Linking tropical large-scale circulation and deep convection to subtropical marine low clouds in the Pacific Ocean

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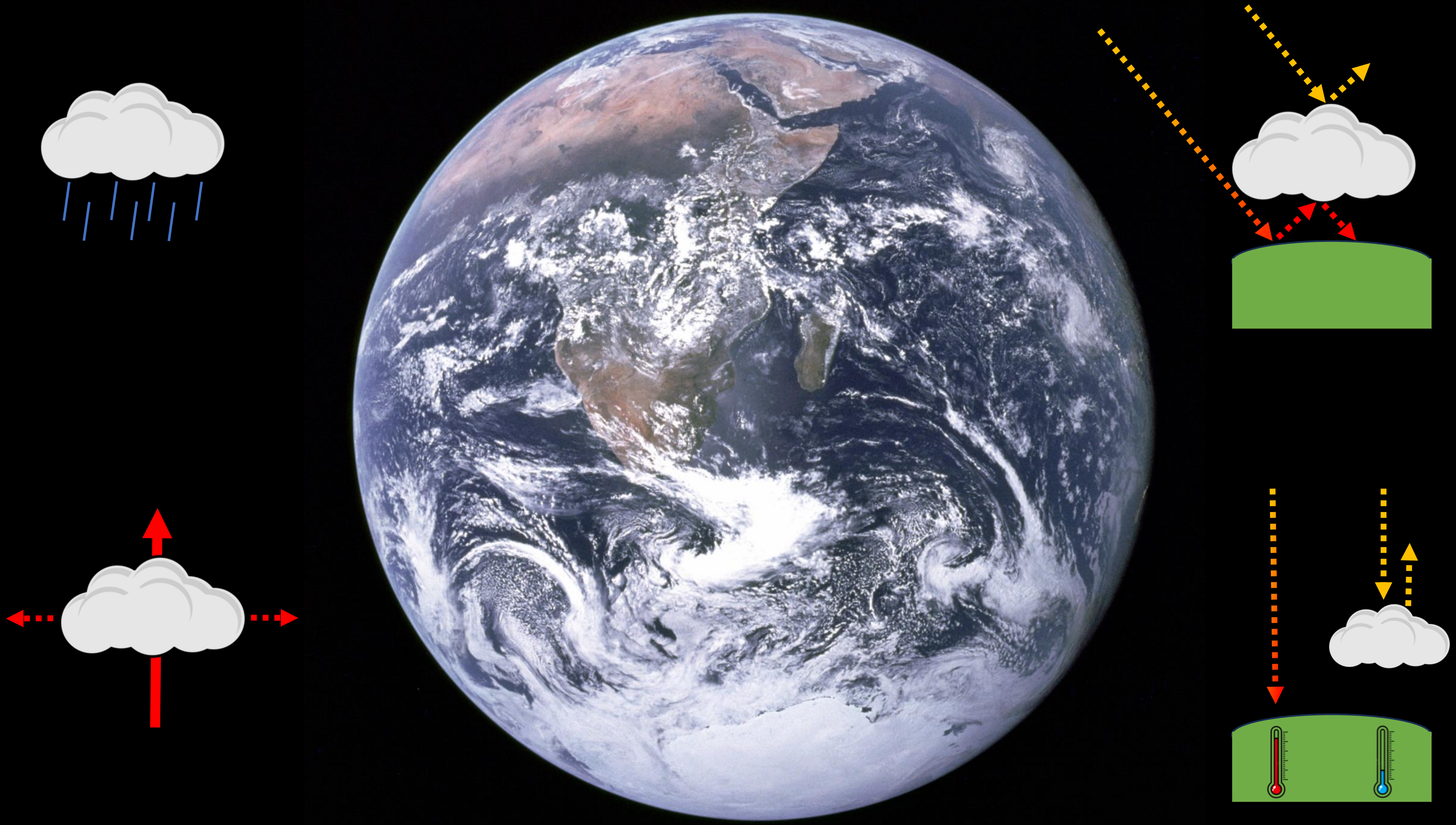
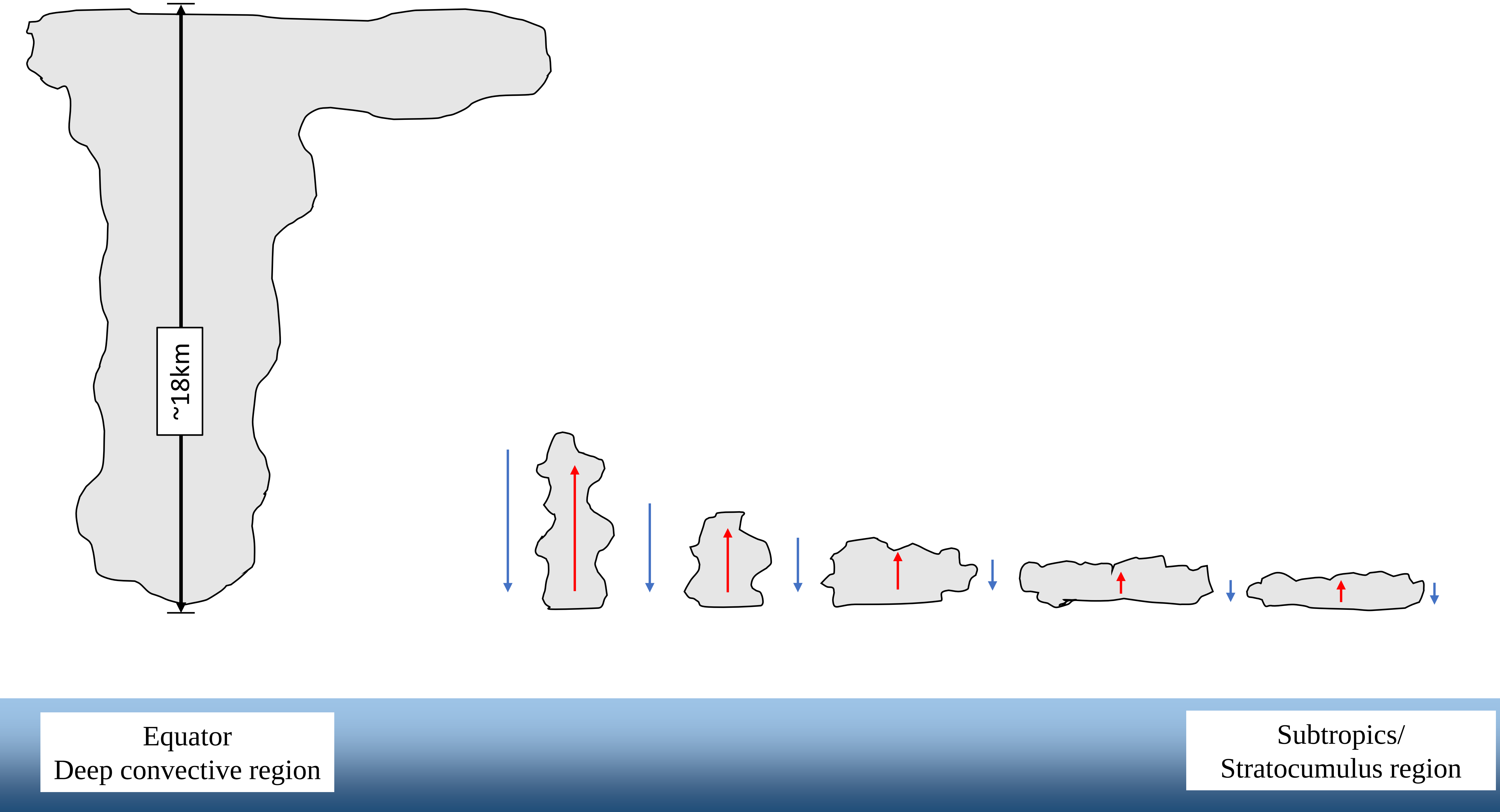
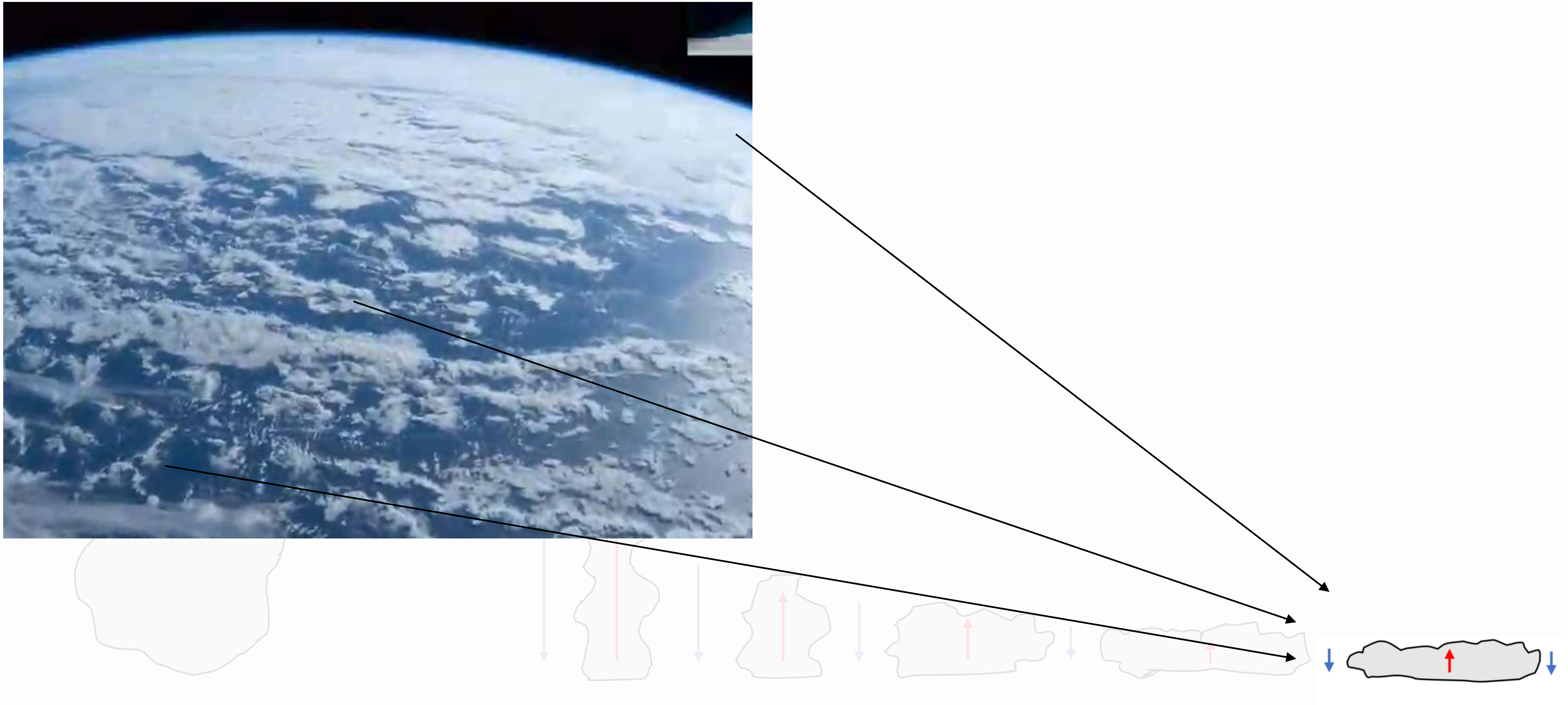
University of Exeter, UK

Hugo Lambert
University of Exeter
Mark Webb
Met Office, UK
Geoff Vallis
University of Exeter

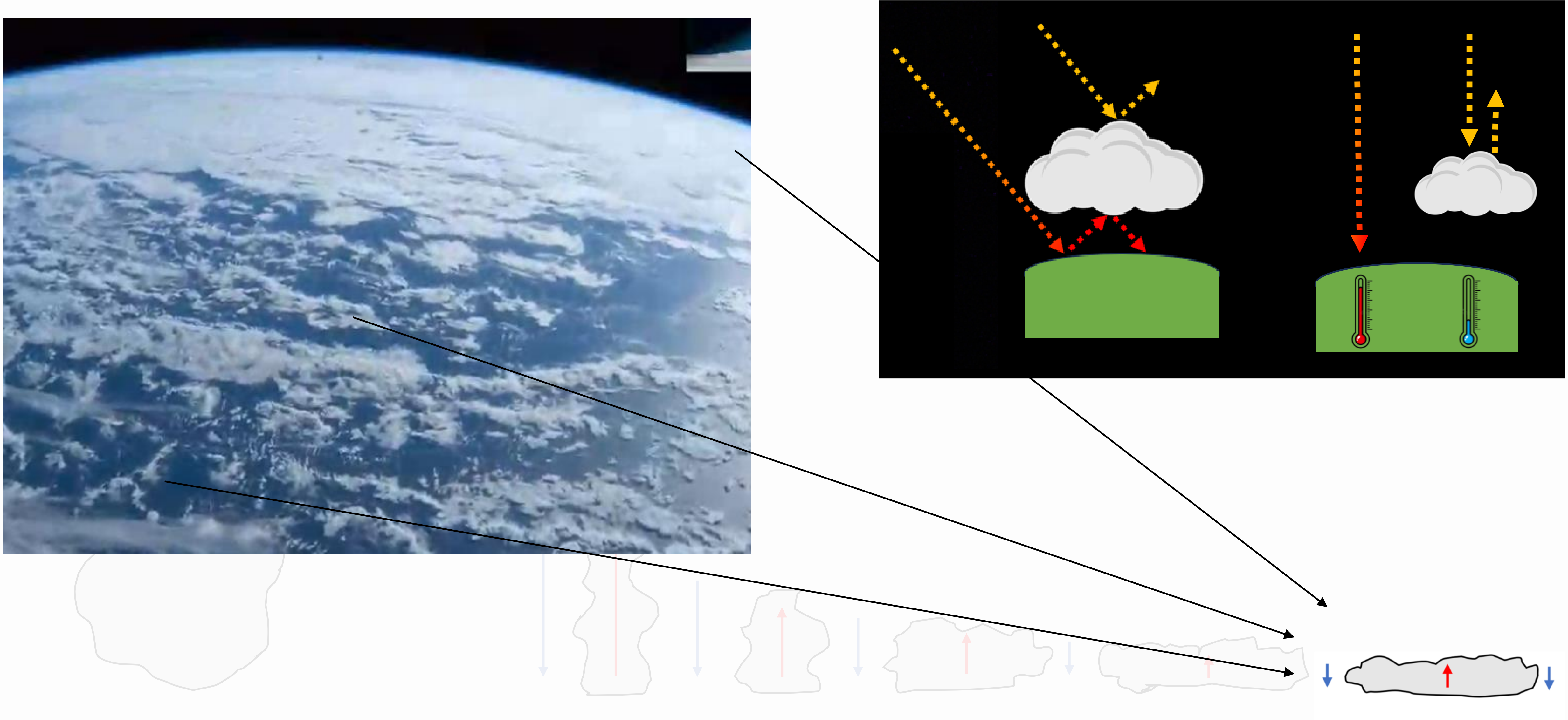



~18km
Equator
Deep convective region
Subtropics/
Stratocumulus region



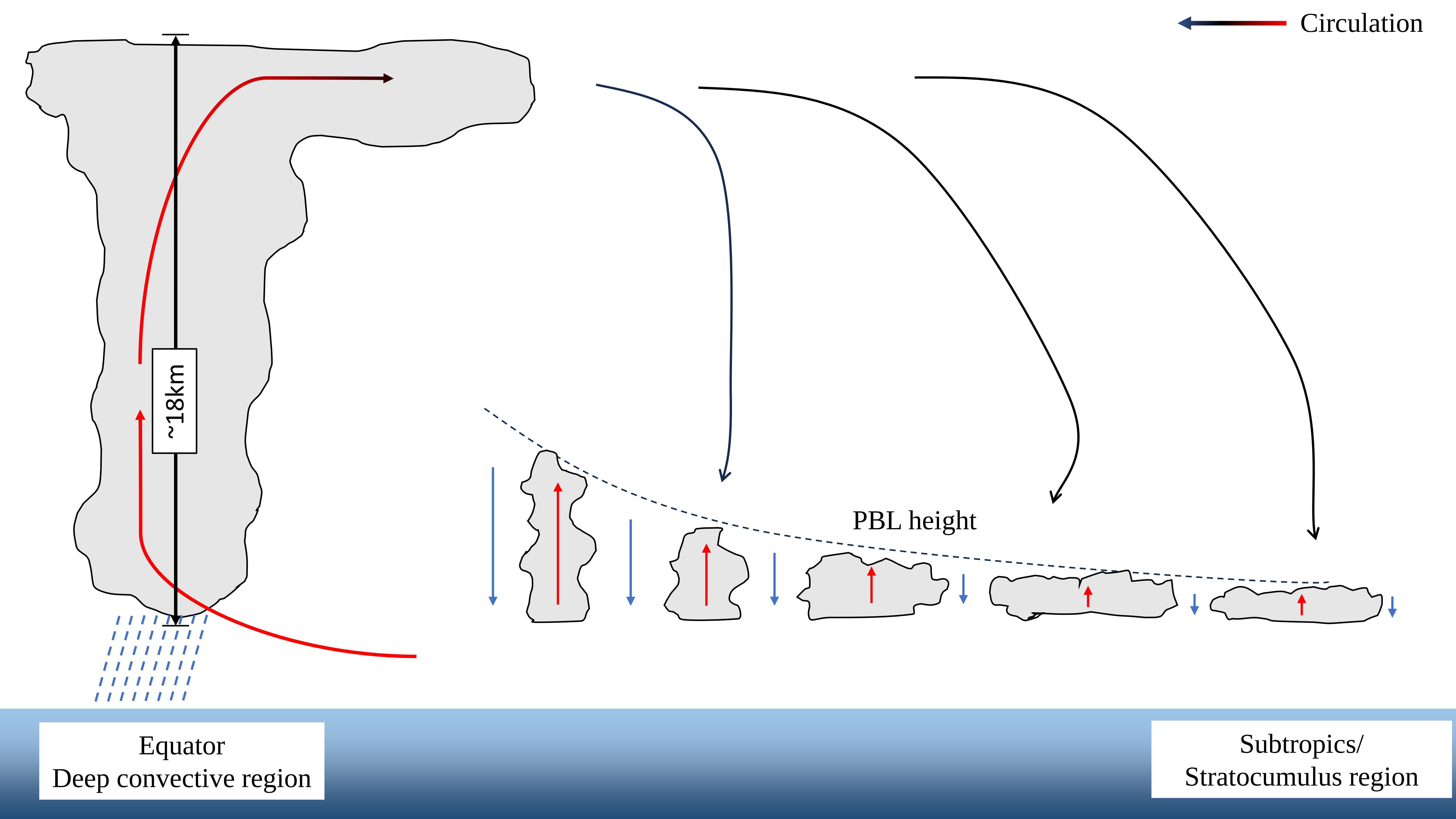
Equator
Deep convective region

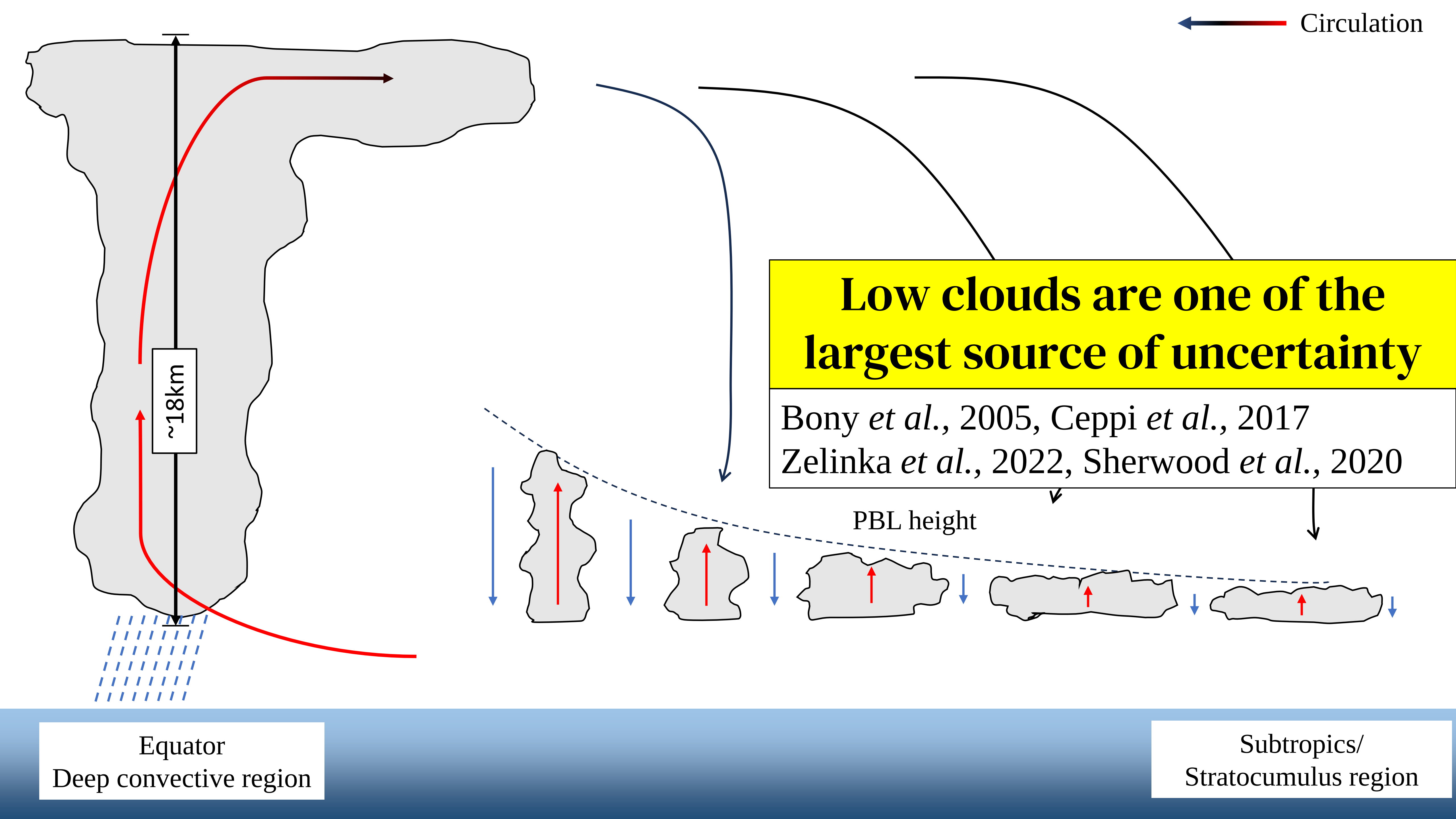
Subtropics/
Stratocumulus region



Equator
Deep convective region

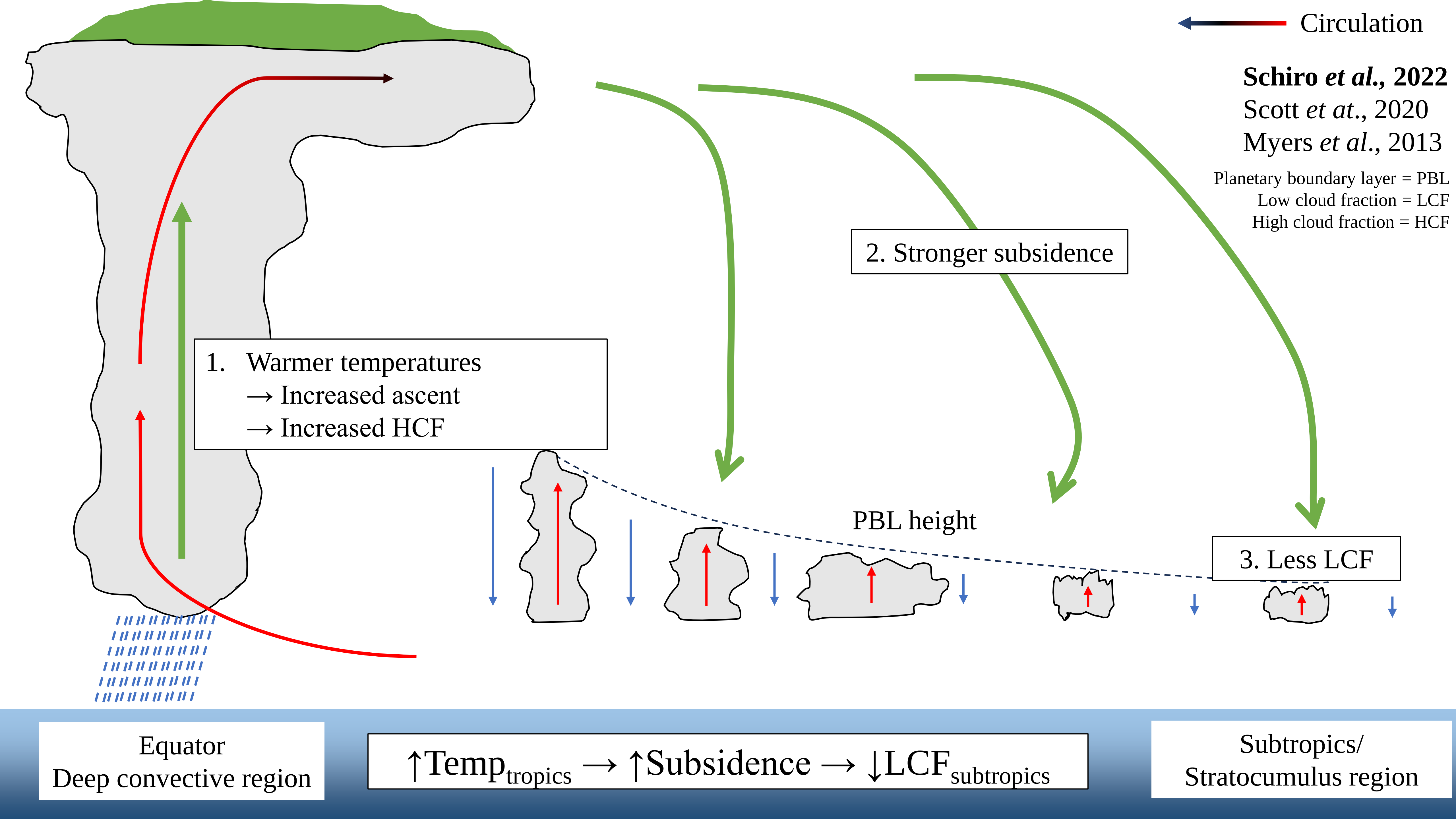
Subtropics/
Stratocumulus region


Circulation
~18km
PBL height
Equator
Deep convective region
Subtropics/
Stratocumulus region

