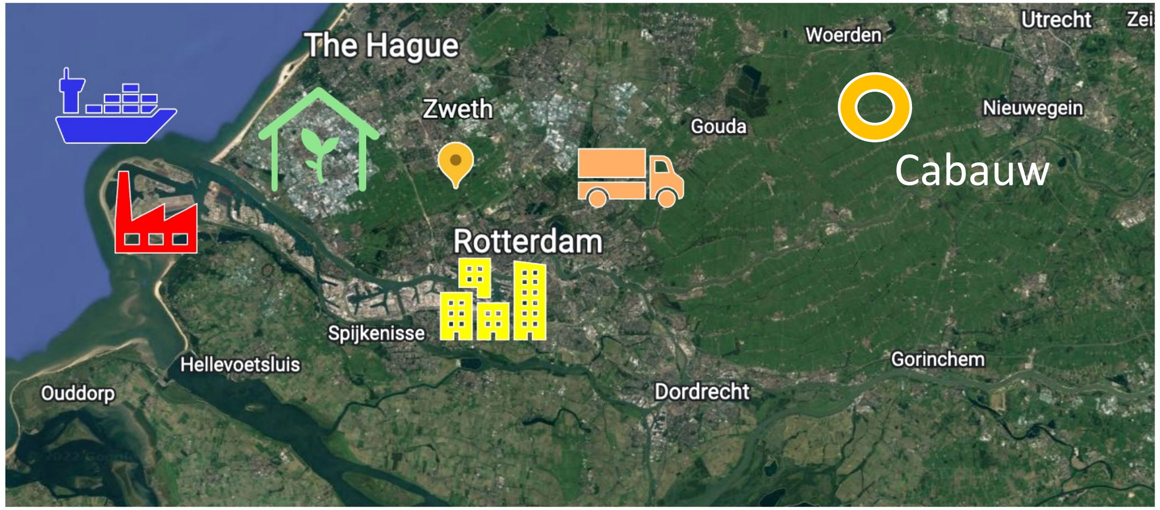
- Currently 2 EU projects are taking O_2 onboard as tracers for CO_2, specifically for estimating fossil fuels, and emission monitoring, based on the methodologies developed by Pickers et al. (2022).
- PARIS (Process Attribution of Regional Emissions) focusses on using inverse methods next to bottom up inventories for country level emission evaluation.
- CORSO (CO2MVS Research on Supplementary Observations): focusses on assessing the added value of new observations for the Copernicus CO_2 Monitoring and Verification System that is developed at ECMWF. Here, O_2 and ^{14}C are assessed side by side.

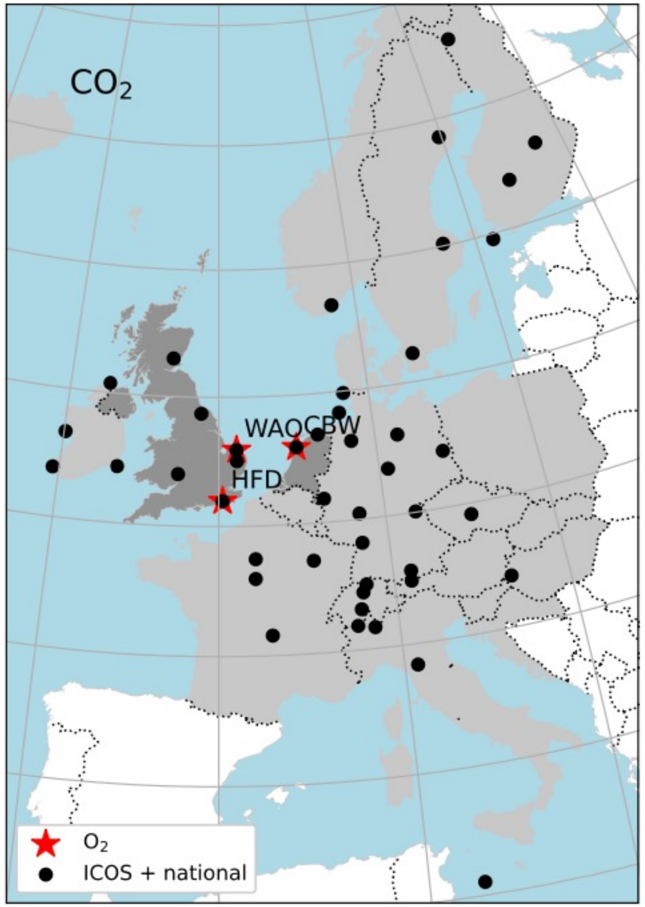
CORSO (Copernicus CO2MVS) & PARIS projects

- New and continued observations at:
  - 2 sites in the UK (WAO, HDF) by University of East Anglia (Penelope Pickers, Karina Adcock and Andrew Manning)
  - all ~18 flask locations (CLASS 1 stations) across Europe by ICOS (Markus Eritt)
  - 2 sites in the Netherlands (CBW, ROT) by University of Groningen and Wageningen University (Lois de Beijl, Katia Savin, Harro Meijer, Ingrid Luijkx)
- O_2 modelling efforts:
  - University of Bristol (Eric Saboya and Matt Rigby, based on the discussion paper by Chawner et al. 2023)
  - Wageningen University (Doris Vertegaal, Joram Hooghiem, Auke van der Woude)
  - ECMWF (Auke Visser)

