Satellites are now critical for observing the air-sea CO_2 fluxes and CO_2 sink: Recent advances and new opportunities

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Importance of the ocean

Global carbon budgets
The global land sink of carbon cannot be measured.

Accurate estimates of CO_2 absorption provide a powerful constraint on global carbon budgets and are needed to inform policies to motivate societal shifts towards reducing carbon emissions.

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Food security and conservation
Identify regions and ecosystems at risk .

Satellite observations already play a critical role in large spatial scale CO_2 sink studies

Examples
Upscaling *in situ* parameterisations eg Ho *et al.*, (2011), JGR

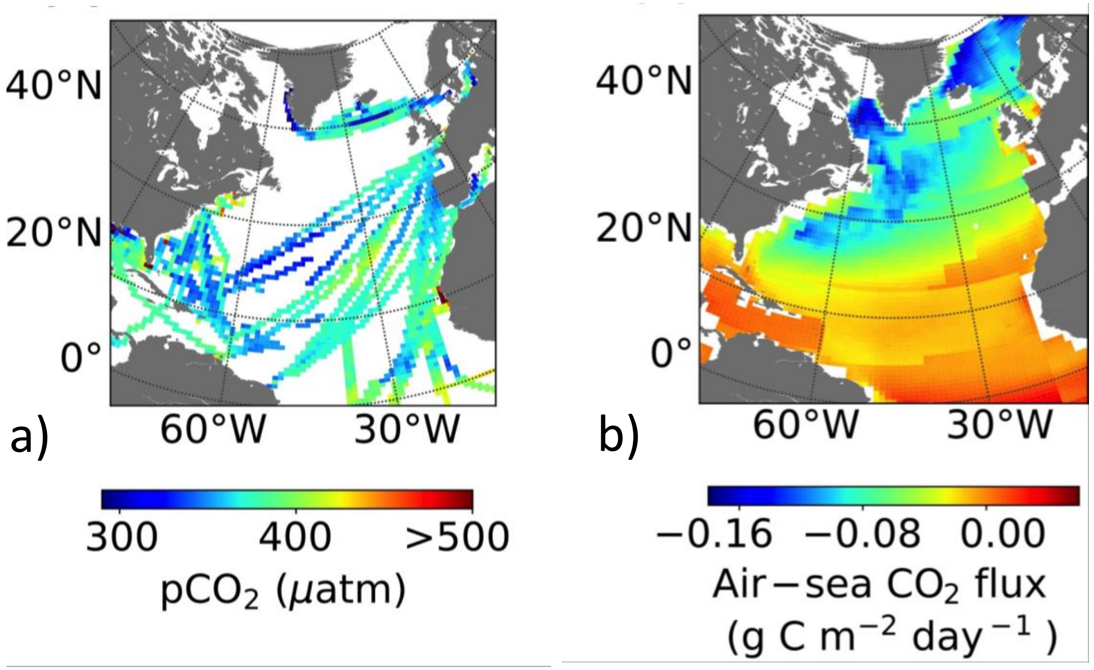
Interpolating data in time and space eg Schuster *et al.* (2013), BG

Studying heterogeneous regions eg Laruelle *et al.*, (2017), BG

Investigating uncertainties eg Woolf *et al.,* (2019), GBC

Investigating biological controls eg Henson *et al.* (2019), GRL

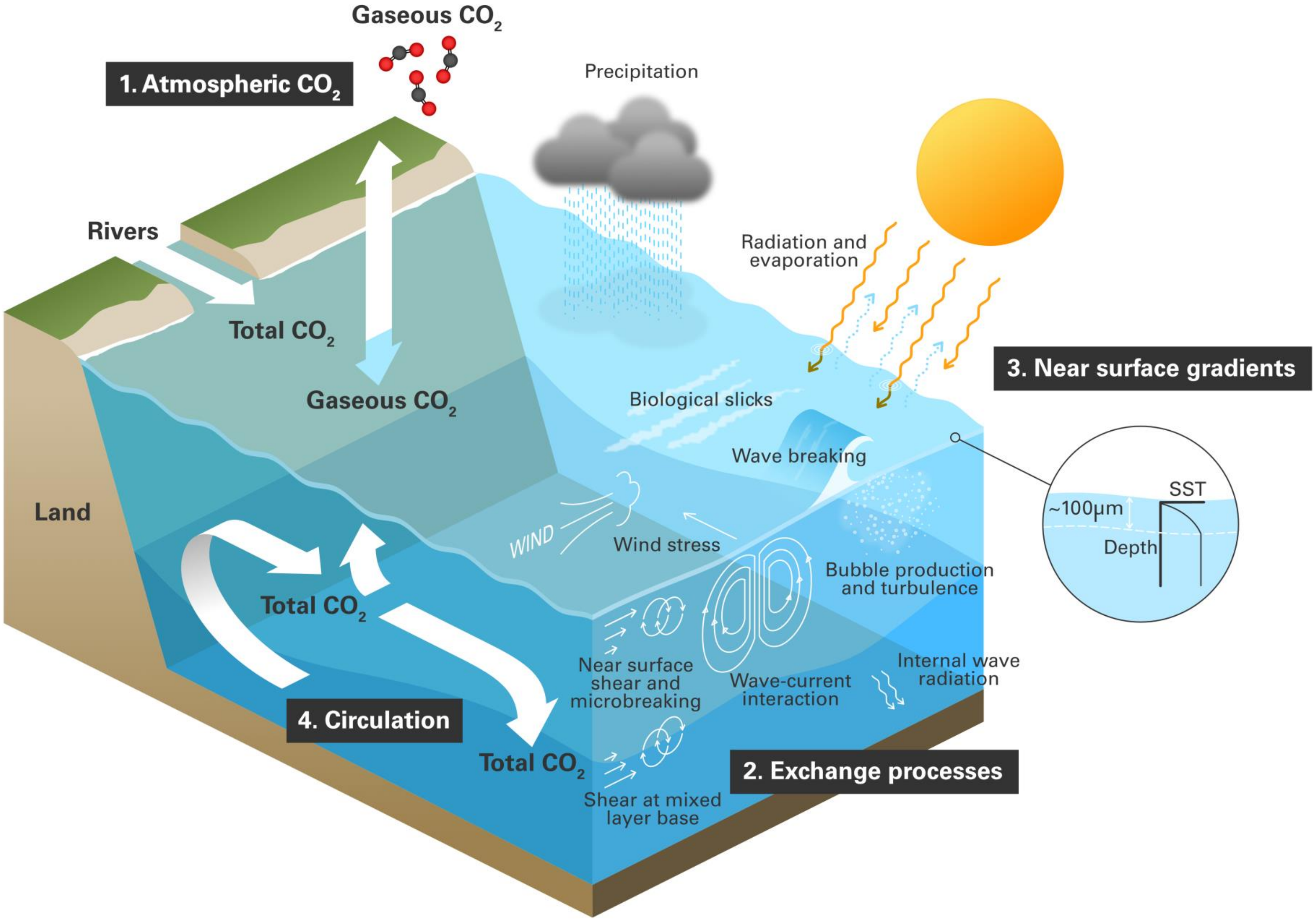
Example satellite observations being used
Sea state, wind speed, temperature, rain, biology, salinity and ice coverage.



a) example *in situ* partial pressure dataset (amount of gaseous CO_2 in the water); b) spatially complete atmosphere-ocean CO_2 gas fluxes calculated using the *in situ* data combined with Earth observation data.

But satellite observations offer much more!

Simplified view of interactions, exchange and circulation of CO_2 within the ocean, identifying where satellite Earth observation can play a leading role in expanding understanding.