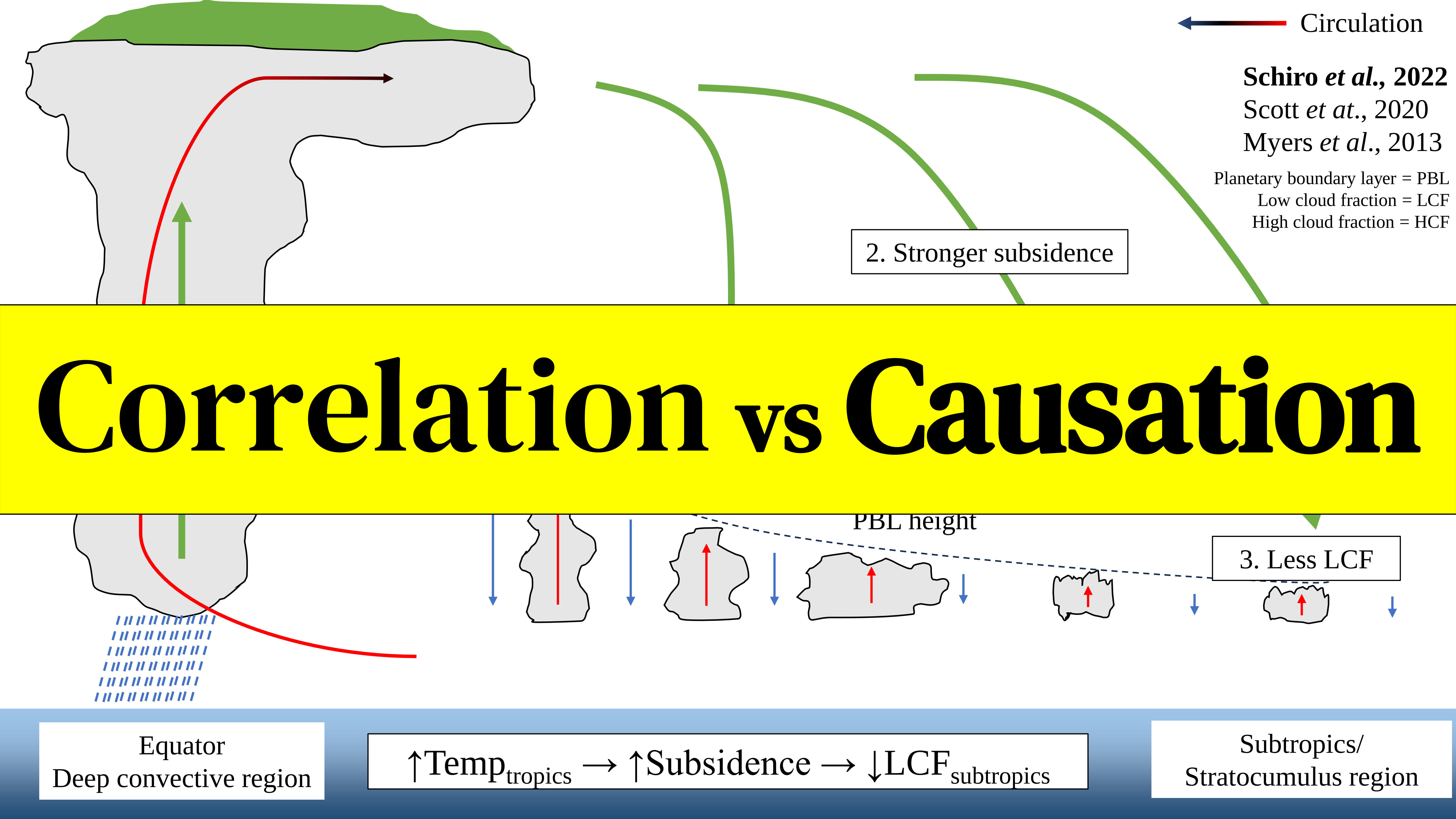


Low clouds are one of the largest source of uncertainty

Bony *et al.*, 2005, Ceppi *et al.*, 2017
Zelinka *et al.*, 2022, Sherwood *et al.*, 2020

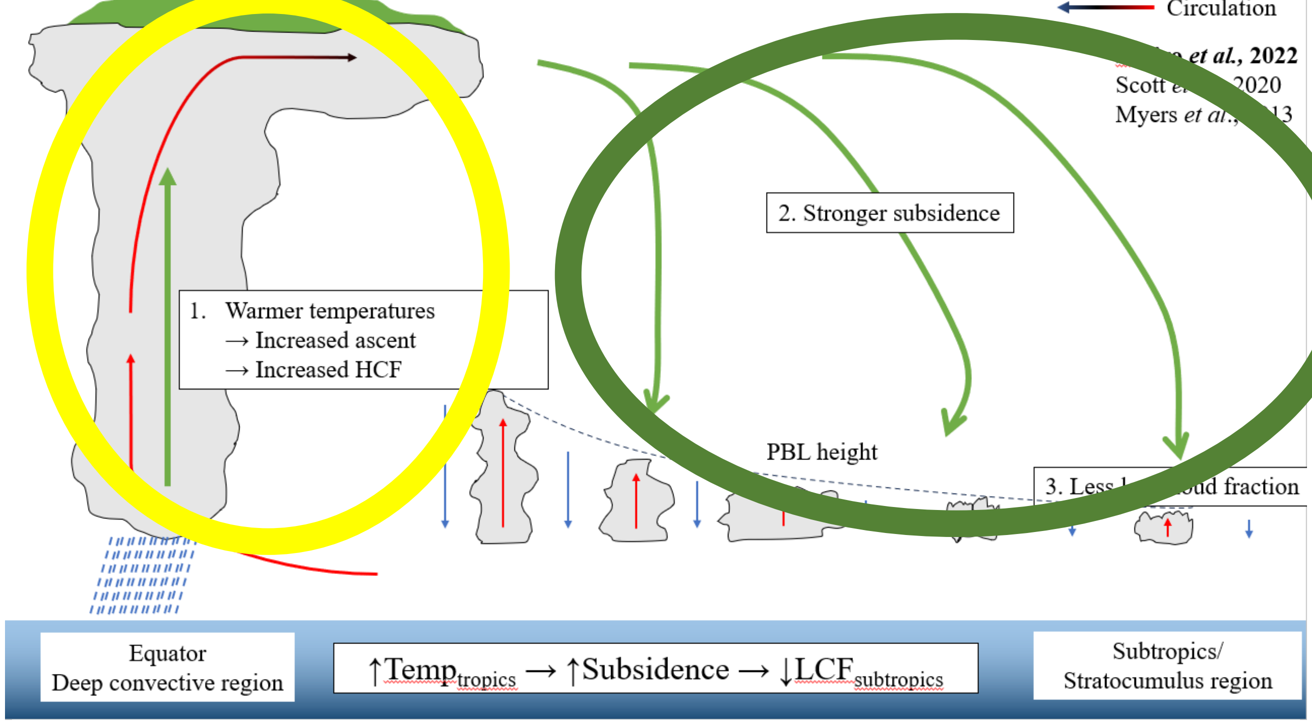

Circulation
Schiro et al., 2022
Scott et at., 2020
Myers et al., 2013
Planetary boundary layer = PBL
Low cloud fraction = LCF
High cloud fraction = HCF
2. Stronger subsidence
1. Warmer temperatures
→ Increased ascent
→ Increased HCF
PBL height
3. Less LCF
Equator
Deep convective region
↑Temp tropics → ↑Subsidence → ↓LCF subtropics
Subtropics/
Stratocumulus region

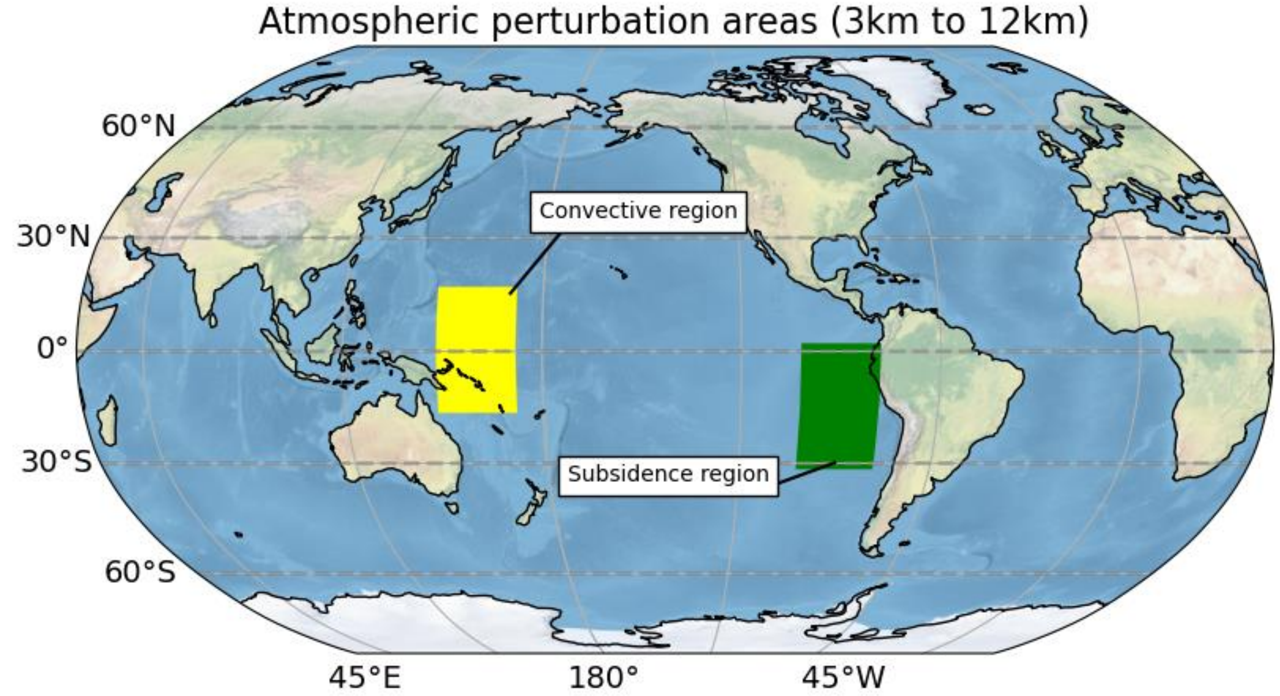
Correlation vs Causation



Technical details:

- Unified Model
- AMIP configuration
- 1985-2005 SST profiles
- GA9.0 configuration
- 20-year seasonal average
- Only March-April-May shown
- +/- 0.216 K per day
- Applied between 3-12km
- 5 scenarios in total
    - Control
    - + 0.216K west Pac
    - - 0.216K west Pac
    - + 0.216K east Pac
    - - 0.216K east Pac





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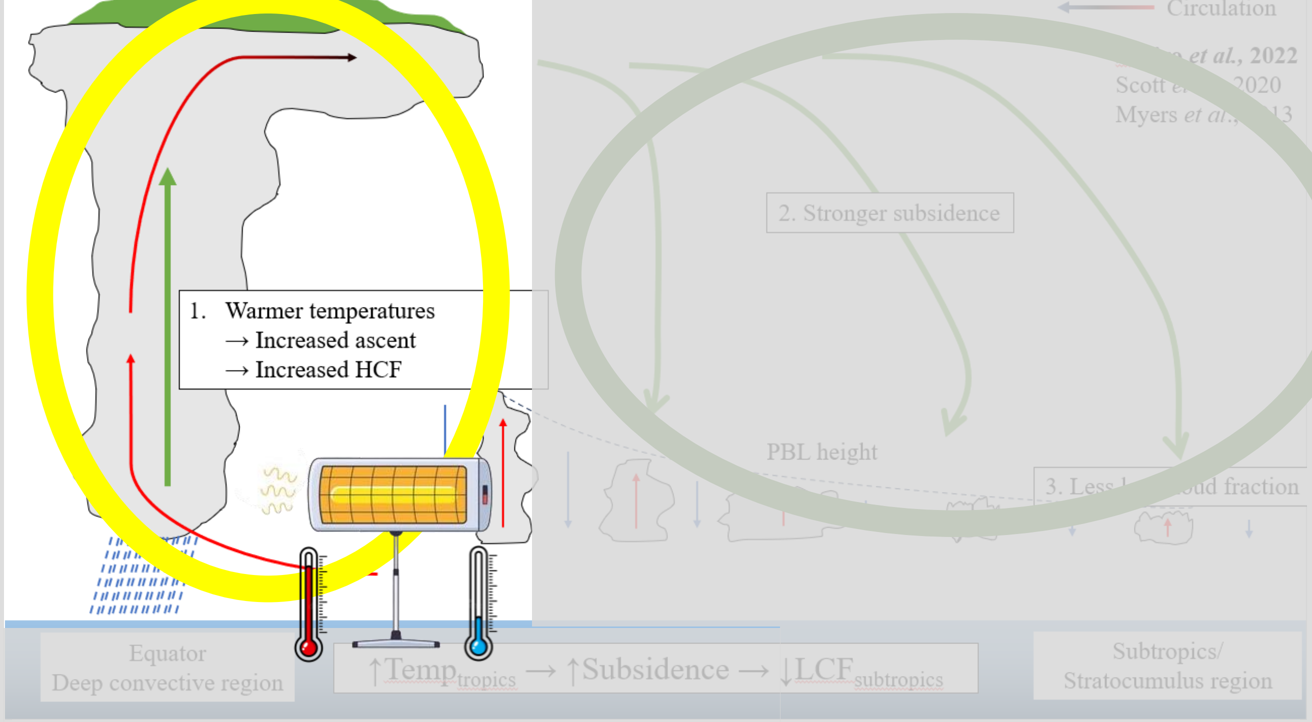
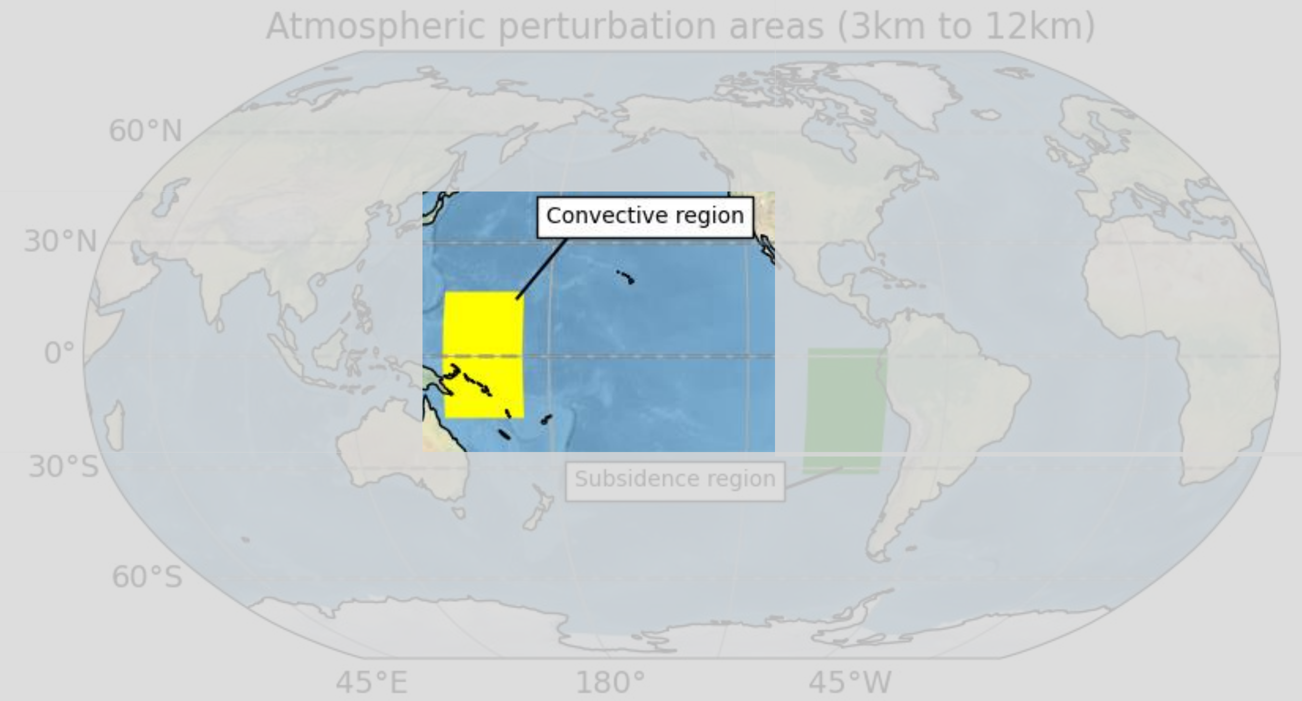
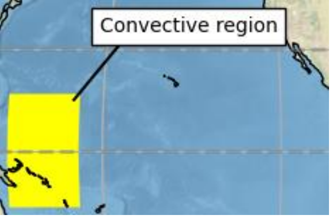
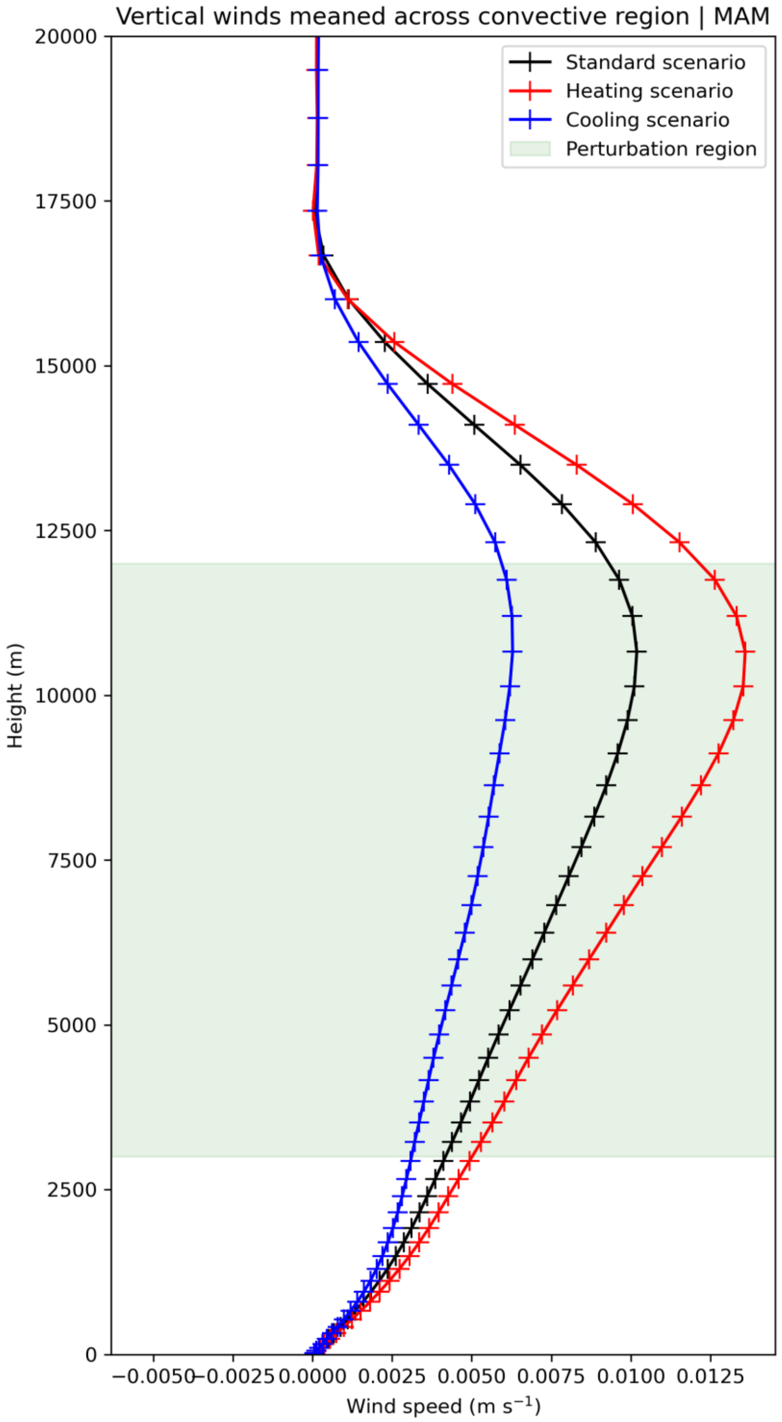
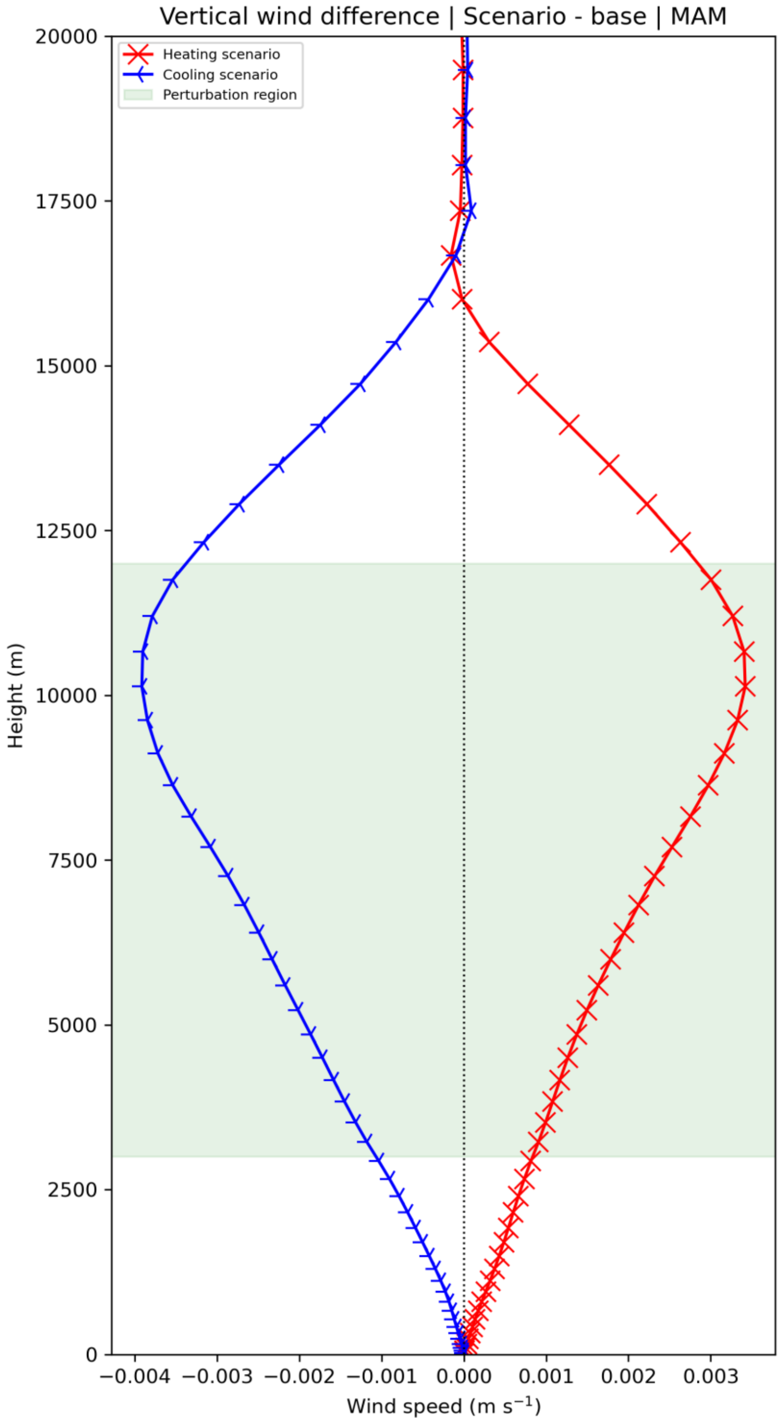
  - Control
  - + 0.216K west Pac
  - - 0.216K west Pac
  - + 0.216K east Pac
  - - 0.216K east Pac