Copernicus CO2MVS, CORSO & PARIS projects







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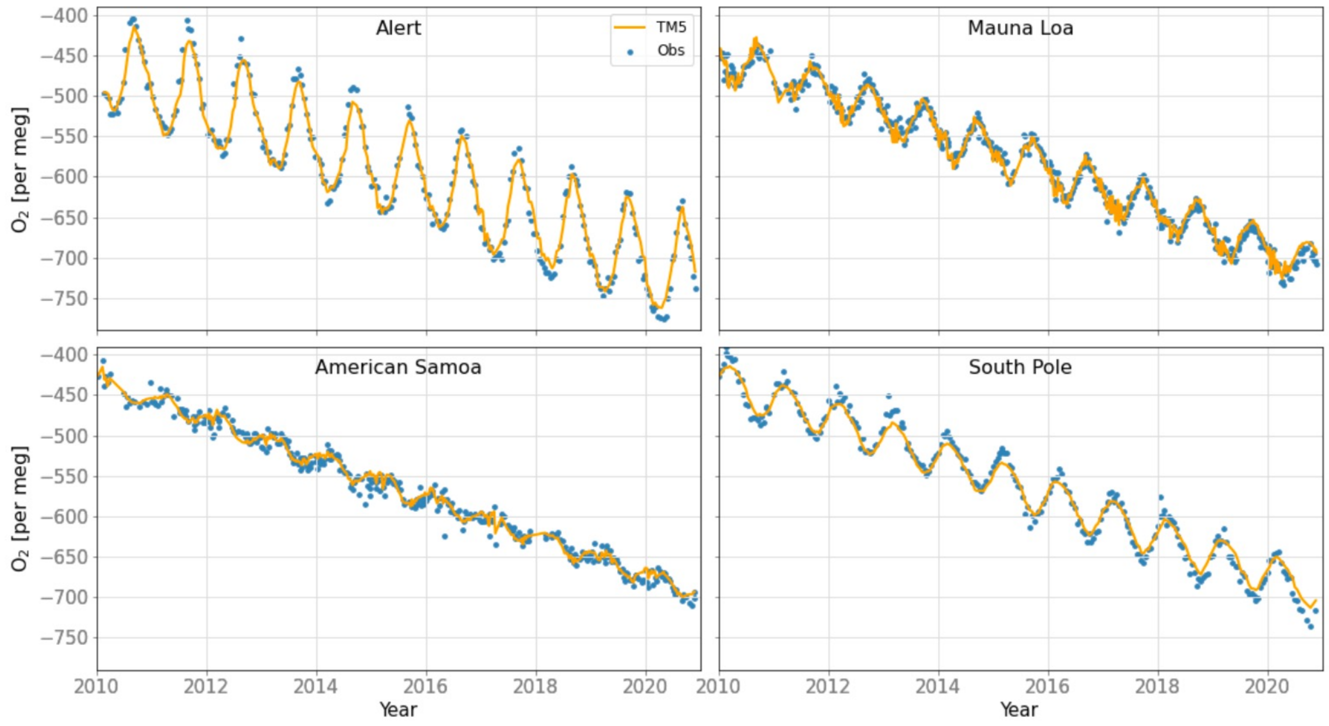
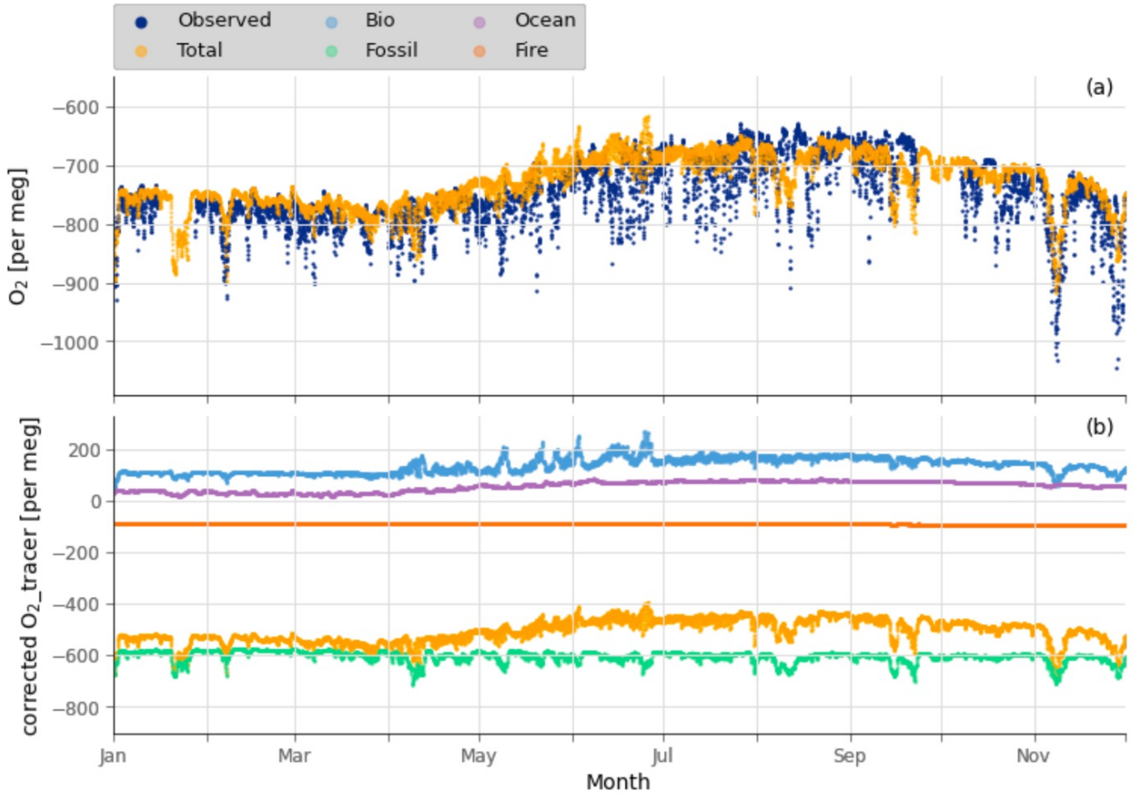
Copernicus CO2MVS, CORSO & PARIS projects

- Intial model results with TM5 (Doris Vertegaal and Joram Hooghiem)
  - More details in Britt's Forward APO MIP tomorrow





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Global Carbon Budget

GLOBAL CARBON PROJECT

- Next cycle in progress (synthesis in September)
- Workshop GCB Exeter 3-6 July 2023
- Current role for O_2
- Discussion on adjustments
- New opportunities for O_2

Earth Syst. Sci. Data, 14, 4811–4900, 2022
https://doi.org/10.5194/essd-14-4811-2022