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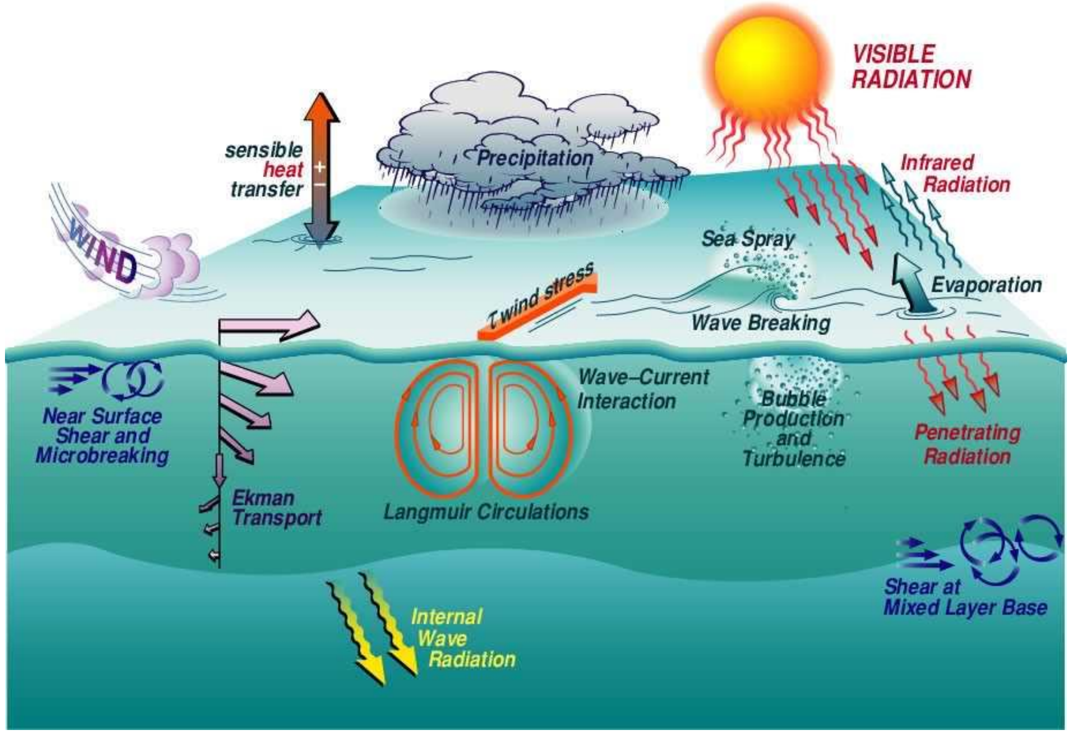
Improving understanding of gas exchange at the water surface

Current
Majority of studies use wind speed to describe atmosphere-ocean gas exchange eg Ho et al., (2011), JGR.

Many other processes influence gas transfer (eg biogenic slicks, fronts) and regional specifics (eg polar waters).

Research focus is now shifting towards more physically-based approaches.



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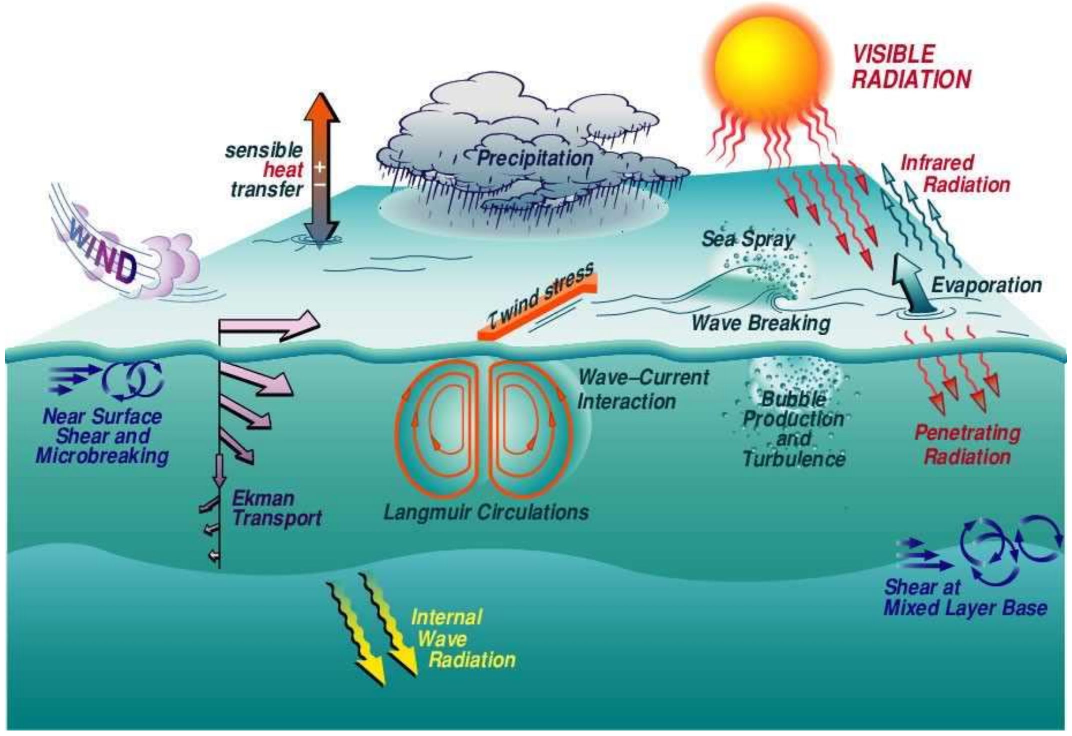
Opportunities

Transfer processes and passive microwave are more closely linked to sea surface roughness and exchange.

Potential for holistic study of gas, momentum and heat fluxes.