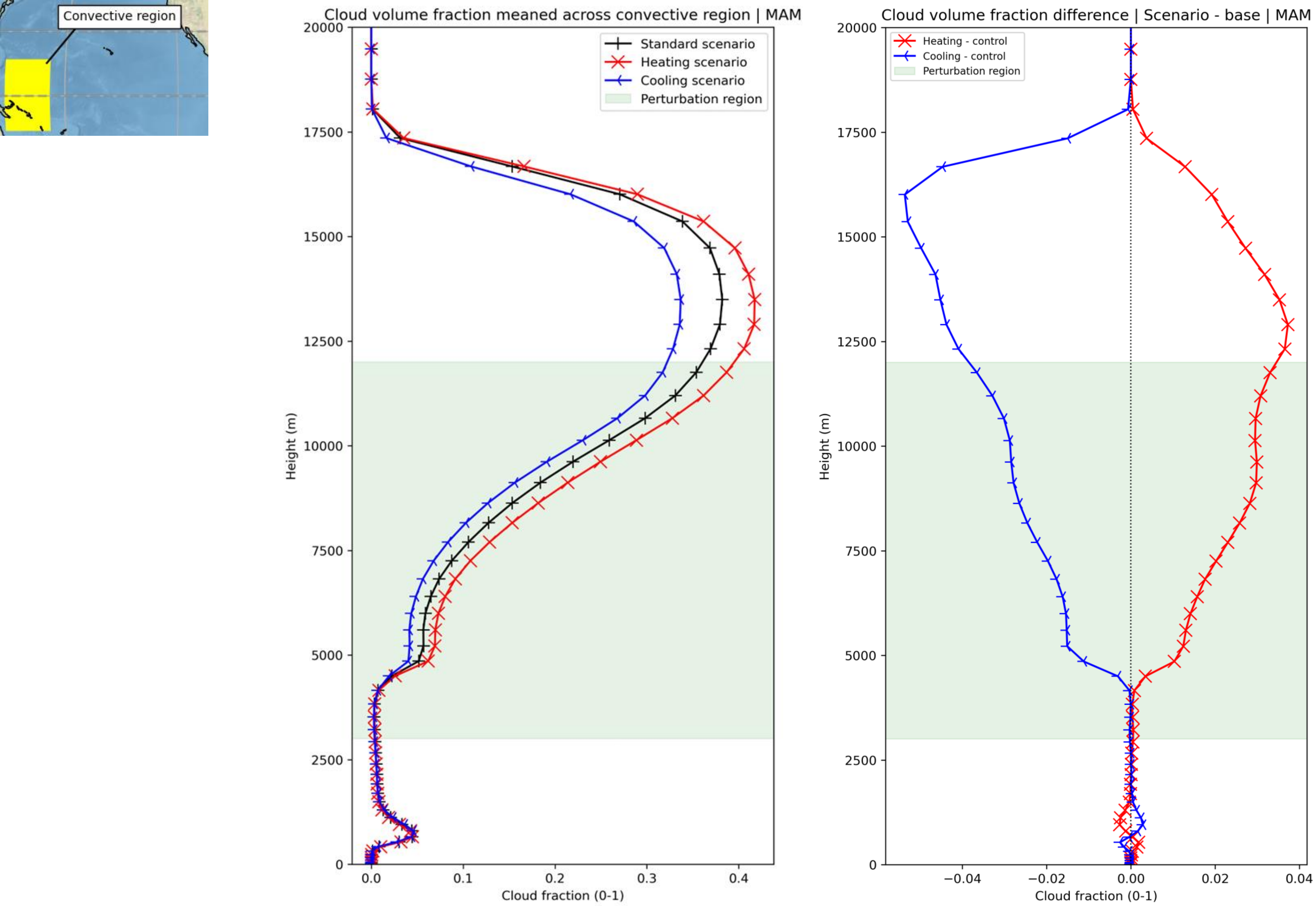




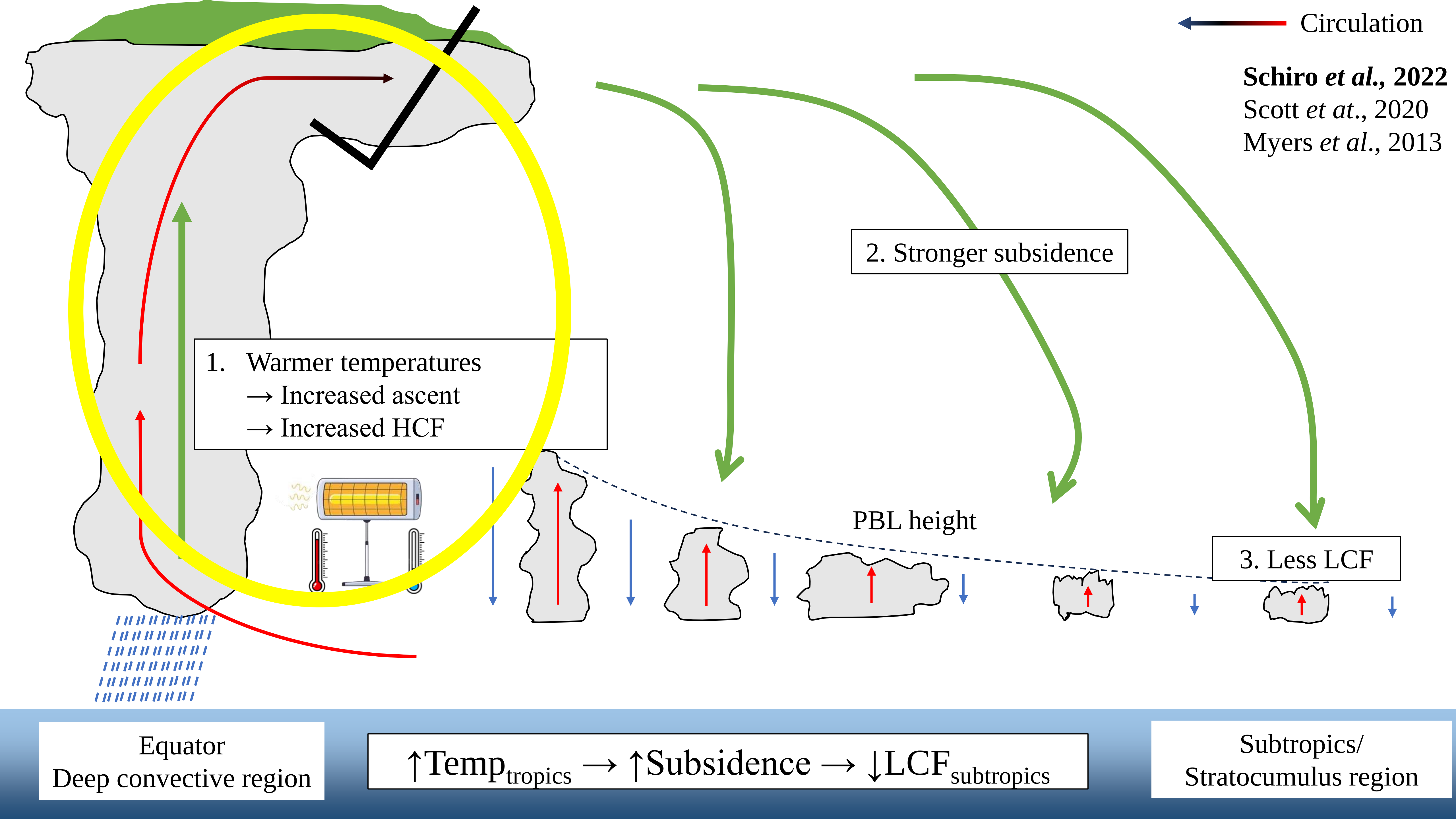

Convective region

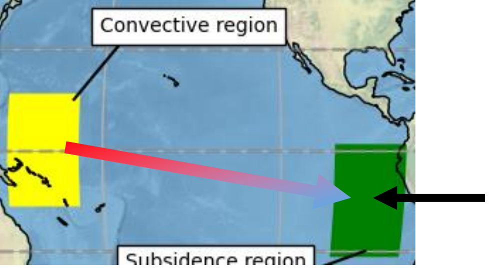

Vertical winds meaned across convective region | MAM
Standard scenario
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Wind speed (m s^{-1})
20000
17500
15000
12500
10000
7500
5000
2500
0
−0.0050
−0.0025
0.0000
0.0025
0.0050
0.0075
0.0100
0.0125

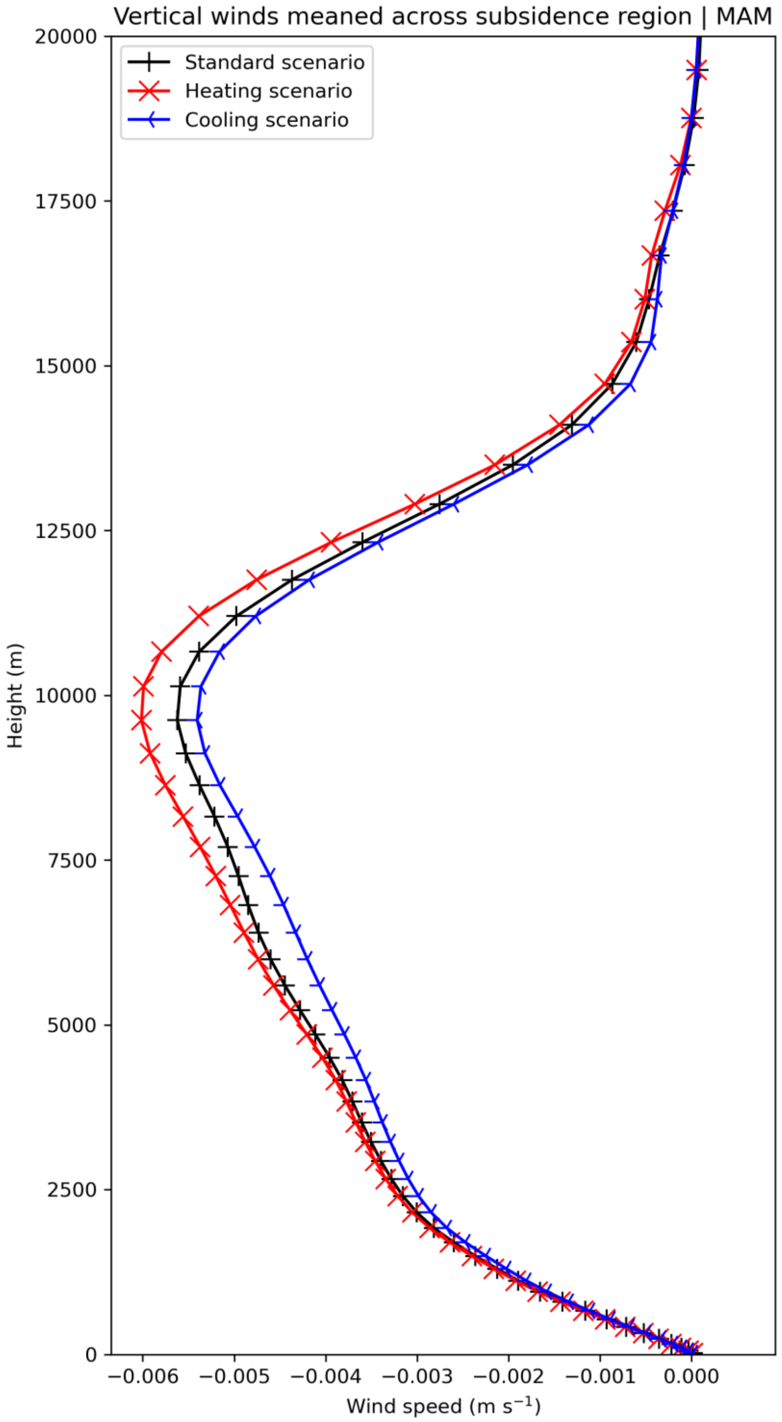

Vertical wind difference | Scenario - base | MAM
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Wind speed (m s^{-1})
20000
17500
15000
12500
10000
7500
5000
2500
0
−0.004
−0.003
−0.002
−0.001
0.000
0.001
0.002
0.003

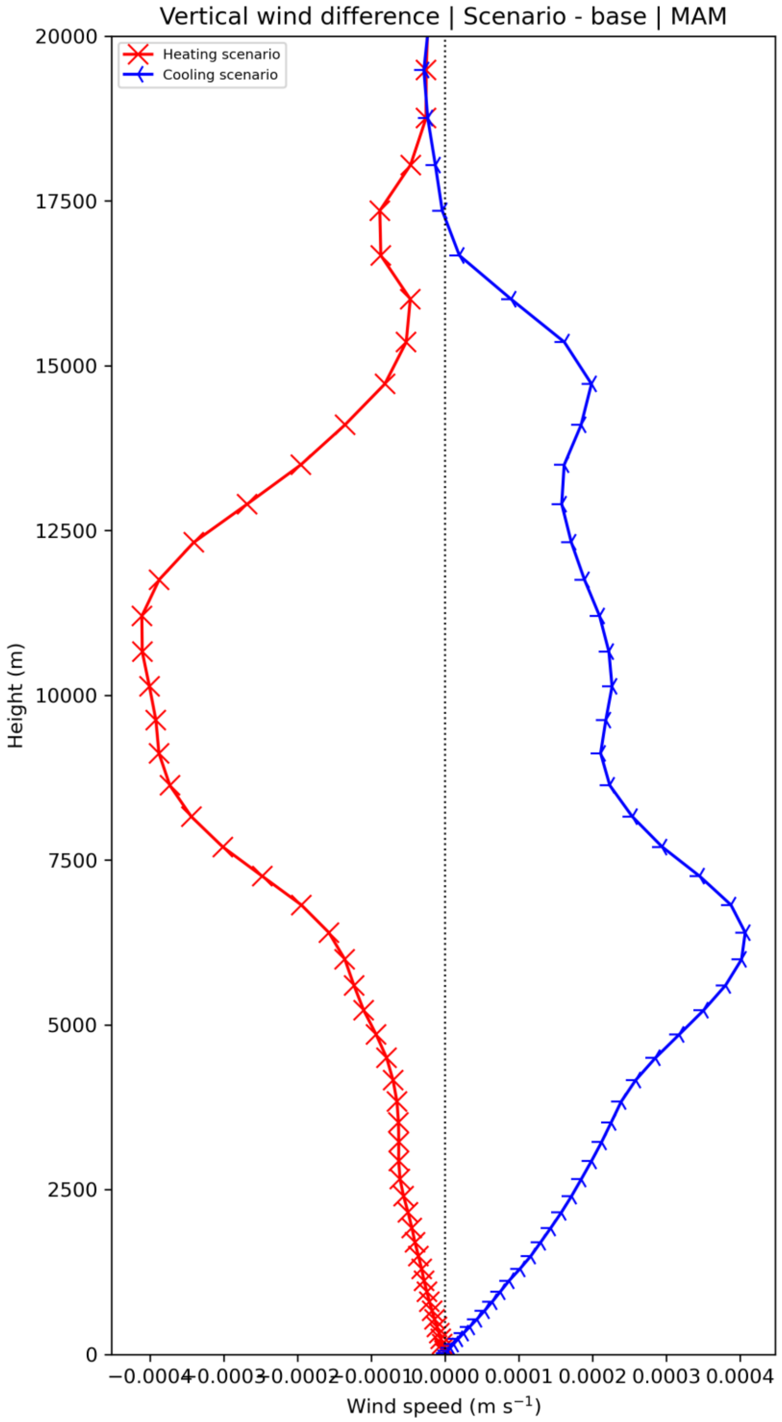


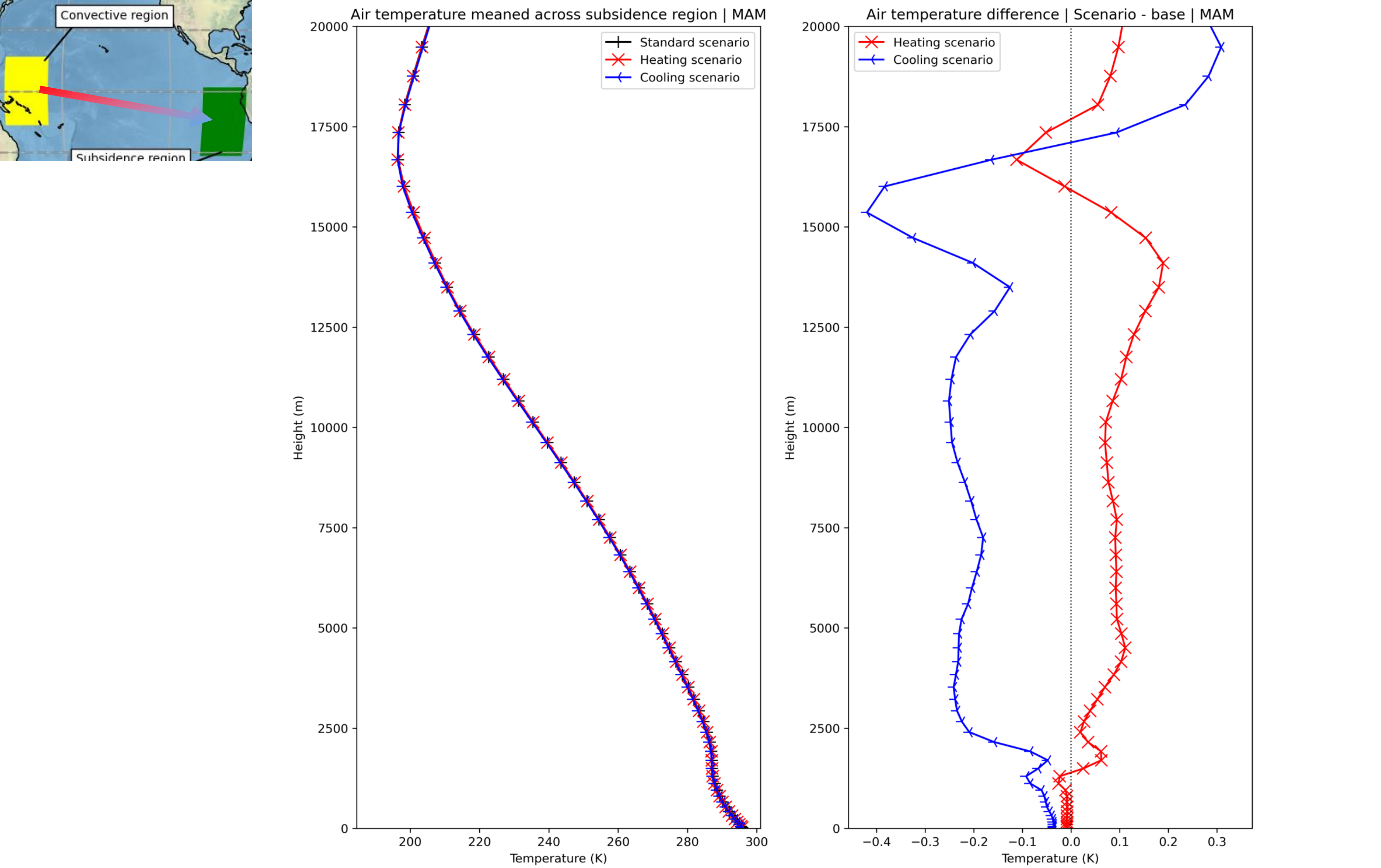
Convective region
Cloud volume fraction meaned across convective region | MAM
Standard scenario
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Cloud fraction (0-1)
Cloud volume fraction difference | Scenario - base | MAM
Heating - control
Cooling - control
Perturbation region
Height (m)
Cloud fraction (0-1)

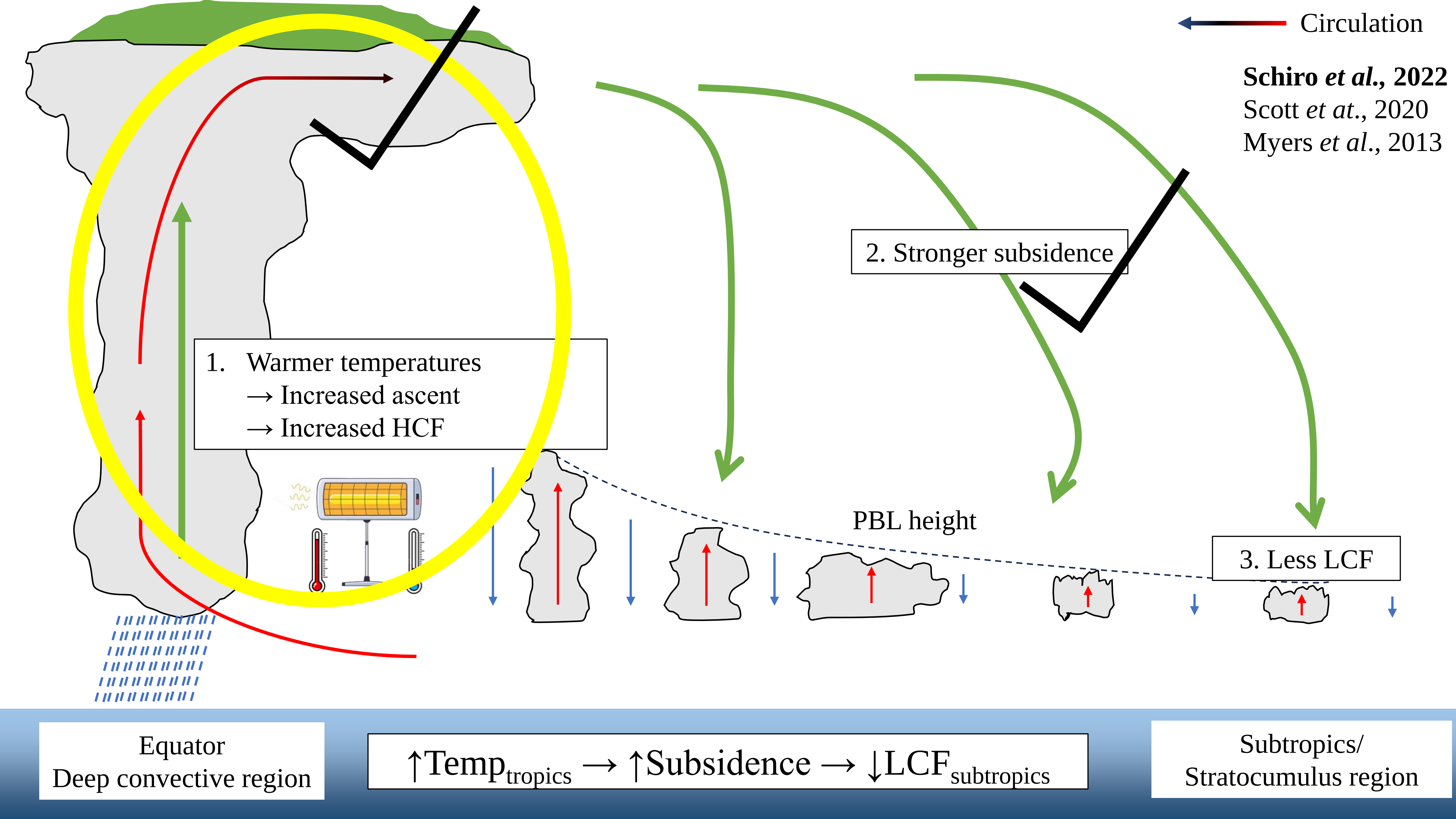

Circulation
Schiro *et al.*, 2022
Scott *et at.*, 2020
Myers *et al.*, 2013
2. Stronger subsidence
1. Warmer temperatures
→ Increased ascent
→ Increased HCF
PBL height
3. Less LCF
Equator
Deep convective region
↑Temp$_{tropics}$ → ↑Subsidence → ↓LCF$_{subtropics}$
Subtropics/
Stratocumulus region


Convective region
Subsidence region


Vertical winds meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Height (m)
Wind speed (m s^{-1})
20000
17500
15000
12500
10000
7500
5000
2500
0
−0.006
−0.005
−0.004
−0.003
−0.002
−0.001
0.000


Vertical wind difference | Scenario - base | MAM
Heating scenario
Cooling scenario
Height (m)
Wind speed (m s^{-1})
20000
17500
15000
12500
10000
7500
5000
2500
0
−0.0004
−0.0003
−0.0002
−0.0001
0.0000
0.0001
0.0002
0.0003
0.0004


Convective region
Subsidence region
Air temperature meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Height (m)
Temperature (K)
Air temperature difference | Scenario - base | MAM
Heating scenario
Cooling scenario
Height (m)
Temperature (K)