Open Access Earth System Science Data

Global Carbon Budget 2022

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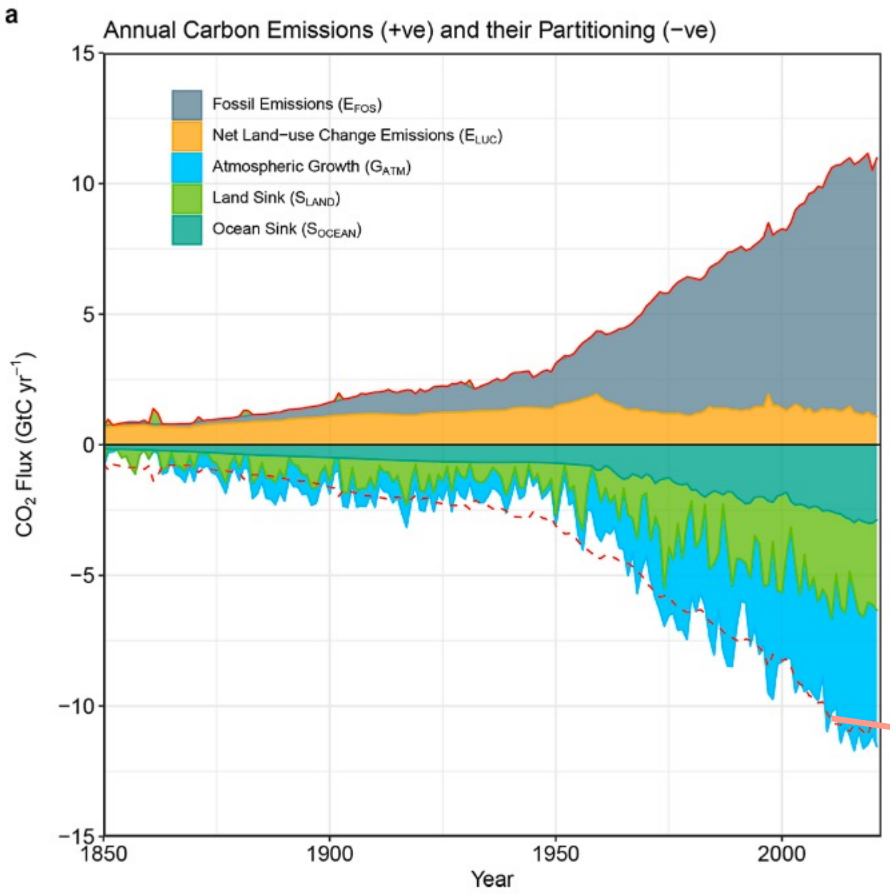
The budget components



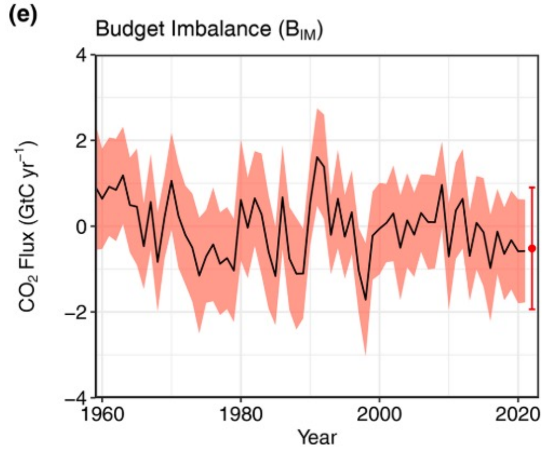
inventories

bookkeeping methods

models (GOBMs) and observation based products

models (DGVMs)

observations



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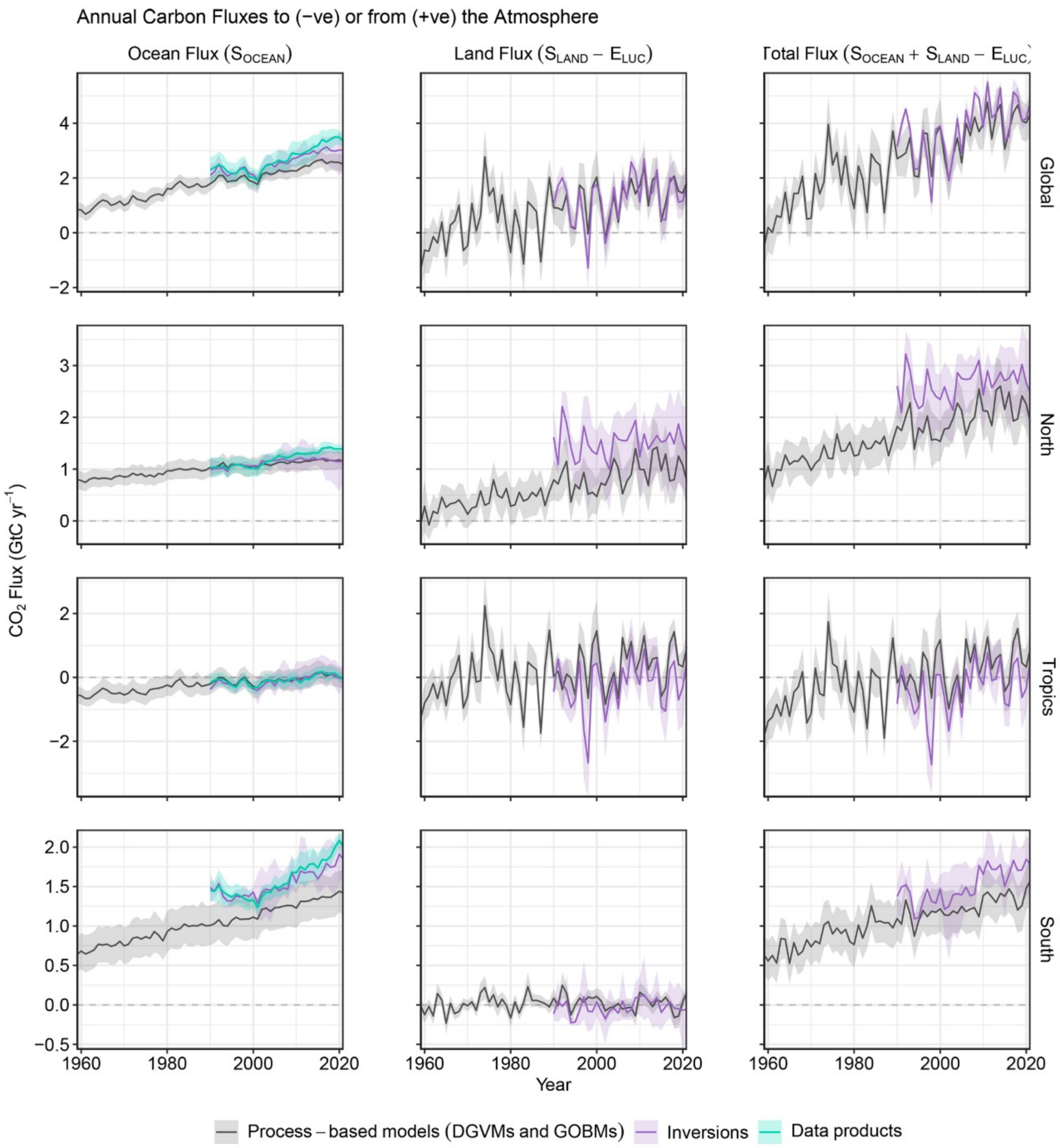
Inverse estimates