30+ year archive of global passive microwave data unexplored



1 GHz Passive microwave 200 GHz

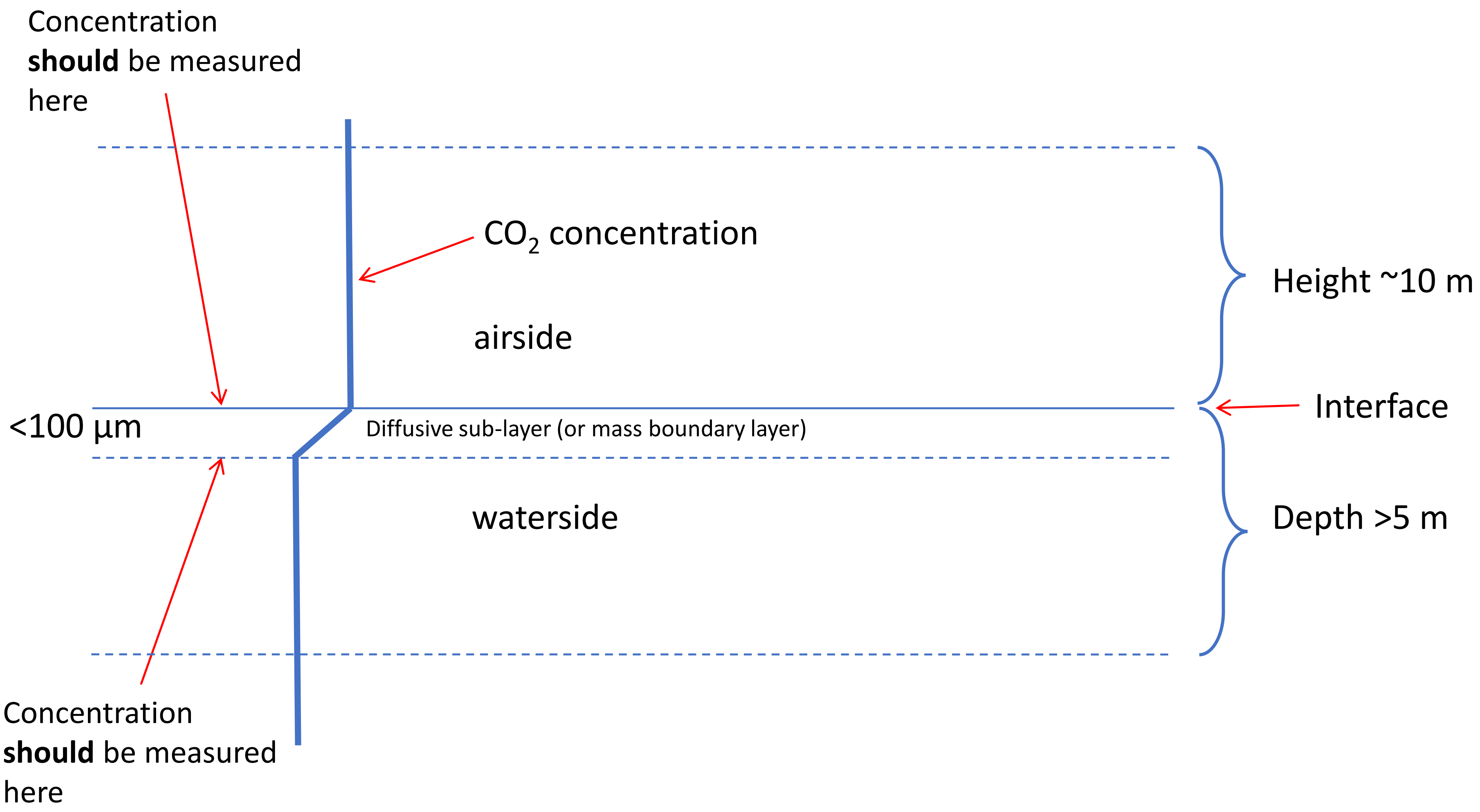
salinity (dielectric) | sea surface temperature | wind | foam | rain | Water vapour | ice

Parameters retrieved from passive microwave

NASA Butterfly mission proposal

ESA Copernicus Imaging Microwave Radiometer (CIMR)

Enabling measurement of near-surface concentrations



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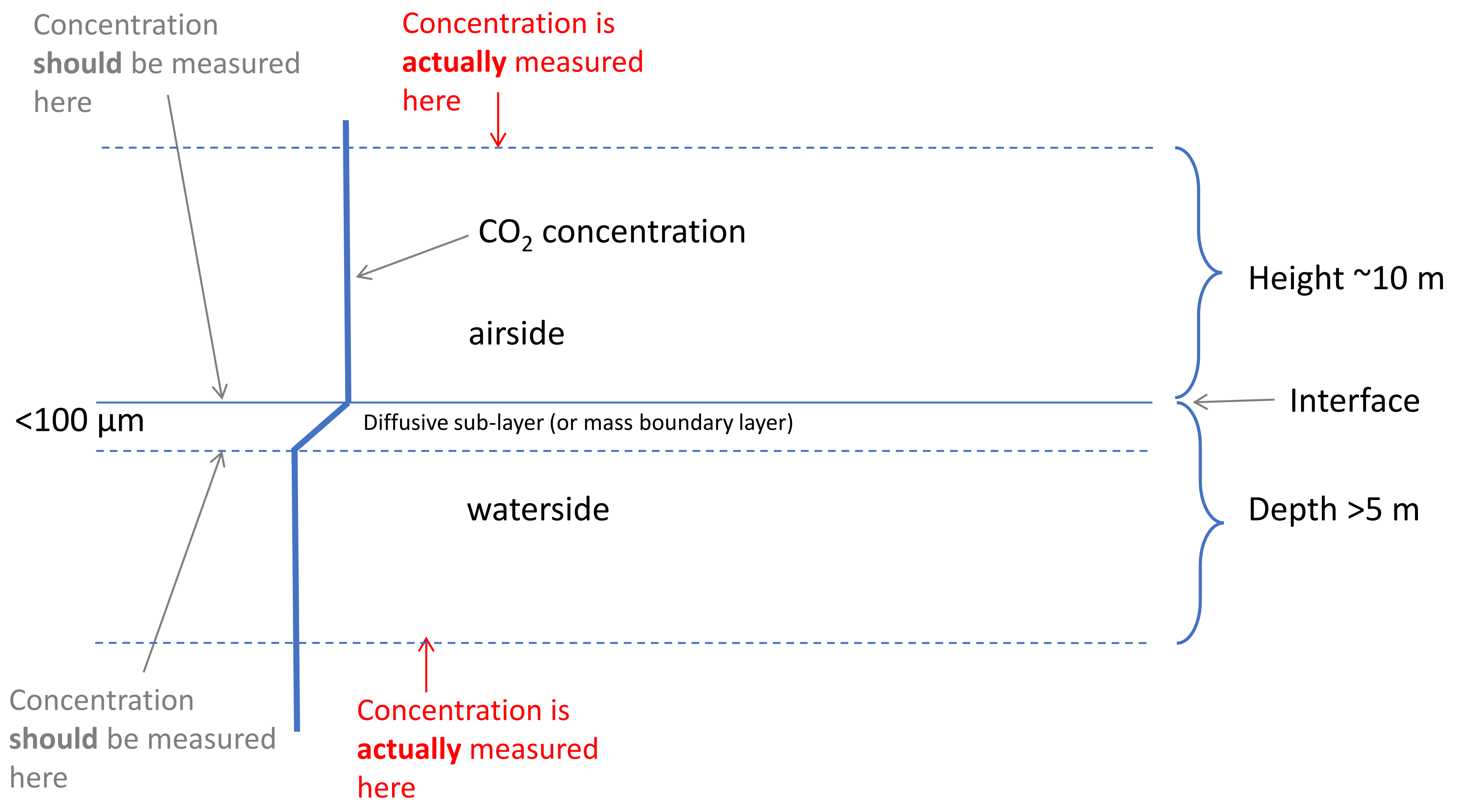