Circulation
Schiro *et al.*, 2022
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2. Stronger subsidence
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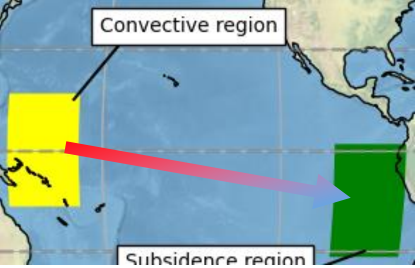
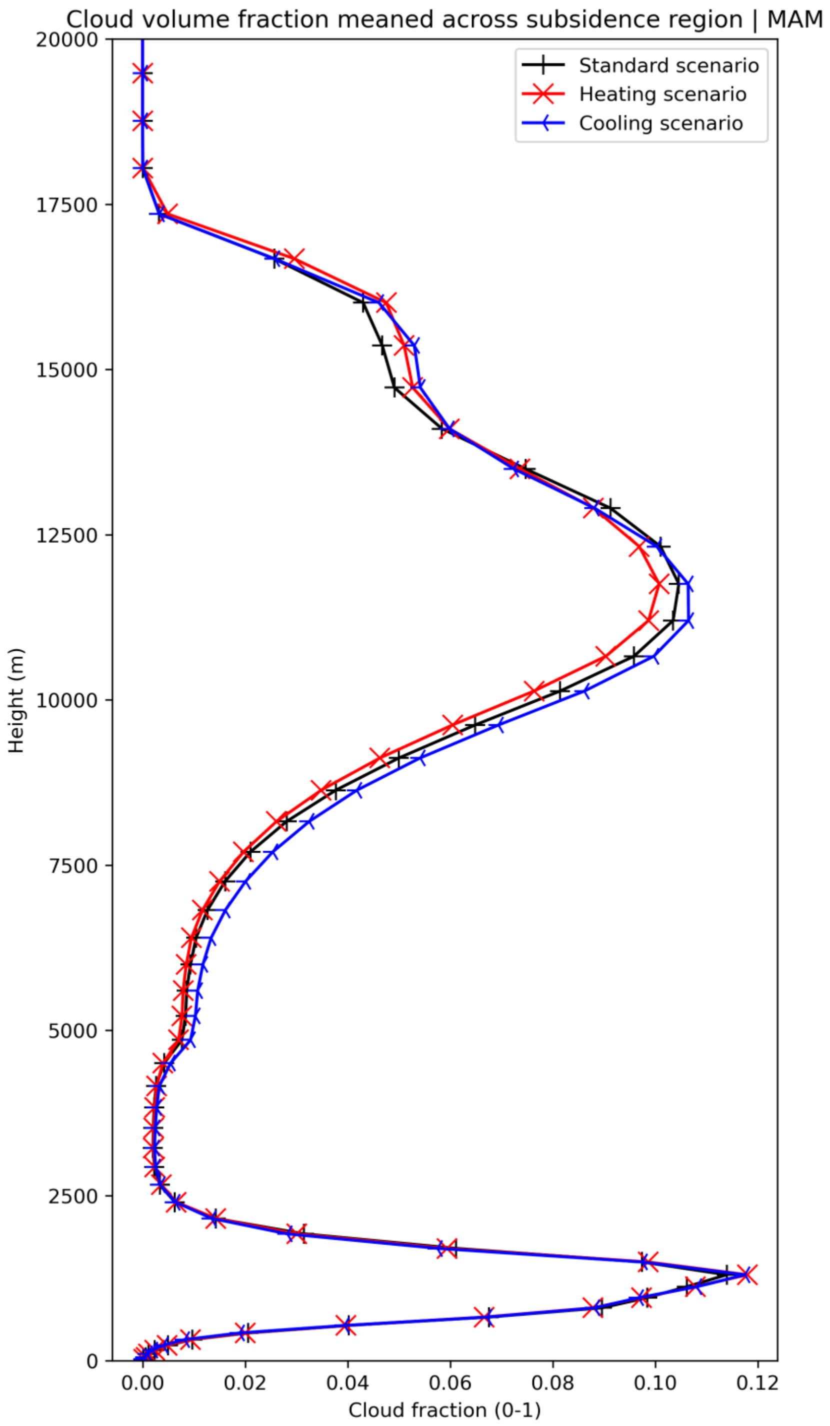
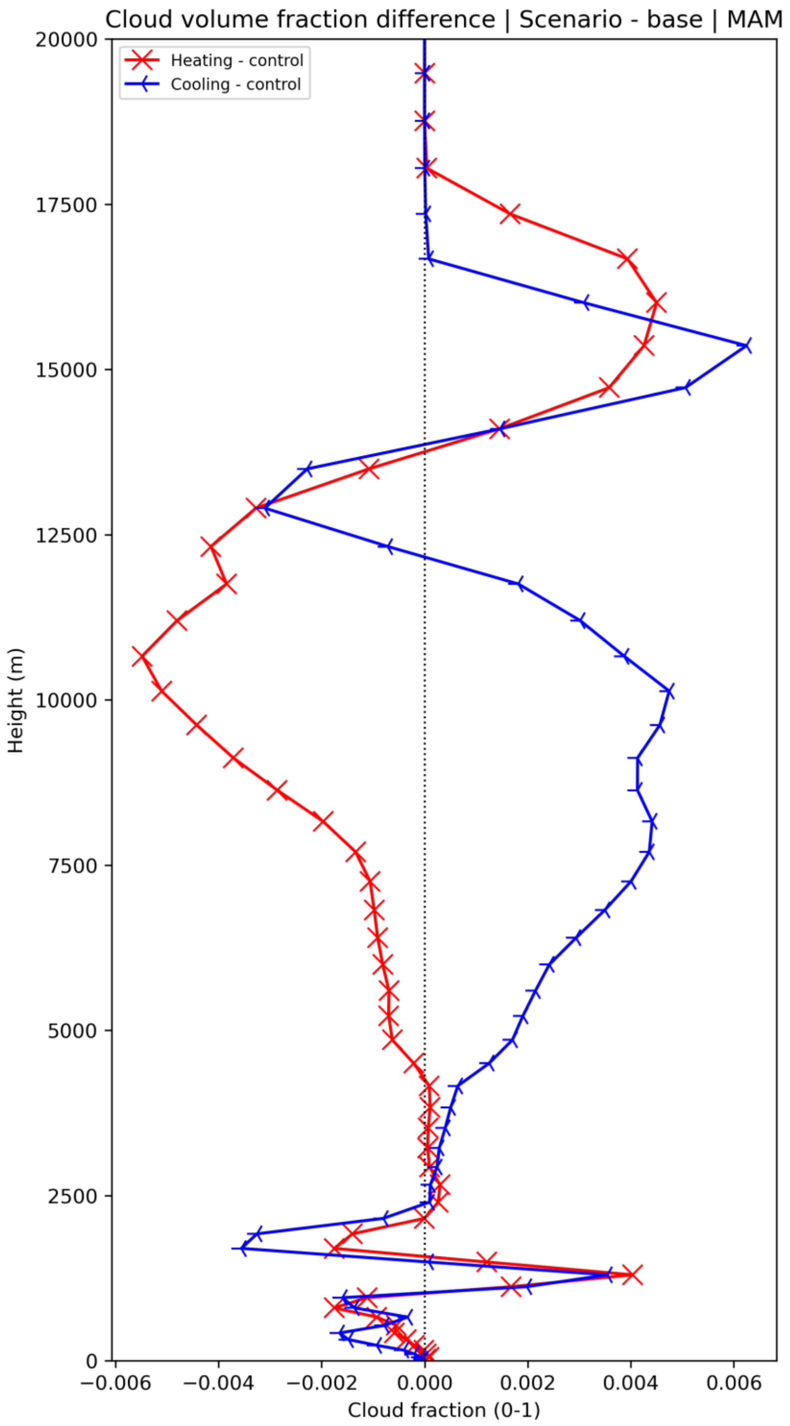
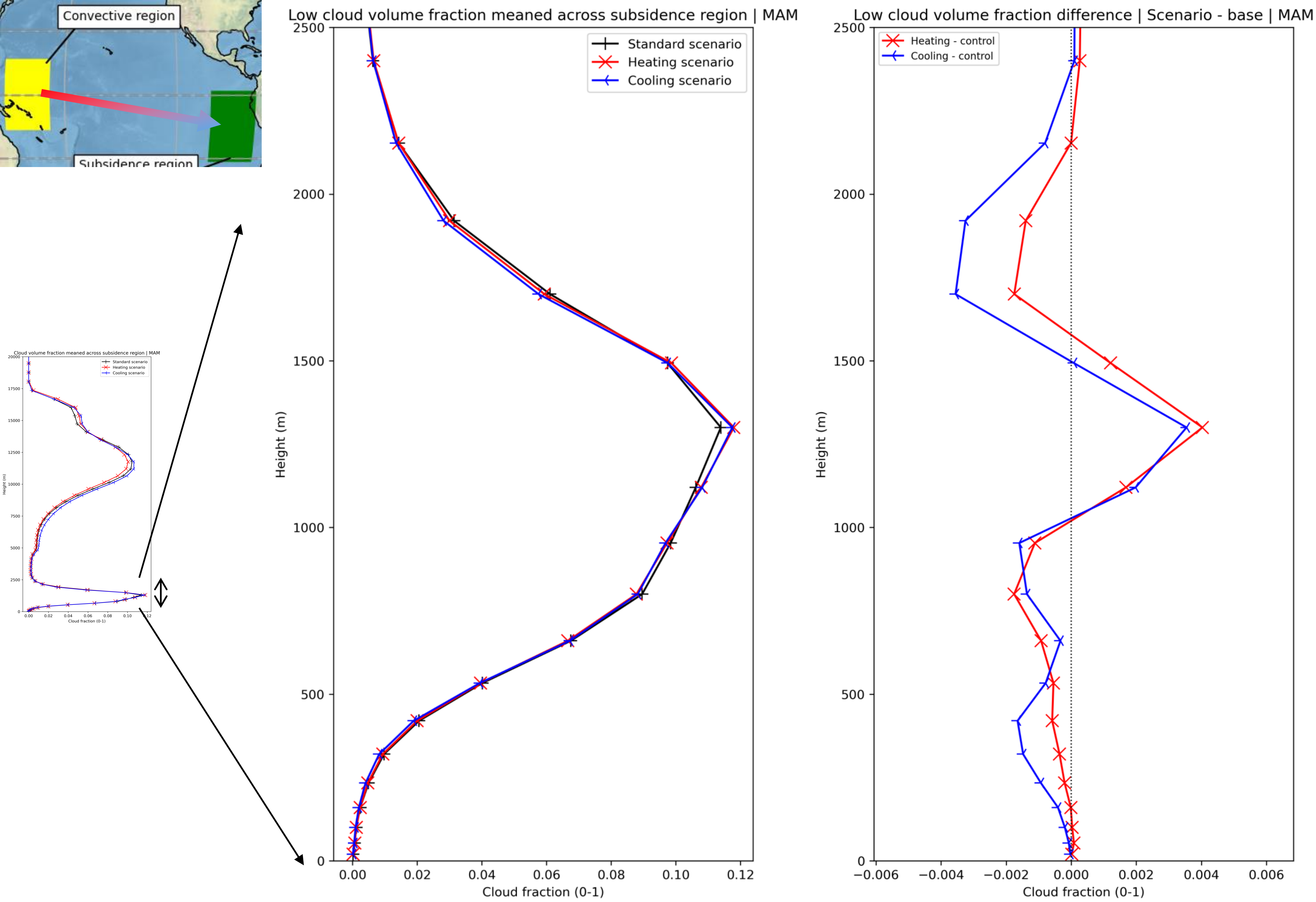
PBL height
3. Less LCF
Equator
Deep convective region
↑Temp$_{tropics}$ → ↑Subsidence → ↓LCF$_{subtropics}$
Subtropics/
Stratocumulus region

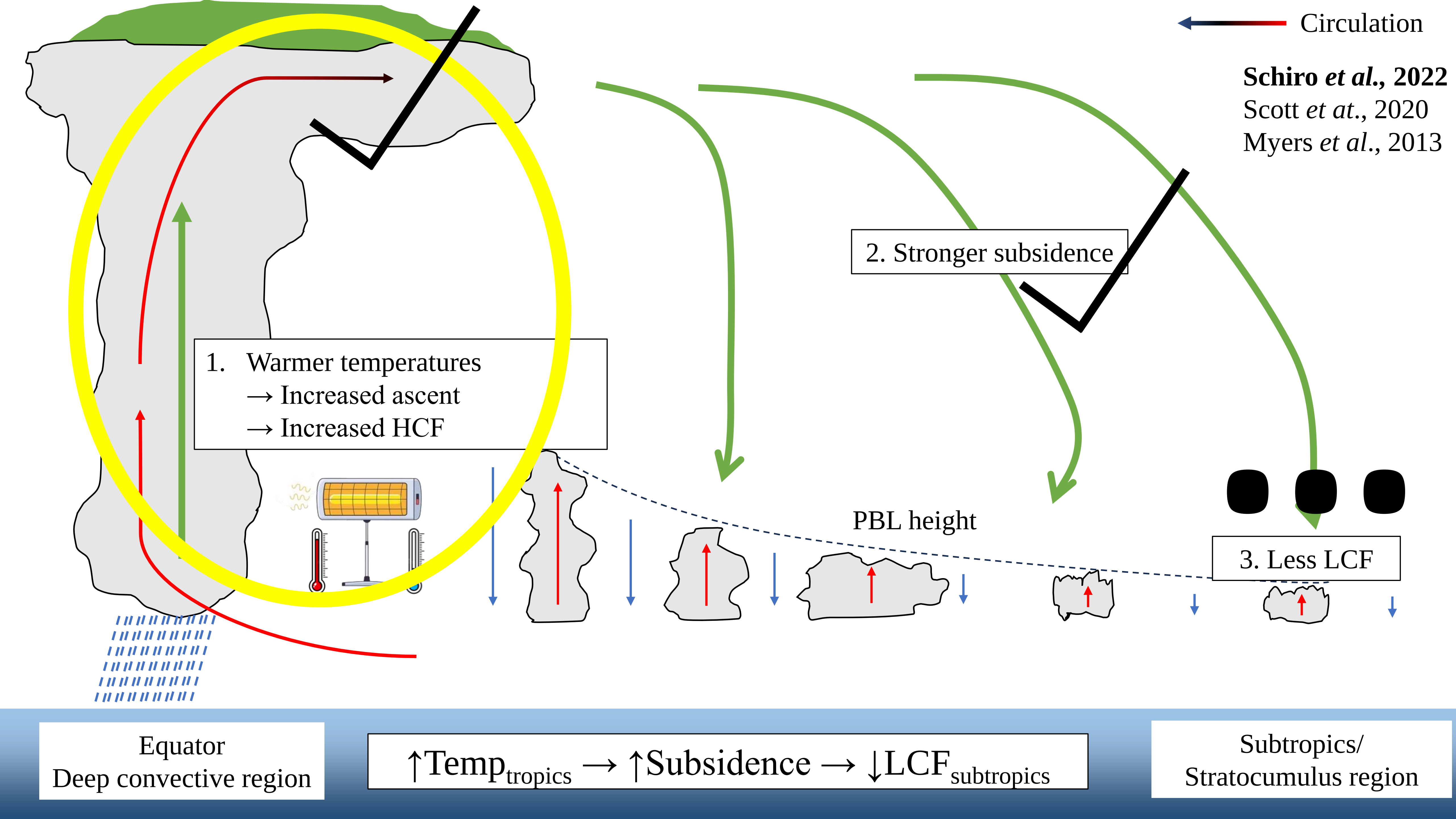

Convective region
Subsidence region


Cloud volume fraction meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Height (m)
20000
17500
15000
12500
10000
7500
5000
2500
0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
Cloud fraction (0-1)

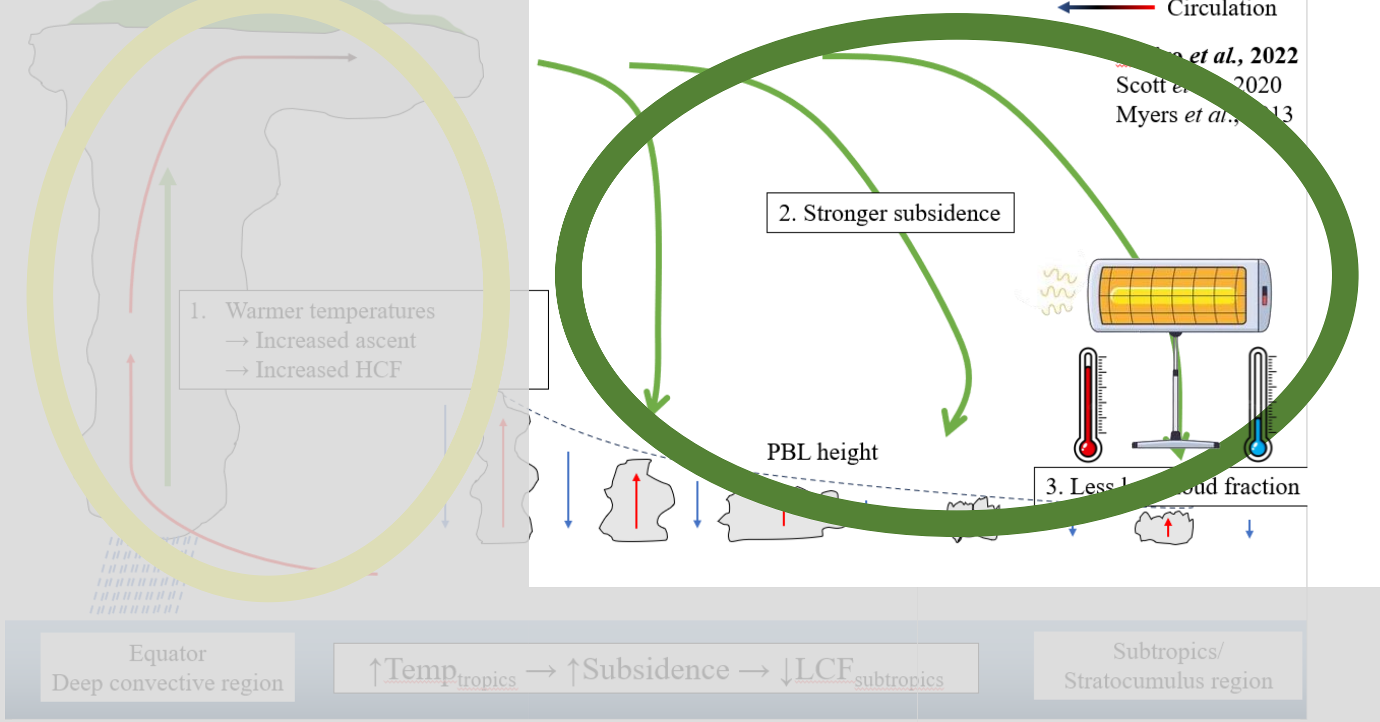

Cloud volume fraction difference | Scenario - base | MAM
Heating - control
Cooling - control
Height (m)
20000
17500
15000
12500
10000
7500
5000
2500
0
−0.006
−0.004
−0.002
0.000
0.002
0.004
0.006
Cloud fraction (0-1)



Convective region
Subsidence region
Low cloud volume fraction meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Height (m)
Cloud fraction (0-1)
Low cloud volume fraction difference | Scenario - base | MAM
Heating - control
Cooling - control
Height (m)
Cloud fraction (0-1)



Circulation
Schiro *et al.*, 2022
Scott *et at.*, 2020
Myers *et al.*, 2013
2. Stronger subsidence
1. Warmer temperatures
→ Increased ascent
→ Increased HCF
PBL height
3. Less LCF
Equator
Deep convective region
↑Temp$_{tropics}$ → ↑Subsidence → ↓LCF$_{subtropics}$
Subtropics/
Stratocumulus region



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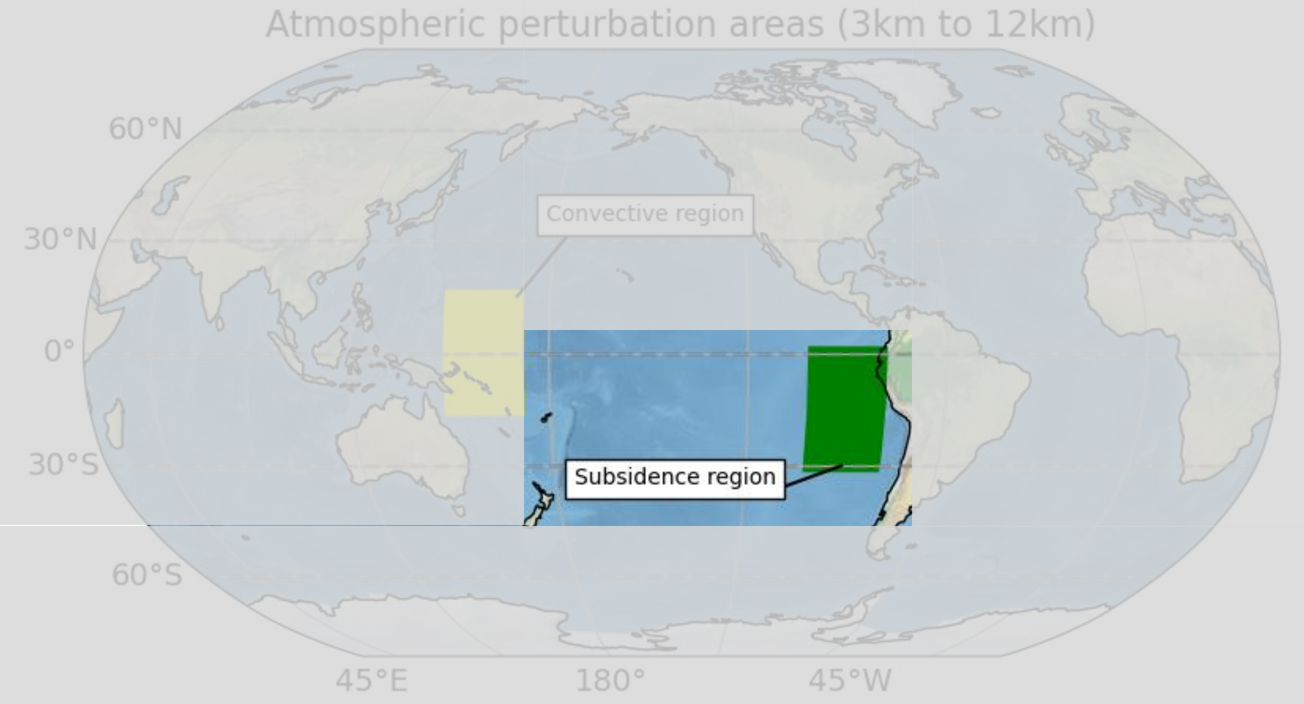
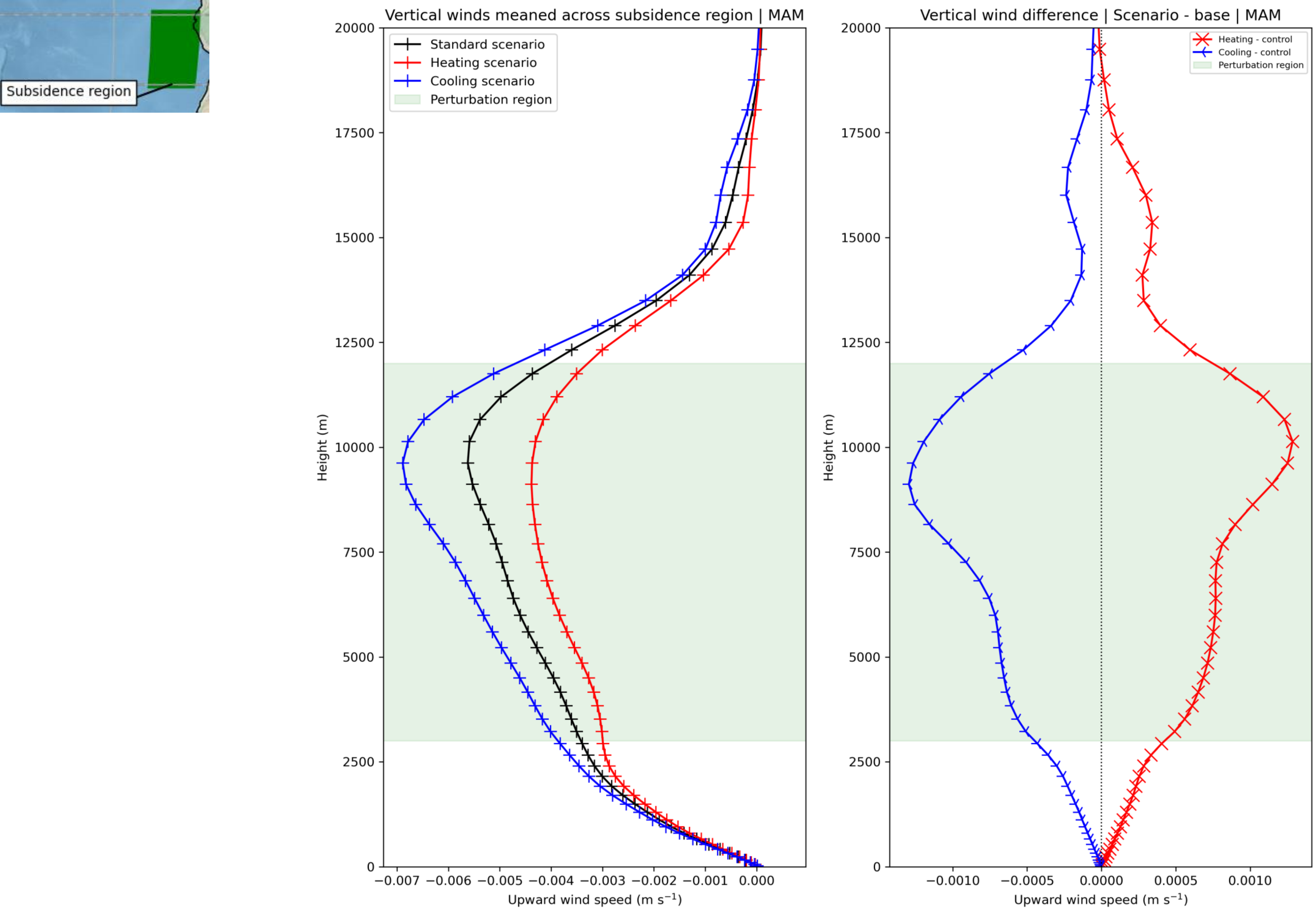
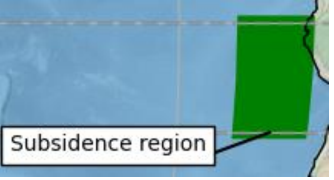
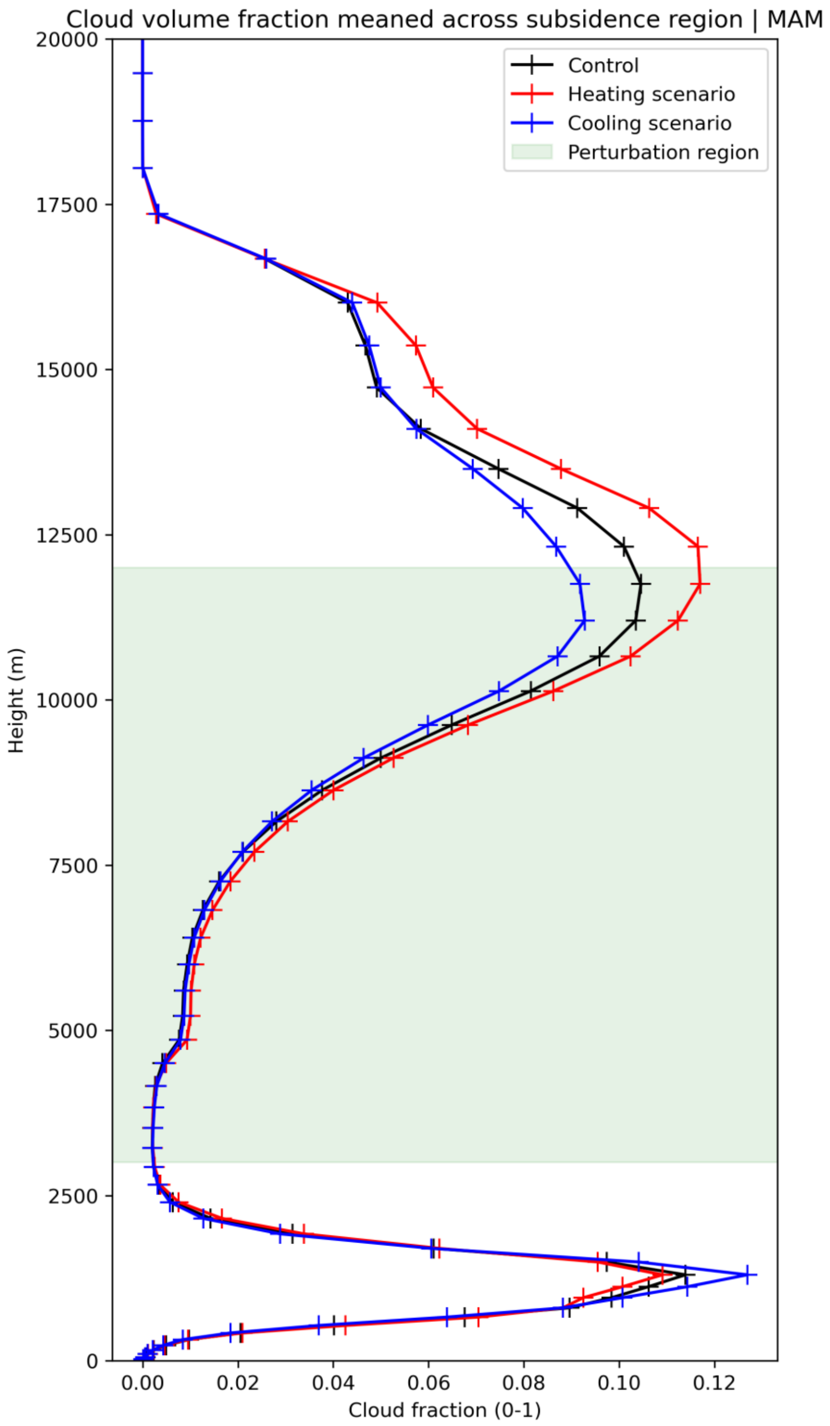
  - \- 0.216K west Pac
  - \+ 0.216K east Pac
  - \- 0.216K east Pac