- Closed carbon balance by design
- Mostly used for latitudinal distribution
- And assessing the budget uncertainties



CARBON PROJECT

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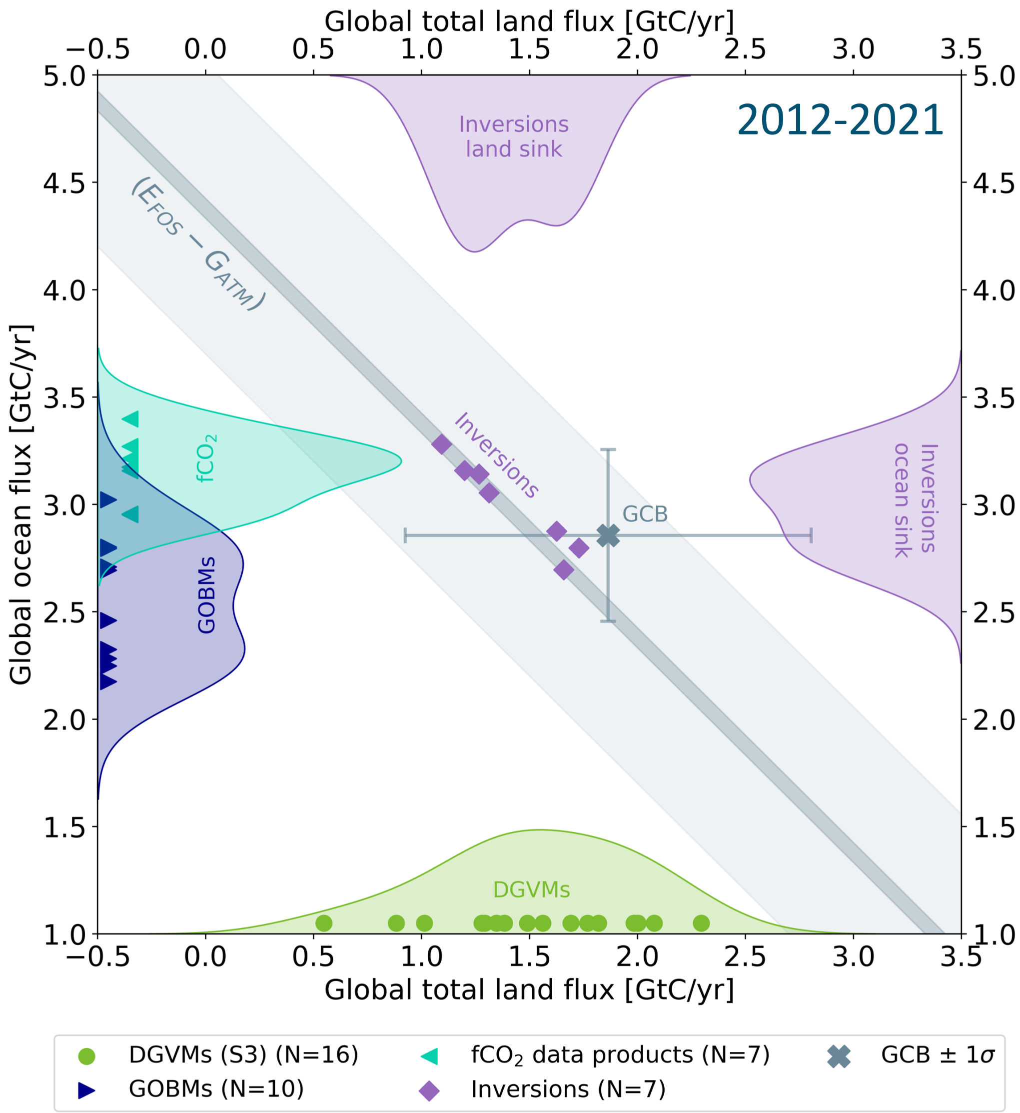
Uncertainties in the budget



GCB2022

Where is O_2 in this budget?

- Ocean models:
  - O_2/N_2 method is used to verify that the GOBMs provide realistic ocean sinks.
  - Values for the 1990s are used from IPCC (Manning and Keeling, 2006; Keeling and Manning, 2014), but not for more recent periods.
  - Estimates from Tohjima et al. 2019 are used for model evaluation, and discussed as indication of possible larger ocean sink for recent years (2012–2016: 3.1±1.5 PgC yr^{-1}).

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GLOBAL CARBON PROJECT

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- DGVMs:
  - O_2/N_2 method land sink is used as 1 of 3 criteria of minimum DGVM realism (Keeling and Manning, 2014) for 1990s and 2000s.
  - 90% confidence interval:
    -0.28 to 2.28 PgC & -0.07 to 2.61 PgC

Table 3 Decadal global carbon budgets allowing for decadal O_2 ventilation exchanges, superimposed on a constant ocean outgassing, Z_{eff}

Time frame	*Ocean sink (Pg C year^{-1})*	*Land sink (Pg C year^{-1})*
1990–2000	2.16 (0.62)	1.00 (0.80)
2000–2010	2.50 (0.60)	1.27 (0.84)

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- Discussion: potentional understanding land-ocean partitioning and budget imbalance

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However... River adjustment is missing

- The global fCO_2-based flux estimates were adjusted to remove the pre-industrial ocean source of CO_2 to the atmosphere of 0.65 GtC yr^{-1} from river input to the ocean (Regnier et al., 2022) to satisfy the definition of S_{OCEAN} (Hauck et al. 2020).
- This is also applied to the inversions, which see the natural fluxes over land, transported by rivers from land to ocean, and outgassed by the ocean.
- The same regional adjustments are applied to allow comparison of the different budget components and inversions.