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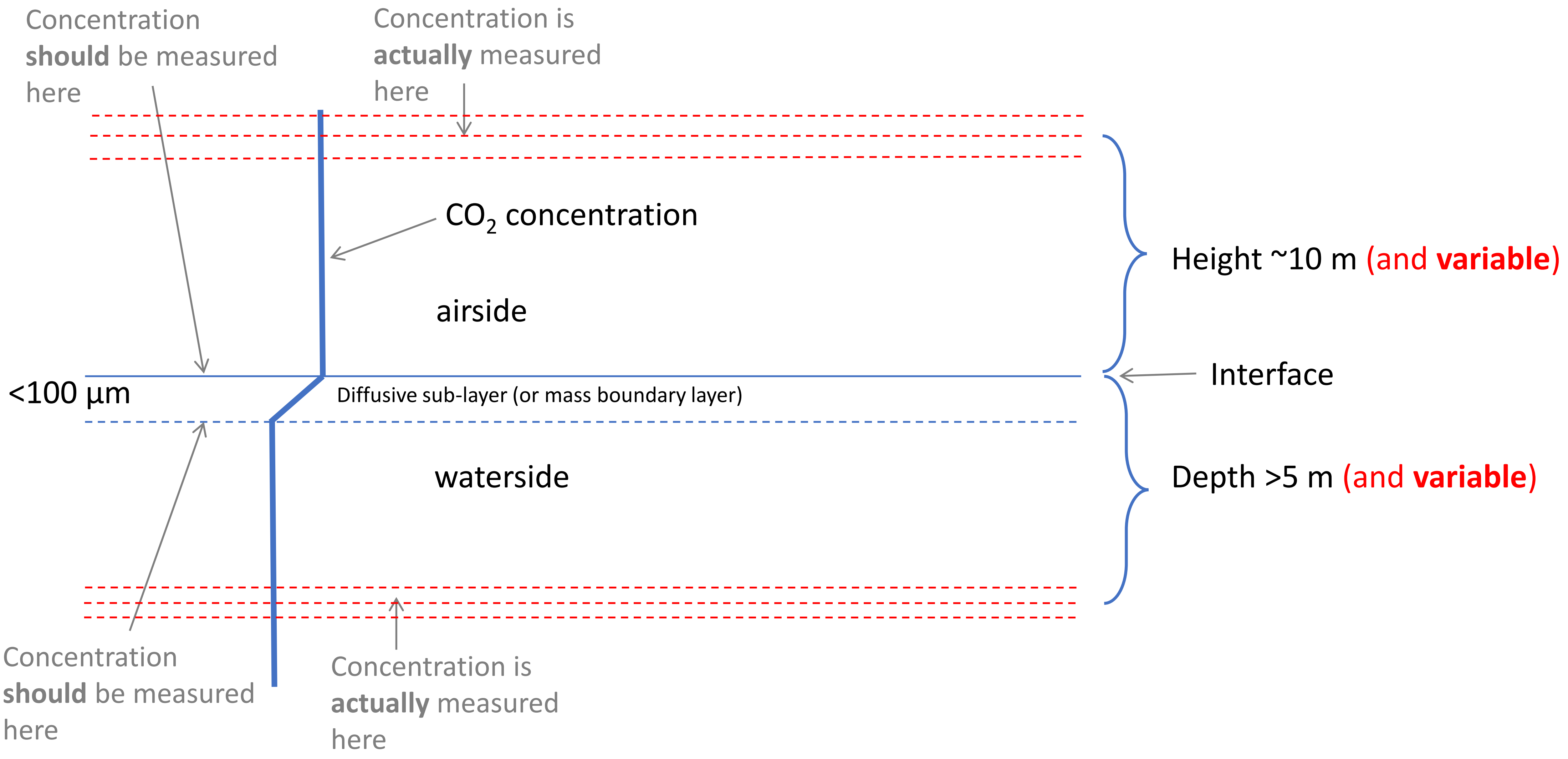

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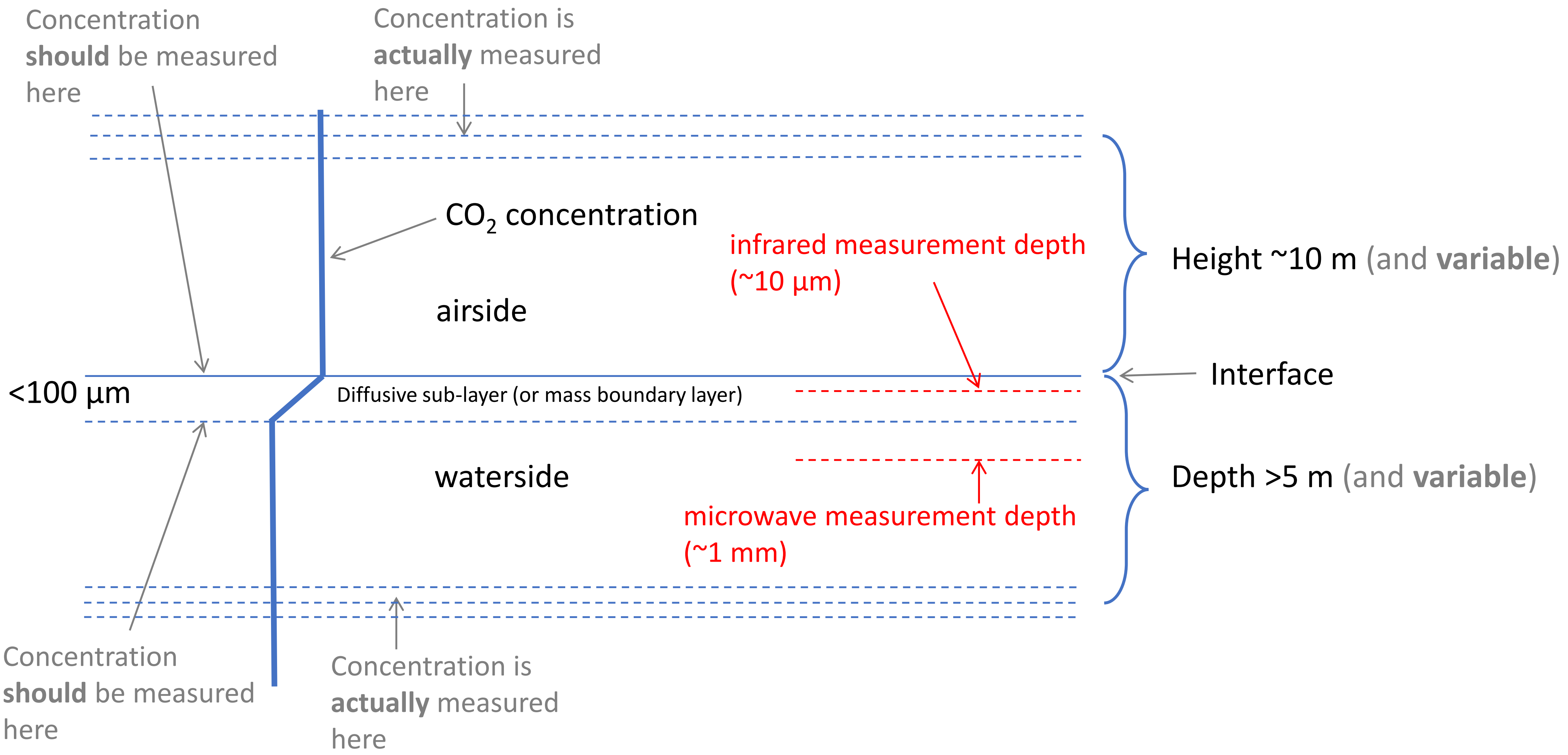
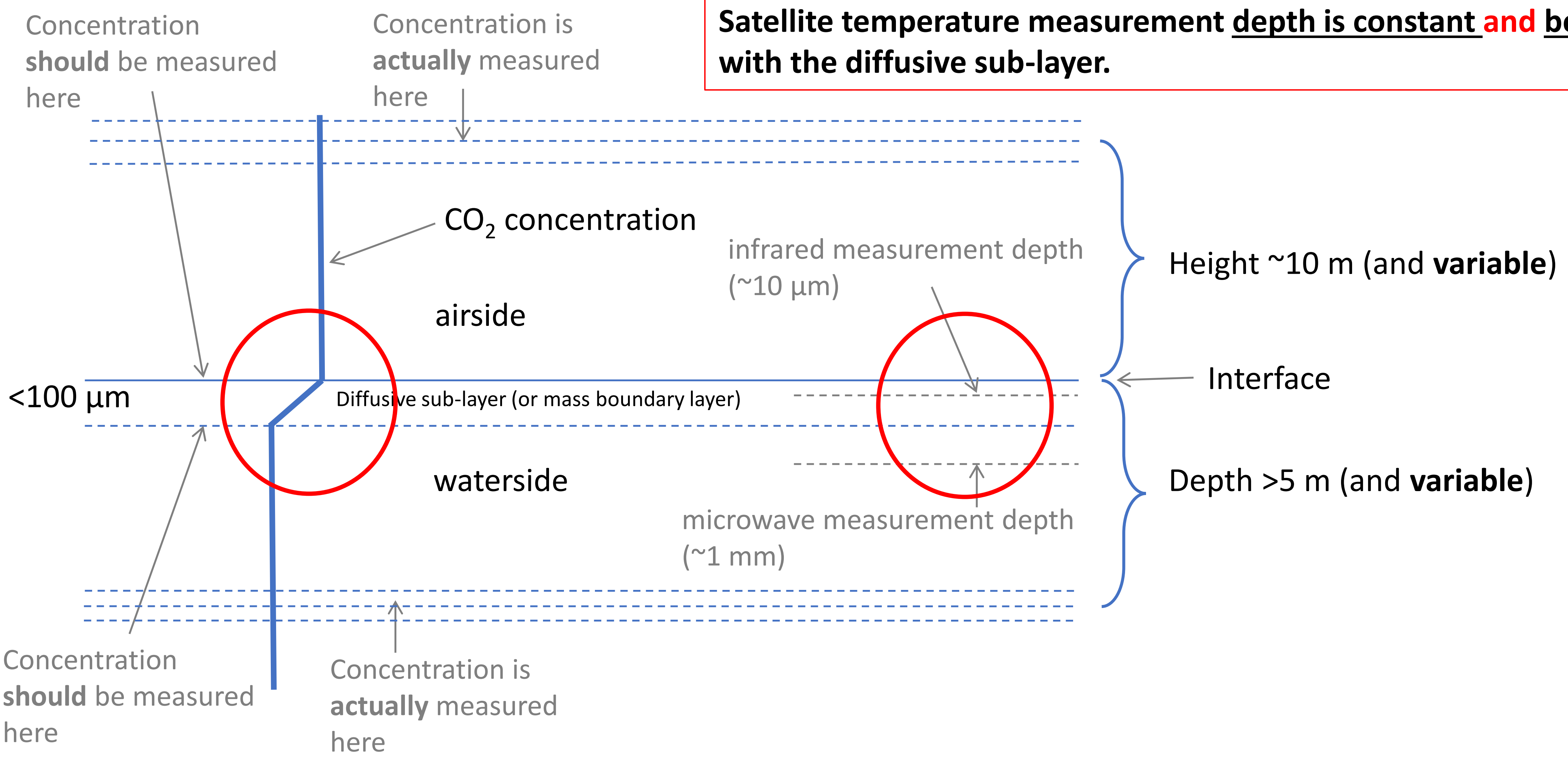