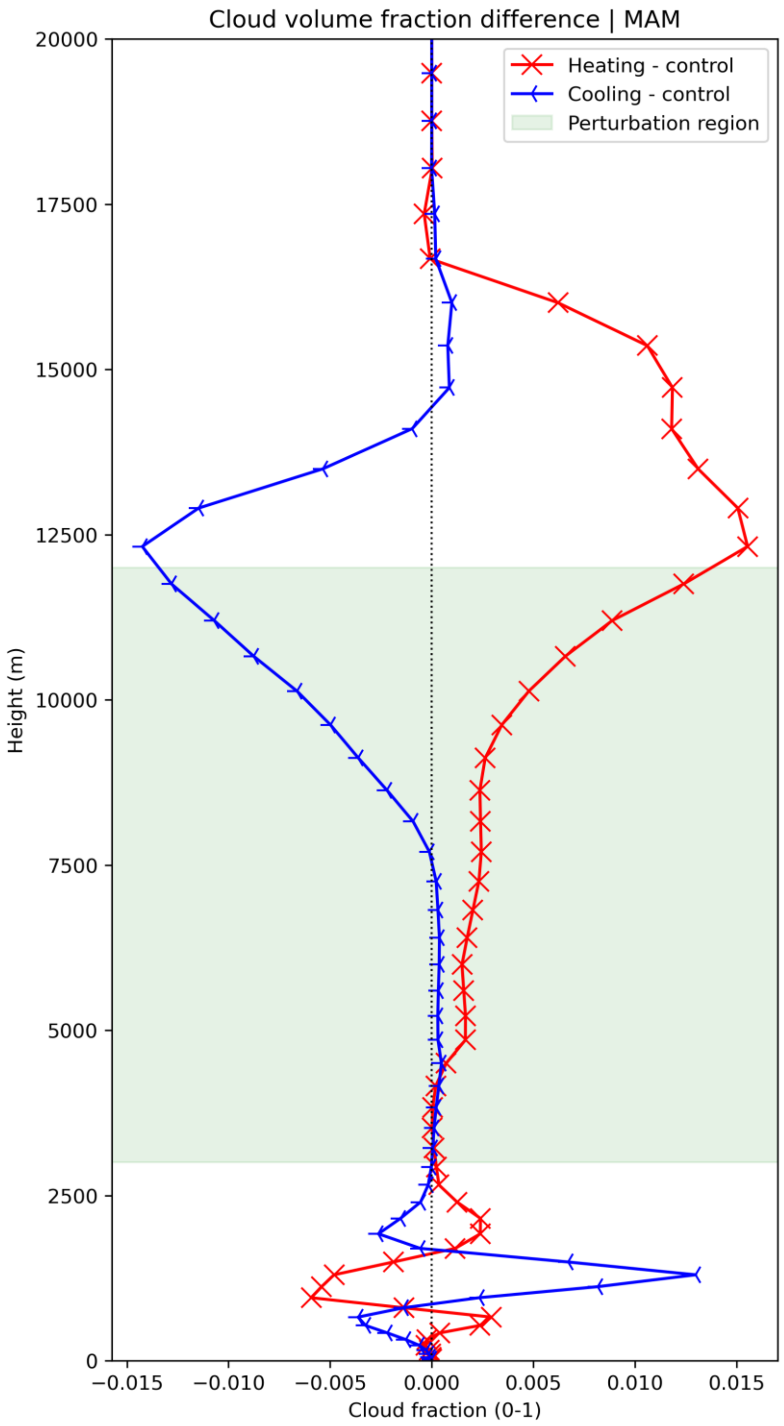


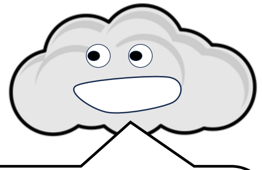


Subsidence region
Vertical winds meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Upward wind speed (m s^{-1})
Vertical wind difference | Scenario - base | MAM
Heating - control
Cooling - control
Perturbation region
Height (m)
Upward wind speed (m s^{-1})

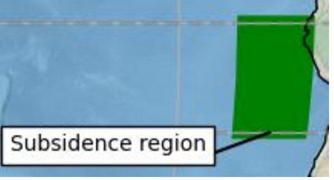


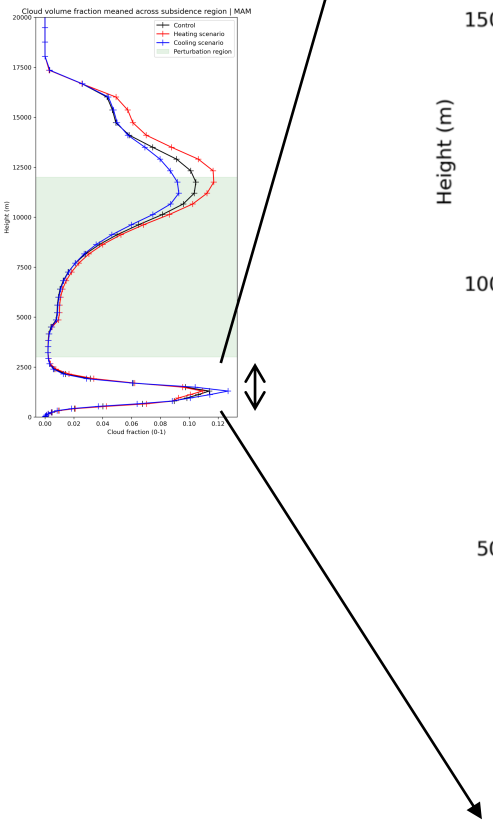


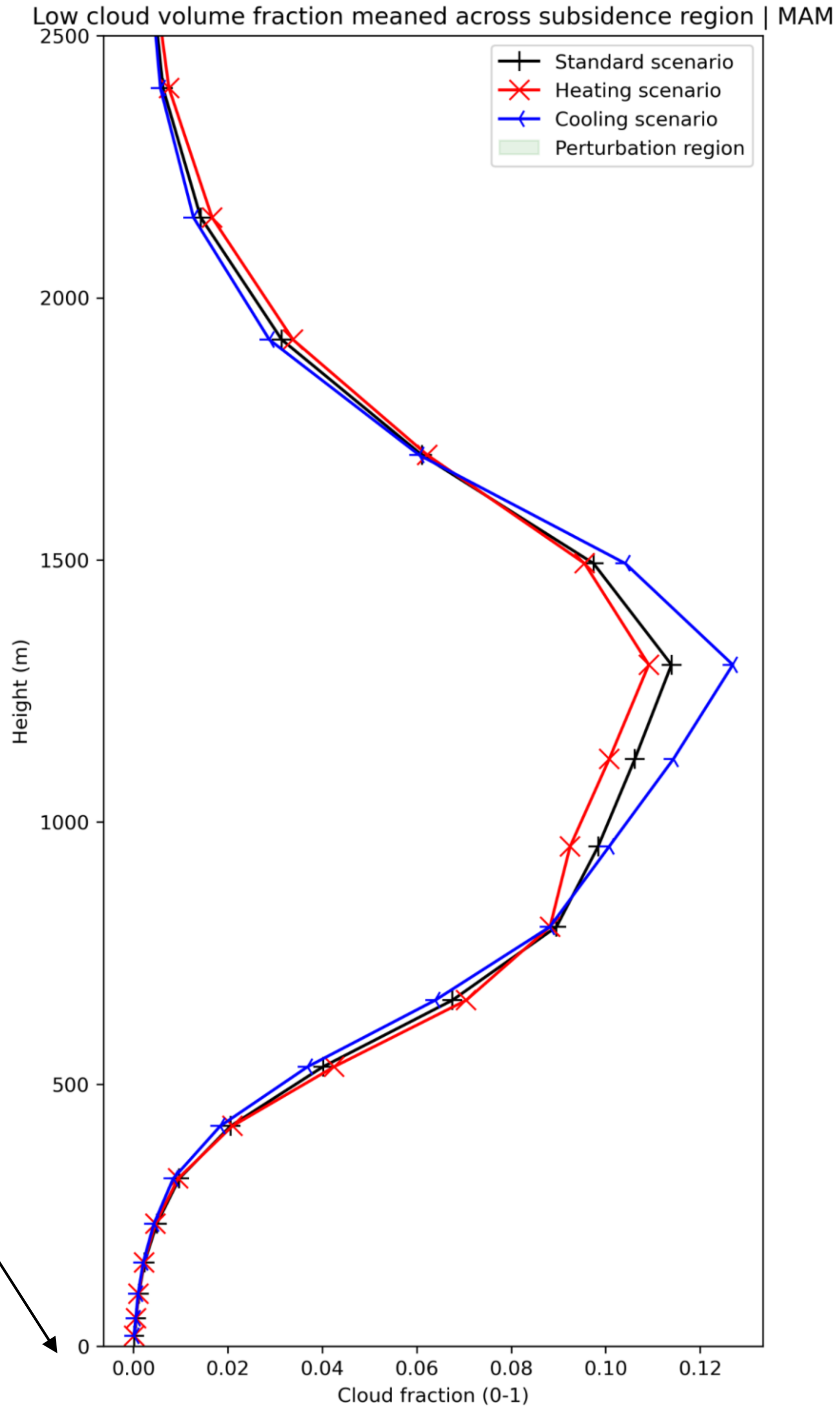


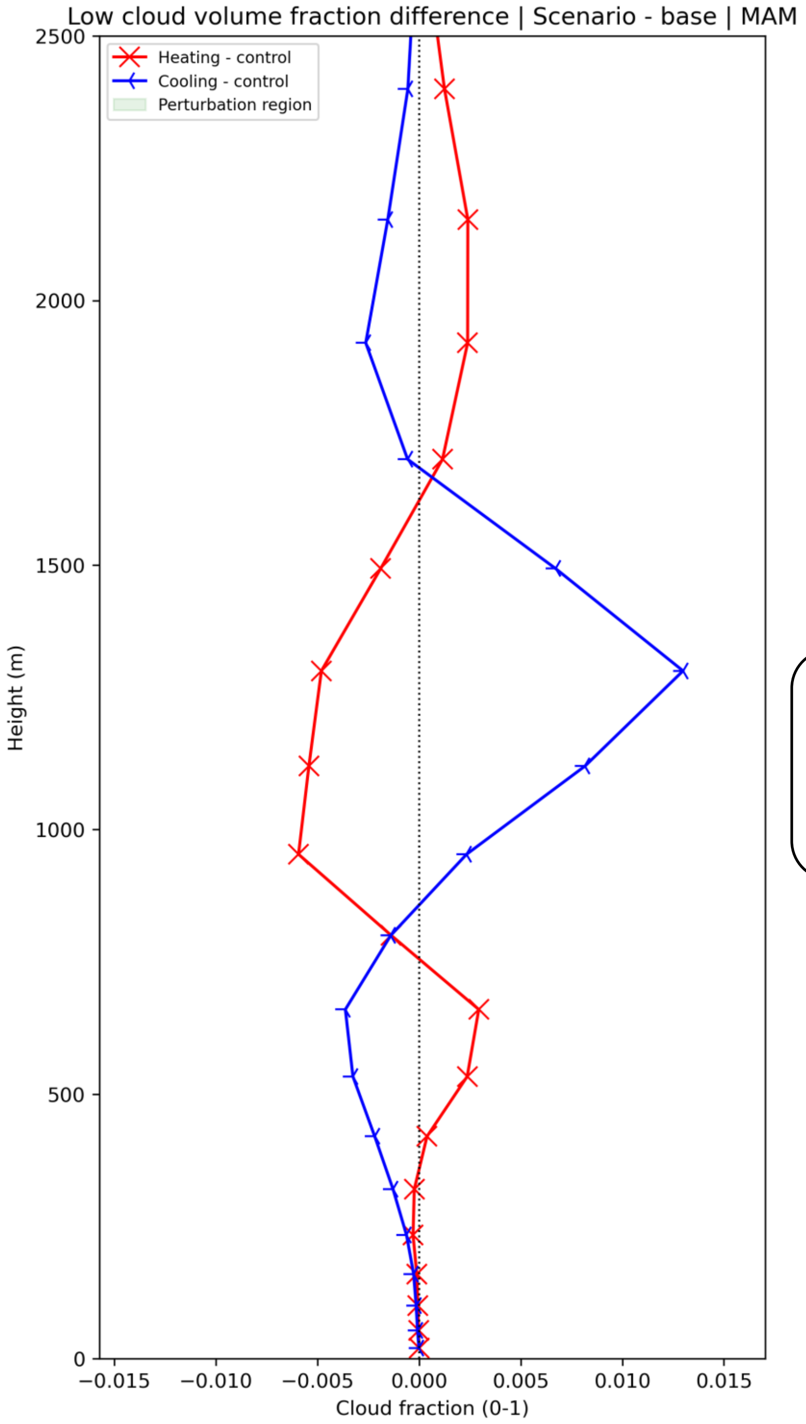


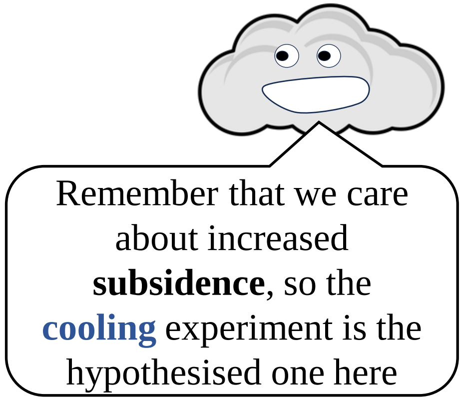
Remember that we care about increased **subsidence**, so the **cooling** experiment is the hypothesised one here


Subsidence region


Cloud volume fraction meaned across subsidence region | MAM
Control
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Cloud fraction (0-1)


Low cloud volume fraction meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Perturbation region
Height (m)
2500
2000
1500
1000
500
0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
Cloud fraction (0-1)


Low cloud volume fraction difference | Scenario - base | MAM
Heating - control
Cooling - control
Perturbation region
Height (m)
2500
2000
1500
1000
500
0
−0.015
−0.010
−0.005
0.000
0.005
0.010
0.015
Cloud fraction (0-1)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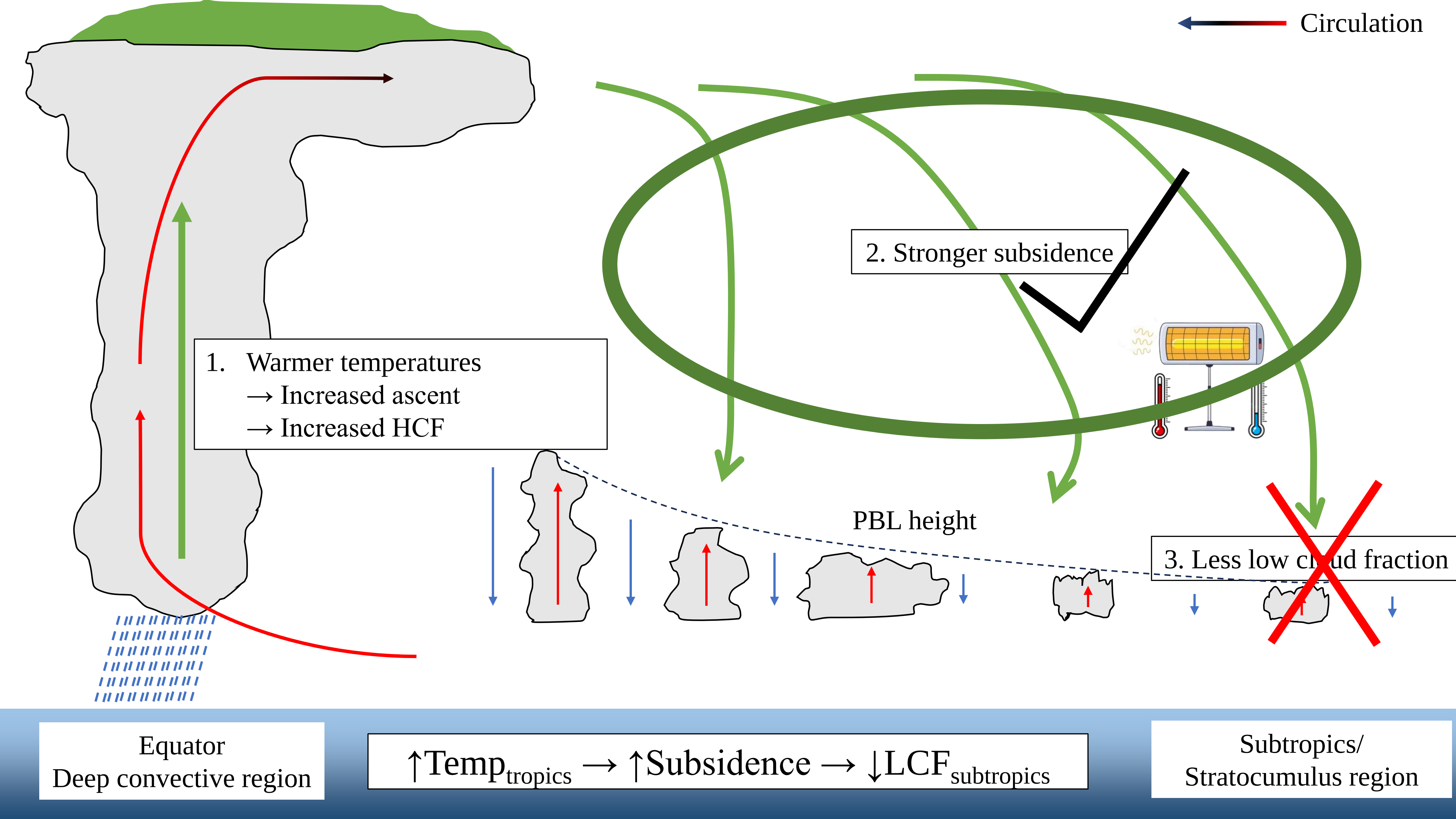


Circulation
2. Stronger subsidence
1. Warmer temperatures
→ Increased ascent
→ Increased HCF
PBL height
3. Less low cloud fraction
Equator
Deep convective region
↑Temp$_{tropics}$ → ↑Subsidence → ↓LCF$_{subtropics}$
Subtropics/
Stratocumulus region

Conclusions

Conclusions:

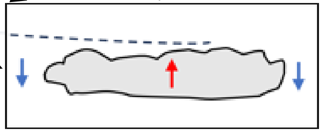
Improve low cloud representation

↓

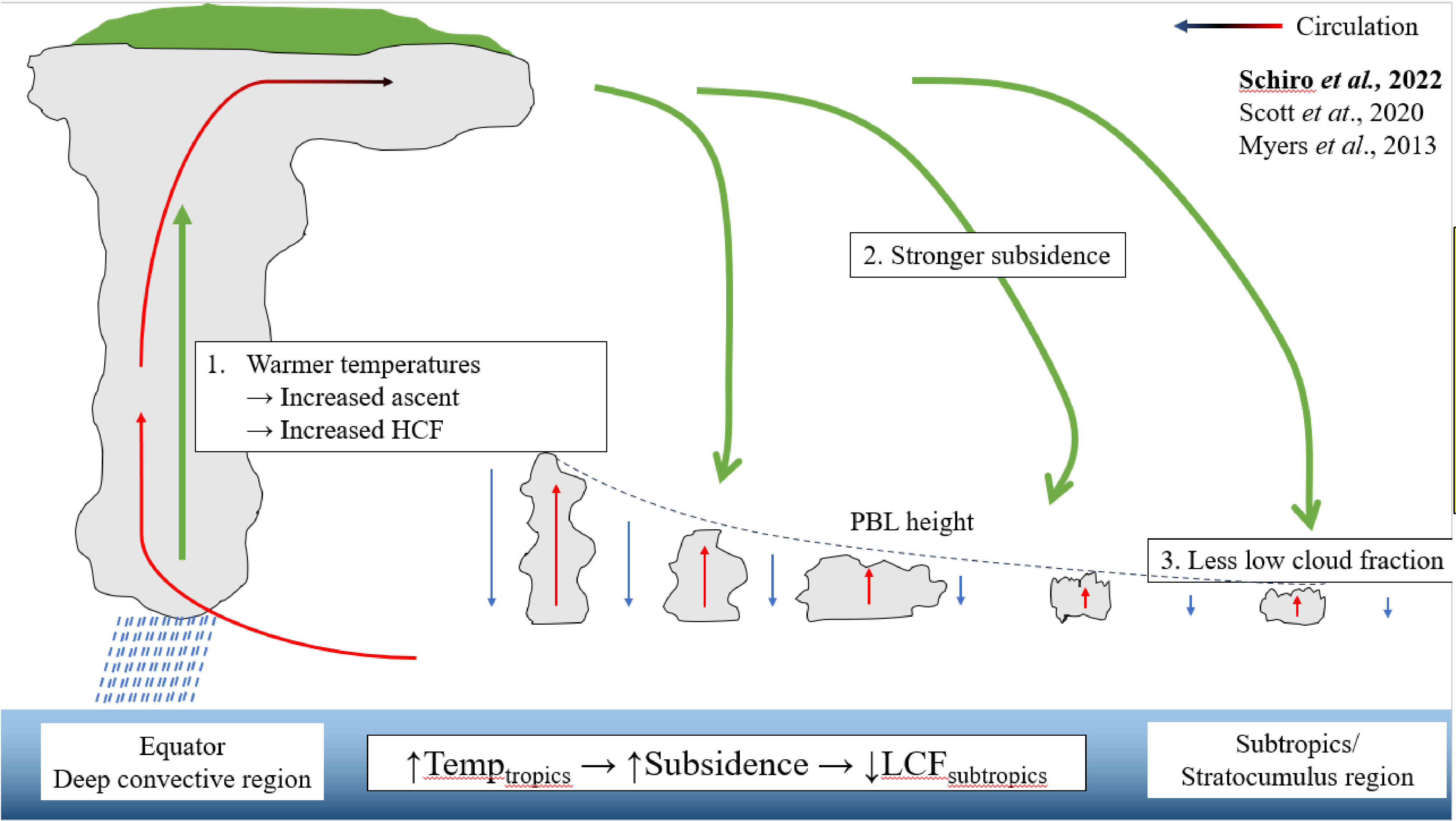
Better predictions

↓

More relevant global climate models



Conclusions:

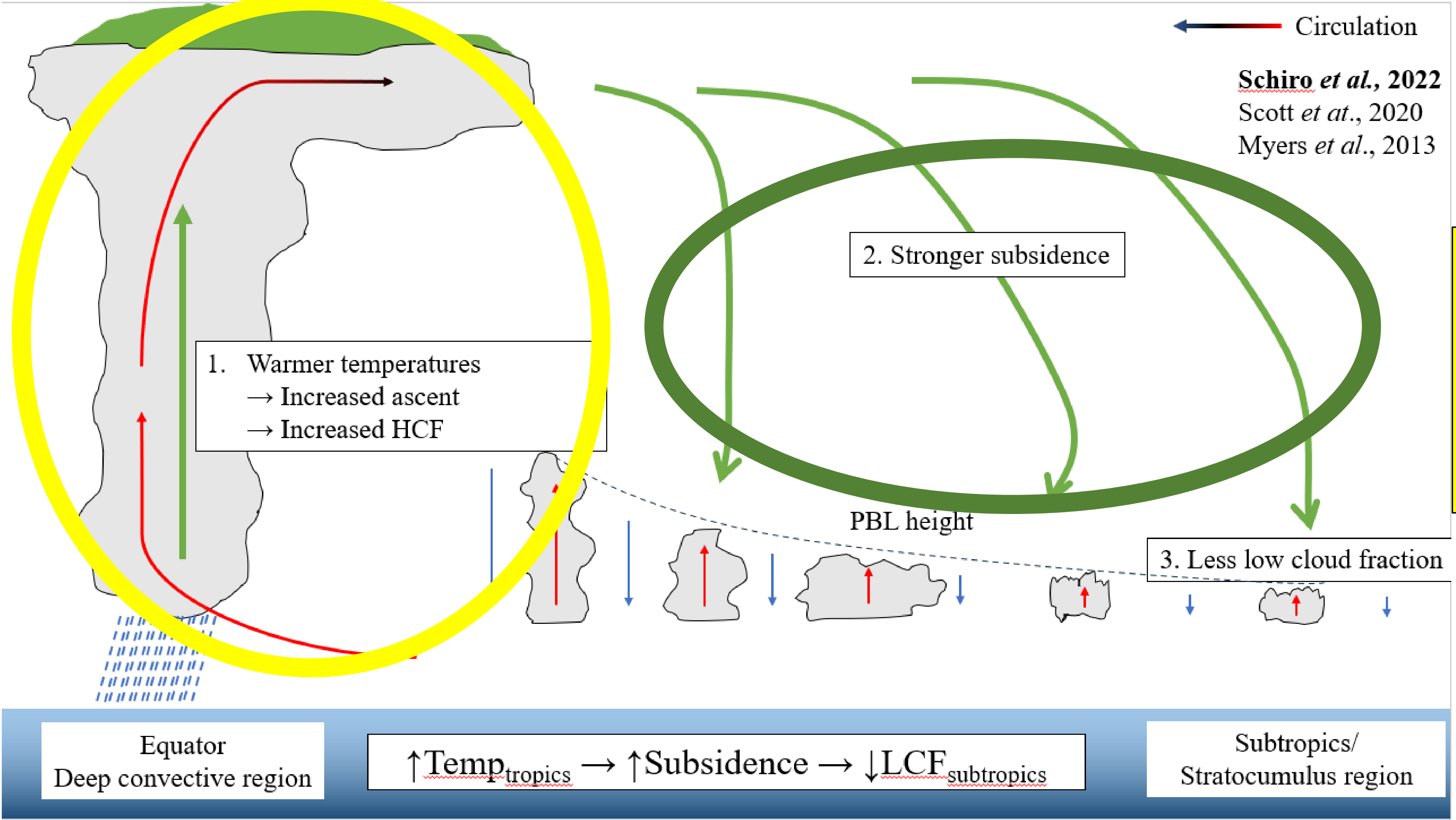


Correlation

vs

Causation

Conclusions:

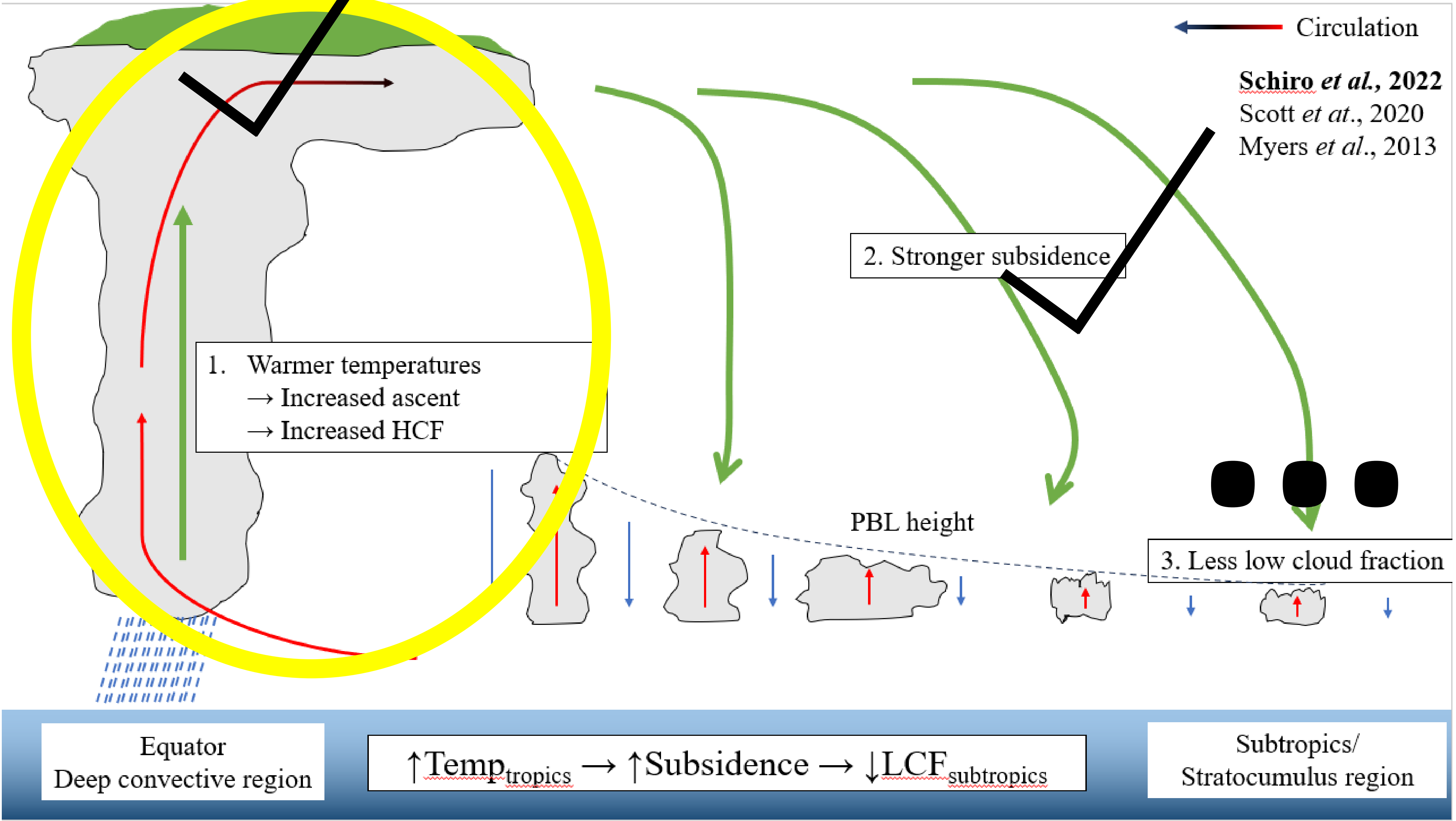


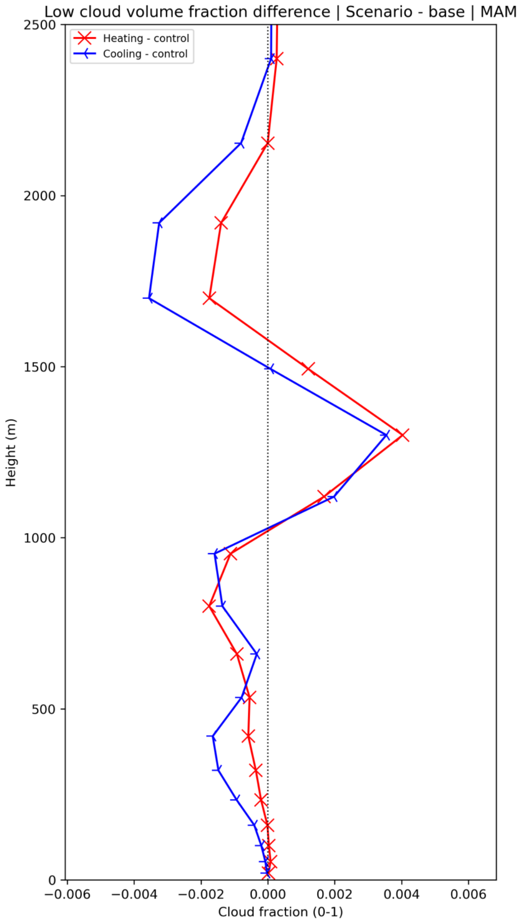
Correlation

vs

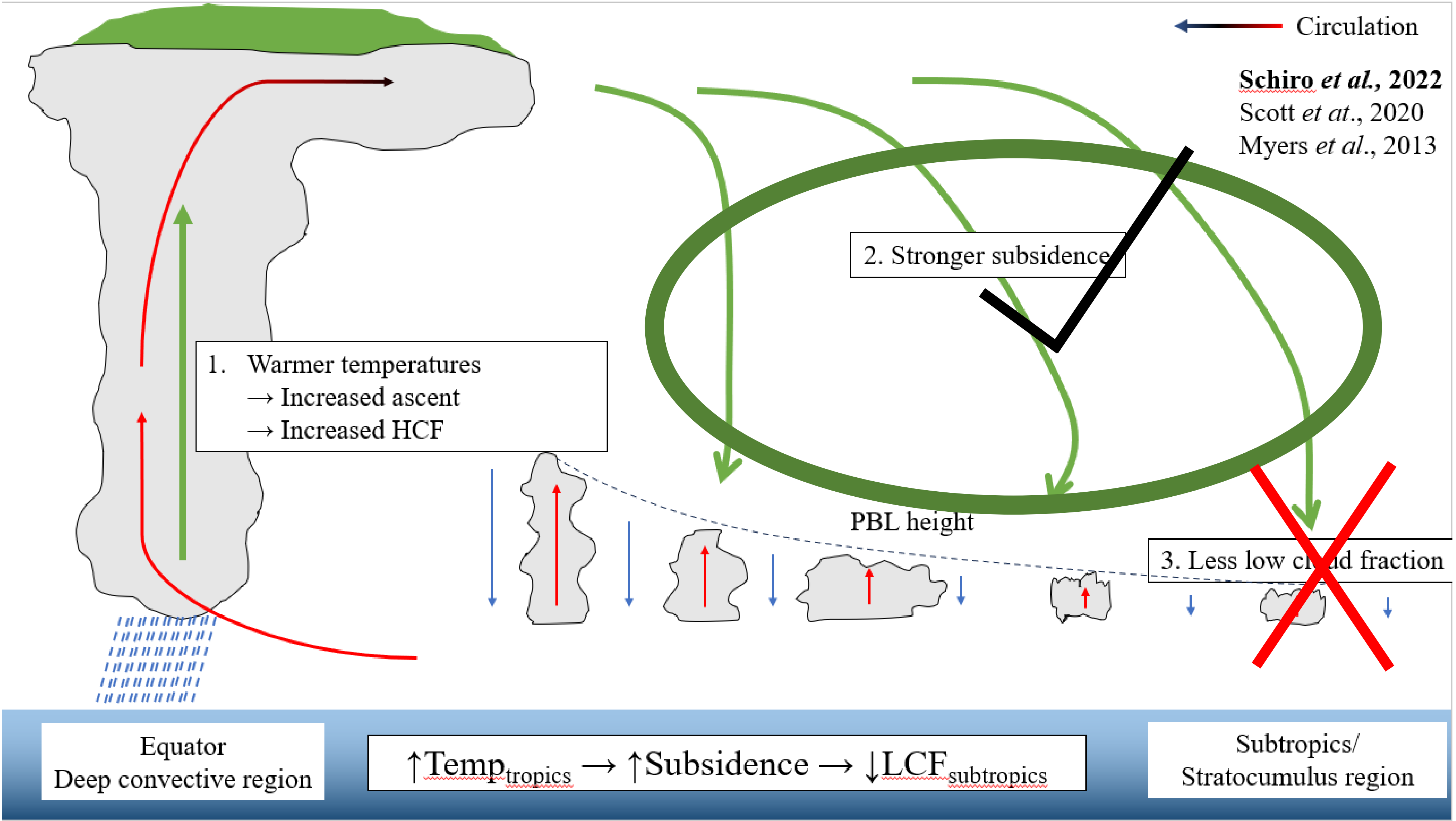
Causation

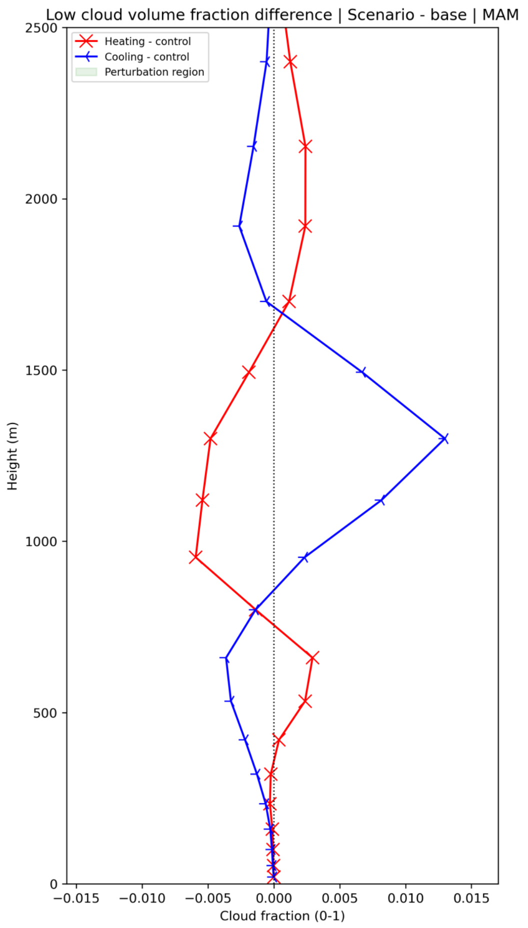
Conclusions:





Conclusions:



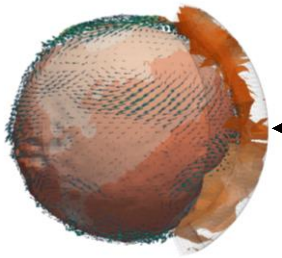


Thanks for listening!

Email:
dm575@exeter.ac.uk

X:
@TheMartianSub

Github:
github.com/dannymcculloch



Visit to see this *cool* gif

1. **Correlative** analysis proposes that: increased tropical warming → less subtropical LCF
2. With **causal** experiments, we directly test individual stages of the hypothesised pathway
3. We find that, in the **subtropics**:

Perturbation	Heating	Cooling
Subsidence ↓ region	No overall LCF change	**More LCF** Opposite to hypothesised
Convective ↑ region	No overall LCF change	No overall LCF change

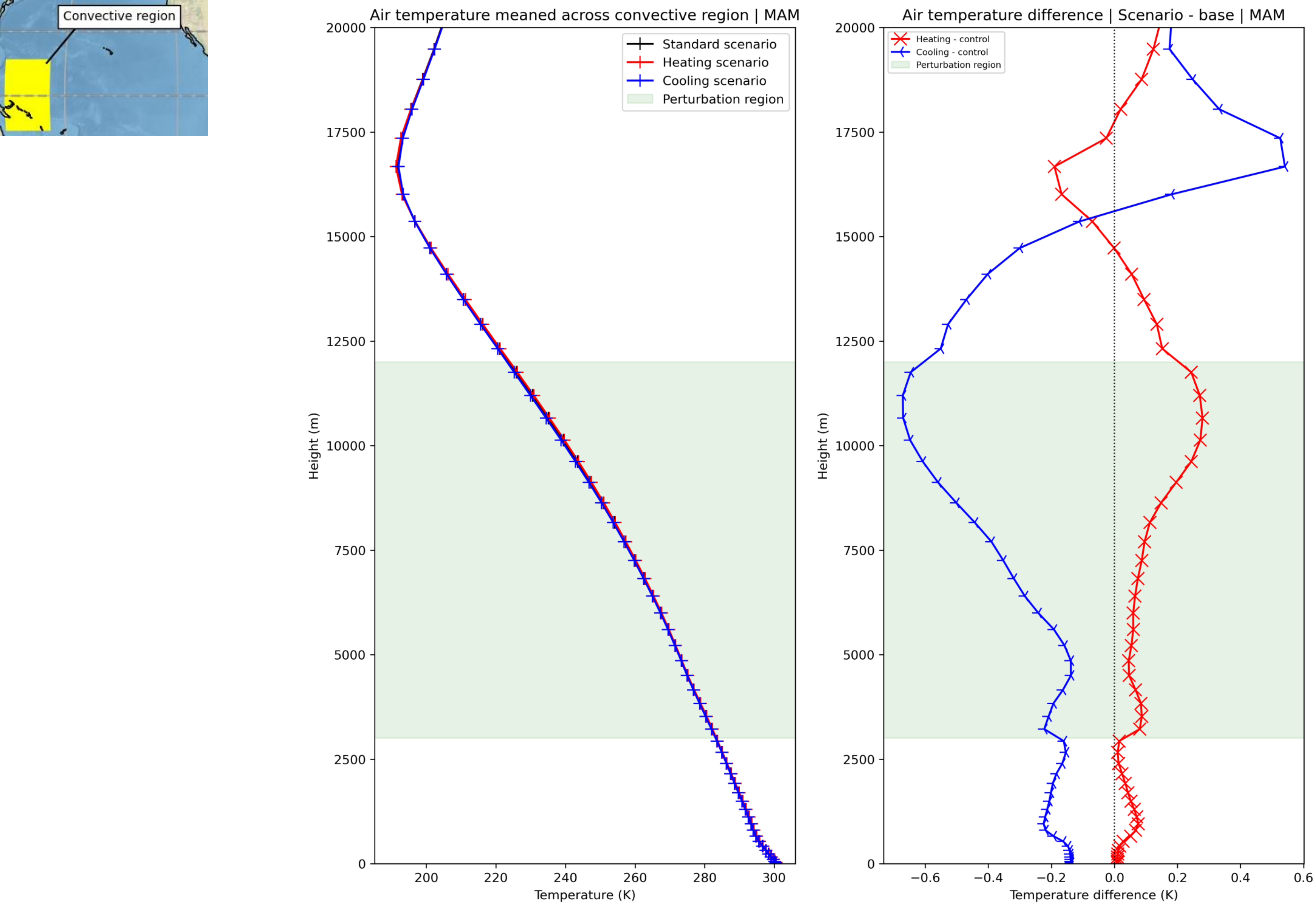
!

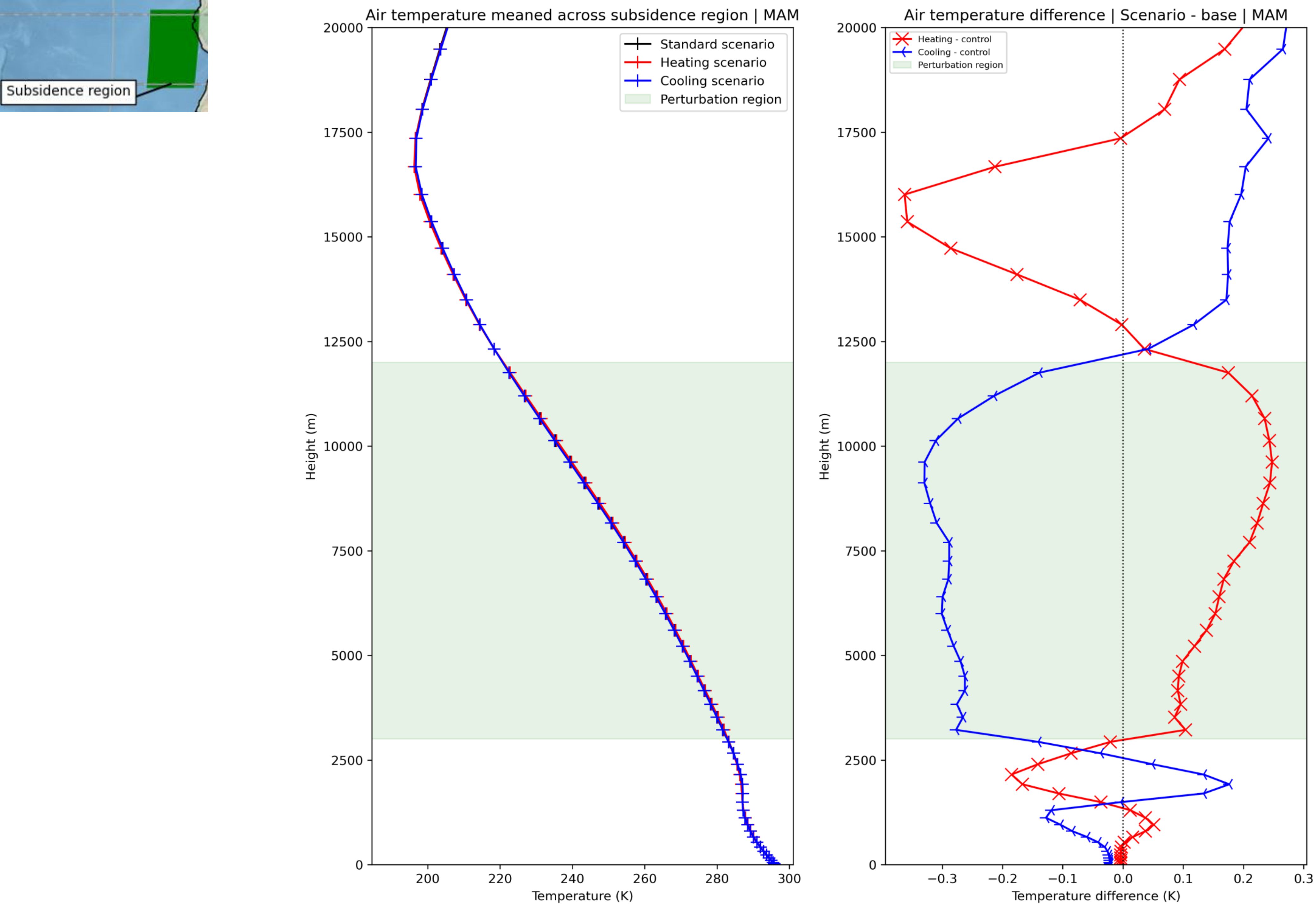
Catch me in the social session at 6 or drop me an email!

Other interests/ talking points:

- Climate visualisation
- Model development
- Mars' climate

Bonus slides 🎉

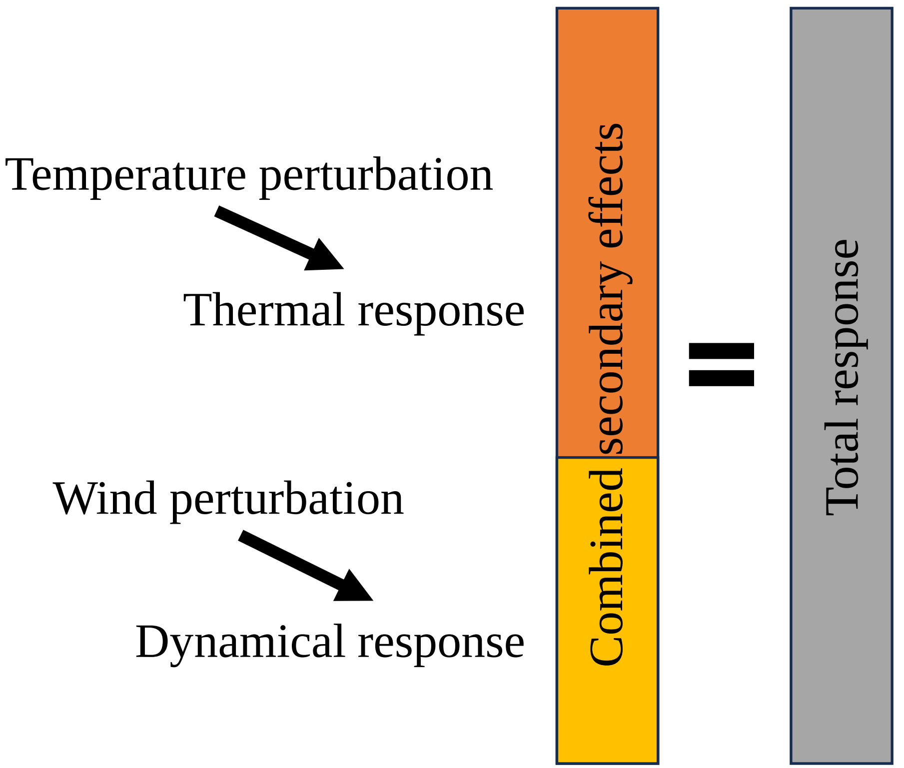

Convective region
Air temperature meaned across convective region | MAM
Standard scenario
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Temperature (K)
Air temperature difference | Scenario - base | MAM
Heating - control
Cooling - control
Perturbation region
Height (m)
Temperature difference (K)