With adjustment

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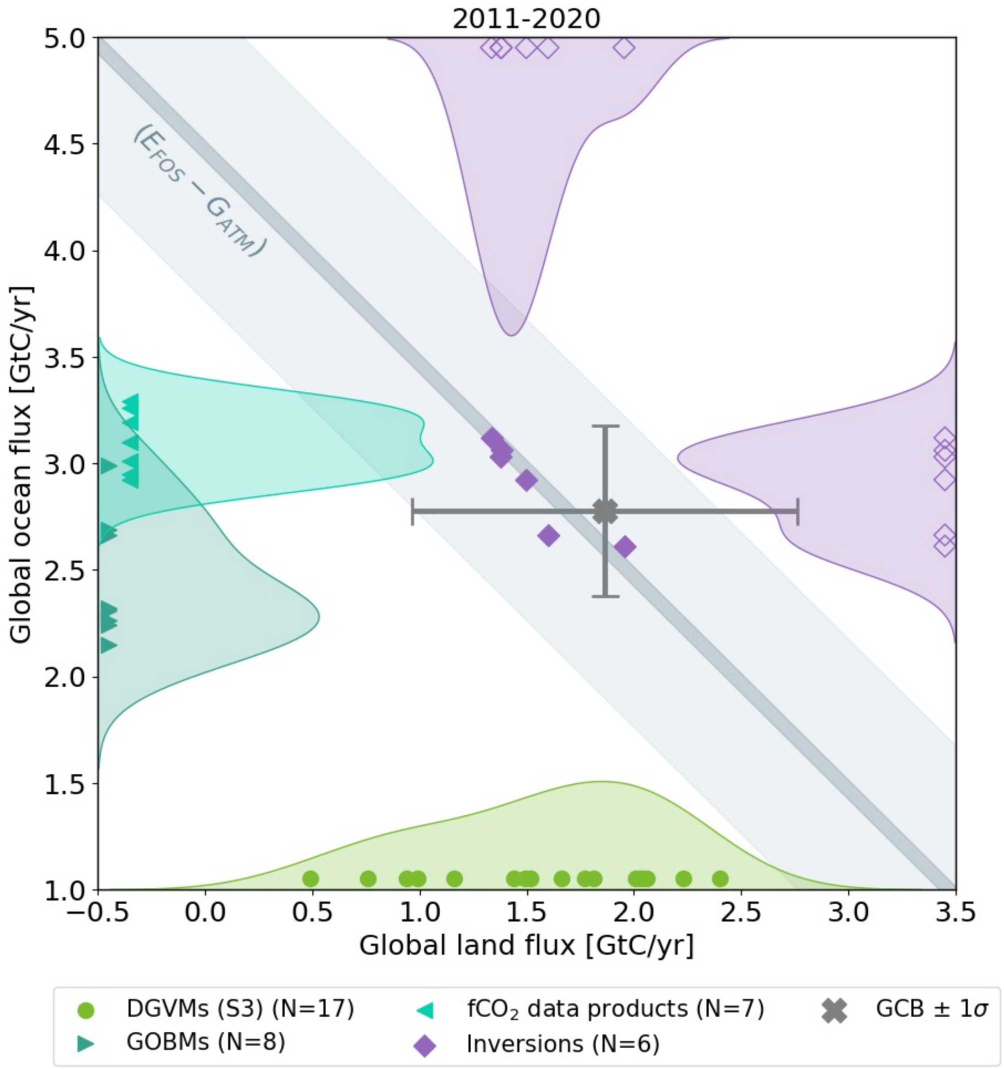

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Without adjustment (not correct)

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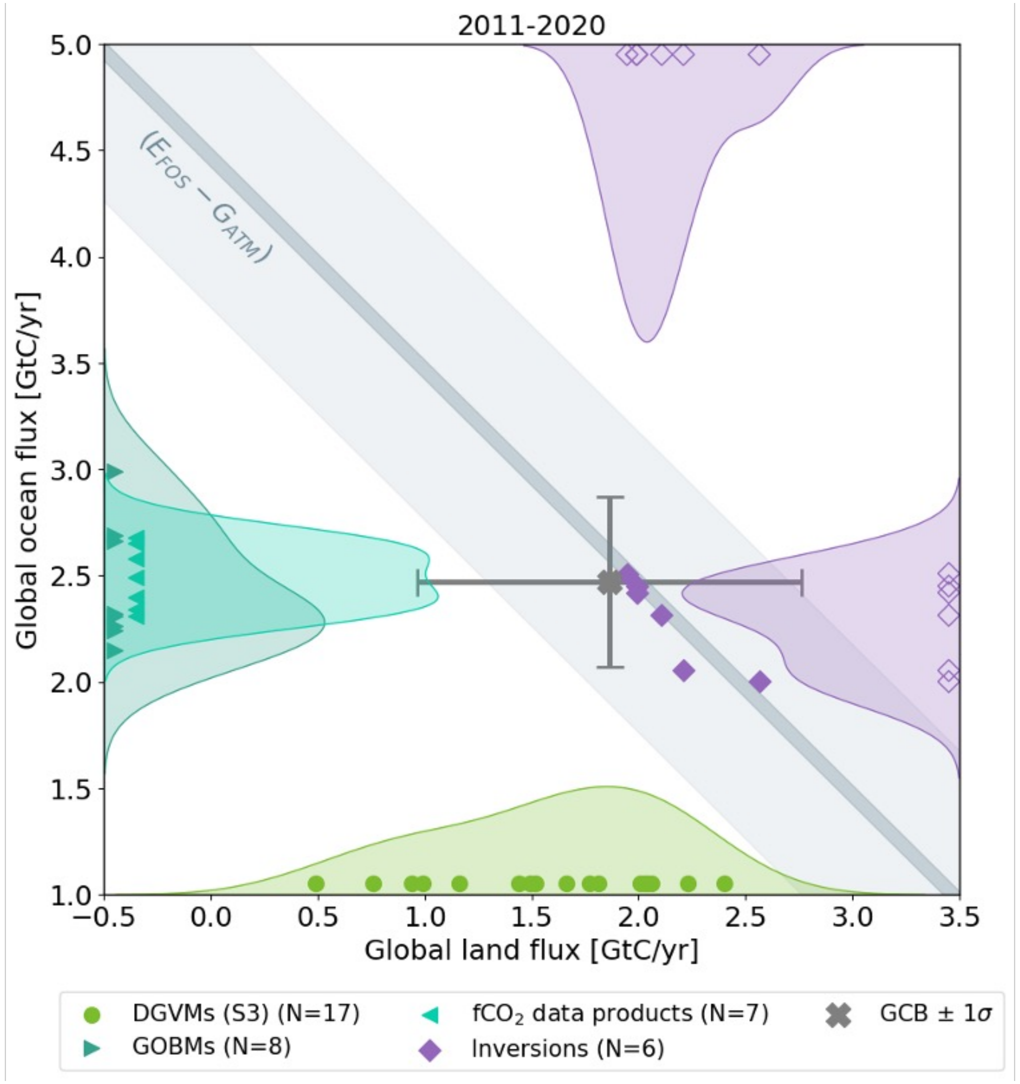