Enabling measurement of near-surface concentrations

Concentration is strongly temperature controlled.
Satellite temperature measurement depth is constant and better aligned with the diffusive sub-layer.



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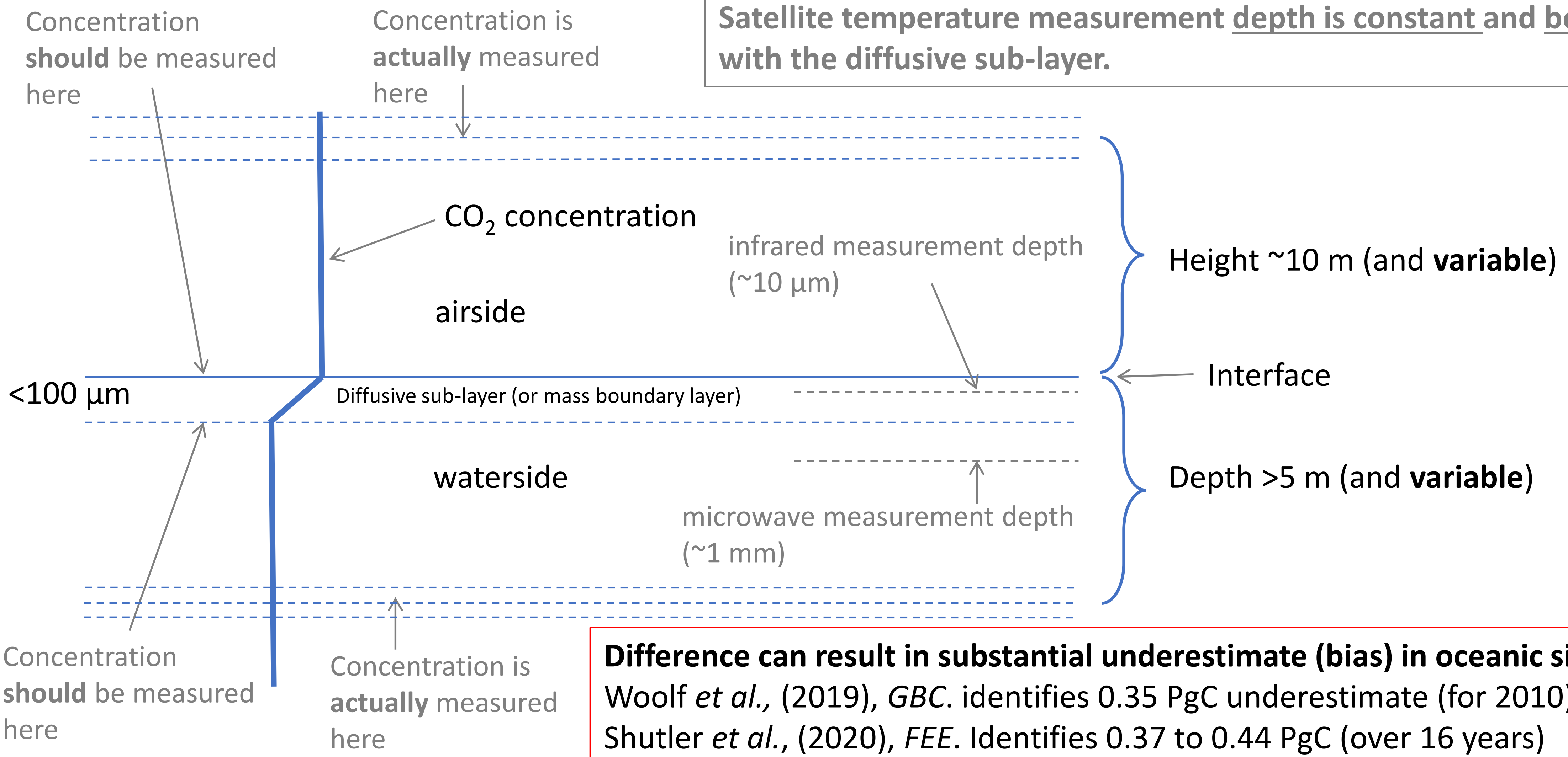