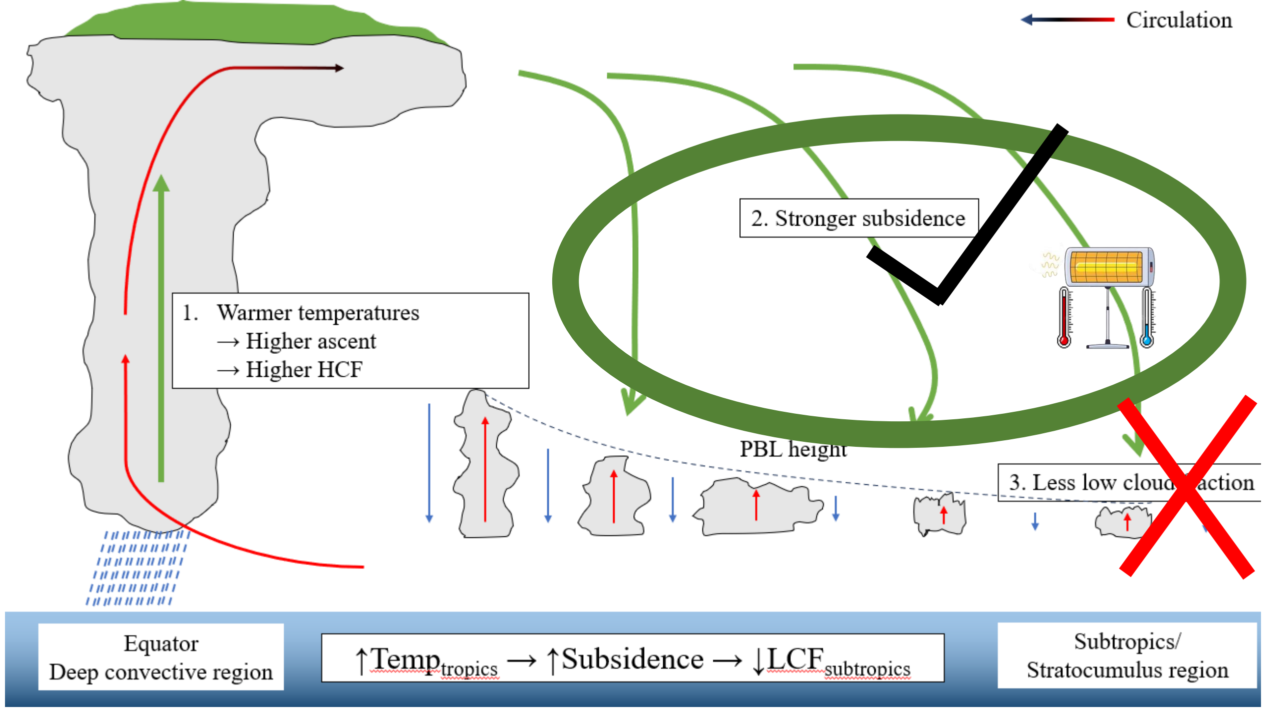


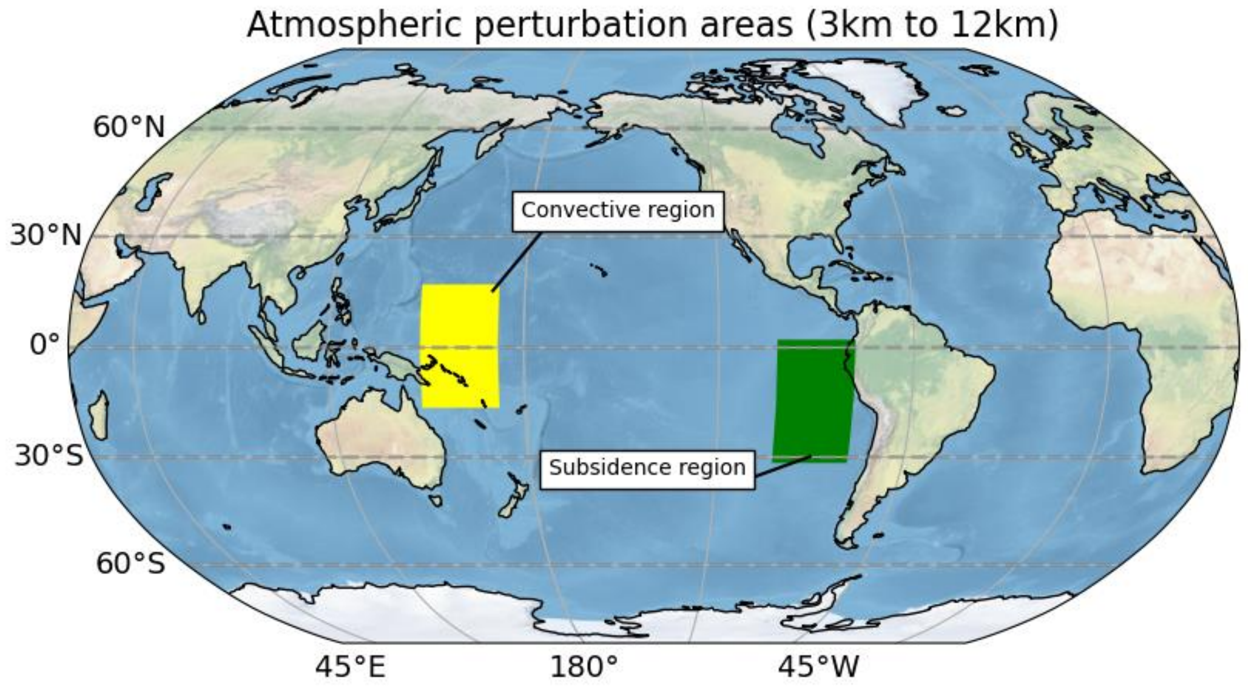
Subsidence region
Air temperature meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Temperature (K)
Air temperature difference | Scenario - base | MAM
Heating - control
Cooling - control
Perturbation region
Height (m)
Temperature difference (K)

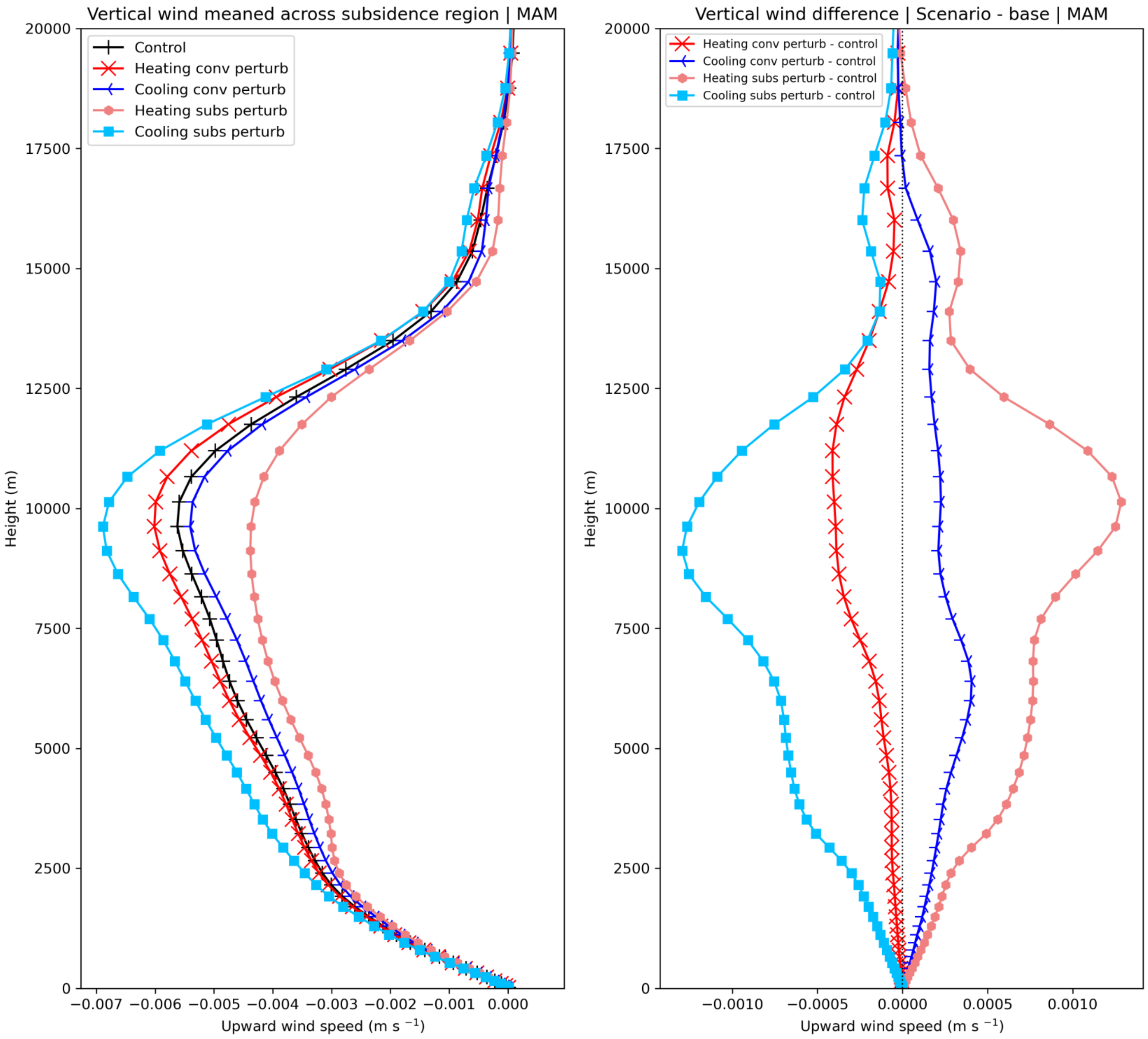
Improvements

	Subsidence region	Convective region
Temperature perturbation	~	✓
Wind perturbation	✓	~

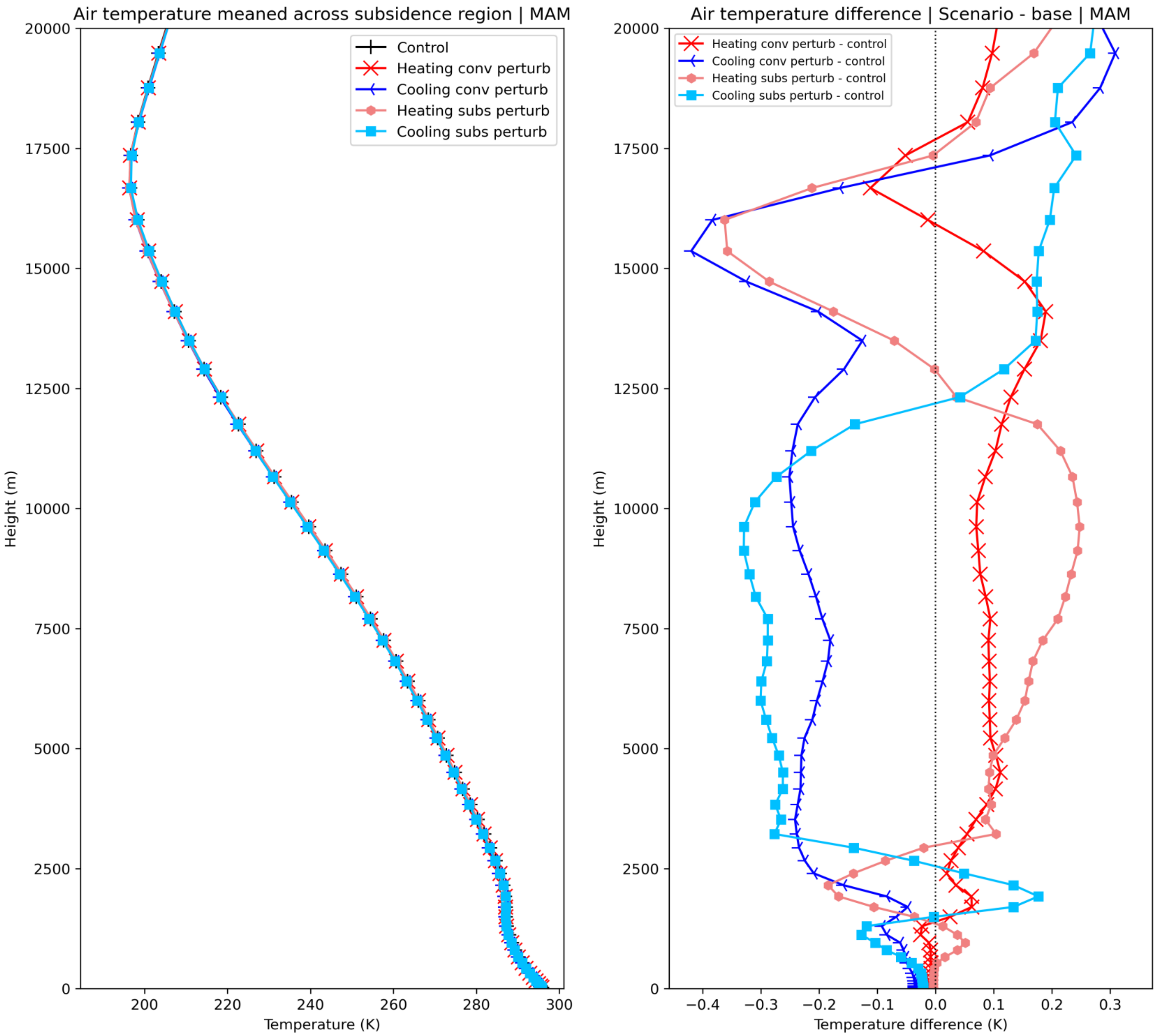




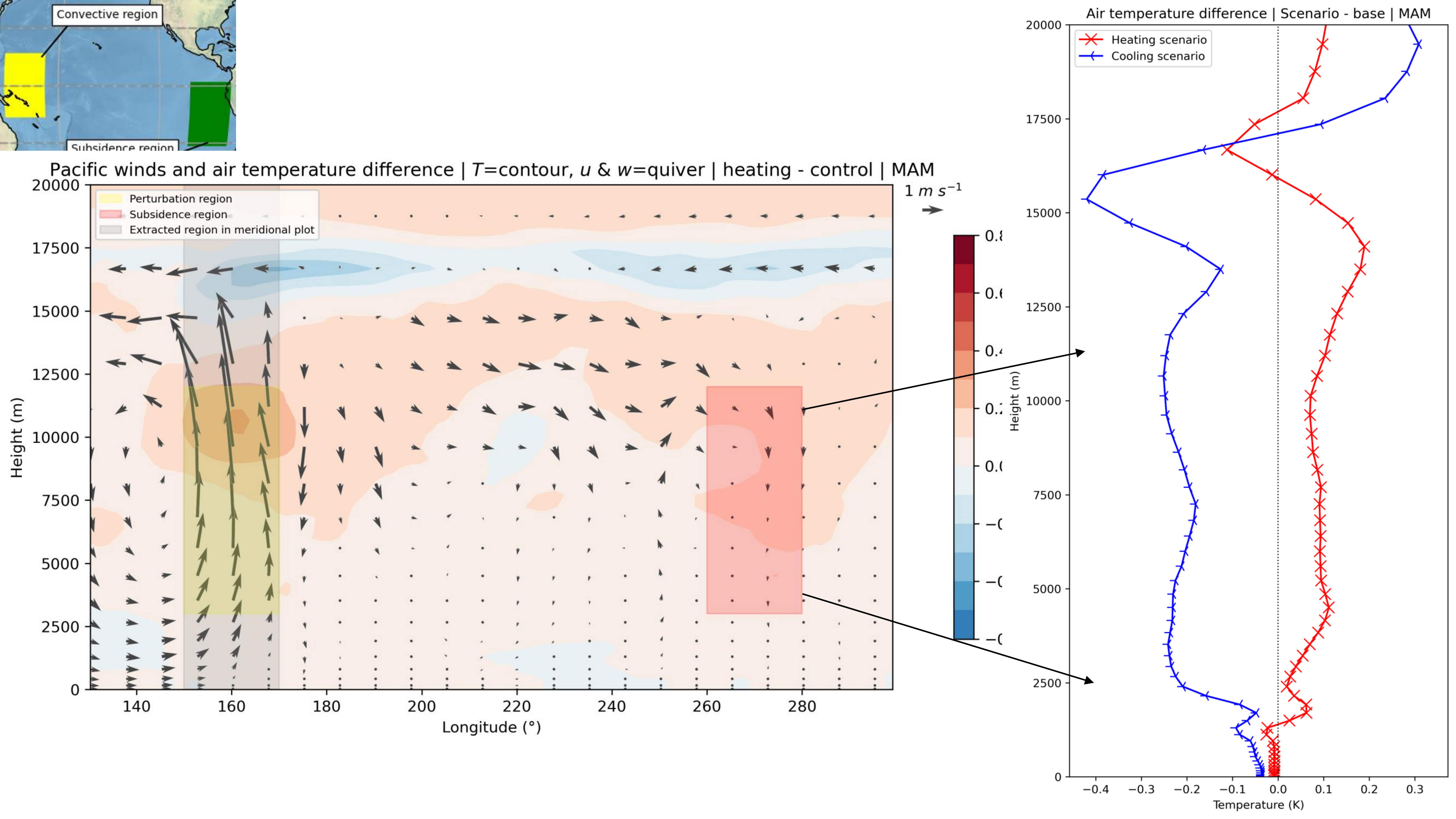




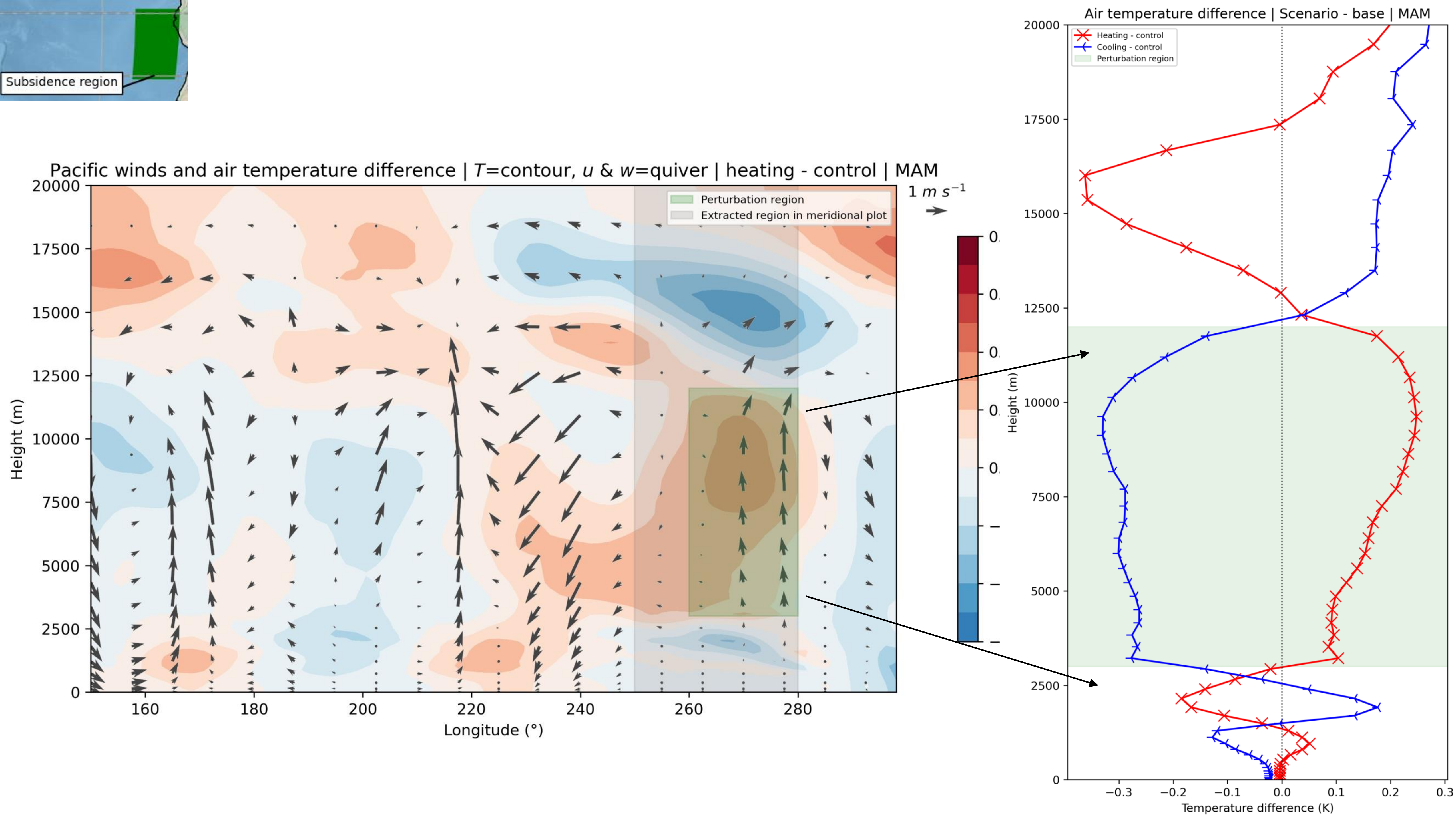
Vertical wind meaned across subsidence region | MAM
Control
Heating conv perturb
Cooling conv perturb
Heating subs perturb
Cooling subs perturb
Height (m)
Upward wind speed (m s −1)
20000
17500
15000
12500
10000
7500
5000
2500
0
−0.007
−0.006
−0.005
−0.004
−0.003
−0.002
−0.001
0.000
Vertical wind difference | Scenario - base | MAM
Heating conv perturb - control
Cooling conv perturb - control
Heating subs perturb - control
Cooling subs perturb - control
Height (m)
Upward wind speed (m s −1)
−0.0010
−0.0005
0.0000
0.0005
0.0010



Air temperature meaned across subsidence region | MAM
Height (m)
Temperature (K)
Control
Heating conv perturb
Cooling conv perturb
Heating subs perturb
Cooling subs perturb
Air temperature difference | Scenario - base | MAM
Temperature difference (K)
Heating conv perturb - control
Cooling conv perturb - control
Heating subs perturb - control
Cooling subs perturb - control



Convective region
Subsidence region
Pacific winds and air temperature difference | T=contour, u & w=quiver | heating - control | MAM
Perturbation region
Subsidence region
Extracted region in meridional plot
1 m s−1
Height (m)
Longitude (°)
Air temperature difference | Scenario - base | MAM
Heating scenario
Cooling scenario
Height (m)
Temperature (K)


Subsidence region
Pacific winds and air temperature difference | T=contour, u & w=quiver | heating - control | MAM
Perturbation region
Extracted region in meridional plot
$1\ m\ s^{-1}$
Height (m)
Longitude (°)
20000
17500
15000
12500
10000
7500
5000
2500
0
160
180
200
220
240
260
280
Air temperature difference | Scenario - base | MAM
Heating - control
Cooling - control
Perturbation region
Height (m)
Temperature difference (K)
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3