GCB2021

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- This is also applied to the inversions, which see the natural fluxes over land, transported by rivers from land to ocean, and outgassed by the ocean.
- The same regional adjustments are applied to allow comparison of the different budget components and inversions.
- Needs to be applied to the O_2 method estimates as well, following the same reasoning.

Requests for larger role for O_2 in GCB

GLOBAL CARBON PROJECT

Discussed at the Exeter workshop, and requested by the core team:

- Extention of validation of GOBMs and DGVMs for more recent decades.
- Inclusion in Table and Figure as separate estimate, next to current budget components (on an annual basis?).

Potential larger role for O_2 in GCB

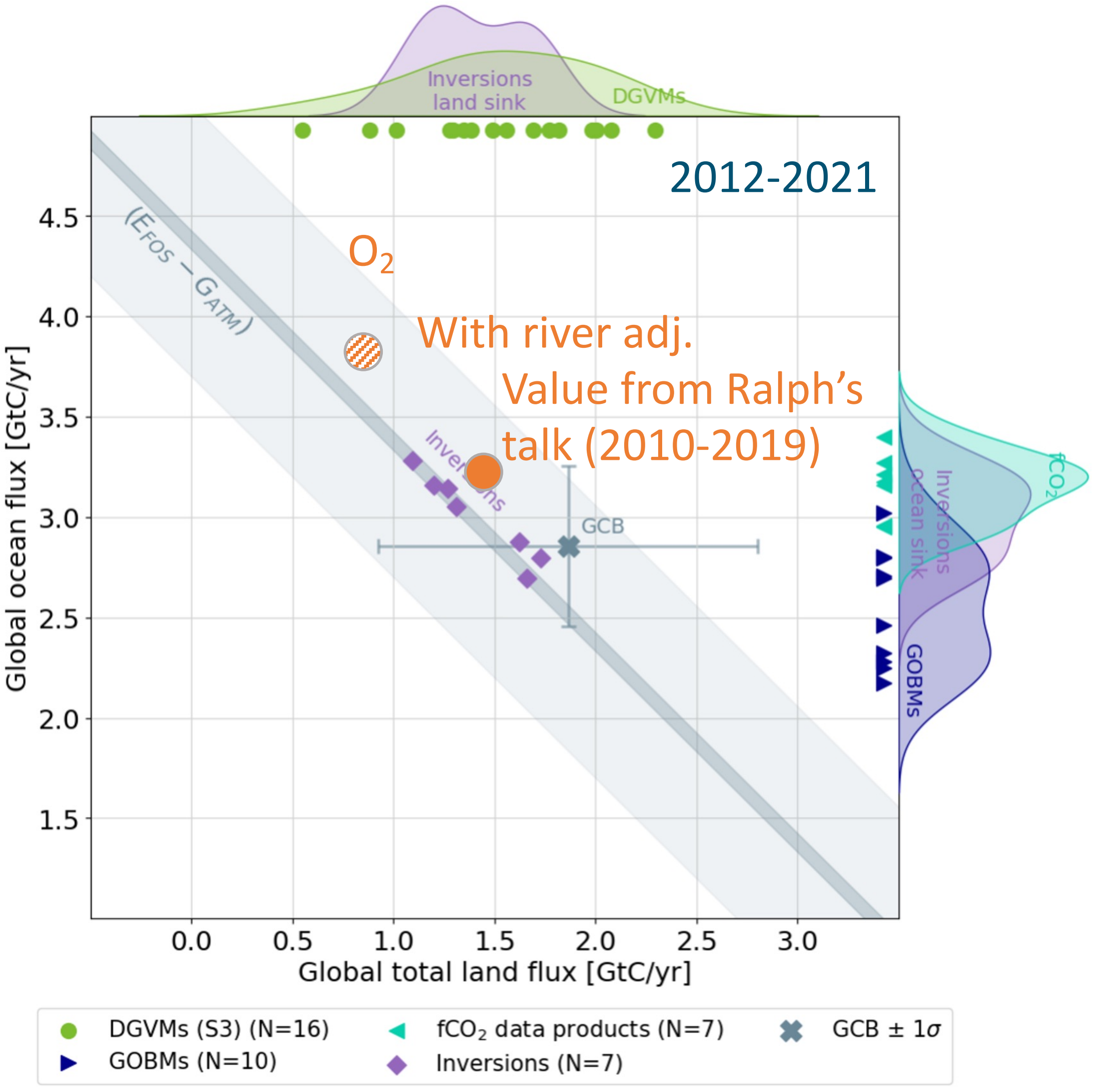

Table 5. Comparison of results from the bookkeeping method and budget residuals with results from the DGVMs and inverse estimates for different periods, the last decade, and the last year available. All values are in GtC yr^{-1}. See Fig. 7 for an explanation of the bookkeeping component fluxes. The DGVM uncertainties represent $\pm 1\sigma$ of the decadal or annual (for 2021) estimates from the individual DGVMs; for the inverse systems the range of available results is given. All values are rounded to the nearest 0.1 GtC and therefore columns do not necessarily add to zero.