Difference can result in substantial underestimate (bias) in oceanic sink
Woolf *et al.*, (2019), *GBC*. identifies 0.35 PgC underestimate (for 2010)
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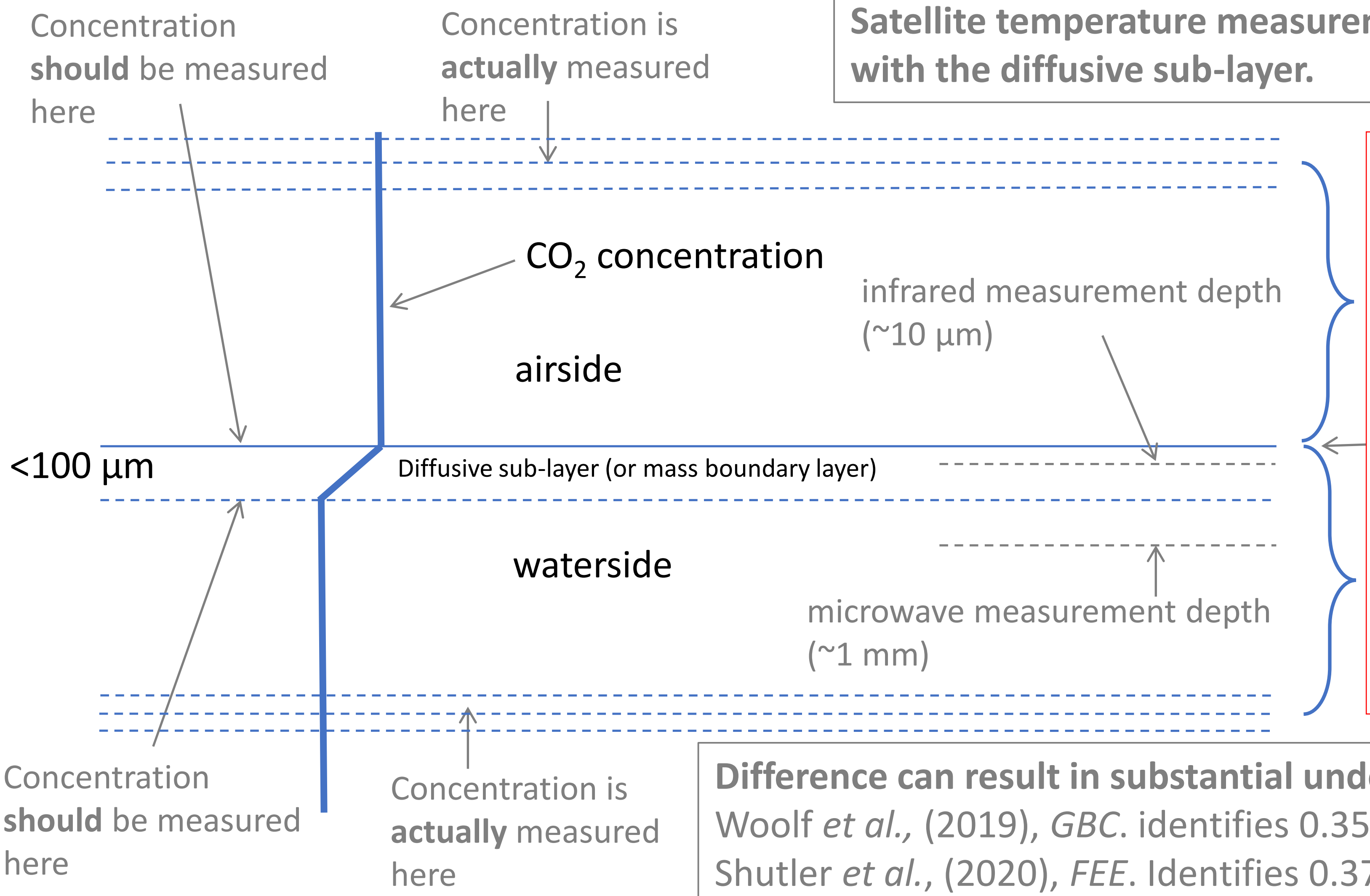

Opportunity
Satellite salinity measurements represent the conditions at constant depth (~1 mm).

Salinity modifies concentration and is likely important in Polar waters.

Salinity can be strongly correlated with alkalinity.

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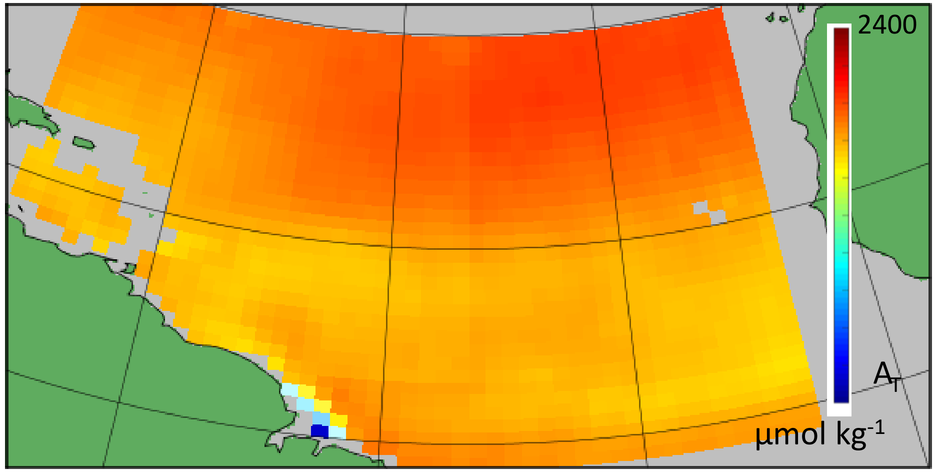
Land-ocean riverine inputs and variability

Current
Potential for systematic underestimation of contribution in global carbon budgets Resplandy *et al.*, (2018), NG.

Magnitude of riverine carbon fluxes has large uncertainties of 100% eg Regnier *et al.,* (2013), NG.

Variability of riverine carbon fluxes not well characterised. Extreme or sudden events may contribute 50% of annual discharge eg Bianchi *et al.,* (2013), GRL.



Satellite observation-based total alkalinity in North Atlantic and Amazon plume. Land *et al.,* (2019)

Land, P. E., *et al.*, (2019) Optimum satellite and *in situ* inputs to carbonate system algorithms in the Global Ocean, the Greater Caribbean, the Amazon Plume and the Bay of Bengal, *Remote Sensing of Environment*.

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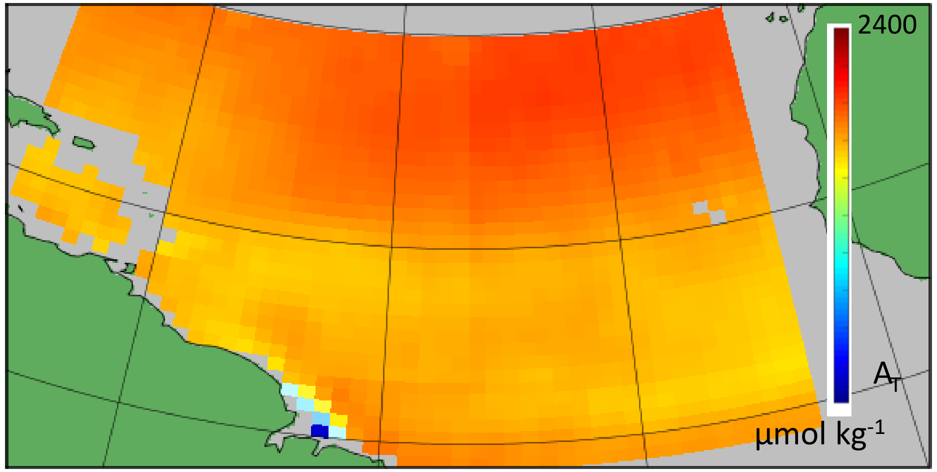

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Opportunities
Satellite observation-based estimates of organic (eg Mannino *et al.*, 2016, JGR) and inorganic (eg Land et al., 2019).

Network of low-cost *in situ* instrumentation for observing variability in large river systems.

Low-cost (€10000) in-water gaseous CO_2 sensor.

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Atmospheric CO_2 near the water surface

Current
All global ocean sink estimates to date have used zonally averaged data from 60 NOAA *in situ* marine boundary layer stations (MBLR).

North-south gradients from continental airflow known to be poorly captured.