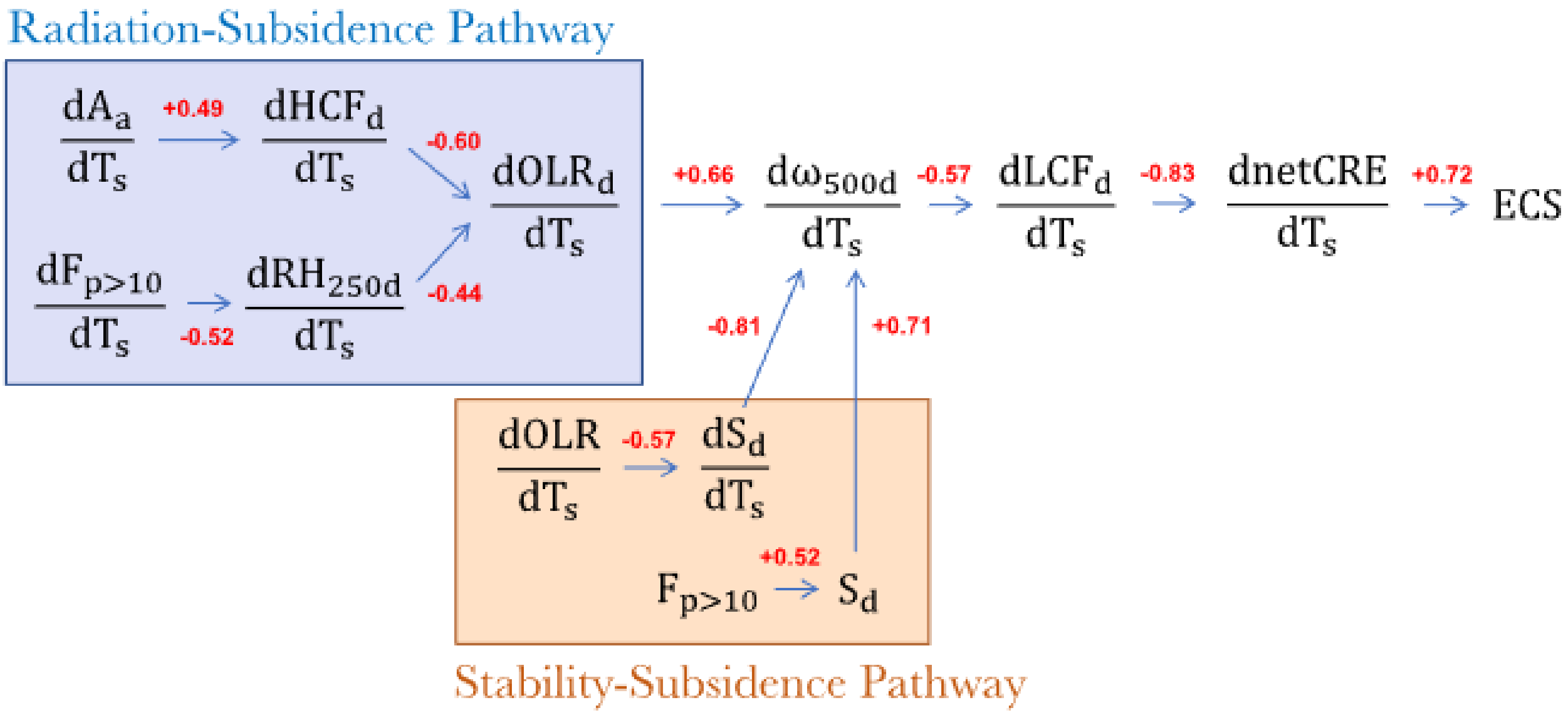
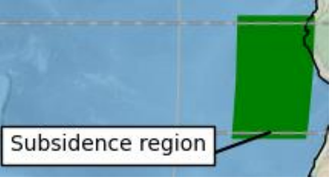
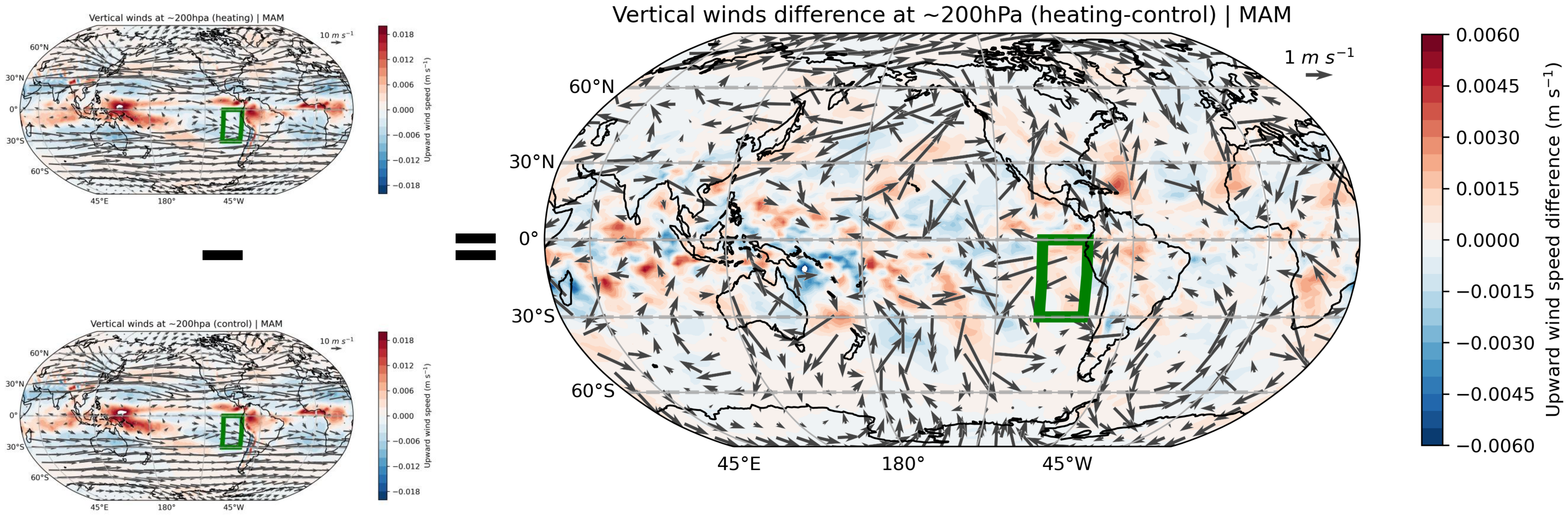
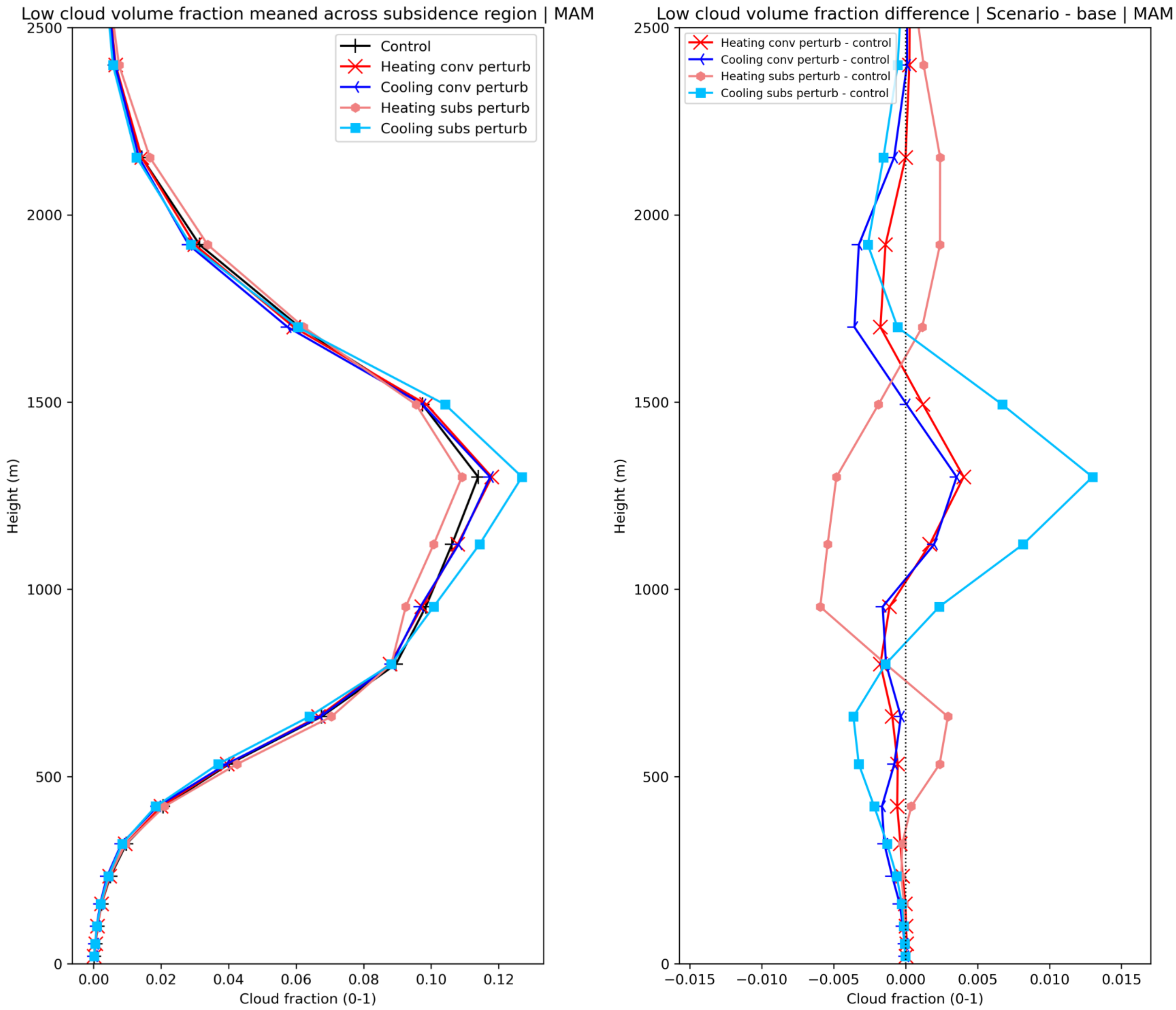


Fig. 9 | A summary of statistically significant correlations between various quantities comprising the Radiation-Subsidence and Stability-Subsidence Pathways. The correlations summarize the results shown in Figs. 2, 4, 6, and 7 among the CMIP6 multi-model ensemble. The Radiation-Subsidence Pathway is shown in blue, whereas the Stability-Subsidence Pathway is shown in orange. The direction of the arrows signifies suggested pathways of causality. Red values are Pearson correlation coefficients. All correlations are statistically significant at the 95% confidence level.

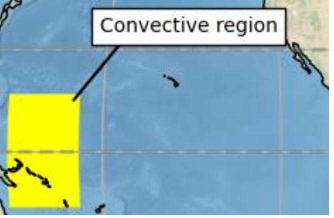
A_a	=	Tropical ascent area
T_s	=	Global mean surface air temperature
HCF_d	=	High cloud fraction in the decent region
LCF_d	=	Low cloud fraction in the decent region
RH_{250d}	=	Descent region upper tropospheric RH
$F_{p>10}$	=	Frequency of heavy precip. (>10 mm day^{-1})
ω_{500d}	=	Monthly mean pressure velocity at 500 hPa
ECS	=	Equilibrium climate sensitivity (amount of warming with 2x CO_2)
S_d	=	Dry static stability

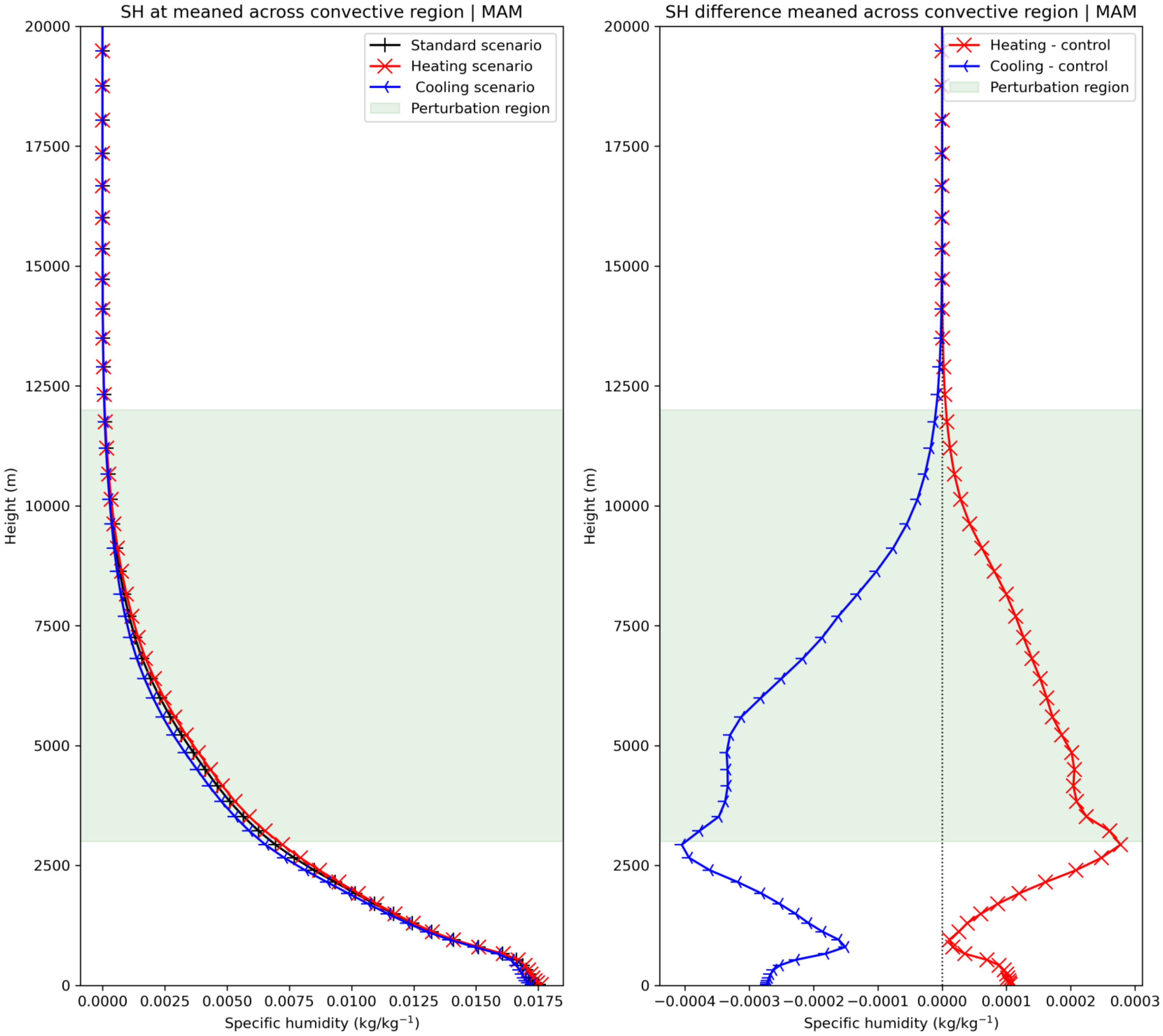

Subsidence region

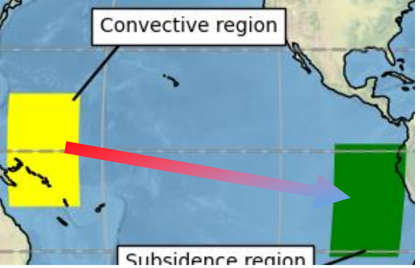

Vertical winds at ~200hpa (heating) | MAM
10 $m\ s^{-1}$
60°N
30°N
0°
30°S
60°S
45°E
180°
45°W
0.018
0.012
0.006
0.000
−0.006
−0.012
−0.018
Upward wind speed (m s^{-1})
−
Vertical winds at ~200hpa (control) | MAM
10 $m\ s^{-1}$
60°N
30°N
0°
30°S
60°S
45°E
180°
45°W
0.018
0.012
0.006
0.000
−0.006
−0.012
−0.018
Upward wind speed (m s^{-1})
=
Vertical winds difference at ~200hPa (heating-control) | MAM
1 $m\ s^{-1}$
60°N
30°N
0°
30°S
60°S
45°E
180°
45°W
0.0060
0.0045
0.0030
0.0015
0.0000
−0.0015
−0.0030
−0.0045
−0.0060
Upward wind speed difference (m s^{-1})

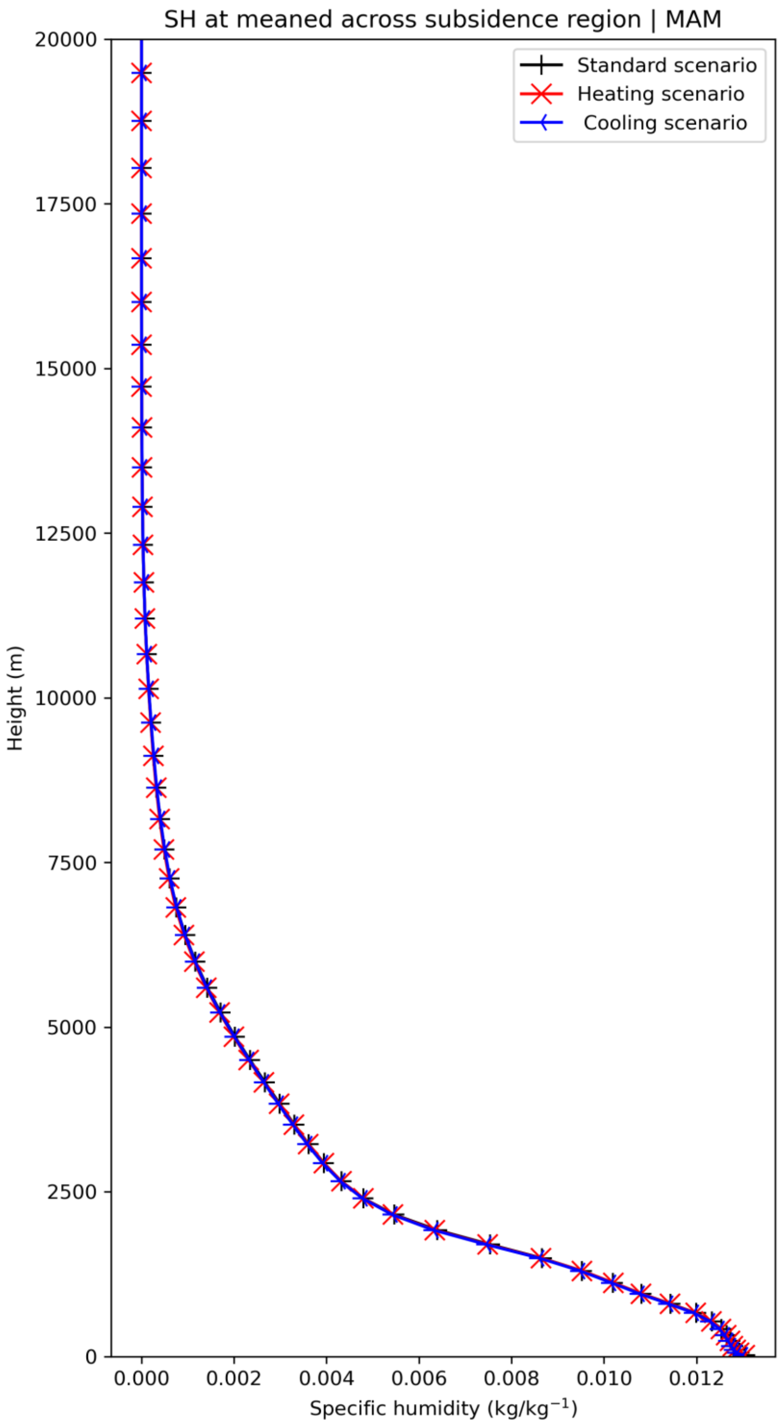


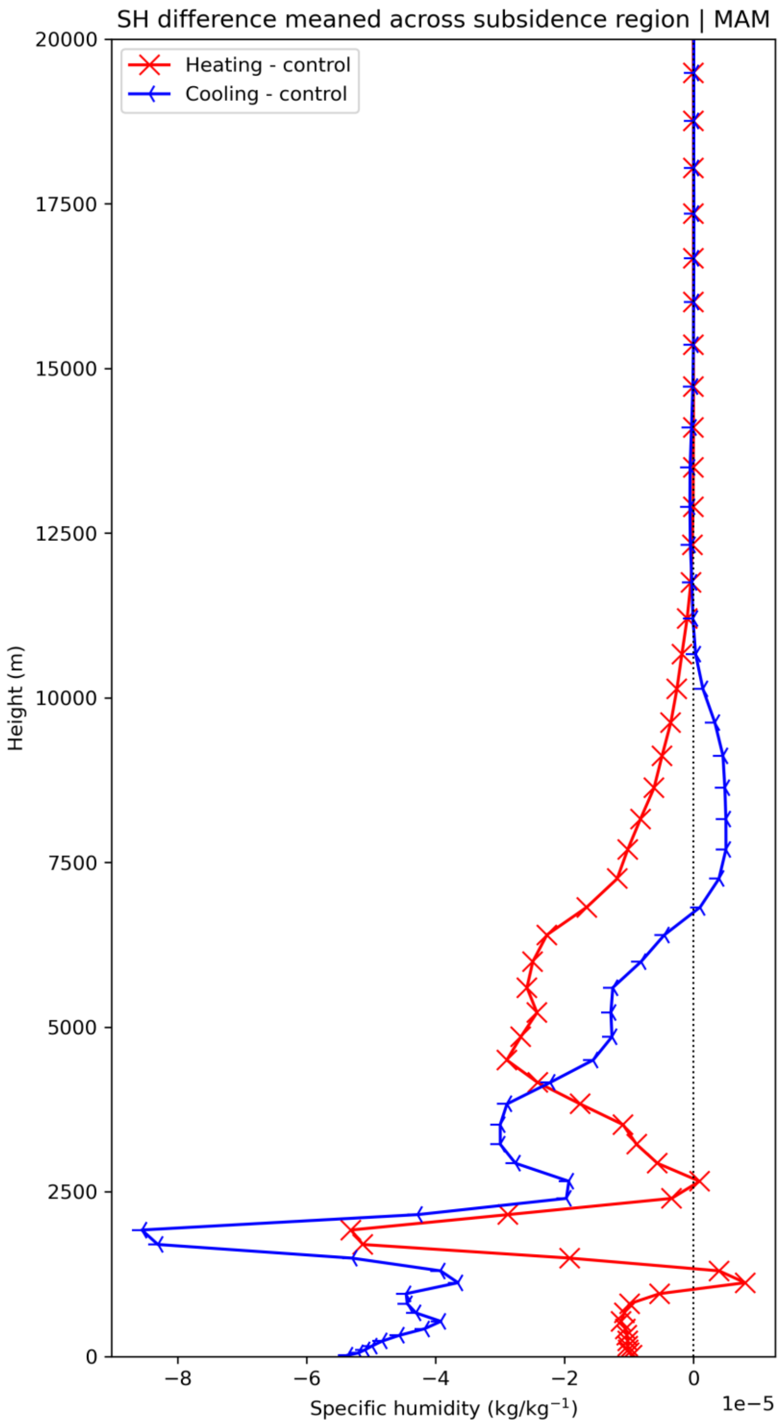
Low cloud volume fraction meaned across subsidence region | MAM
Control
Heating conv perturb
Cooling conv perturb
Heating subs perturb
Cooling subs perturb
Height (m)
Cloud fraction (0-1)
Low cloud volume fraction difference | Scenario - base | MAM
Heating conv perturb - control
Cooling conv perturb - control
Heating subs perturb - control
Cooling subs perturb - control
Height (m)
Cloud fraction (0-1)

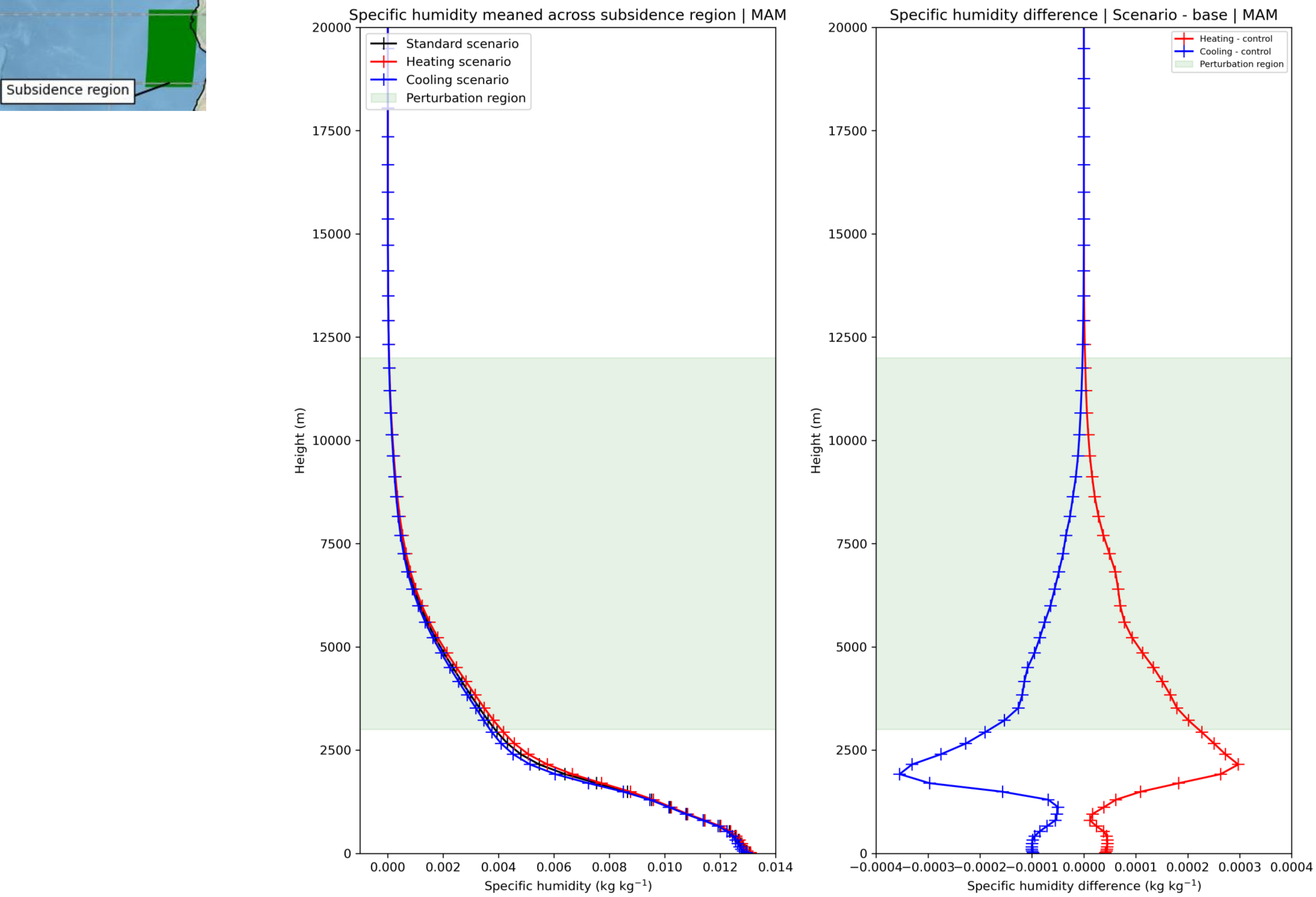

Convective region


SH at meaned across convective region | MAM
Standard scenario
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Specific humidity (kg/kg^{-1})
SH difference meaned across convective region | MAM
Heating - control
Cooling - control
Perturbation region
Height (m)
Specific humidity (kg/kg^{-1})


Convective region
Subsidence region


SH at meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Height (m)
20000
17500
15000
12500
10000
7500
5000
2500
0
0.000
0.002
0.004
0.006
0.008
0.010
0.012
Specific humidity (kg/kg^{-1})


SH difference meaned across subsidence region | MAM
Heating - control
Cooling - control
Height (m)
20000
17500
15000
12500
10000
7500
5000
2500
0
−8
−6
−4
−2
0
1e−5
Specific humidity (kg/kg^{-1})



Subsidence region
Specific humidity meaned across subsidence region | MAM
Standard scenario
Heating scenario
Cooling scenario
Perturbation region
Height (m)
Specific humidity (kg kg^{-1})
Specific humidity difference | Scenario - base | MAM
Heating - control
Cooling - control
Perturbation region
Height (m)
Specific humidity difference (kg kg^{-1})

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"In the tropics, it is in regimes of large-scale subsidence, *where marine boundary layer clouds prevail, that* **the radiative response of clouds** *to a change in surface temperature (1)* ***differs most in climate change*** *among models and (2)* **disagrees most with observations** *in the current climate."*

Bony *et al.*, 2005

*"**Cloud feedback**—the change in top-of-atmosphere radiative flux resulting from the cloud response to warming—**constitutes by far the largest source of uncertainty** in the climate response to CO_2 forcing simulated by global climate models (GCMs)"*

Ceppi *et al.*, 2017

*"**Cloud feedback** — the change in cloud-induced top-of-atmosphere radiation anomalies with global warming — **is the primary driver of differences** in effective climate sensitivity (ECS) across global climate models (GCMs)"*

Zelinka *et al.*, 2022

"Regardless of approach, the total ***cloud feedback is the key quantity driving the uncertainty****, since other feedbacks are well constrained by multiple lines of evidence supported by good basic physical understanding."*

Sherwood *et al.*, 2020

"In the tropics, it is in regimes of large-scale subsidence, where marine boundary layer cl[illegible] **radiative response of clouds** *to a change in surface temperature (1)* **differs mos**[illegible] *and (2)* **disagrees most with observations** *in the current climate."*

Bony *et al.*, 2005

*"***Cloud feedback***—the change in top-of-atmo*[illegible] *warming—* ***constitutes by far the largest source*** [illegible] *lated by global climate models (GCMs)"*

Ceppi *et al.*, 2017

"[illegible] *mosphere radiation anomalies with global warming —* **is** [illegible] *te sensitivity (ECS) across global climate models (GCMs)"*

"Reg[illegible] *oach, the total* ***cloud feedback is the key quantity driving the uncertainty****, since other feedbacks are w*[illegible] *strained by multiple lines of evidence supported by good basic physical understanding."*

Sherwood *et al.*, 2020

Low clouds are one of the largest source of uncertainty