		Mean (GtC yr^{-1})						
		1960s	1970s	1980s	1990s	2000s	2012–2021	2021
Land-use change emissions (E_{LUC})	Bookkeeping (BK) Net flux (1a)	1.5 ± 0.7	1.2 ± 0.7	1.3 ± 0.7	1.5 ± 0.7	1.4 ± 0.7	1.2 ± 0.7	1.1 ± 0.7
	BK – deforestation	1.6 ± 0.4	1.5 ± 0.4	1.6 ± 0.4	1.8 ± 0.3	1.9 ± 0.4	1.8 ± 0.4	1.8 ± 0.4
	BK – organic soils	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1
	BK – re/afforestation and wood harvest	−0.6 ± 0.1	−0.6 ± 0.1	−0.6 ± 0.2	−0.7 ± 0.1	−0.8 ± 0.2	−0.9 ± 0.3	−1.0 ± 0.3
	BK – other transitions	0.4 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.2
	DGVM net flux (1b)	1.4 ± 0.5	1.3 ± 0.5	1.5 ± 0.5	1.5 ± 0.6	1.6 ± 0.6	1.6 ± 0.5	1.6 ± 0.5
Terrestrial sink (S_{LAND})	Residual sink from global budget (E_{FOS} + E_{LUC} (1a) − G_{ATM} − S_{OCEAN}) (2a)	1.7 ± 0.8	1.8 ± 0.8	1.6 ± 0.9	2.6 ± 0.9	2.8 ± 0.9	2.8 ± 0.9	2.8 ± 1
	DGVMs (2b)	1.2 ± 0.4	2.2 ± 0.5	1.9 ± 0.7	2.5 ± 0.4	2.7 ± 0.5	3.1 ± 0.6	3.5 ± 0.9
Total land fluxes (S_{LAND} − E_{LUC})	GCB2022 budget (2b–1a)	−0.2 ± 0.8	1 ± 0.9	0.5 ± 1	1 ± 0.8	1.4 ± 0.9	1.9 ± 0.9	2.4 ± 1.1
	Budget constraint (2a–1a)	0.2 ± 0.4	0.6 ± 0.5	0.3 ± 0.5	1.1 ± 0.5	1.5 ± 0.6	1.5 ± 0.6	1.7 ± 0.7
	DGVMs net (2b–1b)	−0.1 ± 0.4	0.9 ± 0.5	0.4 ± 0.5	0.9 ± 0.4	1.2 ± 0.3	1.5 ± 0.5	1.9 ± 0.7
	Inversions*	–	–	0.3–0.6 (2)	0.7–1.1 (3)	1.2–1.6 (3)	1.1–1.7 (7)	1.5–2.1 (9)

* Estimates are adjusted for the pre-industrial influence of river fluxes and the cement carbonation sink and are also adjusted to common E_{FOS} (Sect. 2.6). The ranges given include varying numbers (in parentheses) of inversions in each decade (Table A4).

	1960s	1970s	1980s	1990s	2000s	2012–2021	2021
O_2 method				xx	xx	xx	xx

Requests for larger role for O_2 in GCB

Discussed at the Exeter workshop, and requested by the core team:

- Extention of validation of GOBMs and DGVMs for more recent decades.
- Inclusion in Table and Figure as separate estimate, next to current budget components (on an annual basis?).
- What do people here think? Is this feasible?
- What does it take to make this happen?
- What would be the time lag? Is an annual basis realistic?
- How about the ocean outgassing and its variability? (difference tables 1 and 3 in Keeling and Manning 2014)

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Discussion on merging datasets and creating an O_2 Obspack product

- What is Obspack? (https://gml.noaa.gov/ccgg/obspack/data.php)
  - Data product merging datasets from different institutes. Compiled and released by NOAA and ICOS for different species. E.g. the most recent CO_2 obspack product (GVP 8.0) has 586 datasets from 66 labs: 30.207.706 datapoints.
  - Data is provided on the X2019 scale, or is converted by NOAA to this scale. Some data are on their own scale (e.g. Tohoku Univ. 2010 scale)
  - Data comes with extensive metadata and DOI
  - In netcdf or txt file format per record (in a zip file)
  - Free and open access, with a license to inform data providers on the use and acknowledge/cite/offer co-authorship where appropriate

Discussion on merging datasets and creating an O_2 Obspack product

- With more and more O_2 modelling efforts being started, there is a growing need for O_2 observational data, and Obspack offers a well used and documented framework that can be applied for O_2 as well.

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- Is this supported by the groups present here?

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Discussion on merging datasets and creating an O_2 Obspack product

- With more and more O_2 modelling efforts being started, there is a growing need for O_2 observational data, and Obspack offers a well used and documented framework that can be applied for O_2 as well.
- Is this supported by the groups present here?
- Which sites? Include campaigns?
- How about the scale?
  - Possibility to have a first package with different scales, but user notes?
  - Scale conversion to Scripps scale? By individual labs? Or central?
  - What can be the role of GOLLUM (or other ICPs) here?
- Differences in types of sampling, and reporting time per sample (integrated/grab samples/continuous)
- Other topics?