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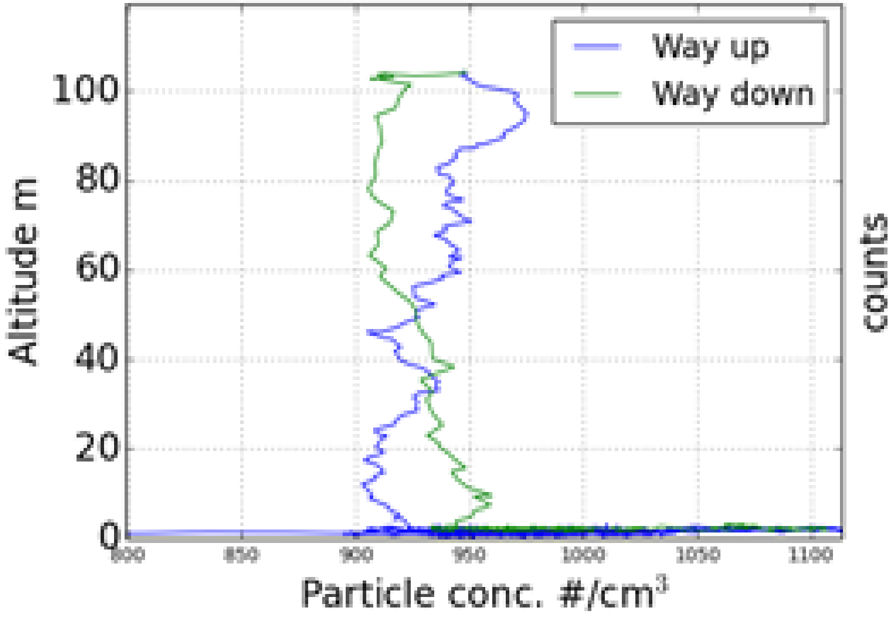
Opportunities
Satellite observed column integrated CO_2 measurements over water are possible (accuracy <1 ppm) and these can be separated into lower (surface) and upper (long range transported) components. eg Kulawik *et al.*, (2017), ACP

Use drones and balloons to identify the accuracy of both satellite and MBLR data.



Example boundary layer aerosol particle measurements collected using a drone

Quantifying Internal circulation and surface transport of total CO_2

Current

Geostrophic currents are calculated from sea level height. Knowledge of location, wind and Earth's rotation enables calculation of Ekman flows.

Re-analysis data used to identify link between upwelling and carbon sink. eg Landschutzer *et al.*, (2015), Science.

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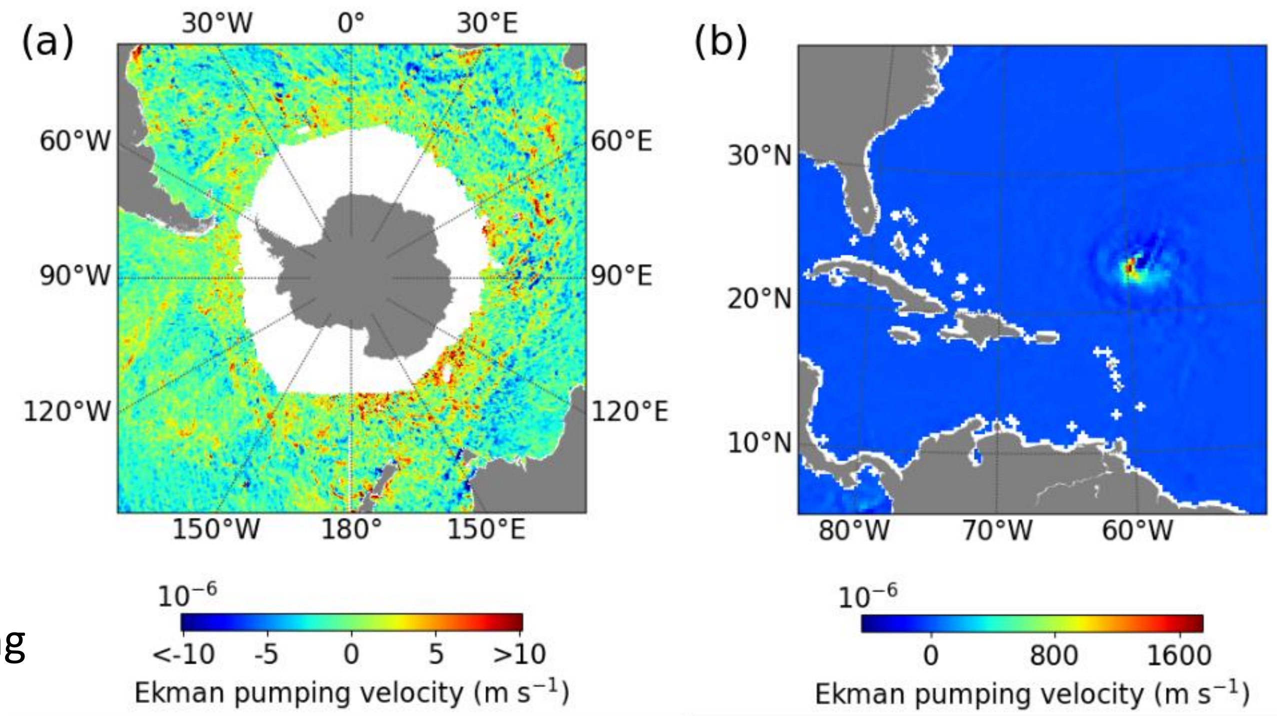
Opportunities

Satellite observations yet to be fully exploited. eg upwelling

Potential to quantify large spatial scale three-dimensional transport of momentum, heat, nutrients and total CO_2.

eg provide constraints on global circulation and identify regions at risk from sudden ocean acidification events.

Future satellite missions could provide direct measurements.



a) Earth observation-based Ekman pumping in Southern Ocean; b) Ekman pumping due to hurricane Igor in 2010.

eg see Quilfen *et al.* (2021), *Remote Sensing of Environment*

Challenge: Full appreciation of uncertainty budgets

Current
In situ datasets, climatologies and/or re-analysis datasets are often missing the combined uncertainty budgets. eg GLODAPv2 contains bias, but no variance; much of WOA contains no uncertainty information.

Incomplete uncertainty information can reduce exploitation of the *in situ* data.

Some communities are working towards providing more complete uncertainty information and recognise the challenges involved (eg Eddy covariance, Dong *et al*., 2021, *GRL*)

Standards exist: eg Fiducial measurements (ESA, 2019) and BIPM (1994, 2008) (Type A uncertainty eg bias and standard deviation of instrument or method, Type B uncertainty is expert opinion)

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Future needs
- Classify combined uncertainties for key historical data using expert opinion eg high, medium, low (type B uncertainties).
- Development of protocols for carbon specific fiducial measurements.
- Follow standard uncertainty frameworks and nomenclature (eg BIPM 1994, 2008)

Routine carbon sink monitoring is now needed and possible, but sustained effort is needed

Required components:

- Computing facilities.
- Traceable calculation software; framework for uncertainties.
- Routine satellite data collection and provision.
- Regular atmospheric *in situ* and model re-analysis data.
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Traceable calculation

FluxEngine: verified, version controlled, open-source, standard outputs

Computing

eg Google Earth Engine

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esa

Copernicus Europe's eyes on Earth

NOAA

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Needs updating to acknowledge
“Long-term man-made climate disaster”
or companies make them routinely available

a for
ges (eg

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Voluntary

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2. Arico S, Arietta JM, Bakker DCE *et al*. (2021) *Integrated ocean carbon research: a summary of ocean carbon research, and vision of coordinated ocean carbon research and observations for the next decade, UNESCO and IOC,* UNESCO, Paris*, 45 pp.*