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Concerns raised by Andrew Kowalski

- Related to O_2 flux calculated by vertical gradient, as no Eddy Covariance O_2 is possible yet

Concerns raised in review to:

Biogeosciences

A Modeling Approach to Investigate Drivers, Variability and Uncertainties in O_2 Fluxes and the $O_2 : CO_2$ Exchange Ratios in a Temperate Forest

Yuan Yan, Anne Klosterhalfen, Fernando Moyano, Matthias Cuntz, Andrew C. Manning, and Alexander Knohl

But applies also to other O_2 ecosystem studies, incl. Faassen et al. 2023 and Ishidoya et al. 2013/2015

Two issues:

- Dilution effect (wet vs dry air)
- Stephan flow and correction

Dilution effect (wet vs dry air)

- O_2 flux is calculated as:
  - $F_{\{O_2\}} = -K_h * \frac{dO_2}{dz}$

- dO_2 is measured in dry air in our community
- K is determined from EC, but has density (water) correction (WPL)

- So: issue solved

- But if O_2 can be measured with EC in the future, the WPL will be large, and can cause uncertainties

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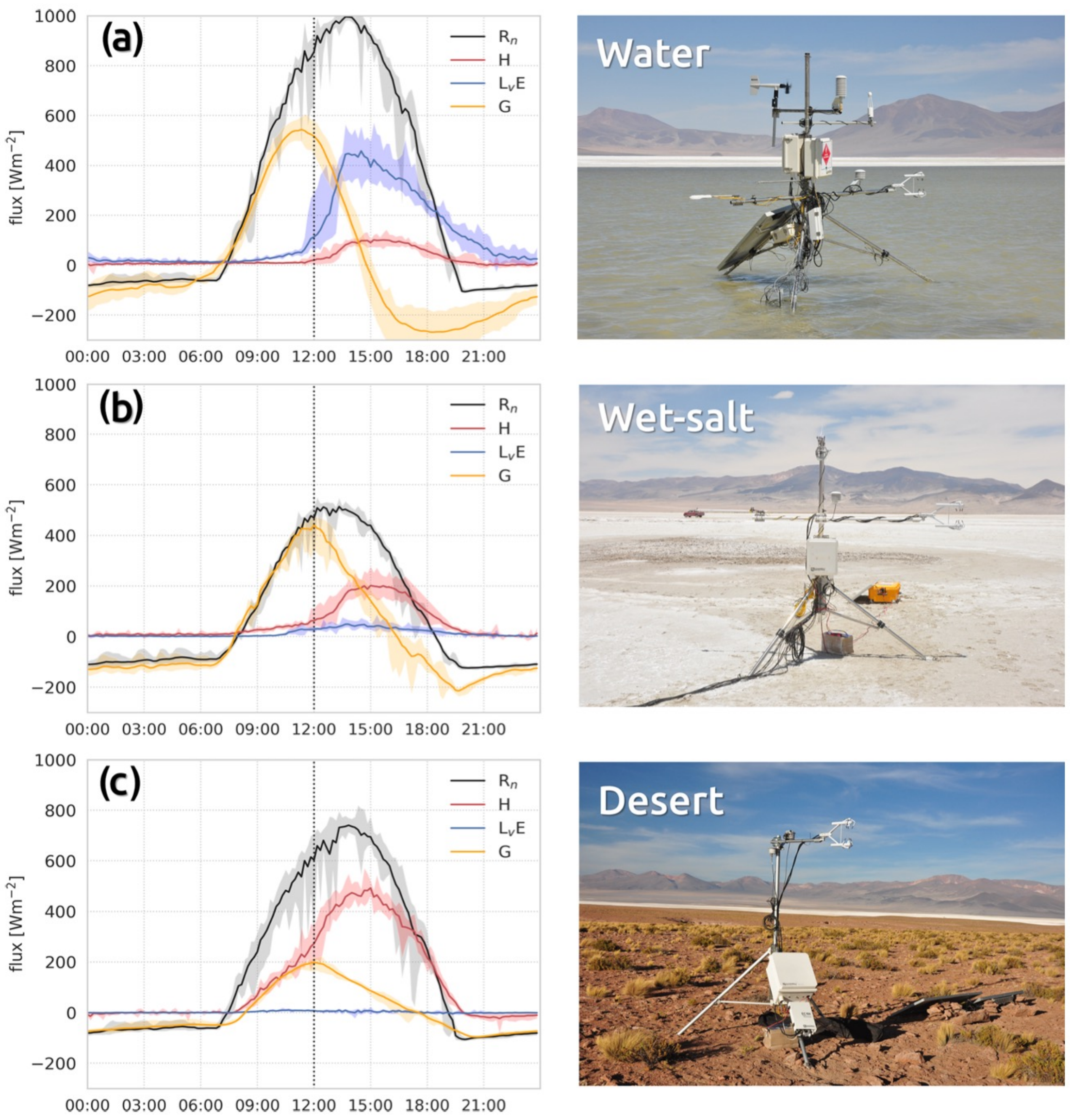
Transport in the atmosphere (background info)

- Molecular diffusion (small scale)
  - Caused by gradient of the species itself
- Turbulent diffusion (larger, atmospheric scale)
  - Caused by gradients in heat (turbulent convection) and wind shear
- Density diffusion or Stephan flow (small scale as induced by molecular diffusion)
  - Caused by gradients in water vapor

- Together these 3 mechanisms cause transport in the atmosphere

Example

- Example Felipe Lobos Atacama desert



Local evaporation controlled by regional atmospheric circulation in the Altiplano of the Atacama Desert

Felipe Lobos-Roco[1,2,*], Oscar Hartogensis[1], Jordi Vilà-Guerau de Arellano[1], Alberto de la Fuente[3], Ricardo Muñoz[4], José Rutllant[4,5], and Francisco Suárez[2,6,7]

Consequences for O_2 measurements?

- Kowalski 2017 and Kowalski et al. 2021:
- $ws = \frac{E}{\rho}$

$$F_c = F_{c,ndiff} + F_{c,diff} = w_s \bar{\rho}_c + \overline{\rho w'' f_c''},$$

- Kowalski: Stephan flow velocity needs to be corrected for, and is currently not done
- E is measured by EC which includes all 3 types of diffusion, incl. turbulence
- Stephan flow is very small, and when measuring dry air not relevant
- So our conclusion is that Stephan flow is not relevant on canopy scale, but only on leaf scale. Confirmed by O_2 ecosystem flux publications in our community that do not show issues
- When modelling O_2 it is important to stick with conserved variables (e.g. mole fractions)

Conclusion / discussion

- Issues raised are valid, but not relevant on the ecosystem scales that we study

- Any further thoughts on this issue?
- Questions?