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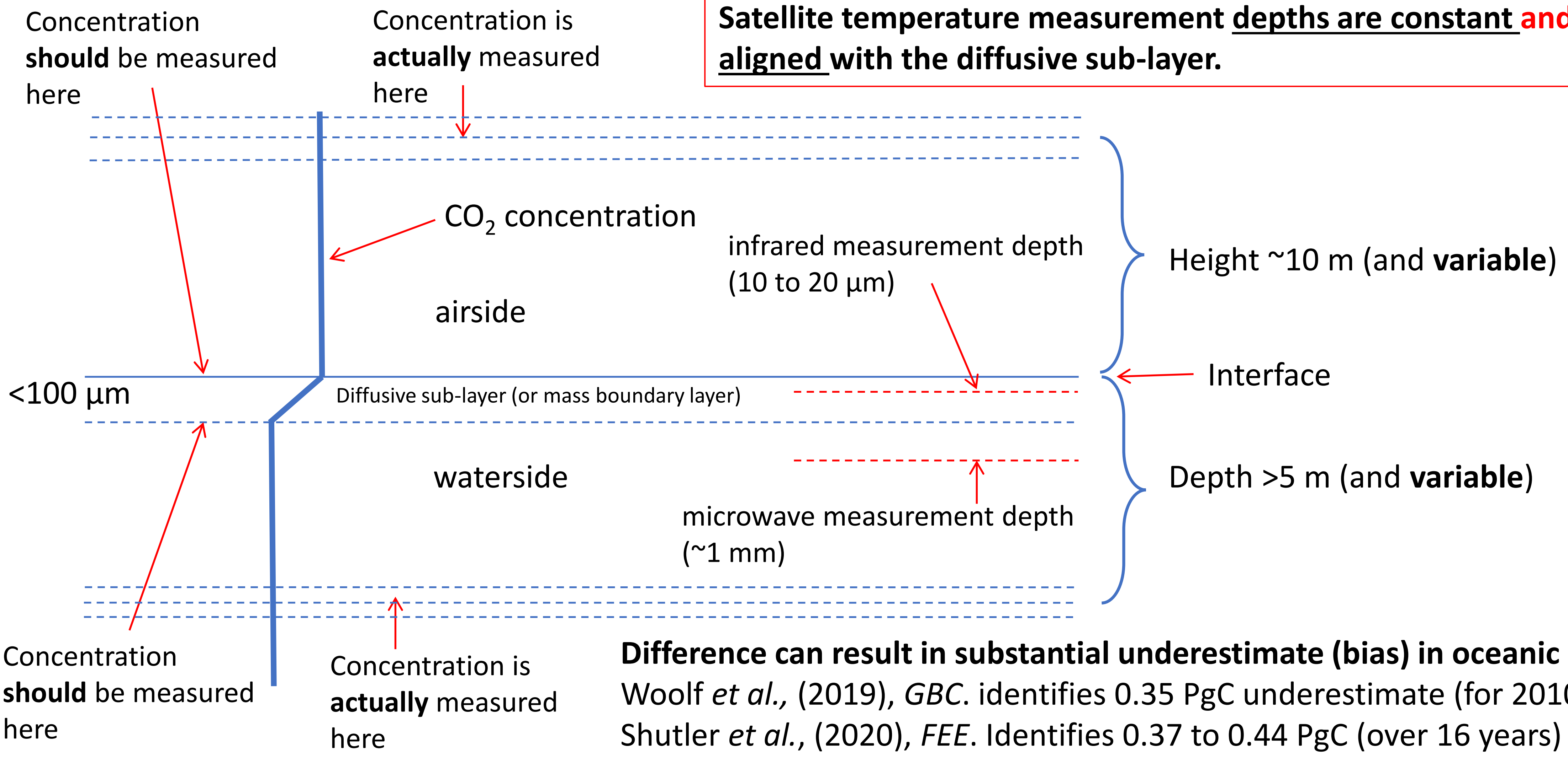

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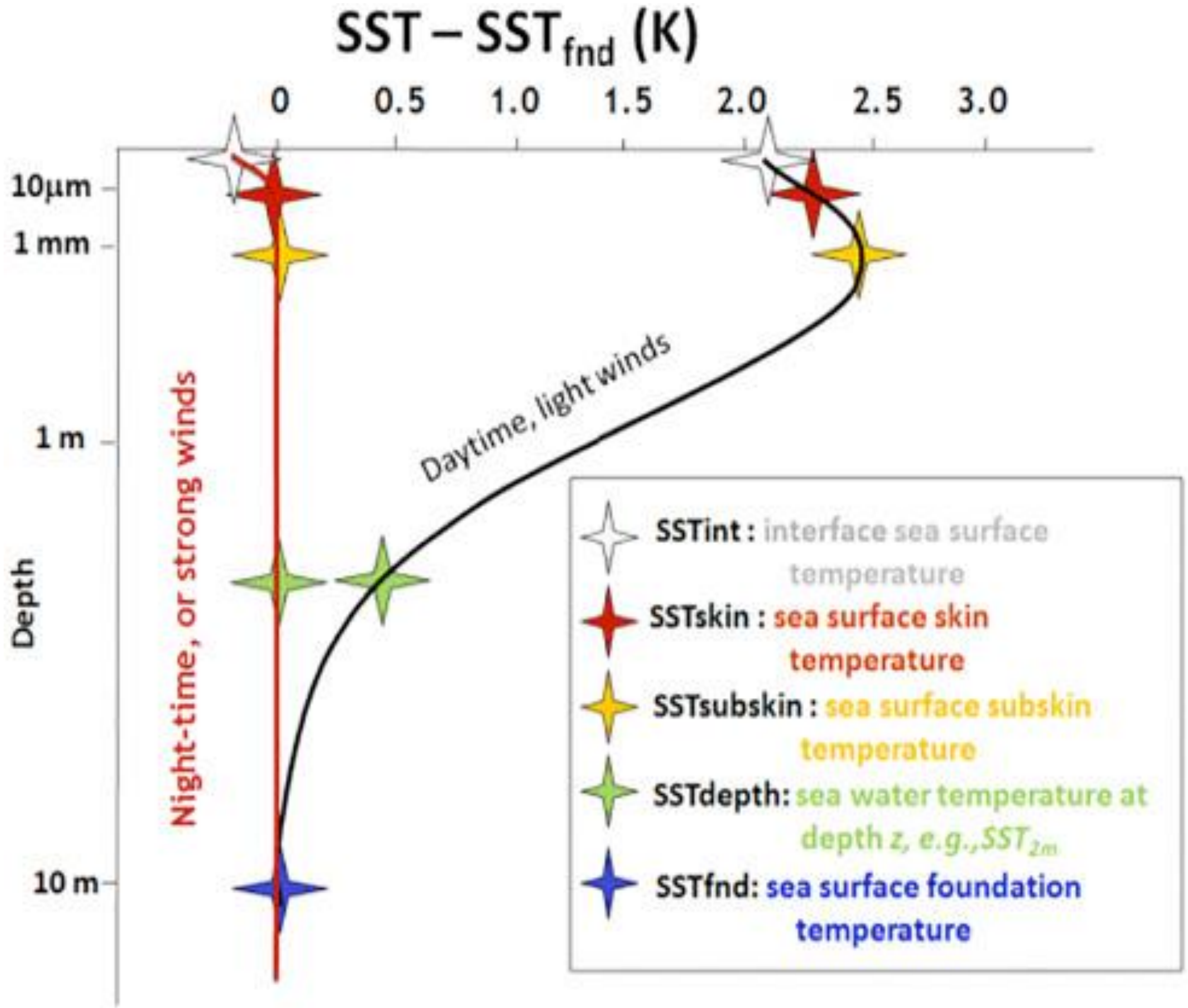

SST – SST$_{fnd}$ (K)
0
0.5
1.0
1.5
2.0
2.5
3.0
10µm
1 mm
1 m
10 m
Depth
Night-time, or strong winds
Daytime, light winds
SSTint : interface sea surface temperature
SSTskin : sea surface skin temperature
SSTsubskin : sea surface subskin temperature
SSTdepth: sea water temperature at depth z, e.g.,SST$_{2m}$
SSTfnd: sea surface foundation temperature